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Sustainable Waste-to-Energy Production: Performance Evaluation of Distributed Generation fuelled by Landfill Gas

By

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Abstract

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The environmental impact of landfill is a growing concern in waste management practices. Thus, assessing the effectiveness of the solutions implemented to alter the issue is of importance. The objectives of the study were to provide an insight of landfill advantages, and to consolidate landfill gas importance among others alternative fuels. Finally, a case study examining the performances of energy production from a land disposal at Ylivieska was carried out to ascertain the viability of waste to energy project.

Both qualitative and quantitative methods were applied. The study was conducted in two parts; the first was the review of literatures focused on landfill gas developments. Specific considerations were the conception of mechanism governing the variability of gas production and the investigation of mathematical models often used in landfill gas modeling. Furthermore, the analysis of two main distributed generation technologies used to generate energy from landfill was carried out.

The review of literature revealed a high influence of waste segregation and high level of moisture content for waste stabilization process. It was found that the enhancement in accuracy for forecasting gas rate generation can be done with both mathematical modeling and field test measurements. The result of the case study mainly indicated the close dependence of the power output with the landfill gas quality and the fuel inlet pressure.

Keywords
Landfill gas, methane, biofuels, biodegradation, aerobic, anaerobic, modeling, environmental, distributed generation, microturbine and power
101 pages, 26 figures, 13 tables

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List of abbreviations

ADG: Anaerobic Digestion Gas

ASTM: American Society for Testing Materials

B&D: Building and Demolition

BF: Biodegradation/Biodegradability Factor

BMP: Biochemical Potential

BOD: Biological Organic Demand

BTU: British thermal unit

CC: Catalytic combustion

CHP: Combined heat and power

CH_4: Methane

$C_6H_{12}O_6$: Cellulose

COD: Chemical Oxygen Demand

CO: Carbone monoxide dioxide

CO_2: Carbone

DER: Distributed Energy Generation

EE: Electrical Energy

FD: Fuel Demand

FFR: Fuel Flow Rate

FID: Flame Ionization Detector

FIP: Fuel Inlet Pressure

GHGs: Greenhouse gases

GWP: Global Warming Potential

HDPE: High density polyethylene

Higher Heating Value

HRU: Heat Recovery Unit

H_2S: Hydrogen Sulfide

ICRE: Internal Combustion reciprocating engine

ISM: Integrated Surface monitoring

LFG: Landfill Gas

LFGTE: Landfill gas-to-energy

LHV: Lower Heating Value

LPC: Lean premix combustion

MSW: Municipal Solid waste

NEHR: Net Electrical Heat Rate

N_2. Nitrogen

NH_3: Ammonia

NMOCs: Non-Methane Organic Compounds

ORC: Organic Rankine Cycle

ppbv: part per billion volumes

pH: Potential hydrogen

ppm: part per million

ppmv: part per million volumes

PVC: Polyvinyl chloride

ROI: radius of influence

TEG: Triethylene glycol

THC: Total Hydrocarbon

TNO: Netherland Technical research center

USEPA: United State Environmental Protection Agency

VOCs: Volatile Organic Compounds

VFA: Volatile Fatty Acid

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List of Symbols

L_0 Total capacity of landfill gas production or ultimate methane generation potential

α_t Landfill gas rate generation in the TNO model

$\frac{d}{dt}$ Derivative with respect to the time

k General rate constant

k_i Rate constant for LFG model according to the speed of degradation

exp Exponential function

ζ Dissimilation factor

$\sum_{i=1}^{n}$ Summation indexes

$\overline{\overline{k}}$ Effective gas permeability tensor

φ Gas filled porosity

$\vec{\mu}$ Darcy fluid vector

$\vec{n}$ Vector normal to the surface

∇ Gradient vector

ρ Density

$\frac{\partial}{\partial t}$ Partial derivative with respect to time

$\dot{Q}$ Volumetric rate of gas

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1 Introduction

1.1 Background

In today’s growth consumption in energy, fossil fuel resources have become a critical issue, due partly to their significant price volatility and their contribution to global warming. In this context the necessity for emergent renewable energy technologies becomes ever more critical **[1]**. Renewable energy sources are then seen as promising solution to complement fossil fuel utilization. Amongst other renewable sources, biomass which encompasses a wide range of energy feedstock to produce biopower could play an important role.

However, owing to its low heat value and high moisture content, proper conversion technologies to make biofuels reliable are still under development. This reality has led biomass to remain an alternative option. Meanwhile, availability is one advantage biomass has relative to other forms of renewable energy because energy is stored in the biomass until it is needed [**2**]. Whenever biomass is transformed into a more convenient form, it is named biofuel, particularly into liquid and gas form [**3**]. Under biofuel scope, biogas and/or LFG present the characteristic to be produced from biological degradation of biomass sources contained in MSW. This aspect has increased their competitiveness within renewable energy sources.

1.2 Statement of the problem

Land filling has long been seen by many countries as a mean to manage the excess volume of MSW. However, buried wastes are rich in organic content, and their biological decomposition yield liquid and gaseous products which are harmful for the environment. Although new waste management practices have improved somewhat the regard toward the land filling process, it is still considered as an environmental burden. Furthermore, the fact that methane presents a GWP 23 times greater than that of Carbon dioxide **[3]** has contributed to strengthen stakeholders’ concern.

Partial solution to such problem has been to capture and flare the gaseous product from the biological decomposition. However, net environmental cutback is achieved through landfill gas project, which can capture around 50% of the methane emitted from land filling of MSW **[4]**. To date, innovations in: energy technology, waste disposal, gas extraction and monitoring techniques have contributed to decrease the direct emissions of CH_4 from landfills.

Toward this end, implementation of energy system utilizing solely LFG as fuel to produce combined heat and power (CHP) requires a detailed sizing of the overall system. Moreover, the viability to set up a distributed generation system capable to burn LFG and meet its rated performances is problematic. They are technical uncertainties surrounding predictive methods used to estimate the amount of gas resource in the landfill reactor. The inconsistency of the rate of generation and its chemical composition affect strongly the system fuel demand.

1.3 Objectives of the study

LFG encompasses the scope of waste management, bioenergy and sustainable development, accordingly its importance is undeniable coupled to these major domains. From the angle of waste management, the study aims to provide an insight toward the benefits of engineered land filling process and the research trend in landfill. With the increasing demand in renewable energy, the study contributes to strengthen the position of LFG as valuable alternative fuel within the broad range of existing biofuels. Finally the study contributes to demonstrate how energy needs can be met via the implementation of distributed generation project in a sustainable way.

Specifics considerations of the study are oriented toward: (1) the development and establishment of LFG extraction, monitoring and processing; (2) the conception of mechanisms supporting the irregularity and variability of LFG generation; and (3) the enhancement of repository database for distributed energy resource using microturbine and fully powered by the LFG.

1.4 Research questions

In order to cover entirely the points set earlier, the forthcoming paper should provide a complete answer to the following questions. How landfill construction and management can be enhanced to lesser its environmental impact? What attributes should be focused on to achieve high gas collection, better processing and thorough monitoring? Finally, to what extent the implementation of distributed generation system with microturbine operating on LFG can meet its rated performances?

