MASTER PLAN FOR LANDFILL MANAGEMENT TO IMPROVE METHANE CAPTURE AND USE IN THE STATE OF ESPÍRITO SANTO - BRAZIL

Phase 3 – Final Report

For:
Environmental Protection Agency

By:
Fundação Promar
AQUAVIX
MRI
MU

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LIST OF ACRONYMS

Definitions of some acronyms represent Brazilian Entity names translated into English.

ABRELPE – Brazilian Association of Public Cleaning and Special Waste Companies
LF – Landfill
CC – Carbon Credit
CEG – Gas State Company
CETESB – Environmental Sanitation Company of São Paulo State
COD – Degradable Organic Carbon
COMLURB – Cleaning Urban Municipal Company
CQA – Construction Quality Assurance
CQC – Construction Quality Control
CTR – Waste Treatment Center
CTRVV – Vila Velha Waste Treatment Center
ES – Espírito Santo
ESTRE – Sanitation and Waste Treatment Company
FUNASA – National Health Fund
GDP – Gross Domestic Product
GGE – Greenhouse Gas Equivalent
GHG – Greenhouse Gases
GM – Geomembrane
GVMR – Great Vitória Metropolitan Region
GWP – Global Warming Potential
HDPE – high-density polyethylene
HSW – Health Service Waste
IBGE – Brazilian Institute of Geography and Statistics
IEMA – State Institute of Environment
IPCC – International Panel on Climate Change
LCRS – Leachate Collection and Removal System
LQI – Landfill Waste Quality Index
MSW – Municipal Solid Waste
NBR – Brazilian National Standard
O&M – Operation and Management
PEAD – High Density Polyethylene
PNSB - Basic Sanitation National Research
REC – Renewable Energy Credit
RMGV – The Great Metropolitan Region of Vitória
SANEAR – Colatina's Environmental Sanitation Service
SUPPIN – Polarization Superintendent of the Interior Projects
TS – Transshipment Stations
USEPA – United States Environmental Protection Agency
UTM - Universal Transverse Mercator
FOREWORD

This report was prepared through the Methane to Markets (M2M) assistance program of the Environmental Protection Agency (EPA). The objective of the M2M program is to promote the reduction of methane gas emissions from its four most critical sources: agriculture, landfill, coal mines and petrol and gas systems. The aim of this report is to present a Master Plan for Landfill Management in the State of Espírito Santo (ES), Brazil that will advance on the reduction of emissions and the capture and use of methane gas as energy source.

This project was developed in three phases: the first phase evaluated, through a State of the Practice (SOP) Report, the current solid waste management situation in the State of Espírito Santo, the second provided a summary of readily available technologies for methane capture and use, and the last phase was the development of a Master Plan which proposes actions to improve production, capture and use of methane generated by urban solid waste.

This Master Plan provides recommendations to improve the current process, including improvement in design, to promote capture and use of methane from existing and future landfills in Espírito Santo. The Master Plan sets guidelines on cost-effective alternatives considering permitting issues and potential sources of financing and provides recommendations for future projects and considers follow-up programs.

DISCLAIMER

The state of the practice of municipal solid waste management described in this study reflects a summary of the current understanding of the situation through the analysis of the data available. Further development of data collection will provide more detailed information and a deeper understanding of the particularities of each municipality.

The guidelines provided by this Master Plan are general recommendations only and not specific advice for any particular landfill design, construction or operation, whose conditions and circumstances will vary. Final decisions should be made on a basis of a final design and cost benefits study for each case.

(1) Biogas generation calculation and methane content were based on mathematical models; samples should be collected to confirm potential;

(2) Cost estimates were based in a single quote for equipment and on country of origin, for implementation more quotations should be solicited and costs for shipping, importation, etc considered;

(3) Manufacturers and equipments recommended were for example purpose and are not necessarily recommended for final design; alternative providers should be studied;

(4) This publication was developed under the Assistance Agreement# XA-83396001-0 awarded by EPA to PROMAR. The views expressed in this document are solely work product of PROMAR, Midwest Research Institute and the University of Missouri, and EPA does not endorse any products or commercial services mentioned in this publication.
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  (IEMA - State Institute of Environment)
- SEDURB - Secretaria Estadual de Desenvolvimento Urbano
  (SEDURB-Secretariat_of_Urban_Development)
- Prefeituras_Municipais
  (Municipal_Governments)
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EXECUTIVE SUMMARY

The use of biogas generated in landfills receiving Municipal Solid Waste (MSW) has increased over the last years worldwide. This use is based on the sustainable development concept which aims to minimize the generation of waste from any process, avoiding generation or reusing resources. The main advantage of the energetic use of biogas is the reduction in the emission of greenhouse gases and, in the case of developing countries such as Brazil, the use of biogas may be financially rewarding, both due to the sale of gas or electricity, and especially through the sale of renewable energy credits (RECs) according to the Kyoto Protocol Clean Development Mechanism.

In Brazil, the disposal solution for Municipal Solid Waste is essentially based on the disposal in sanitary landfills, thus the country presents a high potential for the generation of biogas.

The State of Espírito Santo (ES) is located in the east coast of Brazil, with tropical climate and a population of 3,351,669 inhabitants distributed in 78 municipalities. Most of the population is concentrated along the coast, with 6 municipalities containing almost 50% of the entire population of the State. The estimated generation of municipal solid waste in 2007 in ES was approximately 79,400 tons/month.

This project was developed in three phases: the first phase evaluated through a State of the Practice (SOP) Report, the current solid waste management situation in the State of Espírito Santo, the second provided a summary of readily available technologies for methane capture and use, and the conclusion of the third phase is presented here as a management Master Plan which proposes actions to improve production, capture and use of methane generated by urban solid waste.

The SOP Report includes estimates on location and quantity of methane production by solid waste disposal sites with the objective of identifying future opportunities for landfill gas (LFG) utilization that would later be addressed on this Master Plan.

The data for the SOP Report were collected from the existing database of the IEMA (State Institute of Environment), the IBGE (Brazilian Institute of Geography and Statistics), staff members of the 78 municipalities in ES, interviews with landfill managers and through site visits.

A total of 106 solid waste disposal sites where identified in the state, with 101 sites classified as irregular “Open Dumps” attending small populations. There are three sanitary landfills in operation in the state that are privately owned and operated and only one municipally owned. Most municipalities do not have a system to collect, report and update data concerning the quantitative or qualitative characterization of the waste generated, the coverage and frequency of their collection system or the current situation of the final disposal site in use.

The disposal sites (e.g., controlled and uncontrolled landfills) were evaluated based on the available site capacity, operational conditions and existing infrastructure data. Most of the sites have very limited data available and limited to no operational structure. For this Master Plan only the sites owned and operated by the municipalities were considered and these sites can be grouped as follows:

1. Small dumping sites (active and inactive): Total of ninety two (92);
2. Large dumping sites (active and inactive): Total of nine (9);
3. Controlled Landfills: Only one, closed in 2007, having operated for over ten years attending a population of approximately 100,000 inhabitants.
4. Sanitary Landfills: Only one, still in operation, serving a population of approximately 100,000 inhabitants.

The government of Espírito Santo is sensitive to the large number of irregular dumping sites in the State and has developed the “ES Free of Dump Sites” Program that intends to provide the physical, financial and legal structure necessary to allow each municipality to adequately dispose the municipal solid waste in licensed sanitary landfills.

The Program has divided the state into 6 regions, of which only one is currently served by privately owned sanitary landfills. The remaining five regions will be served by five new regional landfills that should be owned by a consortium of municipalities. All of the municipalities in the five regions considered in the project have populations lower than 100,000 inhabitants (except for the municipality of Cachoeiro de Itapemirim) and most of them have a population of fewer than 50,000 inhabitants.

The regionalization of the disposal site will be positive not only to avoid the use of irregular dumping sites but it will also facilitate the economical feasibility of methane capture and use projects, since most of these municipalities alone generate less than 200 tons of waste/day, which results in very low individual emission of LFG. The regionalization system includes the transshipment stations and sanitary landfills. All facilities will be designed and built following up-to-date and tested techniques in order to meet current legislation.

In this manner, in addition to the four groups presented before, a fifth group comprised of the five planned Regional Landfills was studied.

The potential for LFG generation and energy recovery of all five groups were evaluated using the LandGEM and Mexican models. Those results facilitated the identification of areas with potential for LFG capture and use and areas where only the application of mitigation measures to reduce emission of biogas seems feasible.

Based on the data collected and on the biogas generation modeling results, and considering the Brazilian environmental, social and economical characteristics, the following possibilities of methane capture and use projects were identified and recommendation for those sites are presented in this Master Plan.

For existing facilities:

Considering the small size and the lack of operational structure of most of the disposal sites in ES, only three existing sites were selected as potential candidates, although none of the sites fulfilled the conditions of the Guidance Criteria for International Candidate Landfills: (1) minimum depth, (2) minimum accumulated tons and (3) minimum of tons to be received. The selected sites for further study and recommendations were: Colatina sanitary landfill, São Mateus dumping site and Cachoeiro de Itapemirim, a recently closed controlled landfill.

For future facilities:

Most of the existing disposal sites in Espírito Santo should be closed in the near future and replaced by Regional Landfills. It is our goal that the final results and recommendations from this study are considered by the Regional Consortiums during planning, bidding and supervising for the design, construction and operation of these facilities. The Master Plan presents guidelines for the implementation of infrastructure for biogas collection and use for the regional sanitary landfills. Considering that this state government program is in the initial stage of conceptual definitions, the orientation towards the biogas energy use could be incorporated in each of these landfills’ specifications.

1 The result of the LandGEM was more conservative and therefore was chosen to support the recommendations for LFG use in the next phase of the project.
In this context, this Master Plan provides recommended actions for the selected sites and Future Regional Landfills, based on local conditions and on the data available for each site.

**COLATINA**

The Colatina landfill is the only municipal disposal site attending a population above 100,000 inhabitants. Colatina was designed to be a sanitary landfill, but recent problems in its operation due to weather and expansion works have caused operational problems. When normal operation resumes the site is considered “Adequate” according to the Landfill Waste Quality Index (LQI). By the time of its closure, Colatina is expected to hold approximately 840,000 tons of MSW, which represents an estimated 110,264,584 m³ of methane emitted to the atmosphere (1,600,000 MT CO₂ eq.) from 2000 to 2060, and an expected maximum energetic capacity of 0.24 MW in 2031.

Three alternative solutions were proposed for Colatina.

**Alternative 1 - Electric generation using Sterling engines**

Continue to fill-in the landfill, install a geomembrane composite cover including a geomembrane and one meter of soil on top with vegetation. Cap each well, and collect LFG at a central location, where multiple Sterling engines are located along with a flare to burn the excess LFG. Three Sterling engines can be installed immediately, with a fourth being installed in 2013. All four engines would operate until 2030. Electricity generated would be sold to the local utility at a fraction to be determined of the current retail residential cost of electricity in ES. The selling fraction needs to be negotiated with the local authorities, but an assumption of 60% is used here for financial feasibility estimates.

Analysis on this basis used a value of electricity returned to the grid of US$ 0.15 per kWh, an operating staff of 5 full time people for the 24x7 generating facility, personnel cost of US$ 30,000 per person, which returns an estimated excess of US$ 300,000 through 2030 after all costs are subtracted. The Capital cost of the facility is estimated at US$ 2,250,000 spread over the project period. This includes the cover and gas collection cost of US$ 1,575,000, a cost which is required to simply flare and collect CC. Thus, the incremental cost for generation is US$ 672,000. A formal economic analysis will be completed once the final design plan is approved by ES. When carbon credits are added to the 21 year total, the net return is estimated to be greater than US$ 18,000,000.

This analysis indicates that this capital cost of machinery for electric generation is a reasonable component of current cost of power in ES.

**Alternative 2 - Flaring**

An option for “flaring only” exists, using the high quality landfill cover and collecting and flaring all gas collected, without other use of the gas. The 21 year total of carbon credits that is available under this approach appear to total more than US$ 17 million, with the assumed value of €14 per CC (20USD at time of writing/calculating), and collection at 90% with 97% flare efficiency.

**Alternative 3 - Process Heat applications**

Process heat applications require an individualized analysis, since the cost of piping of LFG to the application location can be very expensive. Possible application ideas are improved operation of the existing medical incinerator. No detailed data on the inadequacies of the incinerator are known. Another use could be a laundry which would use process heat, steam
and or hot water from a boiler. No facility currently exists at or near the landfill, necessitating new building for the purpose. If the building was located on or near the landfill, the length of piping is minimized. Thereafter, the supply of LFG to the facility should be evaluated on the basis of the requirement and its consistency. The price competitiveness of LFG when compared to contemporary natural gas would have to have a significant advantage in order to justify relocation of existing businesses. Social benefits should also be considered. Specific case information is required to perform an accurate analysis.

**SÃO MATEUS**

This is the only dumping site attending a population between 50,000 – 100,000 inhabitants that is still in operation. The main objective for this site is environmental mitigation since this area currently releases methane to the atmosphere and thus causes environmental impacts. Sáo Mateus will hold an estimated 453,570 tons of MSW when it closes in 2010, and will have released to the atmosphere approximately 29,674,563 m$^3$ CH$_4$ (420,000 MT CO$_2$ eq.) from 1990 to 2040. The cost/benefit relation of this project is only reached considering the social and environmental aspects due to the high costs and complexity for the implementation of gas collection structures in dumping sites, as the maximum energetic capacity to the site is estimated to 0.2 MW.

For this landfill, the application of a biocover was considered a promising technology for economically closing the dump and providing some reduction in greenhouse gas emissions. A traditional soil-only cover is the least costly alternative. However, there is minimal to no reduction of GHG emissions from the waste. A thick ($\geq$ 0.6 m) soil cover is highly recommended.

Another alternative is the application of a geomembrane cover with individual flares at each well. Although this alternative is a more expensive measure, it may provide reasonable audit ability and high collection and flare efficiency. If the detailed planning worked favorably, and carbon credits are negotiated, this approach could pay back.

**CACHOEIRO DE ITAPEMIRIM**

The Cachoeiro site is the only municipal landfill that served a population between 50,000 – 100,000 inhabitants. The site was closed, in 2007, but while in operation it was classified as “Controlled” according to the LQI criteria. Currently, the site holds 666,579 tons of MSW, and is estimated to release to the atmosphere approximately 43,501,789 m$^3$ CH$_4$ (640,000 MT CO$_2$ eq.) between 1994 and 2034. The main objective for this site is the environmental mitigation of the area that currently releases methane to the atmosphere and causes environmental impacts. The maximum energetic capacity was calculated to have reached its peak in 2008 at 0.39 MW.

The recommendation is to cover Cachoeiro with a high quality capture system, flare the gas, and negotiate the sale of CCs. No electric generation is recommended unless audit becomes a major factor for the sale of CC, since electric generation can be easily measured, accountability of credits is simpler. This analysis is contingent on fast action, since the gas is quickly escaping the landfill, and prime amounts are lost in the first years after closure.

**REGIONAL LANDFILLS**

Each Regional Landfill will receive approximately 10,000 tons municipal solid waste per month. The five new landfills together should hold approximately 12,270,738 tones, which can be translated as approximately 1,076,000,000 m$^3$ CH$_4$ (16,210,000 MT CO$_2$ GGE) emitted to the atmosphere, during their operational years and a maximum energetic capacity of 8.5 MW at 65% efficiency of collection.
All regional landfills should be operated in a consistent fashion, and based on highest possible gas collection to maximize return. These landfills will operate for 20 years, and continue to make biogas for another 20 years thereafter, making this a 40 year investment opportunity. Two tangible monetary streams are available including electricity generation and carbon credits.

This Master Plan has showed that over the landfills’ lifetimes, they will provide over 2 billion kWh of power to the residents of ES. The wholesale value of that power to the utility is less than the sale to residential users, estimated to be 60% of electricity rates in ES, and totals over US$ 300 million. In addition, the carbon credits, if available at the current rates (14 euro per tonne) add over US$ 200 million to the returns.

While only conceptual costs have been used for the landfill capital and O&M costs for each of the eight sites, the totals have been substantially less than the proposed benefits, such that the ratio of revenue to costs appears to favor these investments.

**FINAL CONSIDERATIONS**

Based on the challenges encountered while developing this study, the following activities/programs are recommended to the State of Espírito Santo:

1. Development of procedures for measuring, reporting and storing data on MSW generation, collection and disposal. Those guidelines should be recommended by the Government of ES and implemented by the municipalities to generate consistent data;

2. After the development of procedures for data collection, a database should be created and maintained in the state’s website and updated by the municipalities. The easy access to consistent data allows the state government, the environmental agencies and the municipalities to make informed decisions regarding their budget, programs and policies; and,

3. The incorporation of the results of this study as guidelines for the continued development of the “ES Free of Dumps Sites” program. This report and some support material will be made available to the State through publication in the State Institute of Environment (IEMA) website. Briefing of government officials on the findings of this study, training of officials on the topics discussed here, identification and evaluation of optional methods to those being considered, use of study participants as consultants or overseers/advisors are all possible ways of implementing and building on the recommendations and findings of this study.
1 INTRODUCTION

1.1 PROJECT BACKGROUND

In 2004 the United States Environmental Protection Agency (USEPA) developed the Methane to Markets partnership with the objective of fostering an international cooperation scenario aiming at the methane recovery and use as a renewable energy source. The Brazilian government has joined this partnership together with thirteen other countries.

This partnership's actions are focused on the development of markets and on the methane recovery and energetic use strategies. The main sources of methane generation considered as critical for these actions are: agriculture, sanitary landfills, coal mining, gas and petrol systems.

In this context the USEPA created in 2008 several projects aiming at activities which promote the reduction in methane gas emissions (EPA–OAR-CCD-08-01). This Master Plan is part of these projects.

1.2 OBJECTIVE OF MASTER PLAN

This Master Plan has the objective of proposing sanitary landfill management actions which aim at capture and energetic use of methane generated by anaerobic decomposition of Municipal Solid Waste (MSW).

1.3 SCOPE OF REPORT

The Master Plan comprises the MSW disposal areas (landfills and dumping sites) in the state of Espírito Santo that are under the responsibility of the local public government, as well as the future sanitary landfills proposed by the “Espírito Santo Free of Dumping Sites” Program.

1.4 LAYOUT OF REPORT

The Master Plan is divided into five chapters. The first chapter introduces the project and provides scope, report layout and overview of the primary work. The second chapter is divided into two sub-chapters. The first sub-chapter presents the state of Espírito Santo current situation regarding the management of MSW and the second sub-chapter presents the currently available technologies for biogas capture and use.

Chapter 3 is divided into seven sub-chapters comprising the sanitary landfill management Action Plan aiming at improvements in the methane gas capture and use.

Sub-chapter 3.1 describes the classes of existing solutions for the sanitary landfill generated methane gas. These solutions vary according to the size, physical and operational structure and resources availability in each area. Sub-chapters 3.2 through 3.6 present cases of study for the municipalities of Cachoeiro de Itapemirim, Colatina and São Mateus. The sub-chapter 3.7 describes the new sanitary regional landfills proposed by the ES Free of Dumping Sites Program.
Chapter 4 comprises the political, financial and management considerations to facilitate the implementation of the energy-to-waste projects and the recommendations presented in Chapter 3.

Chapter 5 provides a summary of the recommendations done for the selected sites, organized in an Action Plan, including preliminary estimation of the resources needed for the implementation of methane use projects, the benefits of those projects, and the costs of the projects. This Chapter also provides suggestions for follow up projects that can improve local expertise, decision-making processes related to solid waste management and continue to promote the implementation of waste-to-energy projects.

Chapter 6 summarizes the bibliographical references.

1.5 BENEFITS AVAILABLE BASED ON THE PLAN

1.5.1 Greenhouse Gas Effect

The actions discussed in this Master Plan are intimately related to the reduction of Greenhouse gases emissions since methane, together with CO$_2$, O$_3$, N$_2$O and water vapor are the main gases that cause global warming. According to Figure 1 the biogas generated by the anaerobic decomposition of solid waste is responsible for approximately 8% of the global methane emissions. (IPCC, 1996, *apud* CETESB, 2006).

![Figure 1: Global distribution of methane sources. Source: IPCC (1996) *apud* CETESB (2006).](image)

The 2007 estimation of MSW anaerobic decomposition methane gas generated in the state of Espírito Santo was of 44,377 ton, which is equivalent to 931,917 credits of carbon. This document presents guidelines for the management of methane energetic use in municipal solid waste final disposal areas and it also proposes alternatives for the reduction of methane emissions in landfills when its energetic use is not feasible for either technical or economical reasons. This Master Plan aims to contribute to the reduction of methane emissions generated in sanitary landfills, which is globally estimated as 8% of total methane emissions from all sources, as shown in Figure 1.
1.5.2 Energy generation

The state of Espírito Santo produces 33% of its energetic demand and imports the remaining 67% (ASPE, 2009). The current energetic matrix in the state of Espírito Santo consists of 22 hydroelectric and 11 thermoelectric power plants, responsible for an energetic production of 1,525 MW (ANEEL, 2009).

Given these facts it is clear that the state of Espírito Santo needs to develop new ways of obtaining energy, and the methane gas, present in the biogas, is an alternative renewable fuel, which not only reduces the need for the consumption of fossil fuels, but also reduces the impacts of its emissions in the atmosphere.

If all of the biogas from the MSW final disposal areas in the state of Espírito Santo in 2007 could be used for energetic purposes, it would have been equivalent to 8.65 MW of electric energy, which corresponds to 0.6% of the current installed capacity.

1.5.3 LF Life

The biogas generation in a sanitary landfill is intimately related to the quantity of organic matter deposited in the landfill area. Some other factors such as the proportion of organic matter in the waste, the temperature and the moisture affect the metabolic activity of methane producing bacteria and consequently define the biogas generation.

The planning of a sanitary landfill with a biogas use project has to consider the nature of the municipal solid waste it will receive in order to guarantee high levels of gas production.

Thus, measures for the reduction of non-organic and potentially recyclable materials disposal contribute to an increase in biogas generation, besides indirectly extending these areas’ useful life.

1.5.4 Quality of Life Improvements

The state of Espírito Santo is now committed to the improvement of the municipal waste final disposal conditions and has created the “Espírito Santo Free of Dumping Sites” Program, with the goal of eradicating the existing dumping sites. This program uses the waste management regionalization strategy, with the implementation of large regional sanitary landfills, each one assisting several municipalities. In this context this Master Plan may, with its proposals for the use of biogas and the consequent generation of profits from electricity generation and the carbon credit system, provide resources for programs of social interest in the affected areas.

The implementation of biogas generation systems in the sanitary landfill also promotes and improves public health and sanitary conditions through the reduction of odor emissions in the areas surrounding the landfills.

Biogas management through combustion or through direct and energetic use requires controlled operational conditions in order to enhance the landfill’s safety, therefore reducing the occupational risks related to explosions and fires.

The improvement in the quality of life of the residential areas within the landfill surroundings may come from the electric energy supply or from the biogas itself, used for cooking.

The generation of employment and profits is another benefit from the implementation of the guidelines listed in this Master Plan. The availability of electric energy from biogas may
encourage the implementation of small-scale businesses within the landfill’s surroundings, especially if this energy is subsidized.
2 BACKGROUND

2.1 SUMMARY OF SITUATION IN THE STATE OF ESPÍRITO SANTO

2.1.1 Introduction

The state of Espírito Santo, with a total area of 46.079 km², is situated in the Southeast region of Brazil. Its borders are: the Atlantic Ocean to the east, the state of Minas Gerais to the West, the state of Rio de Janeiro to the south, and the state of Bahia to the north, as shown in Figure 2.

![Map of Brazil showing Espírito Santo](image)

Figure 2: Geographic situation of the state of Espírito Santo

The state of Espírito Santo occupies 0.54% of the Brazilian territory and it is divided into 78 municipalities situated in two distinct regions: the coastline and the plateau. The climate is predominantly tropical, with variations according to the landscape: humid tropical in the coastline lowlands, and mountainous tropical in the mountain ridges. The state of Espírito Santo has important water bodies such as the Rivers: Doce, Itapapoana, Itapemirim, Jucu, Santa Maria da Vitória, São Mateus and Itaúnas. The main one starts in the state of Minas Gerais and crosses Espírito Santo from west to east flowing to its delta in the Atlantic Ocean, in the municipality of Linhares, with an extension of 977km.

Espírito Santo’s state economy is characterized by large scale industrial enterprises, such as mining, steel making, cellulose production, gas and oil exploration, and portuay activities.

2.1.2 Population Distribution

The state of Espírito Santo (ES) had 3,351,669 inhabitants, according to the population census carried out by IBGE (Brazilian Institute of Geography and Statistics) in 2007. With
this number of inhabitants, the state of ES was placed in the 14th position in the Brazilian states population ranking.

The ES state population is irregularly distributed amongst its 78 municipalities, within a territory of 46,078 km². The highest concentration of inhabitants is within the Great Vitória Metropolitan Region (GVMR), which comprises the municipalities of Vitória (ES capital city), Cariacica, Viana, Vila Velha, Serra, Fundão and Guarapari. The GVMR had a population of 1,624,837 inhabitants in 2007, which is equivalent to 48% of the state’s population. Figure 3 presents the municipalities’ population distribution according to the number of inhabitants and to the population density in the state of Espírito Santo.

Vila Velha is Espírito Santo’s most populated city, with 398,068 inhabitants in an area of 209 km². On the other hand Divino São Lourenço is the municipality with the smallest population: 4,837 (1.2% of Vila Velha’s population) within an area of 176 km² (84.2% of Vila Velha’s area).

The municipalities’ population distribution (Figure 3ª) shows that 86% of the state’s municipalities have populations below 50,000 inhabitants, 58% have populations below 20,000 and only 5% have more than 300,000 inhabitants. While 72% of these municipalities have a population density of fewer than 50 inhabitants per square kilometer (Figure 3b), Vitória, the capital city, has 3,377 inhabitants per square kilometer. Although the municipalities of Linhares and São Mateus have reasonably large populations, 124,564 and 96,390 respectively, they present relatively low population densities, 36 and 41 inhabitants/km², respectively, due to their large areas. This geographic distribution, with low population densities in most of the state’s municipalities is an important issue in the planning of guidelines for the management of solid waste and use of biogas.
2.1.3 **Municipal Solid Waste Management in ES**

Until recently, the management of municipal solid waste, including the collection, transportation and final disposal, were under the responsibility of the municipal government, which could give service concessions to private companies. On July, 2009, the state of Espírito Santo government enacted the Law 9.264 instituting the State Policy for Solid Waste. The solid waste management principles below are amongst other innovative factors in this Law:

- Systemic vision of the solid waste management;
- Participative, shared and integrated management of the solid waste;
- The regionalization of the solid waste management.

These principles are in agreement with the state program “Espírito Santo Free of Dumping Sites”, presented in item 2.1.5 of this Master Plan. This program was developed from the urge to foster the eradication of the existing dumping sites and to revamp the way the municipalities manage their waste.

At the moment, the 78 municipalities in the state of Espírito Santo have conventional collection systems carried out by the municipal governments or by concessions to private companies. The implementation of selective collection programs is still in its beginning. Only two municipalities, Vitória and Serra (still as pilot practices in some neighborhoods), carry out the selective collection of waste.

Among the state’s 78 municipalities, only four have sanitary landfills (3 private and 1 public). Two of these landfills are located in the Greater Vitória Metropolitan Region, one of them is situated in the municipality of Aracruz, 80 km from Vitória, and the last one, the public landfill, is in the municipality of Colatina, 136 km from Vitória.

At the moment the three private sanitary landfills receive waste from 31 other municipalities which have transshipment stations for the centralization and transportation of waste. The remaining 43 municipalities dispose their waste in dumping sites, as shown in Figure 4. Thus, regarding the final destination of waste according to the number of municipalities in the state 55% of these municipalities dispose their waste in dumping sites, 40% of them have transshipment stations in order to transport their waste to sanitary landfills and 5% of the municipalities have sanitary landfills.

An analysis of the municipal solid waste final disposal according to the quantity of generated waste shows that 31% of the MSW is sent to sanitary landfills, 49% of the MSW is sent to transshipment stations and 20% of the waste is sent to dumping sites, as shown in Figure 5.
For many years, due to the lack of sanitary landfills, the municipalities disposed their waste in small dumping sites. As a result of this practice the state of Espírito Santo has 106 sites of irregular waste disposal in its territory, these 101 are dumping sites. Nonetheless, not all areas are currently operational. Figure 6 shows these sites’ localizations.
Quantitative analysis of the municipal solid waste generation

The quantitative analysis of the municipal solid waste generated in the state of Espírito Santo was carried out with the use of the per capita waste generation rate together with population data.

The per capita waste generation rates were adopted according to the municipalities’ population, as presented in the Phase 1 Report – State of the Practice for Municipal Solid Waste Landfill Management in the State of Espírito Santo – Brazil – methodology. Table 1 presents the MSW generation rates adopted in this study.

Table 1: MSW per capita generation rates adopted in this study

<table>
<thead>
<tr>
<th>Population (inhabitants)</th>
<th>MSW per capita generation (kg/inhabitant.day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P ≤ 49,999</td>
<td>0.64</td>
</tr>
<tr>
<td>50,000 ≤ P ≤ 99,999</td>
<td>0.71</td>
</tr>
<tr>
<td>100,000 ≤ P ≤ 199,999</td>
<td>0.84</td>
</tr>
<tr>
<td>200,000 ≤ P ≤ 499,999</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Source: Adapted from PNSB, 2000.

Espírito Santo's estimated MSW generation in 2007 was of 952,457 tons for a population of 3,351,669 inhabitants. Figure 7 shows the MSW generation values by municipality.
Municipal solid waste qualitative analysis

Besides the quantitative analysis, the qualitative analysis of the municipal solid waste generated is also a key point for this Master Plan, once a landfill’s methane gas generation potential is directly related to the fraction of organic matter present in the waste deposited in it. Figure 8 presents ES solid waste composition adopted in this study according to the Phase 1 Report.

Figure 7: MSW generation distribution by municipality.

Figure 8: Composition of municipal solid waste in Brazil. Source: ABRELPE (2006).
2.1.4 Biogas Generation in ES

It is possible to estimate ES landfill and dumping sites’ initial methane generation potential from ES municipalities’ MSW quantitative and qualitative data, as previously described.

In this context, Figure 9 presents the estimated methane generation for ES municipalities considering the state’s population in 2007. This estimation was carried out with the use of the Methane Emissions Simplified Estimation Method from IPCC – Intergovernmental Panel on Climate Change (1996).

![Figure 9: ES landfill and dumping sites annual methane generation potential map.](image)

In 2007, an estimated 952,457 tons of municipal solid waste was generated in the state of Espírito Santo’s 78 municipalities, as described above. From this amount, 80% was directly or indirectly disposed in sanitary landfills and 20% of the waste was disposed in dumping sites.

The MSW deposited in dumping sites represents a methane generation potential of 8,762 ton/year, equivalent to 1.71 MW/year of energy generation and 184,005 carbon credits, which are currently not being used. The 80% of MSW sent to sanitary landfills represent a methane generation potential of 35,615 ton/year, equivalent to 6.94 MW/year of energy generation and 747,910 carbon credits/year.

<table>
<thead>
<tr>
<th></th>
<th>MSW  (ton/year)</th>
<th>Methane (ton/year)</th>
<th>Energy (MW/year)</th>
<th>Carbon Credits (REC/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>952,457</td>
<td>44,377</td>
<td>8.65</td>
<td>931,915</td>
</tr>
<tr>
<td>Dumping sites</td>
<td>188,061</td>
<td>8,762</td>
<td>1.71</td>
<td>184,005</td>
</tr>
<tr>
<td>Landfills</td>
<td>764,396</td>
<td>35,615</td>
<td>6.94</td>
<td>747,910</td>
</tr>
</tbody>
</table>
Table 3 presents the projections for 2030 considering an average population growth rate of 2%/year. Thus, the estimated energy generation potential from the use of methane is of 13.71 MW/year and the carbon credit potential is of 1,476,230 REC/year.

<table>
<thead>
<tr>
<th>MSW (ton/year)</th>
<th>Methane (ton/year)</th>
<th>Energy (MW/year)</th>
<th>Carbon Credits (REC/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>1,508,771</td>
<td>70,297</td>
<td>13.71</td>
</tr>
</tbody>
</table>

2.1.5 Summary of “Espírito Santo Free of Dumping Sites” Program

In 2008, the State of Espírito Santo Government launched the “Espírito Santo Free of Dumping Sites” Program, with the objective of providing the physical, financial and legal structure to allow each municipality to adequately dispose its MSW in licensed sanitary landfills.

The “Espírito Santo Free of Dumping Sites” Program aims at the adequate conception, construction and operation of MSW regional final destination systems in the whole state, considering that the current operational private enterprises (Aracruz, Cariacica and Vila Velha sanitary landfills) continue active.

This project proposes the division of the state into six regions: Metropolitan, East Doce, North, West Doce, Southern Coastline and Southern Plateau, as shown in Figure 10. The municipalities belonging to each of these regions will implement a collection, transportation and final disposal system. The two first regions, Metropolitan and East Doce, already have licensed sanitary landfills and are, therefore, considered as of low priority.
The program also foresees the transportation logistics for the regional Transshipment Stations (TS). Table 4 presents the municipalities that will host the TS in each region.

<table>
<thead>
<tr>
<th>Region</th>
<th>Municipalities hosting Transshipment Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>Barra de São Francisco, Conceição da Barra, Montanha and São Mateus</td>
</tr>
<tr>
<td>West Doce West</td>
<td>Alto Rio Novo, Colatina, Itarana and São Domingos do Norte</td>
</tr>
<tr>
<td>East Doce East</td>
<td>Ibiraçu and Linhares</td>
</tr>
<tr>
<td>Southern Coastline</td>
<td>Anchieta, Apiaçá, Iconha and Mimoso do Sul</td>
</tr>
<tr>
<td>Southern Plateau</td>
<td>Alegre, Conceição do Castelo and Iúna</td>
</tr>
</tbody>
</table>

Table 5 shows the predicted population, received municipal solid waste, emitted methane and energy generation potential for the future sanitary landfills proposed by the ES Free of Dumping Sites Program for the year 2020.

<table>
<thead>
<tr>
<th>Region</th>
<th>Population* (inhabitants)</th>
<th>MSW Quantity (ton/year)</th>
<th>Quantity of collected CH₄ (ton/year)</th>
<th>Energetic Potential (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>469,325</td>
<td>112,828</td>
<td>5,257</td>
<td>1.67</td>
</tr>
<tr>
<td>West Doce West</td>
<td>424,907</td>
<td>109,354</td>
<td>5,095</td>
<td>1.61</td>
</tr>
<tr>
<td>East Doce East</td>
<td>384,513</td>
<td>104,046</td>
<td>4,848</td>
<td>1.54</td>
</tr>
<tr>
<td>Southern Coastline</td>
<td>425,585</td>
<td>102,666</td>
<td>4,783</td>
<td>1.52</td>
</tr>
<tr>
<td>Southern Plateau</td>
<td>567,952</td>
<td>151,163</td>
<td>7,043</td>
<td>2.23</td>
</tr>
</tbody>
</table>

* Population projection based on the 2007 Population Count data (IBGE) and considering an annual population growth rate of 2%.

The landfill with the predicted highest energetic potential will be the one of the Southern Plateau region, with 2.23 MW in 2020. This prediction is due to the larger number of inhabitants, once the municipality of Cachoeiro de Itapemirim has a significant population (app. 253,275 inhabitants by 2020).

### 2.2 TECHNOLOGIES FOR BIOGAS COLLECTION AND USE

#### 2.2.1 Introduction

The collection and use of biogas generated in landfills requires the deployment of specific systems. The biogas management system is typically composed of four parts. The first part is the biogas collection system, which leads the biogas from the point of generation within the waste mass to its point of use. The second is the purification system, which consists of the removal of contaminants including hydrogen sulfide, moisture, siloxane, and carbon dioxide, thus increasing the calorific value of the biogas. The third part consists of energy recovery from biogas, converting the chemical energy of the biogas constituents into other forms of energy such as thermal (boilers, stoves) or electric (gas turbines, internal and external combustion engines, fuel cells, steam turbines). At this stage the biogas can be mobilized and sent to another place to produce energy. The fourth part of the system consists of a combustion flare where the surplus biogas in the process or during the maintenance period can be combusted.
These are the steps in landfills with biogas energy utilization. However, a landfill, depending on the capacity or the financial resources available should take at least minimal measures to control the emission of methane into the atmosphere, even if not using the biogas. Flares are used for this purpose.

Burning the biogas in a flare is the most common solution, but biocovers are being increasingly used to destroy methane presented in the biogas by biomethanogenesis.

Figure 11 shows alternative management solutions for biogas.

![Figure 11: Biogas management alternatives flow-chart.](image)

One alternative of use of biogas is conversion into thermal energy, through the direct combustion of biogas in heaters, such as industrial boilers or even cooking. This usage reaches the highest efficiency when the biogas is previously treated, in order to increase calorific value of gas and avoid problems with odors, resulting in the complete burning of gas.

Another use is the conversion of chemical energy into mechanical energy and then mechanical energy into electrical energy. The chemical energy contained in the constituent molecules of biogas can be converted into mechanical energy through combustion controlled mixture of air and biogas. The mechanical energy, in turn, can be converted into electricity through a generator. Some of these energy conversion technologies are gas turbines, internal combustion engines, and fuel cells.

Biogas can also be used in the system of co-generation of energy, as the case of steam turbines. In this case, the heat generated by burning gas heats the boiler, which in turn releases steam that drives turbines, creating electricity.

Also, biogas can be targeted in its raw form and sent to areas outside the landfill to be used in industrial process heating, or may be connected to a natural gas pipeline. The latter alternative requires the purification of a biogas so that it achieves the recommended levels of methane concentration. This option of biogas pipeline for subsequent use outside the landfill have high capital costs, and should also consider the use of biogas and natural gas costs for the purification system.
2.2.2 Biogas Collection Project

There are multiple levels of collection of biogas depending on the construction quality control and the capital investment in the process of preparing a landfill. Degradation begins immediately with organic waste materials, and proceeds at a rate dependant on the bioactivity of the waste, the oxidizers available and the amount of water available. To the extent these materials are controlled, the waste degradation takes more or less time, and takes different paths. Methanogenesis is an anaerobic process requiring control of oxygen by cover layers of soil that impede oxidation and promote microbial reduction of the waste.

Figure 12 below shows that the best collection results from use of active biogas collections systems. Passive systems operate at lower efficiency as indicated by the reducing triangle width. Biocovers and soil covers provide even less efficient gas collection and destruction. Soil covers can be totally ineffective especially in dry environments due to soil cracking which allows the gas to escape to the environment, even at sites with wells and collection systems installed. Of course, the more effective systems have increasing cost. The ability to predict long term collection to justify electrical generation, and to recover on carbon credits is dependent on low risk methods. Prediction risk increases going down the triangle.

![Figure 12 - Alternatives of Collection Systems](image)

These concepts are discussed below.

2.2.2.1 Type of Covers

Four types of covers for landfills are shown in Figure 13 below for active gas collection systems, with components identified by number according to the legend. In addition their benefits and disadvantages are discussed.
2.2.2.2 Composite Barrier Cover

The best cover providing high collection efficiency (up to 90%) is the composite barrier cover. This cover is made from thick plastic geomembrane (GM) covered with up to one meter of soil, and buttressed with geotextile, drainage layers and vegetation to stabilize the top soil. The composite barrier cover provides an impermeable barrier to direct the flow of biogas and causes the gas to flow to collection wells. This type of cover system works well with biogas collection systems that allow consolidate gas at a central location for electric generation, process heat applications and/or flaring. All three processes reduce the release of methane and carbon dioxide (and other gases) in the atmosphere and can result in carbon credit claims.

2.2.2.3 Final Cover

Final cover is less substantial than the composite cover, in that the geomembrane and drainage layers are not used. Therefore the cover is permeable, and while better than the basic cover, it is subject to drying and cracking that allows biogas to escape, bypassing any gas collection system that may be a part of the design. Final cover is considered to provide significant resistance to biogas, and may provide 50% collection if a gas collection system is installed and maintained. Final cover does allow for some collection and therefore can supply electricity, process heat and flaring potential.
2.2.2.4 Biocover

The biocover uses waste as raw material to cover the MSW. The bioactive waste can be sewage waste or yard waste which reacts with the methane generated through natural process. The reaction can remove most of the methane emissions (up to 100%) when compared to traditional soil cover. However, the reaction is temperature based and methane uptake is optimized at temperatures between 30-36°C. Efficiency is reduced with declining temperatures (single digits °C), and drying of the biocover results in decreased efficiency. Moisturizing of the material could be required (sprinkler system) to maintain system integrity. A biocover can also be used with a gas collection system, or with a geomembrane and window holes covered by the bioactive material which reacts with the methane.

2.2.2.5 Basic Cover

Basic cover is a layer of soil covering the MSW. Often times 0.6 meter to one meter of soil is used, which over time dries and cracks into the MSW below. Without barriers to trap and direct the biogas to a well, the gas escapes into the atmosphere. While the soil keeps people and animals away from the waste, it is not considered an effective method of stopping methane from escaping the landfill. While some reduction of methane through biological reaction in the soil is done the result of basic cover is uncertain and of low quality, usually considered to be less than 10% effective and not easily monitored.

The essential characteristics of these four types of cover are compared in Table 6 below.
Table 6: Summary of landfill cover characteristics.

<table>
<thead>
<tr>
<th>Cover Type</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite Barrier</td>
<td>No aging, deterioration, leakage over</td>
<td>Expensive</td>
<td>1, 2, 3, &amp; 4</td>
</tr>
<tr>
<td></td>
<td>Long-term performance</td>
<td>Professional installation</td>
<td>1+ Or 2+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Availability of Geotextile and Geomembrane</td>
<td>1+</td>
</tr>
<tr>
<td>Final Cover</td>
<td>Material could be found on site</td>
<td>Raw material could not be available</td>
<td>1, 2, 3, &amp; 4</td>
</tr>
<tr>
<td></td>
<td>Easy to install &amp; inexpensive</td>
<td>Reduced performance of the cover with time (Crack allowing infiltration)</td>
<td>1+ Or 2+</td>
</tr>
<tr>
<td></td>
<td>Prevents leakage</td>
<td></td>
<td>1+</td>
</tr>
<tr>
<td>Biocover</td>
<td>Using waste as raw material (Sewage waste, Yard Waste, or MSW)</td>
<td>Decreased efficiency with cold climate (single digit °C temperatures)</td>
<td>1, 3, &amp; 4</td>
</tr>
<tr>
<td></td>
<td>Cheap, no compaction required</td>
<td></td>
<td>1+ Or 2+</td>
</tr>
<tr>
<td></td>
<td>Removes methane (up to 100 %)</td>
<td>Drying of cover reduces efficiency</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>Increases methane removal if used with a gas collection systems</td>
<td></td>
<td>1?</td>
</tr>
<tr>
<td></td>
<td>Best with hot climates</td>
<td></td>
<td>1+</td>
</tr>
<tr>
<td>Basic Cover</td>
<td>Very Cheap</td>
<td>Minimal if no CH4 consumption</td>
<td>1, 2 &amp; 3</td>
</tr>
<tr>
<td></td>
<td>Uses local material (soil)</td>
<td>Least desirable cover type</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy to install</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: If teamed up with a gas collection system


* Financial: [1] Revenue from sale of power (Gas / Electricity)

* Carbon Credit: [1] Potential for trading Carbon Credits
2.2.3 Biogas Cleaning Project

Landfill gas (LFG) is composed of gaseous products of the decomposing solids in the waste pile. Therefore, the gases will be widely varying depending on the composition of the collected waste. Of course this means the LFG constituents can change from season to season and from year to year. The more difficult components of landfill gas come from cosmetics and packaging materials, which bring silicon compounds to the waste pile, and their decomposition results in “siloxanes”. Siloxanes burn and yield a glassy solid deposit that is hard, brittle and abrasive. Siloxanes in the FLG get into machinery and can cause it to wear extremely quickly, and thus must be avoided. Consequently, cleaning the gas of siloxanes is imperative, and two factors need to be considered; first, the amount of siloxanes in the gas, and, second, the machinery being used. Reciprocating engines are more forgiving than microturbines, although both types of machinery can be worn prematurely by presence of siloxanes. However, microturbines rotate at very high speeds and must have very low friction. Capstone turbines use air bearings which are an important feature in their operation and efficiency, but which make them more susceptible to impurities.

Other gases in LFG are also problematic, including CO₂, sulfur oxides, nitrous oxides and water vapor. Fortunately, equipment has been developed to handle separation of problem gases from the waste gas stream to the extent required by different equipment types. As might be expected, the cost of such equipment depends on the complexity of the gas reduction problem. Budget pricing for gas cleaning equipment is US$ 1,000 per kW of electrical generation capacity for equipment required to clean gas for reciprocating engines, whereas US$ 2,000 per kW capacity is the budget pricing required for preparing gas for use in a microturbine.

One engine-driven type generator called the Sterling engine burns LFG directly in a boiler and therefore does not require any gas cleaning equipment. This is discussed further in this report. Sterling engine generators are relatively new and only available in 50kW size.

2.2.4 Biogas Use Project

Landfill Gas (LFG) is a mixture of methane and carbon dioxide with small amounts of nitrogen, oxygen, and other trace gasses. While the methane can be burned for different energy uses, it is most often emitted into the atmosphere, where it contributes greatly to global warming with a Global Warming Potential (GWP) of 21. The GWP is a factor telling how many times worse a particular gas is for increasing global warming when compared to CO₂. Flaring LFG is the very least that should be done to preserve the environment. But while burning the LFG in a flare converts the methane to CO₂ and water, it dramatically reduces the GWP; it is a waste of valuable energy. Depending on the landfill proximity to end users, the amount of LFG being produced, and the amount of capital that is available there are LFG uses that not only reduce the GWP but provide clean, cheap, and reliable energy.

2.2.4.1 Use LFG Directly

There are several different ways that LFG can be used directly without the need to refine the gas. Each has its advantages and disadvantages, mostly depending on the specific location of
the landfill and proximity to an end user. The main advantage to using the LFG directly is the simplicity of the systems. This makes them cheaper, easier to find qualified labor to install the equipment, and cheaper operation and maintenance (O&M) costs. The disadvantage is finding an end user for the gas that is within a close proximity of the landfill. Building a LFG pipeline can be expensive, especially when there are long distances over rough terrain that requires right-of-way rights to be purchased from landowners.

Burning the LFG directly in a boiler to produce for steam or hot water and burning it for heat has many advantages when it is an applicable solution. Many times it is not used because a direct user for the LFG or steam/hot water is located too far away to be able to use the energy. If a user can be identified, the advantages of using this simple and mature technology is that little gas cleanup is required. This can lower the capital cost of a LFG to energy project.

It is also possible to use the gas directly in a leachate evaporator. A leachate evaporator solves two waste problems: it burns the LFG, while evaporating the leachate which will pollute waterways if allowed to reach them, including underground water sources.

In summary, the advantages and disadvantages are listed below.

Burn Gas in Boiler (steam or hot water user)

**Advantages:**

- Can be used in any industrial process that requires steam
- Simple and mature technology
- Little or no gas cleaning required
- Low relative cost of equipment and maintenance

**Disadvantages:**

- End user must be in close proximity to the landfill as building a gas pipeline can be expensive
- End user must have a boiler that can handle LFG or retrofit current boilers which can be expensive

Burn for Heat (uses include kilns, leachate evaporators, greenhouses, etc)

**Advantages:**

- Can be made to work for any application requiring heat
- Simple and mature technology
- Little or no gas cleaning required
- Low relative cost of equipment and maintenance
Disadvantages:

- End user must be in close proximity to the landfill, since building a gas pipeline can be expensive

2.2.4.2 Electricity Generation

Producing electricity with the LFG and using it at the landfill facility or feeding it back to the grid are excellent ways of using the LFG when direct use is not feasible or cost effective. The advantages of electricity generation include the ability to transmit over long distances, the technology is available to cover almost any size landfill, and high efficiencies can be achieved especially when combined heat and power (CHP) technology is used. The disadvantages are the larger capital investment required and the need for pretreatment of the LFG for most of the electricity producing equipment.

Six types of equipment for electricity generation are described below.

2.2.4.2.1 Internal Combustion Engine

The most common power source for LFG generators is the internal combustion (IC) engine. There are several different manufactures of LFG powered IC engines currently on the market all having approximately the same input specifications, power output, and emissions. Some of the larger companies in the industry include GE Jenbacher, Caterpillar, and Cummins. The main advantage of using an IC engine is availability of qualified technicians to install and maintain them as they are an industry standard. They do have disadvantages such as being noisy, producing pollutants, and require maintenance every few thousand hours of operation.

2.2.4.2.2 Stirling Engine

Stirling engines are external combustion engines and therefore have the major advantage that all of the impurities of the LFG never reach the internal moving parts, therefore extending the life of the engine and eliminating the need for costly pre-combustion gas treatment and oil changes. With only half of the moving parts of a typical internal combustion engine, there is less to wear out. They also run quietly which in some situations can be critical. Their disadvantage is they are not a commonly used technology so finding qualified technicians to install and maintain the engines could be more difficult. This is offset by the relative simplicity and lack of parts these engines require. Since there are few installations of Sterling engine generators, reliability is an unknown quantity, and this technology must be considered carefully before purchasing.