1.5 Assumption and delimitations

The study does not intend to tackle the issue related to leachate circulation, nor does it considers the ground water contamination. Unless mentioned in this paper, only MSW are assumed to be buried, no issue related to hazard wastes is investigated. Furthermore, the graphs plotted in the case study have been made possible with data logged of actual project; no experimental set up of the microturbine was done. Finally, the study does not intend to investigate the power conversion and transmission system.

1.6 Stakeholders Presentation

Beneath is briefly described the companies mentioned in the report.

Vestia Oy / Vestia Ltd is a Finnish municipal-owned regional waste management company, main task involves the waste management, waste treatment and disposal and waste consulting. http://www.vestia.fi

Värmekollector AB is a Swedish company, whose main duty encompasses design and constructs landfill gas system and the dimensioning and the sale of collector for heat pump. http://www.varmekollector.se

Bionova Engineering is a Finnish Consulting engineering company, whose main fields of action cover renewable energy and climate change and traffic biofuel. http://www.bionova.fi

2 Landfill gas concept

2.1 Characterization of landfill

The foremost goal of landfill construction is to handle the over flow of the increasing volume of municipal solid wastes. The gases produced from biological decomposition have often been considered as environmental residue from waste disposal instead of renewable energy resource. This is due to the fact that the methane and other gases from landfills were both released to the atmosphere or simply combusted, and not used as energy source. Nowadays, engines capable to combust low grade fuel are available, creating opportunities for LFG.

2.1.1 Waste management issues

Wastes stabilization has long been recognized as an environmental burden and thus, controls the raising of wastes flow becomes a necessity. The presence of organic matter in such bulk flow of wastes forms an indirect renewable energy, which can therefore be considered as energy potential. Waste is generally derived from two main streams, primary economic activity (industrial wastes, food processing, and slaughter house) and urban or household refuse. Within these wastes streams, MSW accounts for the major part. Waste management concern is about minimizing the volume of the MSW and mitigates their effect associated to public health. The minimization of waste starts from cleaner production before moving toward wastes reduction. This latter is achieved by several means such as: recycling or processing, incineration, and land filling.

Processing and treatment also known as recycling are the premium choice almost always used in solid waste management. They are accomplished by material recovery, composting and soil amendment, but such processes require a thorough understanding of the product life cycle.

Incineration or waste to energy on the other hand is another efficient way to minimized MSW volume. It can be done by biogasification, production of refuse-derived fuel or thermal conversion, but remains an expensive mode for waste treatment. It must be pointed out that the different mode of conversion technologies listed for the incineration should always be appropriate to the type of wastes.

Land disposal, although widely used appears to be the least choice for MSW reduction. Moreover, land filling is the only management technique that is both basic and sufficient within these three options. Our interest for landfills option is due to the fact that modern landfills can be turned into economical asset as they are also considered to be more cost-effective than incineration and composting for wastes minimization purposes [**6**]. Finally, utilizing the methane (CH_4) released from landfill as alternative fuel contributes to the mitigation of climate change.

2.1.2 Environmental impact of Landfill

Landfills contribute to local air and water pollution if they are not handled cautiously. It was shown that under the decomposition process, the toxic chemicals release from wastes blend with water and form leachate which then contaminate groundwater or aquifer [**7**]. Therefore high priority should be given to public health whenever landfill construction is planned. Disregarding the emission of anthropogenic gas into the atmosphere, other consequences will directly jeopardize communities surrounding the site, such as offensive odors and vegetation degradation over the landfill site [**8**].

2.1.3 Landfills Description and classification

Landfill is been defined as the pit filled with garbage and covered with dirt [**4**]. The previous definition is in accordance with [**9**] who describes landfills as sites for the disposal of waste materials by burial. From these definitions it is clear that no considerations are paid to the site location, the design and the construction of the landfill. The classification of landfill is in general based on some criteria such as the way wastes are entombed, the solid wastes management practices and other basic characterization of land disposal. From these perspectives, three broad categories reign, as such: open landfill, controlled landfill and sanitary or engineered bioreactor landfills.

Open landfill are types of landfills which are mainly characterized by their poor management but are economically feasible with low initial cost. Open dumps present also great environmental risks since they lack any solid waste management practices and will constitute the major source of greenhouse gas emissions. These types of landfill do not present any significant interest and should be discarded. On the contrary of open dump, controlled landfills have a well defined capacity and, partial or limited management of the gas flow. In order to estimate the amount of gas generated, data record of wastes category and their input rate are recorded and controlled. Nonetheless, they are still at risks with notably environmental contamination caused by leachate circulation. The third category of landfills is of interest, since they are adapted to up-to-date regulations.

2.1.4 Sanitary or Engineered bioreactor Landfills

Sanitary landfills are made of elements known as cells which are built by: thinning out and compressing the MSW into layers within a confined area. Furthermore leachate recirculation is practiced and/or water is simply added so as to achieve higher level of moisture content, greater than 40% by weight. Such landfills are designed to speed up the stabilization process and to minimize the potential post closure effects. The integration of appropriate cover material whose aims is to oxidize the residual CH_4 after LFG extraction and closure is an important aspect of sanitary landfill. Engineered bioreactor landfills have the advantages that they are consistent with sustainable landfill design and optimize the waste emplaced in landfill. Because methane from landfill can be recovered and used as alternative fuel, such landfills are potential to create income stream. **Figure 1** depicts the schematic section of sanitary landfill.

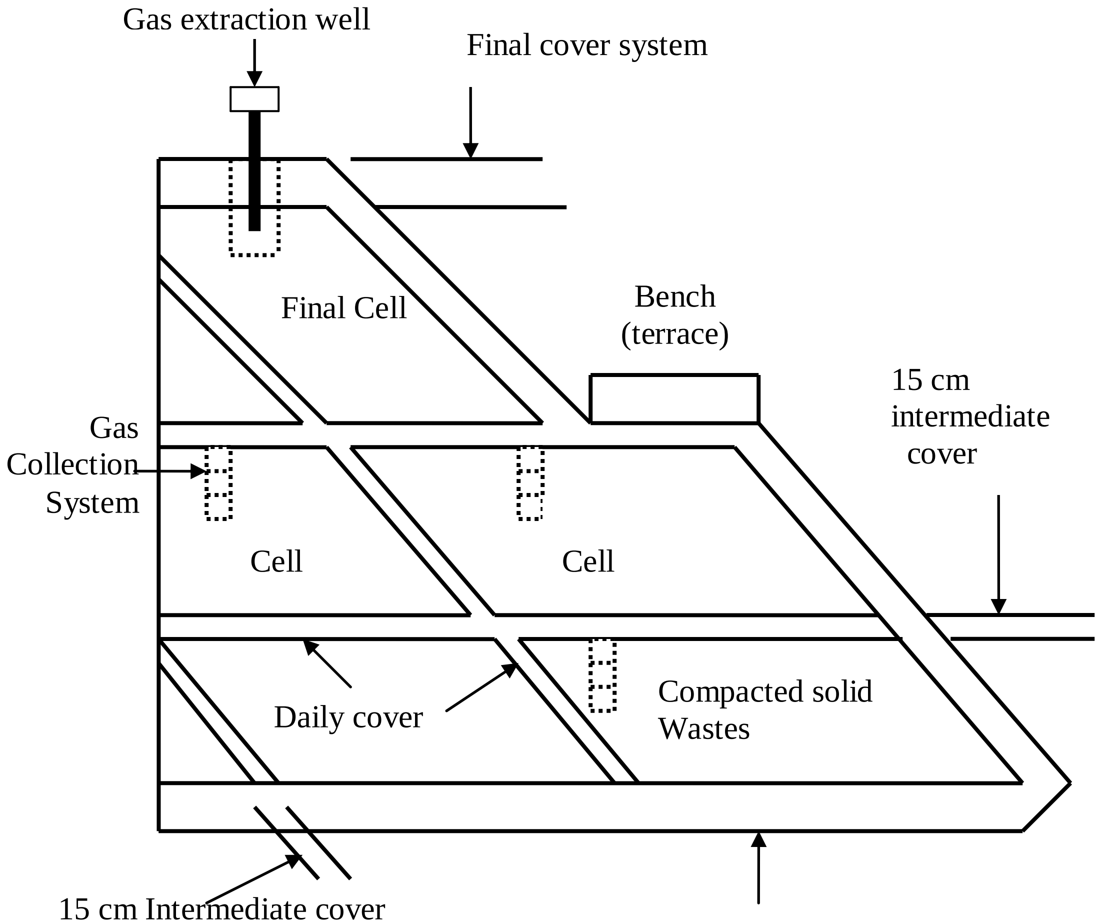

Figure 1: Section view through typical sanitary landfill [**10a**]

2.2 Biodegradation mechanisms of organic wastes

Gases formation within landfills reactors are governed by three different mechanisms, (1) bacterial degradation followed by (2) volatilization and finally (3) chemical reactions. Because these mechanisms do not take place in precise and concise way, it is difficult to describe the gas formation by these mechanisms. A well defined approach to illustrate the whole LFG generation process is by aerobic and anaerobic processes. The aerobic decomposition stage takes place just after the wastes have been dumped. Subsequent to this stage is the anaerobic decomposition, where the wastes undergo the biodegradation once the oxygen is consumed. Additionally, anaerobic phase is subdivided into: anaerobic acid production and methanogenesis degradation.

2.2.1 Biodegradation stages

Some authors such as Tchobanoglous [**10b**] and **[11]** have depicted the biodegradation of MSW into five phases; other such as the USEPA [**8**] conceived that the same mechanism should be broken down into four major phases. However there is no considerable difference in the conception of the phenomenon itself. Here is the five phases of the biological degradation as presented in the next part.

Stage 1: Aerobic biodegradation

Stage 2: Acidogenesis (transition phase)

Stage 3: Acetogenesis (acid phase)

Stage 4: Methanogenesis (methane fermentation)

Phase 5: Stabilization (maturation phase)

Figure 2 and **3** present two approaches of considering the biodegradation processes. The actual decomposition process can take place simultaneously or separately in different location within the landfill reactor. The result of such chaotic changeability contributes to render the actual system more complex than described and hinders the process understanding [**12**].

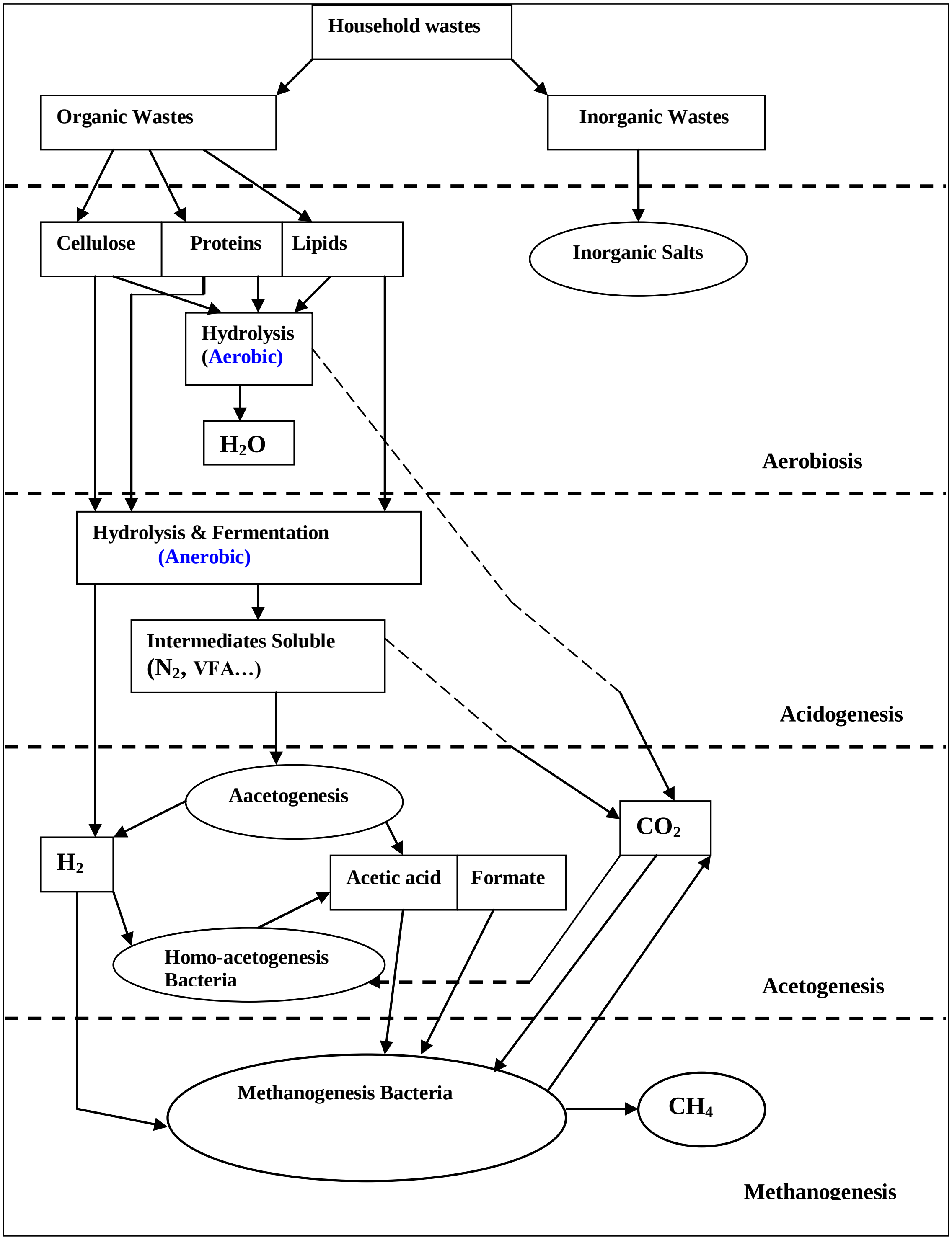

Figure 2: Main Steps in biodegradation of wastes in landfills [13]

2.2.1.1 Phase I: Initial adjustment or aerobic biodegradation

The phase is characterized by the aerobic biodegradation of available organic matter soon after they have been buried into the landfill. The amount of air trapped inside the landfill reactor after compaction will determine the duration of this phase. Its behavior is strongly conditioned by the prior aeration of wastes during the settlement, [**14**] and [**15**]. At the end of the phase, the primary byproduct is carbon dioxide (CO_2) which is released in gaseous form or dissolved in water [**13**]. Further observations is the high content of nitrogen due to it presence in the air, but this latter decrease over time.