2.2.4.2.3 Combustion Turbine Engine

Combustion turbines are large machines typically applied to loads over 5 Mw. There are several manufactures of combustion turbines currently on the market that can run on LFG all having approximately the same input specifications, power output, and emissions. However, the size of available equipment is much larger than can be used in ES, since the anticipated gas flow from the landfills is not adequate for the combustion turbine engine.
2.2.4.2.4 Microturbines

Microturbine technology is becoming more common for converting LFG to electricity at American landfills. They are very efficient and clean running machines which maintain very low emissions of sulfur dioxide and nitrogen oxides. Because they are high rotation speed machines the bearings are precise and require careful operation. Microturbines are sensitive to siloxanes in the LFG, which must be removed, or serious damage to the turbine will occur. Therefore gas cleanup equipment is required which adds cost to the already expensive microturbine.

2.2.4.2.5 Steam Turbine

There are many different manufactures of LFG powered steam turbines currently on the market all having approximately the same input specifications, power output, and emissions. As for combustion turbines, these machines are used for very large power applications, and their use in ES is not warranted by the low gas flows available.

2.2.4.2.6 Fuel Cell

There are several manufactures of LFG powered fuel cells currently on the market all having approximately the same input specifications, power output, and emissions. In summary, they require clean LFG, are comparatively expensive, have limited life and are expensive to operate. Fuel cell technology is state of the art and not well suited to use in landfill applications. In addition, fuel cells membranes, the heart of these machines, require refurbishment or outright replacement every 5,000 to 8,000 operation hours. The short lives of these machines compared to their rivals, makes them a poor choice in general.

The characteristics of these generator types are compared in Table 7.

Table 7: Comparison of generator types.

<table>
<thead>
<tr>
<th>Generator Type</th>
<th>Size range</th>
<th>Installed cost per Kw capacity</th>
<th>Installed cost for gas cleaning equipment</th>
<th>O&amp;M USD/Kwh</th>
<th>Approximate cost per Kwh</th>
<th>LFG volume required (m³/day)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reciprocating Engine driven</td>
<td>50Kw to 5 Mw</td>
<td>1100-2200</td>
<td>1000 $/Kw</td>
<td>9-22</td>
<td>$0.065/Kwh</td>
<td>17,000-1,700,000</td>
<td>Jenbacher is available in Sao Paulo, Brazil</td>
</tr>
<tr>
<td>Sterling Engine driven</td>
<td>25 Kw to 50 Kw</td>
<td>1200-2000</td>
<td>0</td>
<td>10</td>
<td>$0.049/Kwh</td>
<td>1,000</td>
<td>Sterling BioPower not currently in Brazil</td>
</tr>
<tr>
<td>Combustion Trubine driven</td>
<td>500 Kw to 250 Mw</td>
<td>900-3000</td>
<td>500-1000 $/Kw</td>
<td>4-11</td>
<td>$0.049/Kwh</td>
<td>150,000 to 75,000,000</td>
<td>Beyond the available gas flows in ES landfills</td>
</tr>
<tr>
<td>Microturbine driven</td>
<td>30 Kw to 1 Mw</td>
<td>2500-3000</td>
<td>2000 $/Kw</td>
<td>15-30</td>
<td>$0.069/Kwh</td>
<td>15,000 to 300,000</td>
<td>Capstone interested in Brazil market</td>
</tr>
<tr>
<td>Steam Turbine driven</td>
<td>8Mw to 250 Mw</td>
<td>2900-7300</td>
<td>included</td>
<td>5</td>
<td>$0.024/Kwh</td>
<td>very large</td>
<td>Beyond the available gas flows in ES landfills</td>
</tr>
<tr>
<td>Fuel Cell</td>
<td>5Kw to 50 Kw</td>
<td>5000-6500</td>
<td>2000 $/Kw</td>
<td>32-38</td>
<td>$0.38/Kwh</td>
<td>unknown</td>
<td>Costly and no known installations</td>
</tr>
</tbody>
</table>

*Costs are in US dollars.
2.2.4.3 Fuel Applications

LFG can be converted to Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) to be used as a fuel in vehicles or any other commercial use of natural gas (NG). The LFG must be cleaned and refined. To do this, the CO₂, nitrogen, oxygen, and water vapor must be removed along with any other trace gasses present in the LFG. With enough refinement the LFG can reach pipeline grade natural gas. With the high capital costs of building a LFG to natural gas plant, this option is not considered an option at landfills that are producing less than four million cubic feet per day of LFG, assuming methane content of 50%. None of the ES landfills will provide this amount of LFG.

2.2.5 Biogas Flaring Project

Flaring biogas is the basic process for destroying methane in the event nothing else will be done. This is important since flares are a minimum 97% efficient in converting methane to CO₂ when operated properly. In combustion, one methane molecule yields one CO₂ molecule. But methane has been shown to have 21 times greater global warming effect than CO₂. Therefore, destroying methane through flaring reduces global warming impacts.

There are many worldwide vendors of flaring equipment. Quotations from two vendors were obtained for this study, to demonstrate the range of pricing and of approach.

Small landfills may benefit from directly flaring the gas from each well. One company contacted during this project provides a solar powered flare that can be mounted above a gas well, and requires service only once a year. Solar power will maintain ignition ability for over two weeks even in low sunlight exposures, so that cloudy conditions can be accommodated. Approximate cost of such a flare is said to be approximately US$3,500. The flare can be installed in less than one day.

Larger installations will most likely benefit from a central system that will cap each well and capture the gas for transport to the central facility by plastic piping. Usually, an electric powered blower will suction the gas from the wells to the central location using a low suction vacuum. The central flare can be an open or closed unit. Closed flares have covers covering the flame from view, improving the efficiency very slightly, and making cover surfaces cooler. They are significantly more expensive than open flares which are not covered.
3 RECOMMENDATIONS FOR LANDFILL MANAGEMENT TO IMPROVE METHANE CAPTURE AND USE IN THE STATE OF ESPÍRITO SANTO - BRAZIL

3.1 INTRODUCTION

The state of Espirito Santo has waste disposal sites distributed in all of its 78 municipalities. These sites range from sanitary landfills, attending regulatory and technical standards, to irregular open dump sites. Eight sites were selected for recommendations and the total methane generation through the life of those landfills is 822,096 tonnes which corresponds to a GHG emission of 15,206,592 tonnes per year. Among other factors the Master Plan will addresses the amount of reduction of GHG emission that can be achieved.

In order to identify the most adequate solution for each type of waste disposal site, the existing sites and the future sites of the “ES Free of Dumping Sites” Program are separated in the following groups according to the potential to capture and use of methane in each site:

1. Active and inactive small dumping sites;
2. Active and inactive large dumping sites;
3. Controlled landfill of Cachoeiro de Itapemirim closed in 2007, after 10 years serving a population of 100,000 inhabitants;
4. Public sanitary landfill of Colatina, still operational, serving a population of approximately 100,000 inhabitants, and planned for operation until 2030
5. Five future regional sanitary landfills proposed by the Espírito Santo Free of Dumping Sites project in order to serve the entire state and allow closing of all irregular dumps.

Based on the information presented in Task 1 Report, and considering the Brazilian environmental, social and economical characteristics, the following possibilities of methane capture and use projects were identified:

Existing facilities:

Considering the small size and the lack of operational structure in most of the disposal sites in ES, only three existing sites were selected as potential candidates, although none of the sites fulfilled the conditions of the *Guidance Criteria for International Candidate Landfills*: (1) minimum depth, (2) minimum accumulated tons and (3) minimum of tons to be received. The selected sites for further study and recommendations were:

1. Cachoeiro de Itapemirim: The only municipal landfill that served a population between 50,000 – 100,000 inhabitants. The site was closed in 2007, but while in operation it was classified as “Controlled” according to the LQI criteria. The main objective of this project is the environmental mitigation of this area that currently release methane to the atmosphere and cause severe environmental impacts.
2. Sao Mateus: The only dumping site serving a population between 50,000 – 100,000 inhabitants that is still in operation, eight (8) others were recently closed. The main objective of this project is the environmental mitigation of this area that currently release methane to the atmosphere and cause severe environmental impacts. The cost/benefit relation of this project is only reached considering the social and environmental aspects due to the high costs and complexity for the implementation of gas collection structures in dumping sites.

3. Colatina: The only municipal disposal site serving a population above 100,000 inhabitants. Colatina was design to be a controlled landfill, but recent problems in its operation due to weather and expansion works have caused operational problems. When normal operation resumes the site is considered “Adequate” according to the LQI. This landfill is intended for operation until 2030. This landfill has biogas use and electrical generation potential, if design and operations are amended.

Future facilities:

This action plan will present guidelines for the implementation of biogas collection and use infrastructure for the regional sanitary landfills that will be built as part of the “Espírito Santo Free of Dumping Sites” Program. Considering that this state government program is in the initial stage of conceptual definitions, the orientation towards the biogas energy use presented in this Master Plan could be incorporated to each of these landfills’ specifications.

3.2 RECOMMENDED CLASSES FOR REMEDIATION

The identification of alternatives for the capture and use of methane from final waste disposal areas varies according to their size, physical structure, operational conditions and availability of resources. Thus, this item presents the different classes of existing solutions. These classes of solutions range from the simple compensation in order to avoid the release of methane to the atmosphere to the more complex measures of methane energetic use with the conversion to thermal or electric energy. Of the three existing sites selected for recommendations, Colatina provides the best opportunity for electric generation, whereas Cachoeiro and Sao Mateus require remediation. Colatina explanation of treatment is provided more in depth to illustrate the method of study, as well as provide a recommendation. Cachoeiro and Sao Mateus recommendations are presented in brief. Detailed studies of all landfills reviewed are available if requested.

3.3 METHODS FOR CASE STUDY RECOMMENDATIONS

PROMAR determined the expected landfill size and lifetime information using the IEMA database and through interviews with representatives of some of the municipalities and site visits. The gas flow data for the selected landfills were calculated using population data and waste generated rates as published in the SOP report. MU analyzed the available data, and made suggestions regarding the effectiveness of optional techniques for generation, collection and destruction of LFG. MRI and MU have considered options for reducing GHG, and the ramifications of each including the conceptual cost and benefits. The primary methods of dealing with LFG for the selected sites are:

1. Cover landfill with soil or biological barrier, as some landfills are not considered to be amenable to gas collection and utilization.
2. Cover landfill, collect LFG and flare the gas. There are several variations.
   a. Gather gas and flare at a central location, for situations where excess gas cannot be used to generate electricity, using open or enclosed flares
   b. Gather gas and have individual flares mounted at each well head
3. Cover landfill and collect LFG for direct energy (heating) applications, such as
   a. Evaporate leachate
   b. Medical waste incinerator – fuel for combustion
   c. Other to be determined by each site depending on economic conditions
4. Cover landfill and collect LFG and generate electricity, using
   a. Reciprocating engine generator
   b. Microturbine generator
   c. As noted above, flare excess gas when necessary

The first step in each analysis was to calculate the GHG potential, which is used as a reference to base our recommendations on. One measure of our work then is reduction of GHG from the baseline. The essential method of comparison however is return on investment. Since this analysis is preliminary, and future analysis of every site needs to be done on the basis of a detailed study of the exact conditions of design, this analysis will use the simple approach of comparing the revenue generated by any option, to its cost. Commonly, a 5 to 10 year payback of the investment is considered useful for long term community based investments, depending on non-financial factors that also may affect the decision. Such factors may include public welfare, environmental air quality, global warming, esthetics of the site, and many other factors that are site specific. In this analysis only simple payback analysis is used, when possible, due to conceptual nature of the study, and the lack of details regarding installed landfill construction and operation.

3.4 COLATINA LANDFILL - CASE OF STUDY

The municipality of Colatina is situated approximately 100 km from Vitória and has a public sanitary landfill under the responsibility of SANEAR (Colatina Environmental Sanitation Agency). This landfill is located on the BR 259 road, in the district of Córrego Estrela, at the coordinates UTM 24K WGS 84º 7843911/327564 at an altitude of 162 m, with a total area of 50 ha, as shown in Figure 14.
The Colatina landfill was designed to receive MSW and started its operation in the year 2000 with an expected duration of 30 years. The estimated quantities of waste to be received by this landfill in the years 2010, 2020 and 2030 are presented in Table 8.

Table 8: Estimated quantity of MSW received by the Colatina landfill

<table>
<thead>
<tr>
<th>Year</th>
<th>MSW quantity (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>285,096</td>
</tr>
<tr>
<td>2020</td>
<td>557,169</td>
</tr>
<tr>
<td>2030</td>
<td>842,122</td>
</tr>
</tbody>
</table>

### 3.4.1 Potential opportunity for reducing GHG and producing energy

The estimation of Colatina Landfill biogas generation was carried out with the LandGEM Model and with the Mexico Model, as presented in the Task 1 Report.

The methane generation modeling has shown (Task 1 Report) that the biogas generation peak will happen one year after the end of the landfill’s operational life (2031). Table 9 shows the generated biogas flow and the electric energy generation potentials for the years 2010, 2020 and 2031.
Table 9: Biogas and electric energy generation potentials for the Colatina landfill.

<table>
<thead>
<tr>
<th>Year</th>
<th>Parameter</th>
<th>Module</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Biogas flow</td>
<td>318</td>
<td>m³/h</td>
</tr>
<tr>
<td></td>
<td>Electric energy potential</td>
<td>0.18</td>
<td>MW</td>
</tr>
<tr>
<td>2020</td>
<td>Biogas flow</td>
<td>391</td>
<td>m³/h</td>
</tr>
<tr>
<td></td>
<td>Electric energy potential</td>
<td>0.22</td>
<td>MW</td>
</tr>
<tr>
<td>2031</td>
<td>Biogas flow</td>
<td>423</td>
<td>m³/h</td>
</tr>
<tr>
<td></td>
<td>Electric energy flow</td>
<td>0.24</td>
<td>MW</td>
</tr>
</tbody>
</table>

3.4.2 Existing Conditions

Colatina landfill, described in the PROMAR SOP report on page 160-167, has been in operation for nine years, and will continue until 2030. The general design is appropriate but operational performance has not met design requirements at times.

Colatina landfill has a base impermeable liner that consists of compacted clay, a synthetic geomembrane (High Density Polyethylene) at the bottom and on the edges, and gravel. This system has the objective of avoiding the percolation of toxic leachate and consequently avoiding groundwater contamination.

The leachate collection system is a fishbone type system formed by 150 mm diameter perforated pipes placed over a bidim involved layer of gravel with enough inclination to drain the leachate. The collected liquid is then transferred to a recirculation pump and reinserted into the landfill cells. Although this is the originally system for this landfill, the leachate recirculation has not been used due to operational problems.

The storm water drainage system consists of open drainpipes around the waste cells that conduct the rainwater to a surface water pond near the landfill that drains into the Estrela stream. This landfill uses the ramp land filling method, in which the waste is deposited in slightly inclined surfaces, compacted by a tractor, forming ramps and is then covered by a layer of soil at the end of the day. The height of this compacted waste layer is of about 10 meters. Once this first level is completed, it is covered by soil and a new layer is deposited on top of it following the same procedure. The landfill currently has 6 layers, totaling about 60 meters of deposited waste. These layers' final covering must be done with a layer of soil thicker than the daily one.

The daily covering of the compacted waste is done with a 5 cm layer of soil. Nevertheless, for operational reasons, this procedure is currently not being followed. The earth used in the covering is extracted within the landfill's limits. When the cell reaches the maximum capacity it is covered by a 60 cm layer of earth.

Annual rainfall is 1250 mm per year, with average annual temperature of 28ºC, making this a tropical area by Intergovernmental Panel on Climate Change (IPCC) definition. The rainy season is November to January when a large percentage of the annual precipitation occurs. A model of leachate available during the year shows that only the period of November to January creates an excess of leachate, and during the rest of the year excess leachate does not form, but the rain water is either evaporated prior to entering or absorbed in the waste.
The surficial soil at Colatina is loamy sand that is used for daily cover and intermediate cover, and a 0.075 runoff factor was selected for leachate estimation. Based on this, leachate production is expected to be as shown in Table 10.

Table 10: Expected monthly total leachate flow

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liters Leachate/Hour</td>
<td>363</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>829</td>
<td>738</td>
</tr>
</tbody>
</table>

In July 2009, a waste slide occurred that may have been caused by excessive rainfall and leachate injection. This may have been compound by less than optimal waste compaction and lack of a suitable buttress limited the forces resisting the waste slide, which could have also been affected by operations issues, e.g., labor strike, daily and intermediate cover had not been used for extended time intervals.

The biogas collection system consists of drain pipes distributed alongside the leachate collection system, at a distance of 10 to 15 meters from each other. These collection pipes are made of 20 cm diameter perforated concrete and are surrounded by stones ranging from 10 to 40 cm held together by a grid. This structure has a diameter of approximately 1 meter. This landfill does not currently have any gas treatment system. Therefore, all landfill gas generated is vented to the atmosphere, and as such, there is a great opportunity to reduce emissions of GHG, provided it can be done economically. The amount of methane that is expected to be generated at Colatina from 2010 to 2030 is 44,500 tonnes of methane representing 934,500 tonnes of CO2.

### 3.4.3 Recommendations

#### Cover

Different types of intermediate and final cover have different effectiveness in containing and collecting LFG, ranging from considerably less than 50% to perhaps 90% at best. Consideration of efficiency is a critical step in determination of landfill design for cover, collection system, gas cleanup, and utilization. The final economic benefits will depend on the amount of gas that can be usefully deployed; and the more effective collection methods cost more than the less effective, so cost-benefit analysis is required to determine if a more efficient system provides more benefits per unit cost, or vice versa. Also, sizing of generators or of heating applications depend on accurately determining the availability of gas. Seasonality of gas production is an issue in all installations.

Carbon credits have significant returns if they can be validated. A program to establish the value of carbon credits requires a system of capture that is reliable and maintainable over years of operation. Initial and recurring audits are done to determine if the original commitments of the design are being fulfilled in fact. The best cover methods have the highest capture efficiency and lowest risk of degradation over time.

In general, the LandGEM model (US EPA, [http://www.epa.gov/lmop/res/index.htm](http://www.epa.gov/lmop/res/index.htm), last accessed 15 Sept. 2009) provides an annual average amount of LFG potential for the landfill design. The potential can only be realized with appropriate cover and collection systems. The existing Colatina landfill has potential for landfill gas collection and utilization – direct heating or electricity generation both of which can reduce the release of methane (a greenhouse gas) to
the atmosphere (SOP p.163-4). A key element in capturing the landfill gas for any application is the gas containment and collection system. Containment systems consist of a low “gas” permeability cover system while the collection system may be by vertical wells, horizontal pipes or drainage blankets, or combinations of all three methods. The following discussion concerns the types of cover systems available for the Colatina landfill, their relative advantages and budget estimate costs (US$).

When completed, the Colatina landfill will cover approximately 10 hectares (ha) in spatial extent. Thus, the final cover system will be approximately 10 ha. The currently proposed final cover system is 0.6 m of on-site soil cover (SOP p.162). Such a cover will provide a good barrier between human or other vectors and the waste; however, a 0.6 m soil cover will be at best moderately effective at containing the landfill gas within the waste mass. If the cover soil dries out and cracks the gas barrier function is poor (Koerner and Daniel 1997). Regardless of the effectiveness of the landfill cover, the purpose is to trap the landfill gas in the waste mass and prevent its release to the atmosphere. The gas must be collected and removed from beneath the cover otherwise it will either seep through the cover or travel laterally to escape from the landfill and eventually end up in the atmosphere. To counter this, a gas collection system is installed before or after the cover is placed. The cover and the collection system function together to contain and collect the landfill gas making it possible for beneficial use or at the minimum, destruction (through combustion) to lower impact constituents.

At Colatina, gas generation models predict a peak gas generation of approximately 423 m³/hour by 2031 and then a rapid decline in the rate (SOP p. 164). In order to recover most of the gas a cover system must be installed. More effective cover systems produce greater percentages of gas recovery available for utilization. There are many choices for cover systems and each one has its advantages. The following cover systems are recommended for Colatina (Table 11).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Estimated Cost (US$)</th>
<th>Est. Cost per Hectare (US$/ha)</th>
<th>Efficiency of Gas Control</th>
<th>Total Methane Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Cover (0.6 m)</td>
<td>6.00/m²</td>
<td>60,000</td>
<td>Low (30 to 60%)</td>
<td>20 to 50%</td>
</tr>
<tr>
<td>Soil Cover (1.5 m)</td>
<td>1.50/m²</td>
<td>150,000</td>
<td>Moderate (50%)</td>
<td>50%</td>
</tr>
<tr>
<td>Soil Cover (0.6 m) + Geomembrane (≥ 1 mm)¹</td>
<td>Soil 6.00/m² Geomembrane 5.00/m²</td>
<td>110,000</td>
<td>Good (60 to 90%)</td>
<td>59 to 88%</td>
</tr>
</tbody>
</table>

¹A lateral drainage layer may be necessary below the soil cover to facilitate drainage of infiltration so that it does not pond on the surface of the geomembrane thereby reducing the stability of the cover system on slopes.

²For the lifetime of a landfill, say 100 years, US EPA conservatively estimates 75 percent of the landfill gas (methane) will be captured and destroyed given an effective cover and a well-operated LFG recovery system during the operating and post-closure (30 years) period of the landfill. The IPCC (IPCC 4th Assessment Report, Chapter 10 – Waste Management (p. 600).) surveyed landfill practices around the world and estimated that the effectiveness of LFG recovery can be as low as 20% and highly depends on operating practices at a given facility. Spokas et al. (2005) developed data (ultimately used by the French government) to establish default values for percent recovery of LFG as follows: 35% for an operating cell with an active
LFG recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery. The poor hydraulic performance and gas containment performance of soil (only) covers has been well documented: Melchior et al (2008); Suter, Luxmoore and Smith (1993).

\(^3\)Based on a 98% efficient destruction technology, (e.g., open flare)

**Gas and Leachate Collection System**

The existing gas collection system at Colatina is a series of vertical wells through the waste mass. As the final cover is placed over the waste, gas will be directed to the wells. Currently the wells vent the gas to the atmosphere; however, the gas is of sufficient quantity that if collected can be utilized. It is recommended that a manifold system of lateral pipes be placed on the surface of the completed landfill (in areas that have received the final cover) and that the landfill gas be transported to a central location for utilization.

The existing plan for the landfill shows 56 gas wells scattered across the 10 ha site which is about the typical number for a site this size. The well heads will need to be capped and tied into the pipe manifold. Typically HDPE (PAED) piping is used and inside diameter is about 0.15 m to 0.30 m. Since the vertical wells are being installed in concert with the landfilling process, only the piping manifold and tie in to the wellheads remain to be constructed after an area is completely filled with waste.

A budget estimate for Colatina including a soil + geomembrane cover (US$ 110,000) and 2.5 gas wells per ha (US$ 1,500 per well and piping) is approximately US$ 114,000 per ha. This cost assumes that the wells are already installed during the filling of the landfill, i.e., there is no cost included for the construction of the gas well. Thus, gas flow from all of the wells should be able to be tied together and delivered to a central point for about US$ 114,000 per hectare. In addition, an active gas collection system will require a blower and associated appurtenances to maintain a small negative pressure (typically less than 7 kPa (1 psi) in the gas collection system.

A gas system with 56 wells, placed over a 10 ha area, would likely require a 25 hp blower capable of moving at least 3,400 m\(^3\)/hr. A skid-mounted, candle-stick flare capable of moving 3400 m\(^3\)/hr costs on the order of US$ 175,000 to US$ 200,000. Traditional vertical gas wells, installed after the landfill is completed cost on the order of US$ 100 per vertical foot (US$ 300/m) and the lateral piping network (manifold) assuming SDR 17 piping is about US$ 30-40/lineal foot (US$ 100/m). Costs are derived from landfill operators in the Midwest region of USA as of September 2009 (Bowders 2009).

The cover system will also reduce the amount of rainfall infiltration into the waste. Calculations show that one can expect about a 25 percent decrease in the volume of leachate after a 0.6 m thick soil cover is applied (Table 12). The absence of leachate in the month of November for the Clay Loam (CL) compacted soil cover is a result of the increased moisture holding capacity of this soils relative to not having a cover as the case for the uncovered waste mass.

Table 12: Estimated leachate volumes for different cover systems (m\(^3\)/ha)
If the leachate volume is reduced, then the rate of landfill gas production will decrease as well. (Moisture is a critical component of the biodegradation process). Gas production can be accelerated by re-injecting the leachate into the waste mass, as long as the mass remains stable, or the leachate can be held in a pond for later use. This reduces or eliminates leachate treatment costs and accelerates the gas production. Stability of the landfill is a critical issue, and excess leachate in the landfill can be monitored by direct viewing through the injection wells once a certain level is reached.