2.2.1.2 Phase II: Transition phase or acidogenesis phase

The transition phase is described as the starting point of the anaerobic process, and the outcome of oxygen depletion in the reactor. This stage is distinguished by the hydrolysis of macromolecules and acidogenesis. Acidogenesis sub-phases correspond to the decomposition of products from hydrolysis into simple compounds such as hydrogen, water, and volatile fatty acid (VFA). Important detail in this phase is the augmentation in chemical oxygen demand (COD) of the leachate which signals the increased of anaerobic bacteria. The gaseous byproducts of the phase are CO_2 about (80%) and hydrogen (20%) [**13**]. It is essential to mention that the phase is not strictly anaerobic.

2.2.1.3 Phase III: Acid phase or acetogenesis phase

This phase corresponds to the production of acid; it is mainly characterized by a significant production of VFA. Acetate is produced from the reduction of carbon dioxide bacteria, which leads to the decline in carbon dioxide gas. However, CO_2 yet remains the principal gas generated. Further characterization of the phase is the peak in COD and biological organic demand (BOD) levels in leachate and the rapid degradation of pH which contribute to render the medium more acidic.

2.2.1.4 Phase IV: Methane fermentation or Methanogenesis

The fourth phase marks the peak in the landfill gas production; the COD/BOD follows the first order biodegradation with similar decay constants. This stage corresponds to the predominant generation of CH_4 and CO_2 from acetic acid products of the previous phases. The production rate becomes almost constant and the gas is produced at a stable rate. The rise of a pH to a more neutral value, ranging from 6.8 to 7.5 is due to the conversion of acid and hydrogen into CH_4 and CO_2 [**13**].

2.2.1.5 Phase V: Maturation phase or Stabilization phase

Stabilization marks the end of the biodegradation. Owing to the heterogeneity of waste and the random distribution of organic matter, all the biodegradation activity is not completed at the fourth phase. As the moisture continues to migrate through the wastes, recalcitrant molecules undergo biotransformation, leading to the production of humus similar to compost constituents [**16**], [**17**]. The phase is characterized by a drop in gas generation and stable concentration of leachate constituent. **Figure 3** shows the LFG evolution from the anaerobic phase until the stabilization phase.

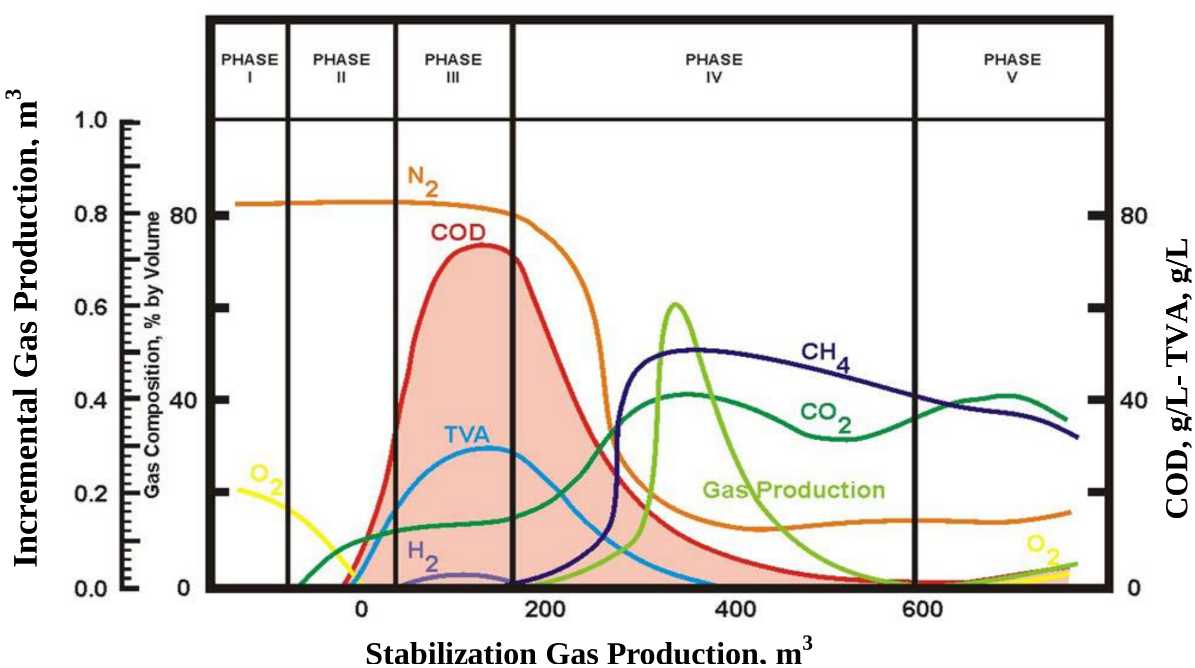

Figure 3: Gases evolution phases **[18]**

2.2.2 Factors influencing the biodegradation

The gas generated within the landfill heart is the most important product from biodegradation of organic MSW. Although the process of gas production is largely uncontrolled, it is yet tightly influenced by some factors which controlled its formation inside the reactor. Moreover, the changes in LFG composition and the rate of the production will deeply be affected by several factors. The subsequent factors have been investigated by [**19**]: wastes characteristics (composition, size, and age of refuse), oxygen in the landfill (ingress of air), moisture content, and the temperature or roughly the atmospheric conditions. Below is presented some factors, whose impacts on the biodegradation process are quantifiable.

2.2.2.1 Wastes characteristics

As the quantity of organic biodegradable matter in the bulk waste will be abundant, the LFG production will increase. Furthermore, the abundance of biodegradable organic matter will play an important role in how long the production will last. Beyond this fact, the pretreatment of wastes or waste segregation leads to a relative homogeneity in the wastes mass and as a result, enhance the availability of organic matter. However, it should be noticed that not all organic matter will degrade under anaerobic condition. The age and size of refuse will impact the gas yield; higher will be the gas production for nearly buried waste as compare to older buried wastes. Besides that crushing waste in small size particle will increase the kinetic of the reaction **[13].**

2.2.2.2 Oxygen in landfill or ingress air

The amount of oxygen presents in the landfill will have a key participation in the pace of the gas production; it role will be mainly to inhibit the rate of CH_4 generation. Aerobic decomposition will be favored with the rise of oxygen within the reactor, thus delaying the methane generation but instead increasing the CO_2 formation. Aeration which results in air ingress should therefore be minimized by high compaction of wastes.

2.2.2.3 Moisture content

Moisture content is amongst the major factor to boost the rate of the reaction, and as mention earlier will enhance the biological degradation and thus gas generation. It was reported by [**19**] and [**11**] that the moisture content of 40% or higher, based on wet weight will foster the LFG production. The biodegradation process of organic matters will stop if a minimum amount of moisture content is not reach, leading to the stopping of methane gas production. This aspect highlights the importance and the impact of moisture content in LFG production.