The gas collection plan for Colatina is shown in Figure 15. The plan indicates 56 vertical gas extraction wells (also acting as leachate injection wells) and 29 lateral leachate collection channels for the completed 10 ha landfill, i.e., at time of closure over the currently operating facility. The plan results in about 5.6 (assume 6) gas extraction wells per hectare covered with waste. Five or six gas extraction wells per hectare is the standard of practice. Koerner and Daniel (1997) recommend five (5) vents/wells per hectare when there is no gas collection blanket beneath the final cover. Vigneault et al. (2004, *Vadose Zone Journal* 3:909–916) recommend that a radius of influence for gas wells is dependent on gas permeability of the waste and waste thickness. They recommend a 30 m radius of influence which translates into a 60 m spacing between wells. Guidance documents in Britain (UK) recommend not more than 40 m spacing of gas wells [www.environment-agency.gov.uk, last accessed 15 Sept 2009] and practice in the USA is on the order of 30 m to 50 m spacing between wells.
LFG Use

Colatina Landfill is a relatively small landfill and therefore produces a relatively small amount of LFG. This limits the methane use options to: (1) burning the LFG in a flare, (2) direct use of the LFG by evaporating the leachate on site, (3) improving the medical waste incinerator or (4) generating electricity. Other heat uses, unknown at the time of this study, may be feasible at Colatina based on the desires of the management at the Colatina landfill. Since Colatina is close to a population center, it might be possible to set up a work center where hot water, steam and heat were available utilities, encouraging small businesses to set up operations there. The options for generating electricity are limited to reciprocating engines, Stirling engines, and microturbines as the other options require a larger volume of LFG than Colatina can produce. These end use situations are further explored below. The equipment discussed is typical of equipment right sized for operation at Colatina, and the equipment appears to be suitable, but no endorsement of these equipment vendors is implied. Final selection of equipment should be done in later studies, specifically devoted to site design. All cost estimates are given in US dollars (US$), unless otherwise specified.
Flare

At minimum, LFG should be flared to reduce the GHG effects. It is well documented that methane is 21 times more deleterious to the atmosphere than CO₂, and so burning the methane to generate CO₂ is a minimal step in environmental protection. This step allows claim on carbon credits, valued in Brazil in 2006 at about 14 Euros per tonne.²

LFG consists of mostly methane and carbon dioxide with small amounts of other trace compounds, with the methane having a higher Global Warming Potential (GWP) than carbon dioxide which makes it important that the methane not be vented directly to the atmosphere. Flaring the LFG destroys the methane and can be done in either a semi-enclosed or fully-enclosed flare. While both semi-enclosed and fully-enclosed flares strive to accomplish a common goal, however the fully-enclosed flare achieves a more complete burn in a quieter, less visible manor. The fully-enclosed flare has NOx output of < 0.025 #s/MMBTU's/Hr and CO output of < 0.06 #s/MMBTU's/Hr while a semi-enclosed flare cannot guarantee any certain level of combustion or exhaust. The negative is that fully-enclosed flares are more expensive to install, build, and maintain.

Flare Industries Inc., offering locations in both the United States and Brazil, has a line of semi-enclosed and fully-enclosed flares that burn LFG. With Colatina producing a maximum 450 m³/hr LFG, the Flare Industries SEF-4 is a semi-enclosed flare that will be able to incinerate the LFG produced throughout the life of the landfill. With a base cost of US$ 20,910³ this is the least expensive method for incinerating the LFG. With the option to add on a spare parts kit for commissioning for US$ 50.00 and a kit containing spare parts for 2 years operation US$ 3,325, it is still the most economical option available.

If a fully enclosed flare is required then the Flare Industries FEF-10, which costs US$ 117,015⁴ would be needed to handle the volume of LFG expected at Colatina. The FEF-10 offers the benefits of >99% destruction and combustions efficiency which meet U.S. and international requirements. Using the 99% destruction figure, the fully enclosed flare will keep 3.7 million m³/year of methane, for a GHG reduction of 58,700 tonnes CO₂, out of the atmosphere in the peak year of 2031. At a cost of US$ 117,015, the enclosed flare is still cheaper than purchasing a genset or leachate evaporator; however they do not produce any usable energy or evaporate any leachate. However, it is possible to use this in order to reduce the amount of methane that reaches the atmosphere. The enclosed flare comes with the additional options of the Ladder & Platform package for US$ 6,875, a kit of spare parts for commissioning US$ 1,640, and a kit of spare parts for 2 years operation for US$ 7,350.

Heat Application

LFG can be burned either in direct fired furnaces or in electric generator engines where the heat of combustion can be used in addition to the generated electricity to provide benefits.

There are two apparent choices available at this time for heat use at Colatina. Evaporation of leachate and heating of medical wastes in the available incinerator are possible applications.

³ See Appendix 1 - Flare Industries Quote
⁴ See Appendix 1 - Flare Industries Quote
Evaporators

Leachate generated during the rainy season could be evaporated using commercially available equipment. Evaporators are available in custom sizes from Ecologix Environmental Systems among other companies. Quotations for 50 gph (gallon per hour), 500 gph and 2000 gph evaporators were received, and are compared in Table 13.

Table 13: Comparison of evaporators from Ecologix Environmental Systems

<table>
<thead>
<tr>
<th>Size gph(lph)</th>
<th>LFGas requirement</th>
<th>Equipment Cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 (185)</td>
<td>31 m³/hr</td>
<td>81,500</td>
</tr>
<tr>
<td>500 (1,850)</td>
<td>310 m³/hr</td>
<td>345,400</td>
</tr>
<tr>
<td>2000 (7,400)</td>
<td>1245 m³/hr</td>
<td>1,178,000</td>
</tr>
</tbody>
</table>

Evaporators for leachate would make sense in a situation where leachate was continuously produced, and where over liquifacation of the landfill would result in waste slides. Generally, leachate requires significant costly treatment prior to releasing into the watershed. Cost justification requires detailed analysis of the environmental costs, both social and financial, prior to making a final judgment on purchase of evaporators. If the landfill generates enough LFG to operate the evaporation, a key question to be answered, then the recurring costs are minor operation and maintenance.

The appropriate size for Colatina would be approximately 200 gph and pricing for such an evaporator was estimated from the available information at about US$ 280,000. Installation would be an additional cost. Since the rainy season is short, and the cost of a holding pond is relatively inexpensive, the utility of re-introducing the leachate to accelerate gas generation is recommended as compared to evaporation.

Incinerator

No details have been provided on the existing medical waste incinerator, but it is assumed to be gas fueled. In this event, converting the incinerator to LFG would likely be a minor technical issue. No cost is provided due to the lack of size information. It has been stated that this incinerator has not been satisfactory, but the reasons have not been given. A comprehensive review of the medical waste incineration issue is recommended to be done exclusive of this report.

Electric Generators

Gas Treatment

When the raw LFG comes in from the collection system, it is mostly methane, carbon dioxide, small quantities of sulfur compounds and siloxanes, and the potential for hundreds of other trace compounds. The gas can also have high moisture which must be removed for most applications. Gas treatment requires the use of consumable materials, which are required to be changed periodically. The intervals between changing consumables can be as long as two years if required by the customer during the design phase of the equipment, so the media holding tanks can be designed with adequate capacity.

Unison Solutions custom engineers each gas treatment skid for the specific requirements needed for an application. Therefore, an exact cost could not be determined without the exact
specifications of the landfill known, but an estimate of US$ 1,000 – US$ 2,000/kW<sup>5</sup> was given for the capital cost of the pretreatment equipment. The equipment would be different for microturbines as it would be for reciprocating engines because while both engines need the moisture and siloxane removed, the reciprocating cannot handle as high of levels of H<sub>2</sub>S as microturbines can handle. The microturbines also require the gas to be compressed to a higher pressure than a reciprocating engine.

For a landfill such as Colatina (approx. 423 m<sup>3</sup>/hr (248 scfm) LFG) and assuming normal siloxanes and H<sub>2</sub>S levels, the consumables would cost approximately US$ 50,000/year<sup>6</sup>. If siloxanes levels are higher than normal or gas production is higher than expected, then the cost of the consumables could rise. Changing out the consumables is an easy process and as they are not considered a hazardous waste, they can be disposed of in the landfill.

![Gas Treatment Skid by Unison Solutions](image)

**Figure 16 - Gas Treatment Skid by Unison Solutions - Unison Environmental Systems, Inc. 056 - West Lafayette - Cropped. Dubuque, IA: Unison Environmental Systems, Inc, 2009. Print.**

**Leachate Treatment**

All landfills create leachate, though some produce more than others, with the amount being collected dependant on several factors. The top liner and rainwater drainage system affect how much water is allowed to reach the waste and the effectiveness of the bottom liner and leachate collection system both contribute to the amount of leachate that is collected. If the landfill is not in close proximity to a municipal sewer line in which they can dispose of the leachate, an option is to use the LFG produced by the landfill to evaporate the leachate produced by the landfill.

With Colatina producing an estimated 415 gallons of leachate per hour on average, an Ecologix EvapoDry ED-500 could be used as a way to evaporate all of the leachate produced by the landfill. The base price for the ED-500 is US$ 572,710<sup>7</sup> and with the necessary add-ons required to burn LFG, the equipment will cost US$ 690,770 which does not include the cost of shipping, insurance or rigging. The advantage to this technology is the use of one waste product from the landfill, LFG, to take care of another problem, leachate. Burning the LFG in the leachate evaporator still achieves the goal of combusting the methane to reduce its GWP. This solution also solves the problem of what to do with the toxic leachate which can harm local water supplies if allowed to reach them. There may be other examples of heat recovery processes that are specific to individual sites, this one in particular can be used generally at any of the landfills.

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<sup>7</sup> See Appendix 2 – Ecologix Environmental Systems EvapoDry EDH-500 Quote
Stirling Engine Genset

The Sterling engine driven gensets are relatively new to the market, and bring a simple concept to landfill management especially suited to small landfills. This is due to their introduction as a small machine capable of generating 50 kW electricity maximum, and to their ability to burn biogas directly in an external boiler negating the need for gas cleanup equipment. The Sterling generator has been in public for only a few years, but renewed interest in alternative fuels has resulted in recent sales increase. These engines are made for outdoor application, and are simple to setup and operate. They are skid mounted and can be set on a gravel pad for operation. Hookup and operation in less than one day are considered normal. These engines cost approximately US$ 118,000, with Stirling Biopower, Inc.

Internal Combustion Reciprocating Engine Genset

The GE Jenbacher line of IC engines range from 0.35 to 3 MW, allowing the landfill operator to choose the size of IC genset that is right for the amount of LFG that is being produced. The main advantage of IC reciprocating engine gensets is that qualified maintenance personnel will be more readily available as the IC engine is an industry standard. Another advantage of using the GE Jenbacher line of engines is that GE has a Distributor/Service Provider in Porto Alegre, RS, Brazil. The main disadvantage is the engines will require the gas to be pretreated, adding more capital and O&M costs to the project. Another disadvantage is the IC Reciprocating Engine does not burn the LFG as efficiently as a microturbine; therefore some contaminates may be emitted though the exhaust.

The GE Jenbacher comes in several different sizes, starting with the Type 2 which is rated at 350 kW maximum output. The Type 3 has an output of 633 kW maximum and the Type 4 has an output of 1,056 kW maximum. With the JGC J208 (355 kW) genset price set at US$ 381,7088 and increasing to US$ 559,4909 for the JGC 312 GS (633 kW) and US$ 740,08510 for the JGC 320 GS (1,056 kW), the reciprocating IC engine is the more economical method for generating electricity per kW. These estimates are for the genset only and do not include the cost of the building to put the genset in, the installation cost or cost of switchgear to handle the electrical output.

8 See Appendix 5 – GE Jenbacher JGC 208 GS Quote
9 See Appendix 6 – GE Jenbacher J312 GS Quote
10 See Appendix 7 – GE Jenbacher JGC 320 Quote
The cost of electricity per kWh increases when using several small engines compared to one large engine though using several small gensets has advantages. Having several small identical units allows maintenance personal to become more familiar with the equipment as well as allow them to keep more spare parts on-site. It also allows one generator to be taken offline for maintenance while leaving the others operating. A more complete analysis should be done on the site to determine the best alternative.


Microturbine Genset

Capstone Microturbine is a microturbine manufacturer that offers a line of microturbines suitable to run on LFG. The advantage of the Capstone line of microturbines is the smallest unit starts at 30 kW, allowing the use of LFG to more closely follow the LFG production curve. Capstone also offers microturbine gensets with electrical outputs of 65 kW, 200 kW, 600 kW, 800 kW, and 1 MW. This wide range of microturbine genset sizes allows the user the ability to use as much of the LFG produced as possible with the least amount of turbines. The disadvantage of the Capstone Microturbines is that the gas must be pretreated before entering the microturbine in order to not destroy the microturbine within days.

With the capital cost of the microturbines starting at US$ 55,000\(^1\) for the 30 kW, US$ 75,000\(^2\) for the 65 kW, and US$ 250,000\(^3\) for the 200 kW, microturbines are more expensive than a regular IC reciprocating genset, when comparing only the initial capital costs. However, these turbines have the advantage of low maintenance and low output of pollutants. The only regular maintenance required is a once a year change of the air filter. At 20,000 hours, the injectors must be inspected/replaced and at 40,000 hours, the turbine needs an overhaul, requiring the turbine to be down for 4-6 hours. At 80,000 hours, the turbine has reached its design life, though usually a new turbine can be installed into the housing using all of the same control components to be able to run another 80,000 hours. The turbine has no oil or grease, eliminating the need for oil and lube services.

\(1\) See Appendix 9 - Capstone Microturbine CR30, CR65, and CR200 Quote
\(2\) See Appendix 9 – Capstone Microturbine CR30, CR65, and CR200 Quote
\(3\) See Appendix 9 – Capstone Microturbine CR30, CR65, and CR200 Quote
One report from an American user indicates the cost of operation of a microturbine is twice the cost of conventionally generated electricity. The great advantage of microturbines is the environmental air quality in their exhaust.


Cost Overview of Equipment

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<thead>
<tr>
<th>Manufacturer</th>
<th>Unit Cost (USD)</th>
<th>Power Produced (kW)</th>
<th>Cost per kW ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flare Industries SEF-4</td>
<td>20,910</td>
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</tr>
<tr>
<td>Flare Industries FEF-10</td>
<td>117,015</td>
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</tr>
<tr>
<td>Ecologix EvapoDry ED-XX</td>
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</tr>
<tr>
<td>GE Jenbaucher, JGC320 GS †</td>
<td>740,085</td>
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<tr>
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<td>GE Jenbaucher, JGC J208 †</td>
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<td>1546</td>
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<td>Stirling Biopower FlexGen w/o radiator</td>
<td>114,680</td>
<td>43</td>
<td>2666</td>
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<tr>
<td>Stirling Biopower FlexGen w/ radiator</td>
<td>118,380</td>
<td>43</td>
<td>2753</td>
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† Requires LFG treatment equipment which is not added into this price

Estimated Total Installation Cost
Master Plan for Landfill Management to Improve Methane Capture and Use in the State of Espírito Santo

<table>
<thead>
<tr>
<th>Semi-enclosed Flare</th>
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<td>Flare</td>
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<tr>
<td>Concrete Pad</td>
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<tr>
<td>Installation</td>
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<td><strong>Total</strong></td>
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<table>
<thead>
<tr>
<th>Fully-enclosed Flare</th>
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<tr>
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<tr>
<td><strong>Total</strong></td>
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<table>
<thead>
<tr>
<th>Leachate Evaporator</th>
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<table>
<thead>
<tr>
<th>Stirling FleXgen 43 kW (344 kW total)</th>
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<tr>
<td>(8) FlexGen Genset w/ radiator</td>
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<tr>
<td>Gravel Pad</td>
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<tr>
<td>Installation</td>
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<tr>
<td>Switchgear</td>
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<tr>
<td>Outside Concrete Pad</td>
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<tr>
<td>Gas Treatment Equipment</td>
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<tr>
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<thead>
<tr>
<th>Capstone Microturbine CR65 (325 kW total)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5) Capstone Microturbine CR65</td>
</tr>
<tr>
<td>Concrete Pad</td>
</tr>
<tr>
<td>Gas Treatment Equipment</td>
</tr>
<tr>
<td>Installation</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

**Summary of Alternatives**

While six particular generator technologies were reviewed in this study, only three have practical implications for the ES landfills. Those are generators powered by (1) sterling engines, (2) reciprocating engines, or (3) by micro turbines (MT). The sterling engine machines are a recent development based on very old technology that has been developed recently by a US company. This company has about 500 machines in service, in several application areas, and so while they provide a convincing story, their reliability and service history will remain something of a
mystery for a while to come. None the less, the technology appears promising, because this
engine is said to operate on raw LFG, which no other engine will do. In fact both reciprocating
engine and micro turbines require substantial gas cleanup prior to introducing the gas to the
engine, and the cleaning equipment has substantial capital cost as well as recurring operating
cost. The cleaning of siloxanes is particularly important for micro turbines since a small amount
of siloxanes in the gas will ruin a turbine in a few hours of operation.

The advantages of reciprocating engines are that they are ubiquitous, and easy to maintain.
They are long lived, and can be rebuilt at intervals to provide more than 20 years of continuous
service.

The advantage of micro turbines is their low environmental gas effluent. MT are used in major
US cities to reduce emissions below requirements, especially for NOx emissions. Their
disadvantage is first capital cost, although MT maker Capstone argues that their long term
operation costs and low downtime justifies the first cost, and make them competitive with
reciprocating engine generators. This is not a commonly held understanding.

Each of the gensets discussed is available in unique sizes favored by their manufacturers, and
so direct comparison is made more difficult, since size overlaps occur for each technology.
Generally, for the ES landfill applications the sizes below are available for consideration. While
several manufacturers are available for each technology, only one manufacturer has been
identified for the purposes of this study, and future studies should make comparisons of
competitive machines for final selection, based on feature set and cost.

The options for gensets as shown in Table 14.

Table 14: The options for gensets.

<table>
<thead>
<tr>
<th>Genset</th>
<th>Kw Rating</th>
<th>Capital cost (US$)</th>
<th>Quote basis</th>
<th>Locate</th>
<th>Installation cost US$</th>
<th>Gas cleanup US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sterling</td>
<td>50</td>
<td>117,000</td>
<td>$US</td>
<td>Outdoor</td>
<td>1,000</td>
<td>0</td>
</tr>
<tr>
<td>Capstone MT</td>
<td>30</td>
<td>46,400</td>
<td>$US</td>
<td></td>
<td>5,000</td>
<td>60,000</td>
</tr>
<tr>
<td></td>
<td>65</td>
<td>81,900</td>
<td>$US</td>
<td></td>
<td>5,000</td>
<td>130,000</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>272,300</td>
<td>$US</td>
<td></td>
<td>10,000</td>
<td>400,000</td>
</tr>
<tr>
<td>Jenbacher reciprocating</td>
<td>335</td>
<td>268,127</td>
<td>EURO</td>
<td>Indoor</td>
<td>200,000</td>
<td>333,000</td>
</tr>
<tr>
<td></td>
<td>633</td>
<td>393,008</td>
<td>EURO</td>
<td></td>
<td></td>
<td>633,000</td>
</tr>
<tr>
<td></td>
<td>1059</td>
<td>519,865</td>
<td>EURO</td>
<td></td>
<td></td>
<td>1,059,000</td>
</tr>
</tbody>
</table>

The recommended options for Colatina are use of Sterling engines or micro turbines, there may
be other manufacturers of reciprocating engine gensets with appropriately sized machinery, but
GE Jenbacher does not make a smaller machine for generating electricity for LFG.

**Final recommendation**

As indicated in the summary, good choices for Colatina are as follows:

**Alternative 1: Electric generation using Sterling engines**

Continue to complete the landfill in working areas of 1 hectare, completing each section prior to
moving onto the next. Upon completion, place a geomembrane composite cover including a
geomembrane and 1 meter of soil on top with vegetation. Cap each well, and collect LFG at a central location, where multiple Sterling engines are located along with a flare to burn the excess LFG. Three Sterling engines can be located immediately, with a fourth being located in 2013. All four engines would operate until 2030. The engines would burn all available gas to capacity of the engines, and excess would be flared. Electricity generated would be sold to the local utility at a fraction to be determined of the current retail residential cost of electricity in ES. The selling fraction needs to be negotiated with the local authorities, but an assumption of 60% is used here for financial feasibility estimates.

Recent evaluation of electric rates in ES was accomplished. Rates are composed of a use portion and an allocated portion. The combination of the two results in a rate of 0.50 Real (US$ 0.26) per kWh. Use of a 60% factor for electricity fed to the grid will result in payments of US$ 0.15 per kWh.

Also, if the gas is used in Sterling generators, it is again assumed that 90% of available gas would be collected and used to generate electricity to the capacity of available generators, with the excess unusable gas being flared at 97% efficiency. During the growth period of LFG between 2010 and 2030, generators would be added when 50% of the capacity of a new generator would be used. LFG is assumed to be composed of 50% methane and 50% non-burnable gases, principally CO₂. In this case three (3) generators would be added immediately, and a fourth generator added in 2013, as shown in Figure 20.

![Power Generation vs. # of Sterling Engines](image)

Figure 20: Number of sterling engines required for Colatina
Analysis on this basis used a value of electricity returned to the grid of US$ 0.15 per kwh, an operating staff of 5 full time people for the 24x7 generating facility, personnel cost of US$ 30,000 per person per year, which returns an estimated excess of about US$ 300,000 through 2030 after these costs are subtracted. The Capital cost of the facility is estimated at US$ 2,250,000 spread through the period. This includes the cover and gas collection cost of US$ 1,575,000, a cost that is required to simply flare and collect Carbon Credits (CC). Thus the incremental capital cost for generation is US$ 672,000. Of course, in addition, a staff is required to operate the generators, while fewer personnel would be needed for a flare only. A formal economic analysis awaits a formal plan.

When carbon credits are added to the 21 years total, the net return is estimated to be greater than US$ 17,000,000, using current world prices for carbon credits that can be verified.

The decision on how many gensets to use depends on the effective use of cover. For purposes of analysis, it is reasonable to assume 45% efficiency for soil cover, and 75% efficiency for a soil plus membrane cover. As an optimistic assumption, one could assume 90% efficiency as an upper limit, and see if it changed the decision on how many gensets to purchase, and when they should be purchased.

A preliminary recommendation based on the range of efficiency and power cost is as shown in Table 15.

<table>
<thead>
<tr>
<th>Option</th>
<th>Type</th>
<th>Number</th>
<th>Cover Efficiency</th>
<th>Total Power</th>
<th>Capital Cost in US$</th>
<th>20 year Power Total considering listed cover efficiency</th>
<th>Power Cost per kwh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sterling</td>
<td>2</td>
<td>45%</td>
<td>100 kW</td>
<td>236,000</td>
<td>18,520,000 kwh</td>
<td>0.013 Real/kWh</td>
</tr>
<tr>
<td>2</td>
<td>Sterling</td>
<td>3</td>
<td>75%</td>
<td>150 kW</td>
<td>354,000</td>
<td>30,870,000 kwh</td>
<td>0.011 Real/kWh</td>
</tr>
<tr>
<td>3</td>
<td>Sterling</td>
<td>4</td>
<td>90%</td>
<td>200 kW</td>
<td>472,000</td>
<td>37,040,000 kwh</td>
<td>0.013 Real/kWh</td>
</tr>
</tbody>
</table>

This analysis indicates that the capital cost of machinery for electric generation is a minimal component of final current cost of power in ES. The minor difference in cost per kilowatt among the options must be considered in light of a final recommendation in later studies.

**Alternative 2: Flaring**

An option for “flaring only” exists, using the high quality landfill cover and collecting and flaring all gas collected, without other use of the gas. The 21 year total of carbon credits that is available under this approach appear to total more than US$ 17,000,000, with the assumed value of 14 Euro per CC, and collection at 90% with 97% flare efficiency. This requires a high quality cover to achieve good collection.

**Alternative 3: Process Heat applications**

Process heat applications require an individualized analysis, since the cost of piping of LFG to the application location can be very expensive. Possible application ideas are improved
operation of the existing medical incinerator. No detailed data on the inadequacies of the incinerator are known. Another use could be a laundry which would use process heat, steam and or hot water from a boiler. No facility currently exists at or near the landfill, necessitating new building for the purpose. If the building was located on or near the landfill, the length of piping is minimized. Thereafter, the supply of LFG to the facility should be evaluated on the basis of the requirement and its consistency. The price competitiveness of LFG when compared to contemporary natural gas would have to have a significant advantage in order to justify relocation of existing businesses. Specific case information is required to perform a good analysis.

3.5 SÃO MATEUS DUMPING SITE- CASE OF STUDY

The municipality of São Mateus is located in the Northern region of the state of Espírito Santo, 222 km from the capital. A dumping site used as the final disposal area with coordinates: UTM WGS 84° 24K (414240/7927880) within the municipality is shown in Figure 21.

![Figure 21: São Mateus dumping site location.](image)

This dumping site started to receive MSW from the municipality of São Mateus in 1990, when its population was 73,895 inhabitants. The amount of waste disposed in this dumping site is estimated to be 453.570 ton from the period between 1990 and 2010, considering that the per capita waste generation for this municipality is 0.71 kg/inhabitant.day, and that 94% of the waste generated is collected (IBGE).
3.5.1 Potential opportunity for reducing GHG and producing energy

The estimation of São Mateus dumping site biogas generation potential was carried out with the LandGEM model – version 3.2, and with the Mexico model. Table 16 shows this dumping sites' biogas emission entry data.