2.2.2.4 Temperature or atmospheric conditions

Assuming the first order decay of biodegradable organic matters, it is obvious from Arrhenius law that, the rate constant of the kinetic reaction will vary with the temperature. Thus, any rise of temperature will enhance the bacterial activities, consequently the LFG production. During the process, the kinetic of gas production increases twofold for an increase of 10^{o} C and ceases at the level of 60^{o} C [**20**]. Further observation is the accumulation of VFA under thermophilic conditions for fast biodegradable wastes [**21**]. Important also to mention is the effect of the atmospheric pressure which affects both the variability in composition of the gas and its volumetric changes.

2.2.3 Landfill gas composition

Roughly, they are two types of gases which are generated from the landfills: the bulk components and the trace components. The bulk components or principal gases at a glance includes: methane, carbon dioxide, ammonia (NH_3), carbon monoxide (CO), hydrogen sulfide (H_2S), nitrogen (N_2), oxygen (O_2), and Hydrogen (H_2). On the other hand, trace components are not stable and will vary somewhat according to the landfill conditions. Trace constituents are sometimes called volatile organic compounds (VOCs) or non-methane organic compounds (NMOC). Typical percentage distribution by volume is presented in the **table 1**. It should be born in mind that there is no predefined LFG composition; however, it varies from one landfill to another.

Table 1: Typical landfill composition

Components	**Percent (Dry volume basis)**
Bulk constituents	
Methane (CH_4)	45-60
Carbone Dioxide (CO_2)	40-60
Ammonia (NH_3)	0.1-1.0
Hydrogen (H_2)	0-0.2
Carbon monoxide (CO)	0-0.2
Nitrogen (N_2)	2-5
Oxygen (O_2)	0.1-1.0
Sulfides, disulfides, Mercaptans etc	0-1.0
Trace Constituents	0.01-0.6
Characteristics	**Value**
Temperature ^{o}F	100-120
Specific gravity	1.02-1.06
Moisture content	Saturated
High heating Value, Btu/sft*	475-550

Source: [**10**], Btu = British thermal unit, sft* = Standard cubic foot

2.2.4 Improving wastes stabilization and gas generation rate

The recent developments in LFG production have brought up new techniques to increase and /or improve the rate of the reaction within landfill. The eligible landfills where such methods are applied are called bioreactor landfill. Improved waste stabilization is done either by optimum design of the landfill integrating leachate recirculation; by mechanical biological treatment of waste; or by combination of these prior techniques.

The first approach aims to design an optimum structure to handle the biological reactions and mitigates their side effects. The second method however is a pretreatment technique aiming to maximize the biodegradation process. This second method has the merit to enhance the degradation and stabilize the waste upon land filled. However, using this technique leads often to low gas production. The third is the combination of the previous techniques; the result is the high yield and the fast stabilization of waste. A sufficient ratio of moisture in the landfill reactor will maintain the biological activity. Achieving this ratio to sustain the level of moisture content and improve the LFG production is mainly done by leachate recirculation [**22**].

2.3 LFG emissions monitoring and measurements

The broad definition of monitoring takes in consideration both measurements undertaken for observations and control purposes, and those carried out to appraise landfill performances. Monitoring emissions from landfill gas and its surrounding is vital due to risks associate with human health. Besides that it assesses the rate and concentration of chemicals and, it quantifies the amount of gases released from the landfill, flare system, stack and others treatment units. Notably target is the measurements of emissions of bulk components, VOCs and other trace elements from the sources mentioned.

Five general categories to monitor gases originating from landfill were addressed by [**8**]. For the sake of our study, three categories will be investigated: (1) surface gas monitoring, (2) subsurface monitoring, and (3) emissions monitoring. While surface and subsurface monitoring carry out measurements to estimate the concentrations of gases from different point of the landfill, emission monitoring assesses the rate at which these gases are released from it. Methane is always the main parameter reported in the monitoring process although other components are also mentioned.

2.3.1 Surface monitoring

The rational of surface monitoring is to determine the constraints for extraction system design and/or, to evaluate if the established collection system meets its function effectively. Surface monitoring is done actively by field measurements, which are split into: integrated surface monitoring and flux method. Integrated surface monitoring (ISM) is achieved with the well known flame ionization detector (FID). In contrast, the flux box method used for measurements is an appropriate and straightforward way to measure normal surface emissions over landfill [**23a**]. The technique presents some restrictions whenever emissions from the entire landfill have to be covered. It is however useful and limited for emission evaluation implemented on a section of the landfill [**24**].

2.3.2 Subsurface and Emissions monitoring

Subsurface monitoring main aim is to meet environmental regulation requirements and to quantify off-site migration of gases. Moreover, it contributes to characterize off-site hazards. The subsurface monitoring is completed with gas probes and landfill gas collection well. Conversely, the purpose of emission monitoring encompasses the scope of surface and subsurface monitoring. Moreover, it assesses the general volume and the composition of LFG over a period of time presents in air surrounding the site.

3 Mathematical Modeling of LFG generation

3.1 Rational

The present chapter covers the different methods used to quantify or estimate the rate of landfill gas production and landfill emissions. The goal here is to highlight theoretical modeling or mathematical description of biological degradation of organic matter often used to forecast the gas rate generation. On the other hand, the chapter intends also to cover a practical method based on direct field measurements and also used to predict LFG rate generation. Understanding the dynamic of LFG generation and predicting the variation in gas production is of great importance in landfills management and emissions monitoring.

The importance in the development of predictive software model with high level of accuracy comes from the fact that modeling objectives are research-oriented and management-oriented [**25**]. Therefore modeling has contributed steadily to increase the accuracy of software model to meet stringent regulations and demand from landfill operators. To date, achieving lower error margin in LFG predictive models will contribute to optimize the construction of the collection systems. Moreover, predictive gas models serve as tool for decision making process to ascertain project viability. Finally, models of rate generation are commonly provided as guidance by organizations to estimate emissions from landfills [**26**].

3.1.1 Model Classification

Before going further, it is important to review the different classes of model that prevail in environmental modeling. There is a wide range of categorization, describing and classifying model according to different factors influencing the phenomena studied or the assumptions formulated. The common modeling approaches used in the field of environmental science are set into three basic categories [**25**]. (1): Physical modeling whereby the model is tailored geometrically and dynamically; (2): Empirical modeling also known as “black box” which focuses on inductive techniques and database approach to build the model; and (3): Mathematical modeling or theoretical model, which finds its foundation in principles and theoretical concept which govern the system.

Another development that exists in classification is the way models describe and analyze at best the phenomenon in study. From this standpoint we survey the stoichiometric model, which assesses the stoichiometric reaction that occurs within the bioreactor, it mainly depicts the maximum theoretical yield of LFG. Biochemical models which come after are based on the first-order decay and parameter estimation. Additionally, they are used whenever the biodegradability of organic materials is the main phenomenon to be investigated. Finally ecological model, which describes the coexistence of the different bacterial population dynamic and substrate within the landfill, is the most complex.

Modeling LFG rate of generation using solely one of the specific modeling approaches mentioned earlier is not feasible and will present ill and/or inaccurate result. In order to provide a complete model description, it is suggested to incorporate sub-models which help to describe fully the actual phenomena [**27**]. Nonetheless, models can predict with accuracy of 50%, and improvement in the accuracy (18%) is achieved by choosing the multi-phase model to describe the degradation process [**28**].

3.2 LFG generation model

3.2.1 Scholl Canyon Model

Widely used in the estimate of methane gas generation, the model was established by EMCON associate [**29**]. It is a mere mathematical model and oriented without any consideration of biochemical mechanism that intervenes during LFG formation. It is widely used and seen as the ground foundation of other models. The model does consider neither the first stages nor the second stage of the reaction process. It assumes instead: a negligible lag phase, degradation rate follows the first order kinetic and, the methane is assumed to be at the peak at the initial placement.

3.2.1.1 Mathematical Derivation

The starting point is the simple first order degradation reaction applied to the unit mass of waste. The mathematical expression of the degradation process is described as follow

$$-\frac{dL}{dt} = kL \qquad (2.1.1)$$

$$\frac{dV}{dt} = kL \qquad (2.1.2)$$

Where L is the potential volume of methane production in unit of volume per mass; V is the cumulative methane volume produced prior to time t in unit of volume per mass; and k is the constant rate of decomposition in unit of reciprocal of time. Integrating (2.1.1) and (2.1.2) yield respectively:

$$L = L_0 \exp(-kt) \qquad (2.1.3)$$

$$V = L_0 \left[1 - \exp(-kt)\right] \qquad (2.1.4)$$

In equation (2.1.3) and (2.1.4) L_0 represents the ultimate potential of methane volume. It becomes clear that L_0 is the total capacity of the LFG production. The total gas production rate is determined by differentiating equation (2.1.4), which leads to the expression (2.1.5)

$$\frac{dV}{dt} = -\frac{dL}{dt} = kL = kL_0 \exp(-kt) \qquad (2.1.5)$$

Letting R be the mass of waste disposed during the year t considered, and Q be the total volume of LFG production rate, we can write (2.1.5) as followed:

$$Q = kRL_0 \exp(-kt) \qquad (2.1.6)$$

Considering the amount of waste disposed in the year i in unit of mass per year. It is possible to generalize the expression (2.1.6). For each sub-mass (amount disposed at the year i) we can write:

$$Q_i = k_i R_i L_{0i} \exp(-k_i t_i) \qquad (2.1.7)$$

And the general expression takes the form

$$Q_{LFG} = \sum_{i=1}^{n} k_i R_i L_{0i} \exp(-k_i t_i) \qquad (2.1.8)$$

Where n is the number of years of waste placement; R_i the amount of waste disposed in year i in unit of (Mg); k_i is the gas generation rate constant account for the amount of waste disposed in year i, in unit of (y^{-1}); L_{0i} is the volume of methane remaining to be produced at $t = 0$ for the amount of waste i (m^3 / Mg); t_i stands for the age in year of the waste section placed in the i^{th} year; and Q_{LFG} is the LFG production in unit of $[m^3 / y]$.

3.2.2 TNO Model or Single Phase Model

The model was developed by the Netherland technical research center. Its basic idea lays on the fact that LFG is formed solely from biodegradation of organic carbon in the waste [**28**]. The model assumes that the organic matters are predominantly cellulose and thus considers the subsequent chemical decomposition.

$$C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$$

Furthermore, the production of methane per kilogram of organic matter (KgOM) and per kilogram of carbon (KgC) should be known. To this end, the following conversions have been made [**26**]:

$$\begin{aligned} &C_6H_{12}O_6 \mapsto 180\,gOM/mol = 72\,gC/mol \\ &3CH_4 \mapsto 48\,g/mol \\ &3CO_2 \mapsto 132\,g/mol \end{aligned}$$

Methane production per kgOM degraded: $\frac{48}{180 \cdot 714} = 0.373 m^3 CH_4 = 0.75 m^3 \text{LFG}$

Methane production per kgC degraded: $\frac{48}{72 \cdot 714} = 0.933 m^3 CH_4 = 1.87 m^3 \text{ LFG}$

The organic carbon in the waste is assumed to follow the first order decay; the rate of loss of degradable matter is proportional to the amount of decomposable matter. The factor limiting this rate is the amount of carbon remaining in the landfill. The last assumption is the non-existence of interaction between factors affecting the decomposition and the rate of methane production [**30**].

3.2.2.1 TNO Model Derivation

The gas generation is proportional to the rate of transformation of carbon

$$\alpha_t = -1.87A\frac{dC}{dt} \qquad (2.2.1)$$

In equation (2.2.1), $\frac{dC}{dt}$ represents the rate of transformation of carbon (degradation of the carbon stock). The degradation of organic material can be described by the n^{th} order reaction equation

$$\frac{dC}{dt} = -k_1 C^n \qquad (2.2.2)$$

From the assumptions made above the rate of transformation follows the first-order decay, hence equation (2.2.2) becomes simply

$$\frac{dC}{dt} = -k_1 C \qquad (2.2.3)$$

Solving (2.2.3) and combining with (2.2.1) lead to:

$$\alpha_t = 1.87AC_0k_1\exp(-k_1t) \qquad (2.2.4)$$

Owing to the heterogeneity of the waste composition, only a fraction of waste is converted into LFG. It must then be added a factor, to account for the proportion of waste which is degradable. Equation (2.2.4) is therefore rewritten as follow

$$\alpha_t = \zeta 1.87AC_0k_1\exp(-k_1t) \qquad (2.2.5)$$

The CH_4 production is determined by assuming its concentration to be 50% in the LFG and multiplying by its volumetric mass: 714gCH_4.m^{-3}. Where α_t is the LFG formation at a certain time in unit of volume per time ($m^3 LFG.year^{-1}$), ζ is called the dissimilation factor 0.58 is without unit, A is the amount of waste deposited in unit of mass (Mg), 1.87 represents the conversion factor ($m^3 LFG.KgC^{-1}\deg raded$), C_0 is the corresponding quantity of organic carbon in waste which undergoes the transformation at the time of deposition ($KgC.Mg^{-1}$), k_1 is the degradation rate constant 0.094 [1/y], and t the time elapse since the deposit (y). The full description of the model is determined by the knowledge of the parameter C_0.Toward this purpose, the degraded organic carbon content presents in the waste has to be known, the table below was constructed to provide information of waste category used by the TNO model.

Table 2: Organic carbon content used in the TNO single-phase model

Waste Category	Organic Carbon Content [$KgC.Mg^{-1}$]
Contaminated soil	11
Construction & demolition waste	11
Shredder waste	130
Street cleansing waste	90
Sewage sludge & compost	90
Coarse household waste	130
Commercial waste	111
Household waste	130

Source: Adapted from [**26**]

3.2.2.2 Afvalzorg multiphase model

In the quest of achieving highly reliable model, the heterogeneity of the organic matter was taken into account to improve the former TNO model. This model distinguishes three fractions of organic matter that degrade at different rates: rapidly degradable, moderately degradable, and slowly degradable [**26**]. For each category of waste, the rate constant and the amount of organic matter are predefined. This will obviously increase the difficulty of parameters identification but the model will gain in accuracy.

$$\alpha_t = \zeta c A [C_{01} k_{11} \exp(-k_{11} t) + C_{02} k_{12} \exp(-k_{12} t) + C_{03} k_{13} \exp(-k_{13} t)] \qquad (2.2.6)$$

In a compact form equation (2.2.6) becomes:

$$\alpha_t = \zeta \sum_{i=1}^{3} c A C_{0,i} k_{1,i} \exp(-k_{1,i} t) \qquad (2.2.7)$$

Where α_t, ζ, A, t and $C_{0,i}$ have the same meaning as in the previous TNO model. The waste fraction is represented by i with its associated degradation rate constant $k_{1,i}$, c is the conversion factor in unit of [$m^3 LFG.KgOM^{-1}_{degraded}$], and $k_{1,i}$ the degradation rate constant in unit of [1/y]. The parameters to be identified in the multiphase model are respectively the rate constant ($k_{1,i}$) for different category of waste, the dissimilation factor (ζ) and the quantity of organic carbon ($C_{0,i}$) for each category. As compare to the previous model, a predefined table providing a thorough composition of specific values for organic carbon according to each category of waste has to be known.