Table 16: Landfill biogas emission modeling entry data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year</td>
<td>2000</td>
<td>Year</td>
</tr>
<tr>
<td>Last year</td>
<td>2030</td>
<td>Year</td>
</tr>
<tr>
<td>Methane generation Constant</td>
<td>0.17</td>
<td>Year⁻¹</td>
</tr>
<tr>
<td>Methane generation potential</td>
<td>65.00</td>
<td>m³ CH₄/ton MSW</td>
</tr>
<tr>
<td>MSW per capita daily generation</td>
<td>0.71</td>
<td>kg/(inhab.day)</td>
</tr>
</tbody>
</table>

The biogas generation flow values in São Mateus dumping site were higher in the Mexico model than in the LandGEM model and the last model has been adopted in this study because it is more conservative. The generation peak happened in 2011, one year after the end of this landfill's operational life. Table 17 shows this landfill's peak flow values.

Table 17: Estimated biogas and electric energy generation potential.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas flow</td>
<td>344</td>
<td>m³/h</td>
</tr>
<tr>
<td>Electric energy potential</td>
<td>0.20</td>
<td>MW</td>
</tr>
</tbody>
</table>

3.5.2 Existing Conditions

This dumping site is located in a former coastal tropical forest area, with sandy soil and does not have any impermeable lining system. The waste is not compacted or covered, which attracts animals, especially vultures and disease vectors. There is not a fence around the dumping site, therefore there is not a control of the entrance of people or animals and consequently there are waste collectors in this place. As soon as the waste arrives in the dumping site it is disposed onto the soil, then the waste collectors select the materials that can be recycled and later the tractor spreads the waste over the soil. The waste collectors have built improvised tents in order to store the selected waste. According to information gathered by the city hall during our technical visit, the solid waste pile reaches a maximum height of 4 meters in this dumping site.

3.5.3 Recommendations

The existing Sao Mateus landfill is operated as an open dump without a liner system beneath the waste and no cover system on top of the waste (SOP pp 167-172). The dump has approximately 380,000 tons of waste in place (2009) and the local population actively collects recyclables from the site. The waste is at maximum 4 m deep. The estimated spatial area of coverage is 16 ha (400 m x 400 m). Landfill gas (methane) estimates peak at 350 m³/hour (~240 ft³/min) in 2010 and begin a rapid decline over the next 20 years (Figure 81 SOP), as shown in Figure 22.
The estimate for gas generation would ensure a 100 m$^3$/hour (~ 60 ft$^3$/min) gas stream for the period between 2010 and 2020. Methane generation at this rate could potentially generate 0.05 MW/yr (50 kW/year) of electricity. This assumes 100 percent capture and utilization of the gas from the landfill. However, the best cover/collection systems are about 90 percent efficient, and soil covers alone are known to provide very poor gas containment (Table 1) (Koerner and Daniel 1997). The most effective cover systems are composite systems consisting of compacted soil and geomembrane layers in tandem. Such systems can range upwards of US$ 50,000 per ha.

This landfill will generate 155,000 tonnes Greenhouse Gas Equivalent (GGE) from 2010 to 2030, which is 97% of the remaining total gas potential. The potential sale of carbon credits requires audit verification of the actually achieved level of protection. Estimates of the value of carbon credits are given in Table 18. The financial incentives at Sao Mateus include carbon credits which require audit verification. Table 19 shows the remediation techniques considered for San Mateus, and their benefit potential. Estimates of the total carbon credit benefits over the landfill life of 20 years, with various remediation techniques starting in 2010 are shown in Table 20. (Basis: 155,000 tonnes CO$_2$, 20 year life, 14 Euro per tonne of CO$_2$).
Table 18: Estimates of the total carbon credit benefits over the 20-year life of Sao Mateus

<table>
<thead>
<tr>
<th>% Destruction</th>
<th>Euro (€)</th>
<th>Real (R$)</th>
<th>US (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>434,000</td>
<td>1,149,358</td>
<td>634,074</td>
</tr>
<tr>
<td>40</td>
<td>868,000</td>
<td>2,298,716</td>
<td>1,268,148</td>
</tr>
<tr>
<td>60</td>
<td>1,302,000</td>
<td>3,448,074</td>
<td>1,902,222</td>
</tr>
<tr>
<td>80</td>
<td>1,736,000</td>
<td>4,597,431</td>
<td>2,536,296</td>
</tr>
</tbody>
</table>

Final Recommendation for Sao Mateus

Given the small amount of power available to be generated coupled with the significant capital costs for generation equipment and subsequent operation and maintenance costs, along with the substantial cost for an effective cover and gas collection system, we recommend that Sao Mateus landfill is not amenable to gas collection for electrical power generation. The low gas production rate and spatially distributed nature of the waste also reduce the economic potential for use of the gas in any direct heating application. There is potential for carbon credits under three options shown in Table 20, including significant payback on a biomembrane cover system that uses flares at each individual well.
## Table 19: Landfill cover options and general characteristics.

<table>
<thead>
<tr>
<th>Cover Type</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Benefits Environmental *</th>
<th>Social *</th>
<th>Financial *</th>
<th>Carbon Credit *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite Barrier</td>
<td>No aging, deterioration, leakage over</td>
<td>Highest Cost (Requires high quality CQC/CQA during installation)</td>
<td>1, 2, 3, &amp; 4</td>
<td>1+ Or</td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>Long-term performance</td>
<td></td>
<td></td>
<td>2+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-cover</td>
<td>Using waste as raw material (Sewage waste, Yard Waste, or MSW) No compaction required</td>
<td>Decreased efficiency with cold climate (single digit °C temperatures)</td>
<td>1, 3, &amp; 4</td>
<td>1+ Or</td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>Removes methane (up to ~40 %)</td>
<td>Drying of cover reduces efficiency</td>
<td></td>
<td>2+</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complements and increases methane removal (if used with a gas collection system)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Performs best in hot climates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Cover Only</td>
<td>Least cost</td>
<td>Minimal to no CH₄ reduction</td>
<td>1, 2 &amp; 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uses local material (soil)</td>
<td>Least desirable cover type in terms of CH₄ reduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy to install</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: If teamed up with a gas collection system


* Financial: [1] Revenue from sale of power (Gas / Electricity)

* Carbon Credit: [1] Potential for trading Carbon Credits
Recommended remedial measures for covering Sao Mateus landfill are provided in Table 19. A promising technology for economically closing the dump and providing some reduction in GHG emission is the application of a bio-cover. Bio-covers include placing cover materials above the waste which incorporate strata (organics) for enhanced methanogenesis bacteria which degrade methane (CH₄) typically into water and carbon dioxide (CO₂) a much less potent GHG. The bio-covers can be constructed in various configurations (spatially continuous, or with specific organic “windows”); however, the microbial conversion of the methane is the principal feature of such covers.

Bio-covers represent a rapidly growing technology for treatment of the emission of GHG from abandoned landfills and facilities at which funding or higher technological treatments are not feasible. They represent a technology that can provide some reduction of GHG and may provide a potential carbon credit return, provided the reduction can be quantified (Abichou, 2005). A bio-cover is strongly recommended to close the Sao Mateus dump.

A traditional soil-only cover is the least costly alternative. It provides a means of reducing human and vector contact with the waste. There is minimal to no reduction of GHG emissions from the waste.

In addition, where feasible, the landfill area can be fenced to further reduce human activities in the waste. A note of caution, fences typically make the area appear more “valuable” to some humans, and actually results in some exploration of the area/waste. A thick (≥ 0.6 m) soil cover is highly recommended with or without the fence.

An expensive measure of applying a geomembrane cover with individual flares at each well is an option which may provide reasonable audit ability, and high collection and flare efficiency. If a detailed planning worked favorably, and carbon credits are negotiated, this approach could pay back at the highest rate of return.
Table 20: Recommendations for remedial measures at Sao Mateus landfill

<table>
<thead>
<tr>
<th>Technology</th>
<th>Estimated Unit Cost (US$)</th>
<th>Est. Cost per Hectare (US$/ha)</th>
<th>Efficiency of Gas Control</th>
<th>Total Methane Reduction²</th>
<th>Cost for San Mateus (US$)</th>
<th>Potential REC (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (Only) Cover (0.6m)</td>
<td>6.00/m²</td>
<td>60,000</td>
<td>Eliminates humans and vectors, reduces infiltration which reduces gas and leachate generation</td>
<td>10%²</td>
<td>960,000</td>
<td>317,037, 10% reduction of methane</td>
</tr>
<tr>
<td>Perimeter Fence</td>
<td>10.0/lineal</td>
<td>assume 16 ha square = 5250 feet perimeter</td>
<td>Reduces human contact with waste</td>
<td>None</td>
<td>52,500</td>
<td>0, no reduction of methane</td>
</tr>
<tr>
<td>Soil Cover Amended with Organics</td>
<td>6.50/m²</td>
<td>65,000</td>
<td>Technology in development experimental values of 10-40%² achieved</td>
<td>1,040,000</td>
<td>317,037 to 1,268,248 based on 10-40% reduction of methane</td>
<td></td>
</tr>
<tr>
<td>Soil Cover with Biodegradation windows</td>
<td>7.0/m²</td>
<td>70,000</td>
<td>Moderate methane reduction</td>
<td>Technology in development experimental values of 10-40%² achieved</td>
<td>1,120,000</td>
<td>317,037 to 1,268,248 based on 10-40% reduction of methane</td>
</tr>
<tr>
<td>Geomembrane with 0.6 soil with flare</td>
<td>(5/m² +1/m²) + (3,000 per flare + 5,000 per well)* 2 wells per ha</td>
<td>110,000</td>
<td>90%</td>
<td>87.3%</td>
<td>1,760,000</td>
<td>2,767,733 based on 87.3% reduction of methane</td>
</tr>
</tbody>
</table>

¹For the lifetime of a landfill, say 100 years, US EPA conservatively estimates 75 percent of the landfill gas (methane) will be captured and destroyed given an effective cover and a well-operated LFG recovery system during the operating and post-closure (30 years) period of the landfill. The IPCC (IPCC 4th Assessment Report, Chapter 10 – Waste Management (p. 600).) surveyed landfill practices around the world and estimated that the effectiveness of LFG recovery can be as low as 20 percent and highly depends on operating practices at a given facility. Spokas et al. (2005) developed data (ultimately used by the French government) to establish default values for percent recovery of LFG as follows: 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery. The poor hydraulic...
and gas containment performance of soil (only) covers has been well documented by Melchior et al (2008) and Suter, Luxmoore and Smith (1993).

3.6 CACHOEIRO DE ITAPEMIRIM INACTIVE LANDFILL - CASE OF STUDY

This municipality has a landfill which has been inactive since 2007. This landfill formally received waste from the municipality’s health units, which was disposed in a specific area and it also received domestic solid waste. Currently, the municipality sends its collected MSW to the sanitary landfill of CTRVV located in the municipality of Vila Velha. The inactive landfill is located at the coordinates: UTM SAD 69 24k (283006/7692455) as shown in Figure 23.

Cachoeiro de Itaperimim landfill started its activities in 1994 and ceased its activities in 2007, when the municipality’s population was 195,288 inhabitants. The estimated quantity of MSW deposited in this landfill was carried out according to the following information: per capita generation rate of 0.84 kg/inhabitant.day and 91.3% of MSW collection. The estimated total amount of MSW deposited in Cachoeiro de Itapemirim landfill is 666,579 tons.

3.6.1 Potential opportunity for reducing GHG and producing energy

Cachoeiro de Itapemirim landfill biogas generation potential estimation was calculated with the LandGEM and Mexico models, as presented in Task 1 Report. The biogas emission modeling entry data are shown in Table 21.
Table 21: Cachoeiro de Itapemirim landfill biogas emission modeling entry data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year</td>
<td>1994</td>
<td>Year</td>
</tr>
<tr>
<td>Last year</td>
<td>2007</td>
<td>Year</td>
</tr>
<tr>
<td>Methane generation Constant</td>
<td>0.17</td>
<td>Year⁻¹</td>
</tr>
<tr>
<td>Methane generation potential</td>
<td>65.00</td>
<td>m³ CH₄/ton MSW</td>
</tr>
<tr>
<td>MSW per capita daily generation</td>
<td>0.84</td>
<td>kg/(inhab.day)</td>
</tr>
</tbody>
</table>

Both biogas generation models presented very similar results, however Mexico model presented slightly higher values than the LandGEM one. Therefore, this study has adopted the LandGEM values. The estimated biogas peak flows (2008) and the electric energy potential are shown in Table 22.

Table 22: Estimated biogas and electric energy generation potential.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas flow</td>
<td>686</td>
<td>m³/h</td>
</tr>
<tr>
<td>Electric energy potential</td>
<td>0.39</td>
<td>MW</td>
</tr>
</tbody>
</table>

3.6.2 Existing Conditions

This landfill does not have a rainwater drainage system. Thus, the rainfall in the landfill’s surroundings flows to its interior, contributing to an increase in the leachate volume. According to Cachoeiro de Itapemirim’s Municipal Environmental Agency (Secretaria Municipal de Meio Ambiente), this landfill’s impermeable liner consists of a compacted layer of clay soil.

When operated, the Cachoeiro landfill used the ramp compacting method. Thus, after the deposition of the waste in the base of the ramp a tractor would spread and compact it. After the compacting the waste was covered with clay. The height of this compacted waste layer was of about 3.0 meters. After the completion of the first layer it was covered with earth and a new layer of waste would be deposited onto it following the same procedures used for the first one. The estimated total height of this landfill’s cells is of about 15 meters.

The former Cachoeiro de Itapemirim sanitary landfill does not have a gas collection system. Therefore all of the gas generated is directly dispersed in the atmosphere as it is released from the landfill’s layers.

3.6.3 Recommendations

Cachoeiro landfill had a 13 year life from 1994 through 2007, and is closed. An estimated 664,000 tonnes waste is in place, and with no leachate collection system. Direct rainfall on the landfill exacerbates the leachate volumes. The design is believed to be 5 layers of 3 meters depth each covered with yellow clay, total 15 meters deep. Greater depth is probable. Daily cover was 5 cm and final cover is thought to be 50 cm. The annual rainfall in Cachoeiro is 1,000 mm and the average temperature is 23.5°C.

The area of the waste in place is 2.24 hectares. There is no gas collection system in place. Maximum gas production occurred in 2007 and maximum electrical generation potential was 0.42 MW, a figure that will drop off to about 0.25 MW in 2010, and which drops dramatically thereafter. Figure 24 shows this dramatic drop in gas generating capacity.
If a project were to be started in 2010 to begin operation in 2011, 100 kW potential capacity could be captured until 2016, and 50 kW potential capacity could be captured until 2020. This constitutes the only electrical generation option for this landfill.

In summary, Cachoeiro is a closed 2.24 hectare landfill with gas generation rapidly reducing due to closure. Future landfill gas generation based on January, 2010 project start is a total of 13,680,000 m$^3$ of methane over 125 years. Ninety-seven percent is released in 21 years through 2030, for a total of 13,300,000 m$^3$ methane. Total destruction of the methane to CO$_2$ yields a potential GHG emission savings of 190,000 tonnes CO$_2$ over 21 years, which is 97% of the total life gas release.
Unfortunately, the plan is to release most or all methane into the atmosphere at this time. Any reduction will be due to natural biodegradation. No active remediation is planned currently.

**Remediation Options**

Partial remediation can be accomplished by placing a geomembrane cover over the landfill along with additional soil, amended soil or organic waste biocover to capture a reasonable percentage of LFG, with two possible methods of gas destruction. The landfill can be covered with a geomembrane, and methane destruction by methanogenesis used to reduce methane emissions. Also, the gas can be flared using a central flare, or individual flares at each well. The landfill has not been prepared for gas collection by lateral transfer in the waste pile, so wells would need to be drilled on a more than usual basis. Using 10 wells per hectare, 24 wells are required. In conjunction with a 0.040" thick geomembrane applied to the LF this will provide an estimated 90% collection of LFG. Assuming 97% efficiency in flaring, and 90% collection efficiency the amount of GHG emission savings actually produced in 21 years is 174,800 tonnes CO².

The capital budget cost of this high efficiency system is US$ 6,000 per well, plus small flares at each well (US$ 3,000) a total of US$ 90,000 per ha, and US$ 110,000 per ha for the bio cover and soil cover, for a total 2.4 ha cost of US$ 480,000. Should this occur, and a contract for carbon credits be executed, the potential value of the carbon credits is US$ 3,496,000. Operations and maintenance costs are not included.

Other less expensive cover systems also can provide remediation, including organic covers, and soil covers with organic windows which promote degradation through methanogenesis. These forms are less expensive are being prototyped in various locations, and have limited efficacy data. Results to date indicate 10 to 40 percent reduction in methane output. Carbon credit audit procedures are established, but are likely to change and improve over time, since the field is new.

**Electrical generation**

One or two Sterling engine electric generators could be applied over the period as noted, and electricity generated. A complete gas collection system and two Sterling engine generators could be installed, and operated. Only the geomembrane type cover will capture gas at efficiency to justify generators. Two generators for 6 years and one for 4 additional years yield an amount of 6,912,000 kwh. The estimated value of this power is US$ 1,036,800, based on a value of US$ 0.15 per kwh. The capital cost of implementing an electrical generating system is biocover, gas collection system including piping from each well and gas suction blower, two generators at US$ 118,000 each, a flare, an electrical switching panel and power line to the grid. In addition, annual operating costs are required. Carbon credit’s are possible with the electric generation approach, and it creates documentation for audit.

**Greenhouse Gas Potential**

This landfill will generate 200,212 tonnes of GHG from 2010 to 2030, which is 97% of the remaining total gas potential. The potential sale of carbon credits requires audit verification of the actually achieved level of methane destruction. Estimates of the value of carbon credits at benchmark points are given in Table 23. Table 24 shows the remediation techniques considered for Cachoeiro, and how they impact the benefit potential. Estimated value of the total carbon credit benefits over the landfill life of 21
years, using the various remediation techniques starting in 2010 are shown in Table 25. (Basis: 174,800 tonnes CO₂, 21 year life, 14 Euro per tonne of CO₂).

Table 23: Estimates of the total carbon credit benefits over the 21-year life of Cachoeiro

<table>
<thead>
<tr>
<th>% Destruction</th>
<th>Euro (€)</th>
<th>Real (R$)</th>
<th>US (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>489,398</td>
<td>1,281,091</td>
<td>716,576</td>
</tr>
<tr>
<td>40%</td>
<td>978,795</td>
<td>2,562,183</td>
<td>1,433,152</td>
</tr>
<tr>
<td>60%</td>
<td>1,468,193</td>
<td>3,843,274</td>
<td>2,149,728</td>
</tr>
<tr>
<td>80%</td>
<td>1,957,591</td>
<td>5,124,365</td>
<td>2,866,304</td>
</tr>
<tr>
<td>90%</td>
<td>2,202,289</td>
<td>5,764,911</td>
<td>3,224,592</td>
</tr>
</tbody>
</table>

**Final Recommendation for Cachoeiro Landfill**

The recommendation is to cover Cachoeiro with a high-quality capture system and negotiate the sale of carbon credits. No electric generation is recommended unless audit becomes a major factor. This analysis is contingent on fast action, since the gas is quickly escaping the landfill, and prime amounts are lost in the first years after closure.

The best cover/collection systems are about 90 percent efficient, and soil covers alone are known to provide very poor gas containment (Table 23 - Koerner and Daniel 1997). The most effective cover systems are composite systems consisting of compacted soil and geomembrane layers in tandem. Such systems can range upwards in cost of US$ 110,000 per ha.

Given the small amount of power available to be generated coupled with the significant capital costs for generation equipment and subsequent operation and maintenance costs, along with the substantial cost for an effective cover and gas collection system, we recommend that Cachoeiro landfill is not amenable to electrical power generation. A contingency consideration is that if it demonstrates carbon credit audit ability, then power generation may be an option. The low gas production rate and lack of structure for good collection of gas also reduce the economic potential for use of the gas in any direct heating application. There is potential for carbon credits under three options shown in Table 25, including significant payback on a geomembrane cover system that uses flares at each individual well.
Table 24: Landfill cover options and general characteristics

<table>
<thead>
<tr>
<th>Cover Type</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Environmental *</th>
<th>Social *</th>
<th>Financial *</th>
<th>Carbon Credit *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite Barrier</td>
<td>No aging, deterioration, leakage over</td>
<td>Highest Cost</td>
<td>1, 2, 3, &amp; 4</td>
<td>1+ Or 2+</td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>Long-term performance</td>
<td>Requires high quality CQC/CQA during installation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bio-cover</td>
<td>Using waste as raw material (Sewage waste, Yard Waste, or MSW)</td>
<td>Decreased efficiency with cold climate (single digit co temperatures)</td>
<td>1, 3, &amp; 4</td>
<td>1+ Or 2+</td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>No compaction required</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Removes methane (up to 40 %??)</td>
<td>Drying of cover reduces efficiency</td>
<td>1, 3, &amp; 4</td>
<td>1+ Or 2+</td>
<td>1+</td>
<td>1+</td>
</tr>
<tr>
<td></td>
<td>Complements and increases methane removal (if used with a gas collection system)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Performs best in hot climates</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Cover Only</td>
<td>Least cost</td>
<td>Minimal to no CH4 reduction</td>
<td>1, 2 &amp; 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Uses local material (soil)</td>
<td>Least desirable cover type in terms of CH4 reduction</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Easy to install</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: If teamed up with a gas collection system


* Financial: [1] Revenue from sale of power (Gas / Electricity)

* Carbon Credit: [1] Potential for trading Carbon Credits
The range of remedial measures for covering Cachoeiro landfill is provided in Table 24. A promising technology for economically closing the LF and providing some reduction in greenhouse gas emissions is the application of a bio-cover.

They represent a technology that can provide some reduction of GHG and may provide a potential carbon credit return, provided the reduction can be quantified (Abichou, 2005). A bio-cover is strongly recommended to cap the Cachoeiro landfill.

A traditional soil-only cover is the least costly alternative. It provides a means of reducing human and vector contact with the waste, but there is minimal to no reduction of GHG emissions from the waste. A thick (≥ 0.6 m) soil cover is highly recommended.

An expensive measure of applying a geomembrane cover with individual flares at each well does provide an option which may provide good audit ability, and high collection and flare efficiency. If the detailed planning worked favorably, and carbon credits are negotiated, this approach could pay back at a high rate of return.
Table 25: Recommendations for remedial measures at Cachoeiro landfill (2.24 ha)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Estimated Unit Cost (US$)</th>
<th>Est. Cost per Hectare (US$/ha)</th>
<th>Efficiency of Gas Control</th>
<th>Total Methane Reduction</th>
<th>Cost for Cachoeiro (US$)</th>
<th>Potential REC (US$), does not include cost of audit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil (Only) Cover (0.6m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.00/m²</td>
<td>60,000</td>
<td>10%²</td>
<td>134,400</td>
<td>340,559, 10% reduction of methane</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perimeter Fence</td>
<td></td>
<td>assume 2 ha square = 1964 feet perimeter</td>
<td></td>
<td></td>
<td></td>
<td>0, no reduction of methane</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10.0/lineal m</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Cover Amended with Organics</td>
<td></td>
<td>6.50/m²</td>
<td>65,000</td>
<td>Some methane reduction</td>
<td></td>
<td>340,559 to 1,362,236 based on 10-40% reduction of methane</td>
</tr>
<tr>
<td>Soil Cover with Biodegradation windows</td>
<td></td>
<td>7.0/m²</td>
<td>70,000</td>
<td>Moderate methane reduction</td>
<td></td>
<td>340,559 to 1,362,236 based on 10-40% reduction of methane</td>
</tr>
<tr>
<td>Geomembrane with 0.6 soil with flares at each well</td>
<td></td>
<td><em>(11/m²</em>+1/m²)<em>10,00 + (3000 per flare + $15,000 per well)</em> 10 wells per ha</td>
<td>290,000</td>
<td>90%</td>
<td>87.3%</td>
<td>649,600</td>
</tr>
</tbody>
</table>

¹For the lifetime of a landfill, say 100 years, USEPA conservatively estimates 75 percent of the landfill gas (methane) will be captured and destroyed given an effective cover and a well-operated LFG recovery system during the operating and post-closure (30 years) period of the landfill. The IPCC (2007) surveyed landfill practices around the world and estimated that the effectiveness of LFG recovery can be as low as 20 percent and highly depends on operating practices at a given facility. Spokas et al. (2005) developed data (ultimately used by the French government) to establish default
values for percent recovery of LFG as follows: 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery. The poor hydraulic and gas containment performance of soil (only) covers has been well documented by Melchior et al (2008) and Luxmoore and Smith (1993).

3.7 FUTURE LANDFILLS

The five future landfills proposed by the “ES Free of Dumping Sites” Program are presented in Section 2.1.5; Table 26 presents the MSW estimated quantity for each of these regional sanitary landfills between the years 2020 and 2030.

Table 26: Estimated quantity of MSW to be disposed in the regional landfills from 2020 to 2030.

<table>
<thead>
<tr>
<th>Region</th>
<th>North</th>
<th>West Doce</th>
<th>East Doce</th>
<th>Southern Plateau</th>
<th>Southern Coastline</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>1,125,252</td>
<td>1,037,666</td>
<td>1,090,603</td>
<td>1,507,564</td>
<td>1,023,906</td>
</tr>
<tr>
<td>2030</td>
<td>2,386,811</td>
<td>2,201,028</td>
<td>2,312,315</td>
<td>3,197,744</td>
<td>2,171,841</td>
</tr>
</tbody>
</table>

3.7.1 Potential opportunity for reducing GHG and producing energy

The estimation of the biogas generation potential for the future sanitary landfills proposed by the “ES Free of Dumping Sites” Program was carried out with the LandGEM and Mexico models presented in the Task 1 Report. The biogas emission modeling entry data are presented in Table 27.

Table 27: Landfill biogas emission modeling entry data.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Module</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year</td>
<td>2010</td>
<td>Year</td>
</tr>
<tr>
<td>Last year</td>
<td>2030</td>
<td>Year</td>
</tr>
<tr>
<td>Methane generation Constant</td>
<td>0.17</td>
<td>Year⁻¹</td>
</tr>
<tr>
<td>Methane generation potential</td>
<td>65.00</td>
<td>m³ CH₄/ton MSW</td>
</tr>
<tr>
<td>MSW per capita daily generation</td>
<td>0.84</td>
<td>kg/(hab.dia)</td>
</tr>
</tbody>
</table>

Both models presented similar biogas flow values, however the LandGEM model presented slightly lower values and has been adopted in this study. Table 28 presents the estimated biogas emission from the year 2020 to 2030 and Table 29 shows the estimated electric energy potential.

Table 28: Estimated biogas flow (m³/h) for the regional landfills.

<table>
<thead>
<tr>
<th>Year</th>
<th>Region</th>
<th>North</th>
<th>West Doce</th>
<th>East Doce</th>
<th>Southern Plateau</th>
<th>Southern Coastline</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>1,272</td>
<td>1,233</td>
<td>1,173</td>
<td>1,704</td>
<td>1,157</td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>1,786</td>
<td>1,731</td>
<td>1,647</td>
<td>2,392</td>
<td>1,625</td>
<td></td>
</tr>
</tbody>
</table>

Table 29: Estimated electric energy potential (MW) for the regional landfills.

<table>
<thead>
<tr>
<th>Year</th>
<th>Region</th>
<th>North</th>
<th>West Doce</th>
<th>East Doce</th>
<th>Southern Plateau</th>
<th>Southern Coastline</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020</td>
<td>1.18</td>
<td>1.14</td>
<td>1.09</td>
<td>1.58</td>
<td>1.07</td>
<td></td>
</tr>
<tr>
<td>2030</td>
<td>1.65</td>
<td>1.60</td>
<td>1.52</td>
<td>2.22</td>
<td>1.50</td>
<td></td>
</tr>
</tbody>
</table>
3.7.2 Technical Considerations

3.7.2.1 Site Location: how to choose the location for the new landfills

The implementation of a sanitary landfill must be planned in order to minimize the environmental impacts and maximize the population acceptance. It has to respect the regional environmental zoning plan and must be designed to be used for a long time interval. These choices must be based on the sanitary criteria listed in the Norma Brasileira 13.896/1997 (technical Standards) which establishes some technical considerations about these criteria as described below.

3.7.2.2 Physical: Ground/Soil/Topography/Water bodies

The local topography must be observed, since it is an important factor in the determination of the construction method and for the earth moving, according to this NBR (National Standard) the most adequate sites are those with 1% to 30% slope. The geology and the soil types are important indicators for the soil purification capacity and for the infiltration velocity. It is therefore recommended that the soil is constituted by materials with permeability coefficients lower than $10^{-6}$ cm/s and a non-saturated layer of at least 3.0 meters in width.

The horizontal distance between the landfill and any water body must be at least 200 m in order to avoid any influence on surface or groundwater in the landfill’s proximities. It is also important to respect a minimum layer of 1.50 m of unsaturated soil between the landfill’s bottom surface and the highest groundwater level measured in the rainy season. The region’s vegetation is also a factor to be observed, since it may reduce the possibility of erosion and the formation of dust, as well as minimize the propagation of odors. A sanitary landfill must not be built in areas susceptible to floods or within the 100-year floodplain.

3.7.2.3 Economical: Proximity to potential user/access to roads

The access to the future landfill area is a crucial element for the determination of its implementation area, once these roads will be used throughout the landfill’s operation. Also, the distance of the site to potential users of LGF, heat and/or electricity that can be generated in the landfill is an important factor to LFG use projects and, in the extent possible, this should be take in consideration, as piping of gas or large distance to communities of to the electrical grid can make a LFG-to-energy project unfeasible.

Besides the access, the size of the area is also a key factor to determine the landfill capacity and consequently its operational life, which should be of at least 10 years.

3.7.2.4 Social

The minimum distance between the sanitary landfill and residential areas is of 500 meters, in order to avoid problems related to the landfill’s operation, to odors and to the presence of animals.
3.7.2.5 Lining

The lining system or base impermeable layer has the objective of avoiding the infiltration of percolates or biogas into the soil. The most commonly used materials for the soil impermeabilization are: clay soils, compacted clay and synthetic geomembranes.

3.7.2.6 Subgrade

Initiation of construction of a solid waste landfill begins with clearing and grubbing the land surface, removal of all organic matter and excavation to suitable subgrade strata. These strata must be competent load bearing material, above the highest ground water level and preferably be a low permeability soil such as clay, clayey-sands or clayey silts. The subgrade is often minimally compacted; the final surface is graded to promote gravity drainage of leachate to collection systems and rolled with a smooth drum roller. The sub grade material lies beneath the bottom layer of the landfill lining system, i.e., below the compacted clay liner shown at the bottom of Figure 25 and provides a competent platform for placement and compaction of the bottom barrier soils.

![Figure 25: Typical Section through a Solid Waste Landfill in the United States](image)

3.7.2.7 Bottom Barriers

The principal function of the bottom barrier is to prevent escape of leachate (water that has flowed through the waste) into the underlying subgrade and potentially contaminating the ground water. Bottom barriers may consist of compacted soil layers combined with an overlying geomembrane to form a geocomposite barrier. The compacted soil layer (CSL) typically consists of 0.15 m layers of compacted clay or clayey soils to form a minimum barrier thickness of 0.6 m. The compacted soil layer must have a permeability (to water) of less than or equal to $1 \times 10^{-7}$ cm/sec. A geomembrane (polymeric, very low permeability sheet) is placed immediately on top of the CSL. Typical US practice is to use high density polyethylene (HDPE) geomembranes with a minimum thickness of 1.5 mm. In some cases, 1 mm polyvinyl chloride (PVC) liners are used in place of the HDPE. The geomembrane coupled with
the compacted soil liner have been shown to be the most reliable in terms of limiting any leachate migration through the bottom liner (Bonaparte et al. 2001).

Some US state regulatory agencies require a “double” composite liner below solid waste landfills. In these cases it is typical to use a geomembrane/geosynthetic clay liner (GM/GCL) for the upper most composite and a GM/CCL for the lower liner. The GM/GCL combination provides the GM/soil composite action, resulting in very low leakage rates but removes the need for compacting soil on top of the lower GM which can result in damage to that composite barrier. Geosynthetic clay liners consist of sodium bentonite sandwiched between two geotextiles or between one geotextile and a geomembrane and have a pre-hydration thickness of about 0.6 cm. The sodium bentonite is a high swell-potential smectite (clay) capable of yielding permeabilities on the order of $1 \times 10^{-9}$ cm/sec (Koerner 1998).

### 3.7.2.8 Leachate Collection

Sanitary landfills must have leachate collection systems, as stated in the NBR 13.896/1997, in order to reduce the pressure these liquids exert onto the waste piles and to minimize the groundwater contamination potential. A leachate collection system should consist of perforated drain pipes surrounded by filtering material and should conduct the leachate to an accumulation tank and then to an adequate treatment system. The collection system dimensions depend on the volume of the leachate flow and on the size of the landfill. The design of the leachate collection system may be include a biogas capture system. It is mandatory that the collected leachate receives adequate treatment in order to meet the established standards, otherwise it may not, under any circumstances, be transported to waterbodies.

The primary function of the bottom liner is to limit the escape of liquids or leachate from the facility into the underlying subsurface. However, if the leachate is not removed from the bottom liner, it could eventually form a “bathtub” and overflow the landfill. Thus, the leachate is collected and removed from the landfill thereby reducing the leachate available for leaking to the subsurface and reducing the driving force (hydraulic head) for leakage through the lining system. Thus, the intent of the leachate collection and removal system (LCRS) is to remove liquids before they can leak to the subsurface. Leachate collection systems typically consist of a combination of granular earthen materials and geosynthetics.

A typical LCRS is shown in Figure 26. The LCRS consists of filtering and drainage layers. From top to bottom, the components include: a geotextile acting as a separator and filter layer to keep the overlying waste from entering and potentially clogging the drainage layer (very coarse sand or rounded aggregate). The layer beneath the filter (Figure 2) typically includes a 0.3 m thick layer of coarse sand or aggregate to facilitate lateral drainage of liquids to central collection perforated polymeric pipes (geopipes). The flow is then transported to a sump (low elevation area relative to the base of the landfill) in the base of the landfill from where it is removed by pumping and transported to an appropriate treatment facility or in some cases the leachate is recirculated into the top of the landfill. Underlying the sand/aggregate layer is a heavy weight (400 to 600 g/m$^2$) geotextile whose sole function is to protect the underlying geomembrane from puncture (Richardson and Johnson 1998).
Note: The leachate has multiple pathways to reach the perforated geopipe either through the geotextile filter or the top of the open aggregate. This allows redundancy in the event of clogging of one pathway.

Leachate Collection and Removal System (LCRS): (a) LCRS situated on the bottom liner, (b) LCRS situated on the side slopes of a landfill.

Since it is often difficult to place aggregate on the side slopes of a landfill (particularly on slopes greater than 3H:1V), it is common practice to use a geocomposite (GT/GN) with some overlying sand for the collection layer (Figure 27). Most geonets have an in-plane flow capability equivalent to about a 0.3 m-thick sand layer (k ~ 0.01 cm/s). Multiple layers of geonet or tri-planar geonets can be employed if larger flows are anticipated. Piping systems are not required with geonets since the geonets have high in-plane flow rates compared with sand drainage layers. Some relative costs for comparisons between natural earthen materials and geosynthetics are shown in Error! Reference source not found.. Although the costs of the earthen materials appear to be much greater than that for the geosynthetics, all of the materials listed are legislated to be use in the US’s Subtitle-D landfills.
### 3.7.2.9 Gas Collection

The landfill generated biogas may attend diverse energetic demands as it may be converted into electric, thermal or mechanical energy.

The implementation of a landfill generated biogas use system depends on several factors, such as the landfill’s structure, localization, local energetic demand, financial investment available and the legislation. The choice of a biogas use systems must be based on these possibilities of use. According to the NBR 13.898/1997, the sanitary landfills must have biogas capture and treatment systems in order to reduce the emissions of methane generated from the organic matter anaerobic decomposition process into the atmosphere. There are basically two types of biogas capture systems for landfills: the passive system and the active one. The first has drain pipes from which the gases flow to the atmosphere. This system avoids the formation of gas deposits and consequently the danger of explosion. The active system has the further steps of exhaustion and compression from the drain pipes in order to send the gases to the systems of use (ENSINAS, 2003). The simplest way of biogas capture is through vertical pierced pipes which may be installed in the beginning of the landfill’s operation and they can later be extended as the landfill evolves; another option is to dig the existing waste cells after the end of their operational lives in order to implement the drain pipes. (DUARTE, 2006). These drain pipes are usually perforated and surrounded by gravel and they vertically intersect the layer of waste.

As the organics in the landfilled waste degrade, gas is generated consisting primarily of methane (CH\(_4\)) and carbon dioxide (CO\(_2\)) with trace other gasses. Both gasses are greenhouse gasses. It is customary to report greenhouse gasses in terms of equivalent units of CO\(_2\) and one unit of methane is equivalent to 21 units of CO\(_2\). Methane is also an energy source and can be combusted to generate heat or used to make electricity. Thus, it is advantageous to capture the landfill gas, utilize the methane and reduce greenhouse gas emissions from the landfilled wastes.

There are numerous designs for collecting and utilizing gas from landfills. Which design is implemented generally depends on the quantity, quality and rate of gas being produced along with the market potential for the gas at the specific landfill site (Table 30). Gas collection systems are only necessary if there is a cover layer on top of the waste which tends to trap the gas. Cover layers may consist of a simple layer of soil to an engineered cover as presented in Section 2.5.

The simplest gas systems consist of passive vents (Figure 28) either with or without flares (methods to combust the methane gas). Passive systems typically do not, but may include wells or deep collection systems in the waste. They are merely outlets in the cover system for any gas accumulating beneath the landfill cover. The pressure generated by the gas drives the gas to the landfill surface and to the vents.
Active gas systems include a blower (Figure 29), or other source, for creating a vacuum (less than atmospheric pressure) to facilitate capture and collection of landfill gas. It is typical for active gas collection systems to have a series of collection wells (vertical and/or horizontal) into the waste to increase gas collection efficiency. Vertical wells are typically designed on about 60 m spacing and are drilled to a depth of about 3 m above the bottom liner of the landfill. Budgeting cost for vertical wells on the order of 20 m depth is about US$ 15,000/well installed. Collection trenches and blankets can also be used to increase gas collection efficient. The US EPA estimates gas collection to be about 60 to 85 percent efficient in general with a comprehensive collection system (US EPA AP-42). Studies on well designed and operated gas collection systems have shown efficiencies of more than 90 percent (SWANA, 2007).

### Table 30: Levels of Landfill Gas Recovery Systems

<table>
<thead>
<tr>
<th>Technique</th>
<th>Considerations for Deployment</th>
<th>Benefits</th>
<th>Relative Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive Vent</td>
<td>Landfill has a cover which tends to trap gas</td>
<td>Controlled emission source. No GHG destruction</td>
<td>Lowest cost</td>
</tr>
<tr>
<td>Passive Vent + Flare</td>
<td>Sufficient gas to burn at a flare</td>
<td>Methane destruction</td>
<td>Modest cost</td>
</tr>
<tr>
<td>Active Collection + Flare</td>
<td>Gas collection network, blower (vacuum source), central candlestick flare</td>
<td>Increased gas capture and methane destruction</td>
<td>Cost can be substantial depending on size of collection network</td>
</tr>
<tr>
<td>Active Collection + Gas Utilization (Heating)</td>
<td>Methane content in the gas sufficient to enable combustion heating</td>
<td>Methane destruction + heating</td>
<td>Substantial capital and operating costs</td>
</tr>
<tr>
<td>Active Collection + Gas Utilization (Electricity)</td>
<td>Methane content, quality, rate of production consistent for electricity generation</td>
<td>Methane destruction + electricity</td>
<td>Highest capital and operating costs</td>
</tr>
</tbody>
</table>

Active gas collection systems allow the possibility of utilizing the methane gas either in a heating application or to generate electricity. Which option is selected, will depend on the amount, quality, and rate of gas production. In addition, the decision to utilize the methane gas will rest on available capital and operational funding along with appropriate end uses for the heat or electricity.
Figure 28: Passive Gas Vent at Municipal Solid Waste Landfill in Brazil (no destruction of the methane gas)

Figure 29: Blower System to Create Lower Pressure to Facilitate Landfill Gas Collection and Candlestick Flare to Combust the Methane Gas

3.7.3 Recommendations

The five regional landfills have a common theme with size ranging from 1.5MW to 2.22 MW in 2030. This is a variation of 1.48 to 1. These sites are all consolidated sites to take advantage of larger amounts of waste in order to make electrical generation and
heat and power uses feasible. Multiple forces combine today to make this even more advantageous including global warming and the desire to reduce GHG in the atmosphere, the increasing cost of energy worldwide, the increasing quality of living standards worldwide, and the improved ability to manage landfills to capture biogas effectively. Carbon credits and the value of electricity and of potential heat applications combine to make powerful economic incentives for development of landfill gas management. The West Doce landfill has not yet been sited, but one potential site is to append it to the existing municipal site. It is instructive to present the analysis of expanding the municipal site to a regional site, since a basis for treatment of Colatina municipal landfill has been presented, and it becomes a baseline for the regional landfill. In addition, a full treatment of West Doce allows an abbreviated treatment of the other four sites, based on use of West Doce as a template.

3.7.3.1 West Doce Regional Landfill

The current site, known as Colatina Municipal Landfill, is described in the PROMAR SOP report on pages 160-167 has been in operation for nine years, and will continue to operate until 2030. This site has been chosen as the site of the West Doce Regional Landfill under the “ES Free of Dumping Sites” Program. This site will service the needs of the following 16 municipalities: Mantenópolis, Águia Branca, São Gabriel da Palha, Vila Valério, Alto Rio Novo, Pancas, São Domingos do Norte, Governador Lindenberg, Colatina, Marilândia, Baixo Guandu, Itaguaçu, São Roque do Canaã, Laranja da Terra, Itarana e Afonso Cláudio.

The current general design of Colatina landfill is not appropriate for the new regional landfill. The operational issues at the current site that need to be addressed before the site should increase in size include: labor strikes and issues, daily and intermediate cover, waste slides, such as one that occurred in 2009, which may very likely have resulted from a combination of excessive rainfall and leachate injection, review of methods used for waste compaction, and formation of a suitable buttress to resist waste slides. Other issues to address include a plan to collect effectively all available gas and use it to generate revenue by process heat use and or electric generation.

The estimated amount of methane that is expected from the municipal Colatina landfill from 2010 to 2030 is 44,500 tonnes of methane. If the municipal site in Colatina is expanded for the new regional landfill, the site would expand from 10 to 50 ha and 108,731 tonnes of methane are expected to be generated from the West Doce Regional Landfill between 2010 and 2050. Release of this amount of methane to the atmosphere would result in a GHG emission of 2,124,671 tonnes of CO₂. Nearly tripling the amount of gas production measurably improves the economic potential for this landfill.

Colatina Regional Landfill should be designed for maximum gas production and utilization resulting in possible energy generation of 383,000,000 kWh electrical power worth an estimated US$ 57,000,000, and with estimated carbon credit value of US$ 40,000,000 over the course of 40 years. This will only be possible using a geomembrane cover with soil overlay, good daily management, and well maintained gas collection and cleaning network, regular O&M and attended and appropriately operated generators and flares. These estimates are preliminary, and need to be re-evaluated during the course of a final design study that takes into account all pertinent factors.
The costs associated with the recommended system include a selection yet to be made between reciprocating engine and microturbine driven generators, either type costing in the range of US$ 6 million over the life of the landfill. Capital equipment costs will be paid out over time as the capacity of the landfill grows according to the plan. Auxiliary equipment for housing, switchgear and gas cleanup equipment is included conceptually. Operations are expected to require 10 full time operators to maintain a 24-7 operation at the landfill to operate the generators, plus associated staff to manage the land filling process and equipment. In the US, the generator operating staff would be expected to have an associated cost of approximately US$ 400,000 per year. Filters and other materials required for operation while not insignificant are relatively small monetary expenditures compared to labor and capital machinery. All costs must be reviewed with final quotations and labor pricing realistic to the region. The nominal summary operating costs over forty years of the factors presented is estimated at US$ 22 to US$ 25 million.

Of course, the costs described above are time based expenditures and the comparison of the present value of expense vs. the present value of operating income requires an in-country analysis with final design factors included. In general, the expenditure of US$ 25 million to gain a return of more than US$ 100 million could be a wise investment.

DETAILED DESIGN INFORMATION

For purposes of this analysis the current landfill site at Colatina is considered the likely expansion site for the West Doce Regional Landfill which is designed to be 500,000 m². Only 100,000 m² are being used currently, as shown in Figure 30. If the site is expanded to the West Doce Regional Landfill in 2010 it will have an operational life of 20 years, therefore the landfill will close in 2030. This is the basis for the current analysis. The site will continue to produce useful gas for 20 years beyond its open life; therefore calculated benefits span 40 years from 2010 to 2050.

Figure 30: Colatina Municipal Landfill in 2009, operating as a local, municipal facility.

The Colatina Municipal Landfill is a 10 hectare site, or 100,000 m² in area. The physical boundary, if square, would be 316 meters on a side; or 1036 feet. This is consistent with the size bar on the Google picture of the site (Figure 30). When expanded to a
regional landfill site, it will be 50 hectares (500,000 m²), therefore if square, would have sides of 707 meters on a side, or 2,320 feet. The location of the 50 ha site is not known at this time. Google views of the surrounding area indicate that the location may support the proposed site.

The site was opened in 2000, and will have approximately 285,000 tonnes of waste in place by 2010. Total volume of waste in place at closure of the regional facility is estimated to be 2,313,000 tonnes. The graph of gas generation based on the LandGEM model and Mexico model (Figure 31 in this report) is shown in PROMAR’s SOP report, Figure 75, page 179. LandGEM figures are used here to be conservative. The estimated power generation using the landfill gas is shown in Figure 32. The model assumes a new LF starting in 2010, whereas there will be a base that is ten years old, making this a very conservative analysis.

Landfill Gas Production Prediction for West Doce - Colatina LandGEM Model

![Graph showing biogas generation as a function of time for the West Doce Regional Landfill](image)

Figure 31: Biogas generation as a function of time for the West Doce Regional Landfill
Figure 32: Electricity generation as a function of time for the West Doce Regional Landfill

The rainfall at Colatina was reviewed in a prior section of this report, and the analysis remains the same. In addition, the arrangement of a collection system was reviewed, and with amendments the approach can be used with this and other regional landfills. Whereas the rainfall at the various locations within ES does vary, the similarity with Colatina is apparent, and the recommendations remain the same within tolerances of this study.

TECHNICAL ANALYSIS SUMMARY

Our analysis considers the following understanding of the future operational design of the West Doce Regional Landfill. The site was originally opened as the Colatina Municipal Landfill in 2000, with an operational life of 30 years, and would close in 2030. As a municipal site it is serving 106,637 residents who were generating 2,687 tonnes of waste a month. After expansion to a regional site serving 16 municipalities the site is responsible for serving 347,884 residents producing 8,629 tonnes of waste a month.

Obviously, the entire landfill is not operational at any one time. Intermediate layers are designed to be 10 meters deep, and daily cover is 5 cm thick. Cells are 1 hectare in area and a cell is filled to 60 meters capacity (6 by 10 meter layers) and capped prior to moving onto another cell. The final cap is 60 cm of soil. The use of a geomembrane is considered optimal and should be included in the regional landfill. Only one cell is assumed to be operational at any time. Since the terrain around the existing landfill appears to provide suitable expansion area, and the area appears to be similar in profile, this study assumes similar operational characteristics for the regional landfill.

Leachate considerations

A capped cell is reasonably impermeable to rainfall, and has channels to divert rainfall to the stream. This runoff water is not leachate, and can diverted to the stream without environmental effect. Similarly, cells of the landfill that have not been lined, and are not
being filled with waste, allow rainwater runoff to the stream, and do not contribute to leachate. Leachate is formed by rainfall falling directly on the active landfill cell where the water can permeate the cover. Runoff factors for different types of cover range from 0.15 for clayey soils to 0.075 for loamy soils, indicating that this fraction runs off the waste, and the remainder soaks into the waste and is subject to contamination referred to as leachate. Part of this water is absorbed into the waste, and some fraction runs to the base of the waste and is collected. Recirculation of the leachate is one effective way of disposing of the leachate since it is partially reabsorbed in the waste and it contributes to accelerated methane generation. An excess of moisture in the waste can cause instability in the pile and waste slides, which must be avoided. Leachate control can be accomplished by active evaporation or by ponding for later reuse.

Leachate recirculation can be done without causing instability, as long as the waste moisture does not exceed about 40% of the void space in the waste pile (Note: 40% void saturation is an estimate. It is strongly recommended that stability analyses be performed prior to operation of any leachate recirculation into the waste to better control the operation and ensure the stability of the waste mass.). When moisture becomes excessive, i.e., leachate is collected at the base of the landfill, other methods of disposal of excess leachate must be considered. There are two options: (1) the leachate can be pumped to a holding pond and held until a drier time, and then reintroduced into the waste to accelerate biodegradation; and, (2) the leachate can be evaporated using LFG as fuel, thereby using the LFG in a process heat operation. The heat for evaporation can be developed either as waste heat from electrical generation or as an independent process heat. The analysis of rainfall and leachate generation at Colatina was based on data from:


When applied to the normally exposed 1 hectare area of active landfill at Colatina, this analysis resulted in excess leachate during November to January, or for three months. Some of this leachate can be usefully recycled into the waste mass. Recirculating all of the leachate into the waste may cause instability. For the purposes of design, assume that all of the leachate will be pumped to a pond and held during the three month accumulation period; or that an evaporator will be purchased and used with LFG to evaporate the leachate, and that the resulting solid waste will be land filled.