Table 3: Organic matter content used in the Afvalzorg multiphase model

Waste Category	Minimum organic matter content [KgOM.Mg^{-1}]				Maximum organic matter content [KgOM.Mg^{-1}]			
	Rap	Mod	Slow	Total*	Rap	Mod	Slow	Total*
Contaminated soil	0	2	6	40	0	3	8	42
C&D	0	6	12	44	0	8	16	46
Shredder waste	0	6	18	60	0	11	25	70
Street cleansing water	9	18	27	90	12	22	40	100
Sewage sludge & compost	8	38	45	150	11	45	48	160
Coarse household waste	13	39	104	260	19	49	108	270
Commercial waste	13	52	104	260	19	54	108	270
Household waste	60	75	45	300	70	90	48	320

Source: Adapted from [**26**]

*Only rapidly, moderately and slowly degradable organic matters have been taken into consideration. The total organic matters content is higher than the sum of these categories due to the presence of organic matters that are not considered biodegradable under anaerobic conditions; examples are lignin and plastic

3.2.3 US EPA Landfill Gas Emission Model (LandGEM)

LandGEM model was proposed and gradually refined latter by the USEPA. It is based on the first-order decay equation. The corresponding model software is widely used because of its clarity and simplicity. The originality of the model comes from the aspect that it considers the kinetic of decomposition of different type of organic waste. The mass of methane generated is assumed to be a function of methane generation potential (L_0) and the mass of degradable waste deposited. In addition, it assumes that the production of methane is not affected by its concentration. For its complete determination, it is further projected the methane capacity to be 50% and 50% carbon dioxide by volume of the total LFG **[31].**

3.2.3.1 Formulation and Derivation of LandGEM

Let us write as the starting point the followings equations:

$$\frac{dM_r}{dt} = -kM_r \qquad (2.3.1)$$

$$\frac{dV}{dt} = kM_r L_0 \qquad (2.3.2)$$

Where M_r is the remaining mass of refuse waste at time t in unit of [Mg]; t is the time elapsed in unit of [y]; k is the first-order rate constant in unit of [y^{-1}]; V is the cumulative volume of methane generated from the beginning of the degradation to time t in unit of [m^3]; L_0 represents the methane generation potential in unit of [m^3/Mg]; and M the mass of degradable refuse waste at the initial time in unit of [Mg]. Integrating equation (2.3.1) yields

$$M_r = Me^{-kt} \qquad (2.3.3)$$

Letting $Q = \frac{dV}{dt}$ where Q is the rate of methane production at time t in unit of [m^3/y] and inserting (2.3.3) into in (2.3.2) gives

$$Q = kL_0 Me^{-kt} \qquad (2.3.4)$$

Considering the methane capacity to be 50% of the total LFG generated, the overall gas production is determined by multiplying equation (2.3.4) by the factor of 2.

$$Q_T = 2kL_0 Me^{-kt} \qquad (2.3.5)$$

Owing to the acceptance rate, which represents the periodic dump of waste within the landfill, the gas generation takes the form

$$Q_T = 2\sum_{i=1}^{n} kL_0 M_i e^{-kt_i} \qquad (2.3.6)$$

Where Q_T is the total LFG production rate at time t in unit of [m^3 / y]; and M_i the mass of waste placed in year i in unit of [Mg].

Expression (2.3.5) and (2.3.6) are applied in the LandGEM to give the total landfill gas composition and the methane composition. The same model also provides the possibility to evaluate the amount of carbon dioxide generate within the landfill. An example of result from the LandGEM model version 3.02 from the USEPA is presented below

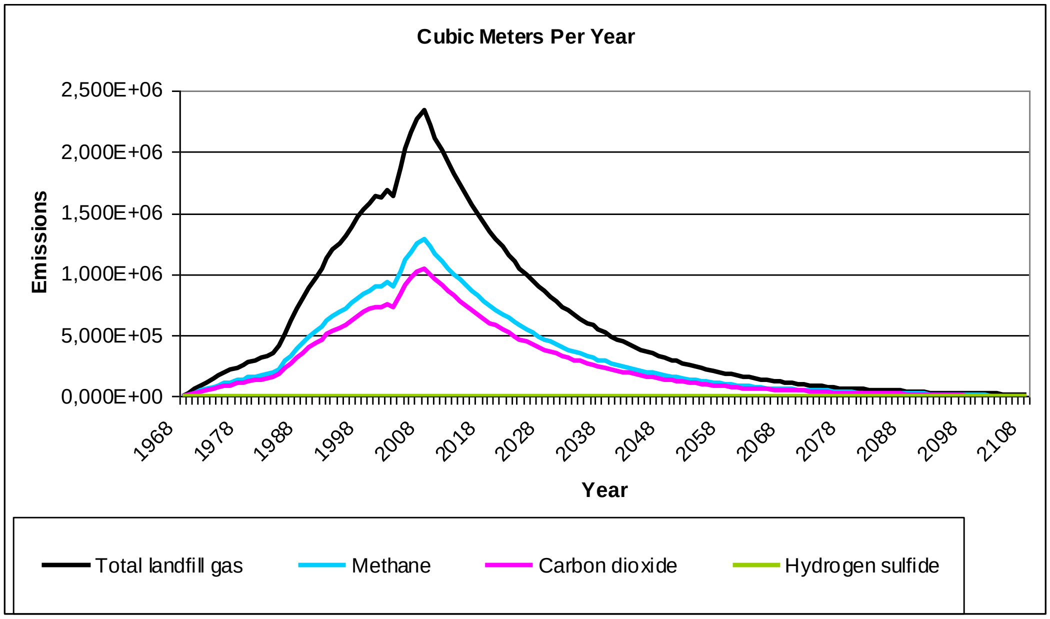

Figure 4: Landfill gas generation curve (LandGEM version 3.02)

The main hurdle presented so far for the better determination of the LFG model rate generation is the parameters identifications. In the case of the LandGEM and Scholl Canyon, the most important parameters are the rate constant (k) and the methane generation potential (L_0); and the rate constant only in the case of the TNO and multiphase model.

3.2.4 Parameters identification for (k, L_0)

The whole validation of the model implies the determination of k and L_0. The tight dependence between (k, L_0) and the site-specific conditions associated with the quality and availability of data increase the complexity of the problem. There is no advanced method which allows the utter determination of L_0 without inaccuracy [**32**]. An existing experimental method, ASTM (E1196-92), for the determination of L_0 is by means of the Biochemical Methane Potential (BMP). The determination of k is merely achieved with field data integration**.** In the paragraph beneath, is presented a theoretical approach for the determination of L_0.