The size of pond required is estimated to be 1,375 m³, with an inverted pyramidal design of 40 meter square base and depth of 3 meters, to hold the three month volume (1,584 m³ actual). The pond will require lining in order to eliminate leachate percolation into the ground water. The cost of the lining geomembrane is US$5 per square meter, or a material cost of US$8,000, in addition to labor to excavate and line the pond estimated to be one man month and use of a bulldozer. Total cost in the US is estimated to be US$18,000.

If the leachate were to be evaporated using the LFG, the evaporator size required would be 800 liters per hour, with an estimated to cost US$ 280,000 in the USA, plus installation. Operation would use the heat of burned LFG, either as direct heat or as waste heat from a generator engine. The evaporator would operate 3 months of the year, and require 127 m³/hr of methane. According to the SOP Brazil study, Colatina can supply 423 m³/hr at maximum output, therefore capacity exists in abundance, and heat can be supplied with available LFG, either direct or as waste heat from electrical generation. Because of the seasonality of rainfall leading to a short season of excess leachate, recirculation of the leachate appears to be the better use since these results in accelerated generation of LFG.
Evaporation of leachate provides better overall use of the heat energy, but does not contribute to the economic condition of the landfill, and requires a significant capital investment, therefore is not recommended. Heat uses that provide economic outputs or environmental benefits might justify the expenditure on equipment, but an evaporator does not provide economic justification.

**Cover considerations**

The GHG reduction depends on effective capture and destruction of the methane which is expected to be less than 100% efficient due to system leaks, combustion efficiency, etc (US EPA 2009 [http://www.epa.gov/landfill/faq-1.htm#q9](http://www.epa.gov/landfill/faq-1.htm#q9)). For the lifetime of a landfill, say 100 years, USEPA conservatively estimates 75 percent of the landfill gas (methane) will be captured and destroyed given a well-operated LFG recovery system during the operating and post-closure (30 years) period of the landfill. The IPCC report (IPCC 4th Assessment Report, Chapter 10 – Waste Management (p. 600),) surveyed landfill practices around the world and estimated that the effectiveness of LFG recovery can be as low as 20 percent and highly depends on operating practices at a given facility. Spokas et al. (2005) developed data for which the French government established default values for percent recovery of LFG as follows: 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery. Table 31 shows the potential GHG reduction at the West Doce Regional Landfill, between 2010 and 2050 depending on the efficiency of LFG capture and subsequent use (or destruction) methods. The table converts tonnes of methane produced to tonnes of CO₂ equivalent reduction into the atmosphere using the well known factor of 21 times the amount of methane.

In view of the known problems with covers relative to long term performance, there is no reason to consider anything but a geomembrane cover system. The return on investment from electricity sales and carbon credits based on this approach, are accompanied by a significantly lower risk factor for the long term.

<table>
<thead>
<tr>
<th>Efficiency of Gas Collection and Destruction Systems (%)</th>
<th>Tonnes of GHG destroyed (in CO₂ equivalents using 21 factor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>899,316</td>
</tr>
<tr>
<td>60</td>
<td>1,348,974</td>
</tr>
<tr>
<td>80</td>
<td>1,798,632</td>
</tr>
<tr>
<td>87 (90% x 97%)</td>
<td>1,956,012</td>
</tr>
</tbody>
</table>

1Efficiencies represent the range of expected LFG recovery and GHG destruction possible given a range of LF operating conditions. Low efficiency is based on a 0.6 m soil (only cover) while high efficiency is based on a composite cover (compacted soil + geomembrane). The range assumes a well-functioning LFG collection system (Spokas et al. *Waste*, 2006)

The recommendations listed herein are based on a start date of January 1, 2010, as a reference point. They must be considered preliminary since a detailed study of the landfill must be undertaken to determine actual operational and site specific conditions. The detailed studies should be commissioned as a future part of the Master Plan for ES.
The LFG at West Doce Regional Landfill should be captured using a manifold system connected to gas wells. A leachate system should be designed to provide a pathway for collecting leachate but also to provide a way to inject the leachate back into the waste. Leachate is primarily formed during the months from November to January, and should be returned to the waste mass, with excess leachate stored in a holding pond. While the amount of waste taken in daily will approximately triple relative to the current Colatina operation, the approach at landfill operations should not change. The main difference is that the active cell will fill and be covered more quickly, but the area exposed to leachate generation will remain the same, and thus the leachate will remain the same from the active cell. However, we can expect some additional leachate from the "closed" cells simply because there will be infiltration through the cover system (assuming a 0.6 m soil cover). A crude estimate is that additional leachate from each closed 10 ha area to be less than 5 percent of the leachate of that calculated for the operating cell. This additional amount does not materially affect the design of a holding pond for leachate. A 40 m² by 3 m deep pond should be sufficient for holding the excess. In order to avoid odor and vector issues, the leachate pond can be covered using a "floating" cover system (Koerner 1998).

Gas produced at the West Doce Regional Landfill should be used to generate electricity using one of two types of generators, those being reciprocating engine gensets or micro turbine gensets. Peak generating potential is 2.27 MW in 2030, whereas the practical range is from 1.5 MW (60%) to 2.27 MW (90% gas collection). The range is determined by the design and construction quality control of final cover and gas collection system. In this analysis, 90% gas collection is assumed and used for electric generation.

Operational considerations

Good construction quality control (CQC) and construction quality assurance (CQA) coupled with good operating practices are essential for effective recovery and economic utilization of landfill gas. While CQC and CQA focus on the construction aspects of the landfill (liner, cover, leachate collection and gas collection systems), the operating practices include: waste handling, placement and compaction, timeliness of cover placement, and operating procedures for the gas and leachate collection system. Guidance is available for maintaining high level CQC and CQA (Daniel and Koerner 2007), along with best management practices for landfill operations, e.g."Landfill Operations Training Course October 10, 2008 - Universidad I-Salud Buenos Aires, Argentina" (http://www.methanetomarkets.org/events/2008/landfill/docs/landfill-10oct08_wrkshp_eng.pdf, last accessed 11 Sept 2009) or “Solid Waste Landfill Guidance” Section 9, (http://www.deq.state.or.us/lq/pubs/docs/sw/SWGuidance09.pdf, last accessed 11 Sept 2009). Solid Waste Association of North America (SWANA) offers numerous training programs for landfill operations and certification of operators also through their education branch (www.swana.org). CQC programs are typically developed in the design phase. Operating procedures developed during design, often undergo frequent modifications and adjustments as practices and/or conditions change. It is recommended that landfill operators routinely participate in updated training sessions regarding specific elements related to their particular facility.

Different types of intermediate and final cover have different effectiveness in containing and collecting LFG, ranging from considerably less than 50% to perhaps 90% at the most. Consideration of efficiency is a critical step in determination of LF design for cover, collection, gas cleanup, and utilization. The final economic benefits will depend on the amount of gas that can be usefully deployed; and the more effective collection methods cost more than the less effective, so cost benefits analysis is required to
determine if a more efficient system provides more benefits per unit cost, or vice versa. Also, sizing of generators or of heat applications depend on accurately determining the availability of gas. Seasonality of gas production is an issue in all installations.

In general, the LandGEM model provides an annual average amount of LFG potential for the LF design. The potential can only be realized with appropriate cover and collection. The West Doce Regional Landfill has potential for landfill gas collection and utilization such as direct heating or electricity generation, both of which can reduce the release of methane (a greenhouse gas) to the atmosphere (SOP p.163-4). A key element in capturing the landfill gas for any application is the gas containment and collection system. Containment systems consist of a low “gas” permeability cover system while the collection system may be vertical wells, horizontal pipes or drainage blankets, or combinations of all three methods. The following discussion concerns the types or cover systems available for the West Doce Regional Landfill, their relative advantages and budget estimate costs (US Dollars).

When completed, the West Doce Regional Landfill will cover approximately 50 ha in spatial extent. Thus, the final cover system will be approximately 50 ha. The currently proposed final cover system is 0.6 m of onsite soil cover (SOP p.162). Such a cover will provide a good barrier between human or other vectors and the waste; however, a 0.6 m soil cover will be at best moderately effective at containing the landfill gas within the waste mass. If the cover soil dries out and cracks the gas barrier function is poor (Koerner and Daniel, 1997). Regardless of the effectiveness of the landfill cover, the purpose is to trap the landfill gas in the waste mass and prevent its release to the atmosphere. The gas must be collected and removed from beneath the cover otherwise it will either seep through the cover or travel laterally to escape from the landfill and eventually end up in the atmosphere. To counter this, a gas collection system is installed before or after the cover is placed. The cover and the collection system function together to contain and collect the landfill gas making it possible for beneficial use or at the minimum, destruction (through combustion) to lower impact constituents.

At the West Doce Regional Landfill, gas generation models predict a peak gas generation of 1,772 m³/hour by 2030 and then a rapid decline in the rate (SOP p. 177). This study will consider gas generated through 2050 as important which will include considerable gas generated after closing, and more importantly, at least 97% of all gas to be generated at this landfill. In order to recover most of the gas a cover system must be installed. More effective cover systems produce greater percentages of gas recovery available for utilization. There are many choices for cover systems and each one has its advantages. The following cover systems are available for West Doce Regional Landfill (Table 32).

<table>
<thead>
<tr>
<th>Technology</th>
<th>Estimated Cost (US$)</th>
<th>Est. Cost per Hectare (US$/ha)</th>
<th>Efficiency of Gas Control</th>
<th>Total Methane Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil Cover (0.6 m)</td>
<td>6/m²</td>
<td>60,000</td>
<td>Low (30 to 60%)</td>
<td>20 to 50%</td>
</tr>
<tr>
<td>Soil Cover (1.5 m)</td>
<td>15/m²</td>
<td>150,000</td>
<td>Moderate (50%)</td>
<td>50%</td>
</tr>
<tr>
<td>Soil Cover (0.6 m) + Geomembrane (≥ 1 mm)</td>
<td>Soil 6/m² Geomembrane 5/m²</td>
<td>110,000</td>
<td>Good (60 to 90%)</td>
<td>59 to 88%</td>
</tr>
</tbody>
</table>
A lateral drainage layer may be necessary below the soil cover to facilitate drainage of infiltration so that it does not pond on the surface of the geomembrane thereby reducing the stability of the cover system on slopes.

For the lifetime of a landfill, say 100 years, US EPA conservatively estimates 75 percent of the landfill gas (methane) will be captured and destroyed given an effective cover and a well-operated LFG recovery system during the operating and post-closure (30 years) period of the landfill. The IPCC surveyed landfill practices around the world and estimated that the effectiveness of LFG recovery can be as low as 20 percent and highly depends on operating practices at a given facility. Spokas et al. (2005) developed data (ultimately used by the French government) to establish default values for percent recovery of LFG as follows: 35% for an operating cell with an active landfill gas (LFG) recovery system, 65% for a temporary covered cell with an active LFG recovery system, 85% for a cell with clay final cover and active LFG recovery, and 90% for a cell with a geomembrane final cover and active LFG recovery.

The poor hydraulic performance and gas containment performance of soil (only) covers has been well documented by Melchior et al (2008) and Suter, Luxmoore and Smith (1993).

Based on a 98% efficient destruction technology, (e.g., open flare).

The existing gas collection system at Colatina Municipal Landfill is a series of vertical wells through the waste mass. As the final cover is placed over the waste, gas will be directed to the wells. It is recommended that a manifold system of pipes be placed on the surface or buried in the cover soil of the competed landfill (in areas that have received the final cover) and that the landfill gas be transported to a central location for utilization.

The existing plan for the landfill shows 56 gas wells scattered across the 10 ha site which is about the typical number for site this size. Additional wells will need to be installed as the site expands. The well heads will need to be capped and tied into the pipe manifold. Typically HDPE (PAED) piping is used and inside diameter is about 0.15 m. Since the vertical wells are being installed during the land filling process, only the piping manifold and tie-in to the wellheads exist after an area is completely filled with waste. A budget estimate of the cost for wellhead tie in and piping manifold per well is US$1,500. Thus, gas flow from all of the wells should be able to be tied together and delivered to a central point for about US$119,000 per hectare (includes wellhead, piping and cover system, but not wells). In addition, an active gas collection system will require a blower and associated appurtenances to maintain a small negative pressure (typically less than 7 kPa (1 psi)) in the gas collection system. A gas system with 280 wells, placed over a 40 ha area would likely require blower of about 25 hp capable of moving at least 3,400 m³/hr. A skid-mounted, candle-stick flare capable of moving 3,400 m³/hr costs on the order of US$ 175,000 to US$ 200,000. Traditional vertical gas wells, installed after the landfill is completed, cost on the order of US$ 100 per vertical foot (US$ 300/m) and the lateral piping network (manifold) assuming SDR 17 piping is about US$ 30-40/lineal foot (US$ 100/m). The US practice is to drill the wells after the landfill is capped. The mentioned costs were obtained from landfill operators in the Midwest region of USA as of September 2009, (Bowders 2009).

The cover system will also reduce the amount of leachate infiltration into the waste. Calculations show that one can expect about a 53% decrease in the volume of leachate after a 0.6 m thick soil cover is applied (Table 33).
If the leachate volume is reduced, then the rate of landfill gas production will decrease as well, since moisture is a critical component of the biodegradation process. Gas production can be expanded by re-injecting any leachate back into the waste mass. This saves leachate treatment costs and accelerates the gas production.

The absence of leachate in the month of November for the CL compacted soil cover is a result of the increased moisture holding capacity of this soil relative to not having a cover as the case for the uncovered waste mass.

A budget estimate for Colatina including a soil + geomembrane cover and six (6) gas wells per ha (US$ 1,500 per well) is US$ 119,000 per ha. This cost assumes that the wells are already installed during the filling of the landfill, i.e., there is no cost included for the construction of the gas well. However, typical costs for vertical well installation (Midwest USA) is US$ 300 per meter of depth. A revenue stream is possible from the sale of the gas (or electricity generated from the gas) and also for the carbon credits associated with destruction of the greenhouse gas (methane). Colatina landfill depth is 60 meters, so an individual well will cost about US$ 18,000.

Covers have been described in other reports from this program, but we reiterate here that soil covers alone lack long term continuity to provide good seals over the LF, and therefore the precipitation infiltration and gas leak rate is high. Geomembranes in combination with an active gas collection system achieve perhaps 50-70% effectiveness, while good covers using geomembranes and deep soil cover provide perhaps 90% efficiency of harvesting the potential of the landfill (Spokas et al., 2006).

### Flare considerations

At a minimum, LFG should be flared to reduce the GHG effects. It is well documented that methane is 21 times more deleterious to the atmosphere than CO$_2$, and so burning the methane to generate CO$_2$ is a minimal step in environmental protection. This step allows claim on carbon credits, valued in Brazil at about 14 Euros per tonne.$^{14}$

If the LFG is piped to a central location for use in direct heat or electrical generation applications then a single flare can be used to flare the extra LFG or when the generation equipment is down for maintenance. Flares, such as the line of flares offered by Flare Industries, Inc., can be purchased to be able to flare the entire amount of gas generated by the landfill. They offer semi-enclosed flares and fully-enclosed flares. The semi-enclosed flares, also called open flares or candlestick flares are considerably cheaper while only having a slight decrease in combustion efficiency.

### Heat applications

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LFG can be burned either in direct fired furnaces or in electric generator engines where the heat of combustion can be used in addition to the generated electricity to provide benefits.

There are two apparent choices available at this time for heat use at Colatina. Evaporation of leachate and heating of medical wastes in the available incinerator are possible applications.

**Evaporators**

Evaporators were studied for the Colatina LF and found not to be economical. The same recommendation is made for all regional landfills.

**Incinerator**

No details have been provided on the incinerator, but it is assumed to be gas fueled equipment. In this event, converting the incinerator to LFG would likely be a minor technical issue. No cost is provided due to the lack of size information. It has been stated that this incinerator has not always performed satisfactorily, but the reasons have not been given. A comprehensive review of the medical waste incineration issue is recommended to be done exclusive of this report.

The much larger landfill that the regional option provides should definitely provide an electrical generation option. The amount of waste heat still available after generator operation is substantial, and an effort to use this energy would potentially improve an already good economic project.

**Electric Generators (Gensets)**

While six particular generator technologies were reviewed in this study, only three have practical applications for the ES landfills. Of those three, only two are practical for the West Doce Regional Landfill, as the Sterling engine capacity is too small. The two types include gensets powered by reciprocating engines or micro turbines (MT). Both of these engines require substantial gas cleanup prior to introducing the gas to the engine, and the cleaning equipment has substantial capital cost as well as recurring operating cost. The cleaning of siloxanes is particularly important for micro turbines since a small amount of siloxanes in the gas will ruin a turbine in a few hours of operation. The sensitivity of microturbines to siloxanes makes gas cleaning about twice as expensive for these engines, when compared to reciprocating engines (US$ 2,000 per Kw capacity vs. US$ 1,000 per Kw capacity).

The advantages of reciprocating engines are that they are a well established technology, and easy to maintain. They are long lived, and can be rebuilt at intervals to provide more than 20 years of continuous service.

The advantage of micro turbines is their low environmental gas emissions. MTs are used in major US cities to reduce emissions below requirements, especially for NOx emissions. Their disadvantage is first capital cost, although MT maker Capstone argues that their long term operation costs and low downtime justifies the first cost, and make them competitive with reciprocating engine generators. This is not a commonly held understanding.

Each of the gensets discussed is available in unique sizes favored by their manufacturers, and so direct comparison is made more difficult, since size overlaps
occur for each technology. Generally, for the ES landfill applications the sizes below are available for consideration. While several manufacturers are available for each technology, only one manufacturer has been identified for the purposes of this study, and future studies should make comparisons of competitive machines for final selection, based on feature set and cost. The options for gensets are shown in Table 34.

Table 34: Comparison of Candidate Generators for West Doce

<table>
<thead>
<tr>
<th>Genset</th>
<th>Kw rating</th>
<th>Capital cost</th>
<th>Quote basis</th>
<th>Location</th>
<th>Budget Installation cost US$</th>
<th>Gas cleanup US$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capstone MT 30</td>
<td>30</td>
<td>46,400</td>
<td>US$</td>
<td>outdoor</td>
<td>46,400</td>
<td>60,000</td>
</tr>
<tr>
<td>&quot; 65</td>
<td>81,900</td>
<td>&quot;</td>
<td>81,900</td>
<td>130,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&quot; 200</td>
<td>272,300</td>
<td>&quot;</td>
<td>272,300</td>
<td>400,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jenbacher reciprocating Model 208 335</td>
<td>335</td>
<td>268,127</td>
<td>EURO</td>
<td>Indoor</td>
<td>382,456</td>
<td>335,000</td>
</tr>
<tr>
<td>&quot;Model 312</td>
<td>633</td>
<td>393,008</td>
<td>EURO</td>
<td>&quot;</td>
<td>561,716</td>
<td>633,000</td>
</tr>
<tr>
<td>&quot;Model 320</td>
<td>1059</td>
<td>519,865</td>
<td>EURO</td>
<td>&quot;</td>
<td>741,535</td>
<td>1,059,000</td>
</tr>
</tbody>
</table>

The choices for West Doce Regional Landfill are use of either GE Jenbacher reciprocating engines or Capstone micro turbines. There are other manufacturers of both types of gensets, however these are the companies used for evaluation of the technology.

**Equipment recommendation for West Doce**

The regional landfills have been designed to take advantage of the amount of waste by consolidating it into larger quantities, making gas generation and use a viable option. The best option for gas use is generation of electricity, and two options are available for West Doce, including a reciprocating engine driven generator such as the GE Jenbacher 312, and the Capstone Microturbine 200 Kw generator. This does not minimize options for process heat that may arise, but lacking particular direction from Brazil for process applications, no process application is presented. The exhaust gas from the microturbine exits at approximate temperature of 260°C (500°F). The gas
Figure 33 is based on 90% collection efficiency, and maximum utilization of the capacity of the machinery to follow the gas generation curve. This can be done by installing equipment as soon as it is capable of being utilized at a minimum level, and then installing similar machinery prior to the equipment in place becoming capacity loaded. For the Jenbacher, the utilization range is between 0 and 335 Kw, with emissions being guaranteed for 50% load and above. For purposes of this study, the load range is taken to be 165 Kw to 335 Kw. Thus, this machine can be started in use as soon as gas to generate 165Kw is available. From that time on, all gas being generated by the landfill can be usefully burned in generators without losses. Very little gas is wasted, and that amount would be flared, thereby providing ability to claim carbon credits. Of course, carbon credits can be claimed on the generated electricity, since the methane is converted into CO₂ in combustion.
Figure 33: Estimated potential energy and number of gensets over time at the West Doce Regional landfill.

The situation is similar for the Capstone microturbines, except there is no starting amount of gas where gas is not utilized. Microturbines can operate from 0 to 100% of capacity rating, so as long as another microturbine is available at the time gas capacity is reached, the next microturbine is effectively used immediately without delay. Therefore the microturbine gas utilization curve is the same as the availability curve, providing a slightly better gas use than the reciprocating engine generators. Both, however, provide significant use of available LFG.

The cost of Jenbacher 312 generators is €393,008 each, and the cost of auxiliary equipment, switchgear and building indoor facilities should be budgeted to be a comparable investment. The cost in US is then US$ 1,123,432. Gas cleanup should be budgeted at US$ 1,000 per Kw capacity, or US$ 335,000 additional, for a total of US$ 1,458,432. Since four Jenbacher 312 generators would be used in the approach suggested, the total investment is 4 x $1,458,432 = US$ 5,833,728 over the period. Operating expenses are not included, and a facility of 4 generators is expected to require two full time operators, on a 24-7 basis. Approximately 10 persons are expected to be associated with a well functioning generator operation, generally throughout the life of the LF.

The Jenbacher 312 generator has generating ability from 315 Kw to 633 Kw with emissions within specification. The next larger size is the Jenbacher 320 which is rated for output from 528 to 1056 Kw. Two of these machines could also be used, but the smaller machines provide more flexibility.

Capstone 200 Kw micro turbines can be located outside, but still require switchgear, and housing for the switchgear. MTs are considerably quieter than reciprocating engines. Budget for auxiliary equipment, switchgear and facilities, should be
considered the same as the capital cost of the generators. However, cost of gas cleanup is more expensive for microturbines, and should be budgeted at US$ 2,000/Kw of capacity, therefore US$ 400,000 per generator. The budget installed cost of each machine is then US$ 800,000. During the life of the LF eleven generators are required, thus the final investment is US$ 8,800,000. While more than for the Jenbacher equipment, the uptime of the MT should be better than the JB, and the cost of rebuilding is lower. Operational personnel are expected to be similar to the Jenbacher approach, but filter materials and maintenance should be considered in an operational situation. Actual gas quality will affect the capital cost of gas cleanup equipment for both types of machinery, their maintenance schedules, and frequency of overhaul.

Operational maintenance will be easier to do for the Jenbacher since the technology is common to all reciprocating engines, and technical support will be easier to find. Training for microturbines can be purchased from Capstone, and trained mechanics will be specialists. Both machine types provide sophisticated maintenance computer monitoring and control, and include significant operator aids to insure good operation. Both companies have Brazilian operations, but are not located in ES. The approach of using multiple machines for either machine type insures that downtime maintenance can be scheduled without significant affect on operating to capacity.

The Jenbacher approach is expected to generate slightly less energy than the Capstone approach, since there are some time intervals in the run up to 1000 Kw that are not covered fully; and the rundown after closing also has the same feature. Either approach should reach the estimated power generation of 380,000,000 kWh. At a value of US$ 0.15 per kWh, the value is about US$ 57,000,000. Either equipment approach appears to have a favorable payback, and final decision should be made on a basis of a final design and cost benefits study. This should include a review of equipment offers from other vendors as well.

The value of carbon credits over the life of the landfill appears to be in the range of US$ 40,000,000 based on current carbon credits at 14 Euro per tonne CO₂.

Summary recommendations

Based on the preceding analysis and information, it is recommended that:

- The existing landfill be completed (filled in) in working areas of 1 hectare, completing (closing) each section prior to moving onto the next.

- Upon completion, place a composite cover including a geomembrane and 0.6 to 1 meter of soil on top of the waste and vegetation the cover with appropriate (native) vegetation while being careful not to use deep rooting plants which tend to destroy the integrity of the cover system.

- Cap each well, and collect LFG at a central location, where reciprocating engine gensets or microturbine gensets are located along with a flare to burn the excess LFG. The engines would burn all available gas to capacity of the engines, and excess would be flared.

- Electricity generated would be sold to the local utility at a fraction to be determined of the current retail residential cost of electricity in ES. The selling fraction needs to be negotiated with the local authorities, but an assumption of 60% is used here for financial feasibility estimates.
Recent evaluation of electric rates in ES was accomplished. Rates are composed of a use portion and an allocated portion. The combination of the two results in a rate of $0.50 Real (US$ 0.26) per kWh. Use of a 60% factor for electricity fed to the grid will result in payments of US$ 0.15 per kWh.

An option for “flaring only” exists, using the high quality landfill cover and collecting and flaring all gas collected, without other use of the gas. The 41 year total of carbon credits that is available under this approach appears to total more than US$ 40,000,000, with the assumed value of 14 Euro per carbon credit, and 90% collection efficiency and with 97% flare efficiency.

Analysis on this basis used a value of electricity returned to the grid of US$ 0.15 per kWh, an operating staff of 10 full time people for the 24x7 generating facility, personnel cost of US$ 30,000 per person per year, which returns an estimated excess of US$ 38,000,000 through 2050 after all costs are subtracted. The capital cost of the facility is estimated at US$ 19.5 million spread through the period. This includes the cover and gas collection cost of US$ 7,875,000, a cost which is required to simply flare and collect carbon credits (CC). Thus the incremental capital cost for electrical generation when compared to only flaring gas is US$ 6 to 8 million. A formal economic analysis will be completed after a final design plan for West Doce is approved. The GHG emission potential of the landfill totals 107,060 tonnes methane, or 2,250,000 tonnes of CO₂. Appropriate landfill management can minimize the effect on the environment to 481,000 tonnes CO₂ for a reduction of 87% of the potential effect. When carbon credits are added to the 41 year electricity revenue total, the net return is estimated to be greater than US$ 100,000,000.

This analysis is preliminary and does not include all costs associated to the implementation of such a project, but the study indicates that the capital cost of machinery for electric generation would be financially rewarding.

### 3.7.3.2 All Regional Landfills

All regional landfills should be operated in a consistent fashion, and based on highest possible gas collection to maximize total return. These landfills will operate for 20 years, and continue to make biogas for another 20 years thereafter, making this a 40 year investment opportunity. Two tangible revenue streams are available: electricity generation and carbon credits. Intangible benefits mentioned earlier in the report include reduced dependence on externally controlled sources of power, better quality of life, and reduced global warming.

Table 36 below provides a comparison of the five regional landfills and the benefits that would accrue from high gas collection approach to management. Less efficient gas collection approaches still return financial incentives, but they offer substantial reductions in return and significant increases in risk of poor performance. The primary differences between excellent gas collection and the other options are the geomembrane, and its lifetime maintenance. Of course, appropriate maintenance of all functional equipment for the landfills is required.
Table 35. Tangible benefits from recommended treatment of 8 landfills.

<table>
<thead>
<tr>
<th>LANDFILL NAME</th>
<th>Methane 20 year tonnes</th>
<th>Methane 40 year tonnes</th>
<th>Methane tonnes CO₂ (21 factor)</th>
<th>Efficiency (generate/heat/flare)</th>
<th>20-40 year CC @ 14 Euro (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colatina</td>
<td>33,485</td>
<td>33,485</td>
<td>703,185</td>
<td>87%</td>
<td>$12,583,902</td>
</tr>
<tr>
<td>Cachoeiro</td>
<td>9,483</td>
<td>9,483</td>
<td>199,143</td>
<td>87%</td>
<td>$3,563,645</td>
</tr>
<tr>
<td>San Mateus</td>
<td>7,691</td>
<td>7,691</td>
<td>161,511</td>
<td>87%</td>
<td>$2,890,418</td>
</tr>
<tr>
<td>South Plateau</td>
<td>148,658</td>
<td>148,658</td>
<td>3,121,818</td>
<td>87%</td>
<td>$55,866,531</td>
</tr>
<tr>
<td>Norte</td>
<td>110,959</td>
<td>110,959</td>
<td>2,330,139</td>
<td>87%</td>
<td>$41,699,030</td>
</tr>
<tr>
<td>East doce</td>
<td>102,113</td>
<td>102,113</td>
<td>2,144,373</td>
<td>87%</td>
<td>$38,374,554</td>
</tr>
<tr>
<td>West doce</td>
<td>107,601</td>
<td>107,601</td>
<td>2,259,621</td>
<td>87%</td>
<td>$40,234,169</td>
</tr>
<tr>
<td>South Coast</td>
<td>100,514</td>
<td>100,514</td>
<td>2,110,794</td>
<td>87%</td>
<td>$37,773,594</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>50,659</strong></td>
<td><strong>569,845</strong></td>
<td><strong>620,504</strong></td>
<td><strong>87%</strong></td>
<td><strong>$232,985,843</strong></td>
</tr>
</tbody>
</table>

The table indicates the tangible benefits based on the best collection approach that is based on use of a geomembrane. Two landfills – Cachoeiro and San Mateus - have short lives, and Colatina municipal has a remaining life of 20 years. Five regional landfills have lives of 40 years (20 years collection plus 20 years useful gas generation). The total GGE generated by each landfill over its useful life is listed, and the expected GGE converted to CO₂ by appropriate processes as identified previously is also listed. Based on the conversion the value of the carbon credits is also provided, and the values are substantial.

The table below adds information about the electrical generation possible based on maximum capture.

Table 36: Comparison of electrical Generation Value and Carbon Credits.

<table>
<thead>
<tr>
<th>LF</th>
<th>Lifetime Total energy generation</th>
<th>Total value of Power</th>
<th>Carbon Credits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Kwh</td>
<td>$(US)</td>
<td>$(US)</td>
</tr>
<tr>
<td>Colatina</td>
<td>85,857,346</td>
<td>$12,878,602</td>
<td>$12,583,903</td>
</tr>
<tr>
<td>Cachoeiro</td>
<td>0</td>
<td>0</td>
<td>3,563,645</td>
</tr>
<tr>
<td>San Mateus</td>
<td>0</td>
<td>0</td>
<td>2,890,419</td>
</tr>
<tr>
<td>South Plateau</td>
<td>531,712,969</td>
<td>$79,756,945</td>
<td>$55,866,532</td>
</tr>
<tr>
<td>Norte</td>
<td>396,872,949</td>
<td>$59,530,942</td>
<td>$41,699,030</td>
</tr>
<tr>
<td>East Doce</td>
<td>365,981,465</td>
<td>$54,897,220</td>
<td>$38,374,554</td>
</tr>
<tr>
<td>West Doce</td>
<td>384,652,288</td>
<td>$57,697,843</td>
<td>$40,234,170</td>
</tr>
<tr>
<td>South Coast</td>
<td>361,128,357</td>
<td>$54,169,254</td>
<td>$37,773,595</td>
</tr>
<tr>
<td><strong>All Total</strong></td>
<td><strong>2,126,205,375</strong></td>
<td><strong>$318,930,806</strong></td>
<td><strong>$232,985,848</strong></td>
</tr>
</tbody>
</table>

Table 36 shows that over their lifetimes, the landfills will provide over 2 billion kWh of power to the residents of ES. The value of that power to the generator is less than is the ultimate sale to residential users by the utility, but still totals over US$ 300 million.
In addition, the carbon credits, if available at the current rates add over US$ 200 million to the returns.

While conceptual costs have been used for the landfill capital and O&M costs, in each case the totals have been substantially less than the proposed benefits, such that the ratio of revenue to costs appears to favor these investments.
4 FINAL CONSIDERATIONS

The State of Espirito has demonstrated interest and initiative towards the goal to improve the way municipal solid waste is management in the State. The recommendations described in the previous section set guidelines to attain more secure and environmental operations and better profitability in the landfills in ES. However, in order to implement those recommendations a series of factors should be considered, as present below.

4.1 FINANCIAL CONSIDERATIONS

According to the Ministry of Science and Technology the projects involving Clean Development Mechanisms may be financed by some organs. The credit mechanisms are split into onerous and non-onerous.

The non-onerous financial resources are those offered by the Union General Revenue or by the municipalities without the guarantee of return. The onerous financial resources are those from Institutional Investors such as the National Bank for Social and Economical Development (BNDES), the Caixa Econômica Federal (CEF), or even international organizations such as the International Bank for Reconstruction and Development, the Interamerican Bank of Development and other international financial agencies.

4.1.1 State Support

The FINEP (Project and Studies Financing), a public enterprise associated to the Ministry of Science and Technology, has the Development of Clean Mechanisms Program, called Pró – MDL. This program finances scientific and technological development of clean mechanisms and has two financial categories: with or without refund. The first one comprises the aid to pre-investment projects and to the technological development of solutions. On the other hand the financial category without refund is focused on the creation of new technologies and on the development of methodologies to calculate and monitor the emissions. In 2008 the BNDES created the Brazilian Sustainability Fund (FBS), which is a new financing category specifically intended to mechanisms of clean development. Caixa Econômica Federal also offers financing for clean development and sanitation projects.

The BM&F Market, in a partnership with the Ministry of Development launched in 2005 the project Brazilian Market of Emissions Reduction (MBRE), with the objective of establishing an efficient carbon credits negotiation system.

4.1.2 Carbon Credits

Besides reducing the environmental impacts and minimizing the energetic demand for non-renewable sources the conversion of methane gas into carbon dioxide in the combustion of engines or another energy conversion system causes the potential reduction of emissions of biogas related to the Global Warming. The use of biogas in the generation of energy can, therefore be classified as a Mechanism of Clean Development in the categories of external financing was cited in the Kyoto Protocol.
This mechanism is a flexibility instrument, with the objective of fulfilling the GHG emission reduction goals in the countries listed in the United Nation Climate Change Panel. Thus developing countries, as in the case of Brazil, may implement projects which contribute to the reduction of GHG emissions, obtain certificates of reduced emissions (CERs) and sell them to the global markets. One CER represents the equivalent to a metric ton of carbon dioxide (ton CO₂e).

The activities of a mechanism of clean development project follow the same steps as the project cycle:

1. Elaboration of the Project Conception Document;
2. Validation;
3. Approval by the hosting country;
4. Registry;
5. Monitoring;
6. Verification/Certification;
7. Approval of the CERs.

The 1st cycle of activities comprises the MCD project implementation phase, whereas the 2nd cycle comprises the activities that should happen during the project’s operation. In this step the Designated Operational Entity (DOE), either nationally or internationally accredited by the Executive Council or by the highest organizations of the United Nations Climate Change Panel has the function of certifying the reductions in the emissions of greenhouse effect gases and the removal of CO₂.

4.1.3 International Banks

The main sources of external financing to environmental projects are described below:

The IDB (Inter-American Development Bank) was founded in 1959, and is one of the main sources of financial resources dedicated to the social and economical sustainable development in Latin America and in the Caribbean. The International Bank for Reconstruction and Development (IBRD), created in association with the International Monetary Fund (IMF) in 1944, dedicated, since 1960, most of its resources to developing countries. This bank is known by giving financial assistance, and by its commitment to the social area.

The Andean Development Corporation (CAF) is a financial organization dedicated to the sustainable development of the member countries and to the regional integration. This corporation offers short, medium and long-term loans, financing and organization of projects without resources or without guarantees, multilateral partnerships and financial consultancy services.

The Financial Fund for the Development of the River Plate Basin (FONPLATA) has the objective of giving technical and financial support to initiatives of sustainable
development and of the integration of the member countries. The Japan Bank for International Cooperation (JBIC) finances social and economical development projects in developing counties. This bank offers resources for environmental projects, economical and social infrastructure projects, social development, amongst others, through the Official Development Assistance (ODA).

The KfW Bankengruppe invests in economical and social infrastructure projects, financial and environmental protection systems, more specifically on renewable energies and natural resources conservation and management in developing countries.

4.1.4 Grants

The National Environment Fund (FNMA) from the Ministry of the Environment was created in 1989 and has the main objective of maintaining the environmental quality. This fund attends the direct or indirect governmental administration entities, Brazilian non-governmental environmental organizations with at least one year of legal existence and non-profit Brazilian organizations with more than two years of legal existence, which have the environmental quality involved in their missions. The FNMA has resources from a loan contract with the IDB, with a Technical Cooperation contract with the Netherlands, part of the environmental infraction fines collected by IBAMA (Brazilian Environment and Renewable Resources Institute) based on the Law of Environmental Crimes and resources from the financial compensation system (Law 9.478, Aug. 8th, 1997).

The Global Environment Facility (GEF) is an international cooperation organism created in 1991 with the objective of financing projects devoted to the protection of the global environment. The initiatives must be approved by the Brazilian Federal Government in order to receive the GEF financing approval. The Federal Government approval is done through the Ministry of Planning and Budget.

The United States Trade and Development Agency (USTDA) is an independent U.S. Government foreign assistance agency that is funded by the U.S. Congress. The USTDA aims to promote economic growth in developing and middle income countries, while simultaneously helping American businesses to export their products and services and, therefore it provides grant funding to overseas project sponsors for the planning of projects that can result in demand for consulting with US companies and/or US products. The USTDA has provided in the past resources for numerous feasibility studies for renewable energy projects and studies to evaluate technologies, legal and regulatory frameworks for the development of the renewable energy field.

The Methane to Markets (M2M) is an international initiative of the United States Environmental Protection Agency (EPA) to advance cost-effective, near-term methane recovery and use as a clean energy source. The goal of the Partnership is to reduce global methane emissions in order to enhance economic growth, strengthen energy security, improve air quality, improve industrial safety, and reduce emissions of greenhouse gases. The Program provides grants to projects that are aligned to its objective and this report was produced with the funding of the M2M Program.

4.2 POLITICAL CONSIDERATIONS

The Master Plan political effectiveness depends on the following:
Municipal Authorities Support

Local Community Support.

4.2.1 Support from the Municipality

According to the Brazilian Legislation the municipal authorities are responsible for the collection, treatment and final disposal of the solid waste generated by the population. Thus, all of the solid waste final disposal areas are under the municipal authorities’ responsibility.

Any action towards using the solid waste final disposal areas, as in the case of methane capture and use, is therefore subject to the municipal authority’s approval.

This means that a methane recover project, as the one stated in this Master Plan, depends on the City Halls permission or initiative.

Considering that the municipalities do not usually have financial resources to organize a project of the complexity of a sanitary landfill methane capture system, it is probable that private companies receive concessions to develop projects of this nature.

On the other hand, private companies will only raise interest in the project if it represents a favorable financial balance, that is, if it is profitable.

It has been observed that the sanitary landfill methane capture in inactive landfills is not financially attractive. This fact forces the direct action of the municipal government, which does not always happen.

The Brazilian Public Ministry, associated to the Governmental Constitutional Power, has at times questioned the omission of the municipal power regarding the issues of inadequate disposal of municipal solid waste, demanding that the inactive sanitary landfills do not represent environmental risks.

The municipal authority may, in some cases, minimize the inadequately implemented sanitary landfills environmental impacts by collecting the methane, but this is not a common practice.

The Public Ministry has managed to have the Municipal Authorities sign the Conduct Adjustment Term (CAT), which have being representing instruments of commitment to environmental issues related to the municipal solid waste. Thus, the Municipal Authority has the constitutional right over the matters related to the solid waste final disposal and its consequences; however its actions do not prioritize the adequate solution of this problem.

According to this Plan’s understanding, the Municipal Public Power shall participate as a partner and has legal responsibility in the intermediation, together with the state and Federal Governments, of the resources for the implementation of methane capture and environmental protection actions, including the reduction of greenhouse gases emissions In the present context the municipal authorities in the state of Espírito Santo are starting to support the Espírito Santo Free of Dumping Sites project and this process may help future actions for the remediation of degraded areas and the implementation of future regional sanitary landfills.
4.2.2 **Participation of the Community**

The lack of commitment from the part of the Municipal Public Power may be the result of low participation from the community.

Although the community is responsible for all of the costs related to the Municipal Public Power, it does not demand the development of actions that may result in the environmental protection, as in the case of the solid waste final disposal.

The community’s participation is, therefore a key point for this Plan, especially with the realization that it may demand the development of more actions from the Municipal Public Power in order to preserve the natural resources.

The communities’ involvement in methane capture projects has a more educational than practical meaning. It is very important that the methane use projects include the community participation, including the academy in its operation as a way of improving the local knowledge on the solid waste issue.

On the other hand, a way of directly involving the communities in the methane recuperation issue is related to the possibility of the use of gas by the population.

This is an initiative that may take place in some cases with the community’s participation in the project, however the only way to guarantee the future rewards of the project is the political involvement of the population. This is the reason why the communities’ involvement must be predicted in the methane capture projects. It is worth reminding that communities’ involvement may happen at two levels. The first one is the direct level, related to the use of gas, which may be possible or not and the second one is the political involvement, which may be present in all of the initiatives.

4.3 **MANAGEMENT OF THE SITES**

4.3.1 **Responsibilities/Liabilities**

The implementation of methane recovery projects in the state of Espírito Santo should, according to this Master Plan, involve the Municipal Public Power, which has the legal rights of the solid waste final destination. The municipal authority may transfer its legal responsibility according a concession based on its legislation.

In the case of the Espírito Santo Free of Dumping Sites project the municipal authorities have been developing the legal apparatus in order to establish partnerships with private enterprises for the projects’ implementation. In this situation, the Municipal Authorities constitutional responsibility has been transferred to the State of Espírito Santo, which is now transferring it to private companies based on the current legislation.

The private enterprises are therefore assuming all the legal responsibilities for the implementation of the necessary projects.

In the state of Espírito Santo, especially in the Great Vitória Metropolitan Region, there are solid waste final destination solutions, including the methane recuperation, totally developed by private companies, operating under the permission of the Public Power through the Environmental Licensing according to the current laws.
The initial responsibility for the remediation of Cachoeiro de Itapemirim and Colatina landfills belongs to Municipal Authorities, but it may be transferred to private companies according to the current Law.

4.3.2 Oversight

The methane recovery, under the conditions presented in this Master Plan, shall be submitted to Environmental Licensing. In this case the supervision of issues related to the project’s environmental impacts will be carried out by the competent environmental organization according to the current laws.

Regarding the carbon credits negotiation according to the mechanisms of clean development, the supervision will be carried out by an accredited entity appointed by the project’s financial agents.

4.3.3 Data Collection, monitoring and reporting

A monitoring plan must be implemented together with the methane capture and use project following the methodology presented in the Project Conception Document.

The responsibility for the Monitoring Plan belongs to the part which holds the Environmental License for the capture and use of methane.

On the other hand the analysis and supervision of the information generated by the monitoring process will also be done, independently, by the competent environmental organization and by the certification entity which will accredit the project’s results.

The certification entity will inform the financing agents the results obtained from its monitoring process.

4.3.4 Transparency: database

The data obtained in the monitoring of the actions developed for the recovery of methane are of public domain as a requirement of the Environmental Licensing process. After receiving the monitoring data the competent environmental organization shall precede the due analysis and then make the information available as stated in the current legislation.
5 SUMMARY OF RECOMMENDED ACTIONS AND FUTURE PROGRAMS

5.1 ACTION PLAN

This Master Plan provides recommended actions for the following landfill sites: Colatina, São Mateus, Cachoeiro de Itapemirim and for the Future Regional Landfills. The proposed recommended actions are based on local conditions and on the data available for each site and are presented in Table 37.

Table 37: Summary of Recommended Actions.

<table>
<thead>
<tr>
<th>SITE</th>
<th>RECOMMENDED ACTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colatina</td>
<td><strong>Alternative 1 - Electric generation using Sterling engines</strong></td>
</tr>
<tr>
<td></td>
<td>Continue to fill-in the landfill, install a geomembrane composite cover including a geomembrane and one meter of soil on top with vegetation. Cap each well, and collect LFG at a central location, where multiple Sterling engines are located along with a flare to burn the excess LFG. Three Sterling engines can be installed immediately, with a fourth being installed in 2013. All four engines would operate until 2030. Electricity generated would be sold to the local utility at a fraction to be determined of the current retail residential cost of electricity in ES. The selling fraction needs to be negotiated with the local authorities, but an assumption of 60% is used here for financial feasibility estimates. Analysis on this basis used a value of electricity returned to the grid of US$ 0.15 per kWh, an operating staff of 5 full time people for the 24x7 generating facility, personnel cost of US$ 30,000 per person, which returns an estimated excess of US$ 300,000 through 2030 after all costs are subtracted. The Capital cost of the facility is estimated at US$ 2.25 million spread over the project period. This includes the cover and gas collection cost of US$ 1,575,000, a cost which is required to simply flare and collect CC. Thus, the incremental cost for generation is US$ 672,000. A formal economic analysis needs to be completed once the final design plan is approved by ES. When carbon credits are added to the 21 year total, the net return is estimated to be greater than US$ 18,000,000.</td>
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<tr>
<td></td>
<td><strong>Alternative 2 - Flaring</strong></td>
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<tr>
<td></td>
<td>An option for “flaring only” exists, using the high quality landfill cover and collecting and flaring all gas collected, without other use of the gas. The 21 year total of carbon credits that is available under this approach appear to total more than US$ 17 million, with the assumed value of €14 per CC (US$ 20.00 at time of writing/calculating), and collection at 90% with 97% flare efficiency.</td>
</tr>
<tr>
<td></td>
<td><strong>Alternative 3 - Process Heat applications</strong></td>
</tr>
</tbody>
</table>
Process heat applications require an individualized analysis, since the cost of piping of LFG to the application location can be very expensive. Possible application ideas are improved operation of the existing medical incinerator. No detailed data on the inadequacies of the incinerator are known. Another use could be a laundry which would use process heat, steam and or hot water from a boiler. No facility currently exists at or near the landfill, necessitating new building for the purpose. If the building was located on or near the landfill, the length of piping is minimized. Thereafter, the supply of LFG to the facility should be evaluated on the basis of the requirement and its consistency. The price competitiveness of LFG when compared to contemporary natural gas would have to have a significant advantage in order to justify relocation of existing businesses. Specific case information is required to perform a good analysis.

**São Mateus**

For this landfill, the application of biocover was considered a promising technology for economically closing the dump and providing some reduction in greenhouse gas emissions. A traditional soil-only cover is the least costly alternative. However, there is minimal to no reduction of GHG emissions from the waste. A thick ($\geq 0.6$ m) soil cover is highly recommended.

Another alternative is the application of a geomembrane cover with individual flares at each well. Although this alternative is a more expensive measure, it may provide reasonable audit ability and high collection and flare efficiency. If the detailed planning worked favorably, and carbon credits are negotiated, this approach could pay back at a reasonable rate of return.

**Cachoeiro de Itapemirim**

The recommendation is to cover Cachoeiro with a high quality capture system and negotiate the sale of carbon credits. No electric generation is recommended unless audit becomes a major factor. This analysis is contingent on fast action, since the gas is quickly escaping the landfill, and prime amounts are lost in the first years after closure.

**Regional Landfills**

All regional landfills should be operated in a consistent fashion, and based on highest possible gas collection to maximize total return. These landfills will operate for 20 years, and continue to make biogas for another 20 years thereafter, making this a 40 year investment opportunity. Two tangible revenue streams are available: electricity generation and carbon credits.

This Master Plan has showed that over the lifetimes, the landfills will provide over 2 billion kWh of power to the residents of ES. The value of that power to the generator is less than the sale to residential users, but still totals over US$ 300 million. In addition, the carbon credits, if available at the current rates add over US$ 200 million to the returns.

While conceptual costs have been used for the landfill capital and O&M costs, in each case the totals have been substantially less than the proposed benefits, such that the ratio of revenue to costs appears to favor these investments.
5.2 RECOMMENDATION FOR FUTURE PROJECTS

The approval of the “ES Free of Dumping Sites” Program is a great accomplishment in the direction of a better management of municipal solid waste in ES. We hope that the recommended actions laid out in this study are incorporated to the Program in order to not only advance the capture and use of a valuable energy resource – LFG – but also to improve the safety, environmental and financial aspects of the landfills in the State.

In addition to the actions recommended in this study, during the course of this project a series of potentially beneficial projects were identified that we believe will contribute to address some difficulties encountered and/or results in capacity building. The following is a brief description of valuable follow-up projects for the State of Espirito Santo.

1- Development of a MSW Database:

Create a set of procedures for measuring, reporting and storing data on MSW generation, collection and disposal. Those guidelines should be recommended by the Government of ES and implemented by the municipalities to generate consistent data that should be entered into a database in the state’s website. The easy access to consistent data allows the state government, the environmental agencies and the municipalities to make informed decisions regarding their budget, programs and policies.

2- Worshops/Outreach to promote the “ES Free of Dumping Site” Program:

There are still some pending questions on how the Municipal Consortium will be developed and managed and how the oversight of its activities will done. In the case of implemention the recommendations described in these results, some additional questions will need to be addressed about the sale of electricity produced at landfills.

3- Workshop/Outreach to promote the findings of this study:

There may be questions related to the current study that require more than a casual answer, and, therefore require substantial time for review, recalculation or new work.

4- Capacity Building:

Develop an educational program for the design, construction, operation, financing, management of large projects and regulation of landfills with beneficial use of the landfill gas and resulting reduction in greenhouse gas emissions for the government and regulatory officials of Espirito Santo, Brazil.

5- Assessment of the Impacts of the closure of existing dumps:

Assess the impact of those and study alternatives to minimize cost and negative environmental effects (odor, GHG emission, visual pollution), as well as ease the transition and public acceptance and use.
6 BIBLIOGRAPHICAL REFERENCES


Environmental Research and Education Foundation, Landfill Covers. URL: http://www.erefdn.org/educationact1/Landfill%20Covers.pdf