3.2.5 Theoretical Estimation of L_0

It is clear that approximate L_0 theoretically gives an ideal value which, in practice cannot be reached. Nonetheless, it provides an understanding of the maximum possible value of the methane generation. For the reason that the actual system presents some constraint related to its physical aspect, biochemical and boundary conditions; the biodegradability factor must be used to adjust the theoretical value of L_0. It was suggested that the biodegradable fraction varies with the temperature solely [**33**]; such assumption has lead to consider the expression below:

$$BF = 0.0014 Temp + 0.28 \qquad (3.1.1)$$

Where $Temp$ refers as the temperature in degree Celsius [^{0}C]. In our first attempt, let us consider the stoichiometric resolution of the problem.

3.2.5.1 Stoichiometric Determination of L_0

Let us consider the stoichiometric equation describing the decomposition inside the landfill.

$$C_aH_bO_cN_dS_e + wH_2O \rightarrow xCH_4 + yCO_2 + zNH_3 + tH_2S \qquad (3.1.2)$$

The coefficients w, x, y, z and t are determined by balancing the equation (3.1.2), this yield:

$$\begin{aligned} &C_aH_bO_cN_dS_e + \left[\frac{4a-b-2c+3d+2e}{4}\right]\cdot H_2O \rightarrow \\ &\left[\frac{4a+b-2c-3d-2e}{8}\right]\cdot CH_4 + \left[\frac{4a-b+2c+3d+2e}{8}\right]\cdot CO_2 + d\cdot NH_3 + e\cdot H_2S \end{aligned} \qquad (3.1.2')$$

The number of kilo-mole for the total LFG is expressed as the sum of the coefficients of the products of equation (3.1.2')

$$n_T = x + y + z + t = \frac{4a+b-2c-3d-2e+4a-b+2c+3d+2e}{8} + d + e$$

$$n_T = a + d + e \qquad (3.1.3)$$

It is accordingly possible to evaluate the theoretical methane generation potential by using the molar volume of gas.

$$L_0 = n_T \cdot V_0 \qquad (3.1.4)$$

Where L_0 is the methane generation potential in unit of [Nm^3/Mg]; n_T the total number of mole of the LFG in unit of [$Kmol/Mg$]; and $V_0 =$ 22,414 $Nm^3/kmol$ is the molar volume of gas in standard natural temperature and pressure.

3.2.5.2 Further Determination of L_0

A more recent and practical approach to approximate L_0 was presented by [**34**]. For this purpose, the method has considered default values of (BF) for each category of waste. In addition, it considers the methane generation from organic waste component (C_m) and the water consumption according to the following stoichiometric equation

$$C_aH_bO_cN_d + wH_2O \rightarrow xCH_4 + yCO_2 + zNH_3 \qquad (3.2.1)$$

In contrary of equation (3.1.2), which assumes also the formation of hydrogen sulfide (H_2S), the subsequent is limited to ammonia (NH_3); balancing such equation yield:

$$C_aH_bO_cN_d + \left[\frac{4a-b-2c+3d}{4}\right]\cdot H_2O \rightarrow \left[\frac{4a+b-2c-3d}{8}\right]\cdot CH_4 + \left[\frac{4a-b+2c+3d}{8}\right]\cdot CO_2 + d\cdot NH_3 \qquad (3.2.1')$$

The potential of methane L_0 is determined by the following expression

$$L_0 = \frac{\sum_{i=1}^{n} BF_i \cdot FR_i \cdot C_{mi}}{1+w} \qquad (3.2.2)$$

In the expression above, BF_i is the biodegradable fraction of waste component i; FR_i represents the organic fraction of waste, or waste component i; C_m is the methane generation potential of the MSW organic matter for the category i in unit of [$m^3CH_4/dry-Mg$]; and w the water content on dry basis. **Tables 4** and **5** provide respectively the computed values of BF and C_m.

Table 4: *BF* values suggested in the technical literature

Author	Biodegradable fraction (BF)					
	Paper	Card-board	Food waste	Garden	Wood	Textiles
[10a] and [35]	0.44	0.38	0.58	0.45	0.61	0.40
[14b]	0.19-0.56	0.39	0.70	0.70-0.34	0.14	---
[36]	0.30-0.40	0.44	---	0.20-0.51	0.30-0.33	0.17-0.25
[37] – adapted	0.40	0.41	0.64	0.35	0.17	0.32

Source: Adapted from **[34]**

Table 5: Methane Generation (C_m) and water consumption

Waste Organic Component	$C_m [m^3 CH_4 / dry - Mg]$	H_2O consumption ($H_2O Kg / dry.Kg$)
Food Wastes	505.01	0.26
Paper	418.51	0.20
Cardboard	438.70	0.16
Textiles	573.87	0.41
Leather	759.58	0.64
Yard wastes	481.72	0.28
Wood	484.94	0.24

Source: Adapted from [**34**]

3.3 Direct Estimation Method of LFG rate generation

At the moment they are four methods used which enable the direct estimation of LFG rate generation. Respectively they are (1) Extraction well testing; (2) Surface Isolate Flux Chamber testing; (3) Differential Pressure testing; and (4) Baro-pneumatic testing method. The first method is useful only in estimating the LFG yield and its quality; the second should be carried out within a long period of time and the third method depicts large errors from its assumptions. The limitations highlighted by the methods (1)-(3) have led us to consider only the baro-pneumatic method. In the paragraph beneath it will be presented a brief description of the baro-Pneumatic method.

The baro-pneumatic testing method was developed to complement the lack in accuracy of mathematical model and other techniques. As an example, methods associate to site measurements are overwhelmed by heterogeneous gas permeability and LFG production [**38**]. Moreover, Parameter estimation for the rate constant (k) and methane potential (L_0) for models presented earlier, does not take into account site-specific conditions which influence LFG generation.

3.3.1 Concept of Baro-pneumatic Technique

Baro-pneumatic method is based upon the empirical relation (4.1) established by Young **[39].** In his assumptions, the volumetric changes in LFG are due to the pressure fluctuation and can be expressed as:

$$\text{Gas flux} \approx \alpha + \beta \frac{dP_{atm}}{dt} \qquad (4.1)$$

Where P_{atm} is the atmospheric pressure, α is the total gas rate generation within the site, and β is a constant depending on the physical parameter of the landfill. From this equation, LFG rate generation can be approximated indirectly under certain conditions. Baro-pneumatic method takes advantage of expression (4.1), by determining the parameters of that equation. From this expression it is possible to measure the fluctuation of the barometric pressure at a certain depth from the landfill surface. The resulting data of the transient pressure, combined with the variation of barometric pressure are used to calibrate the site-specific and the distributed parameters gas flux of the landfill. The combined information of site-specific data and gas flow principles corroborates somewhat the hurdles of the previous methods.

3.3.2 Experimental Set-up

The description of a landfill cross section equipped to undertake the test measurements is presented in **figure 5**. In such measurements, landfill site parameters will dictate the number of probes installed to gather the pressure data inside the reactor. Owing to the difficulties in estimating the size, the depth and location, the number of probes can be projected based on sensitivity analysis. Result data are time-series measurements of barometric and subsurface pressures and, the time period for data collection range from 2 to 5 days.

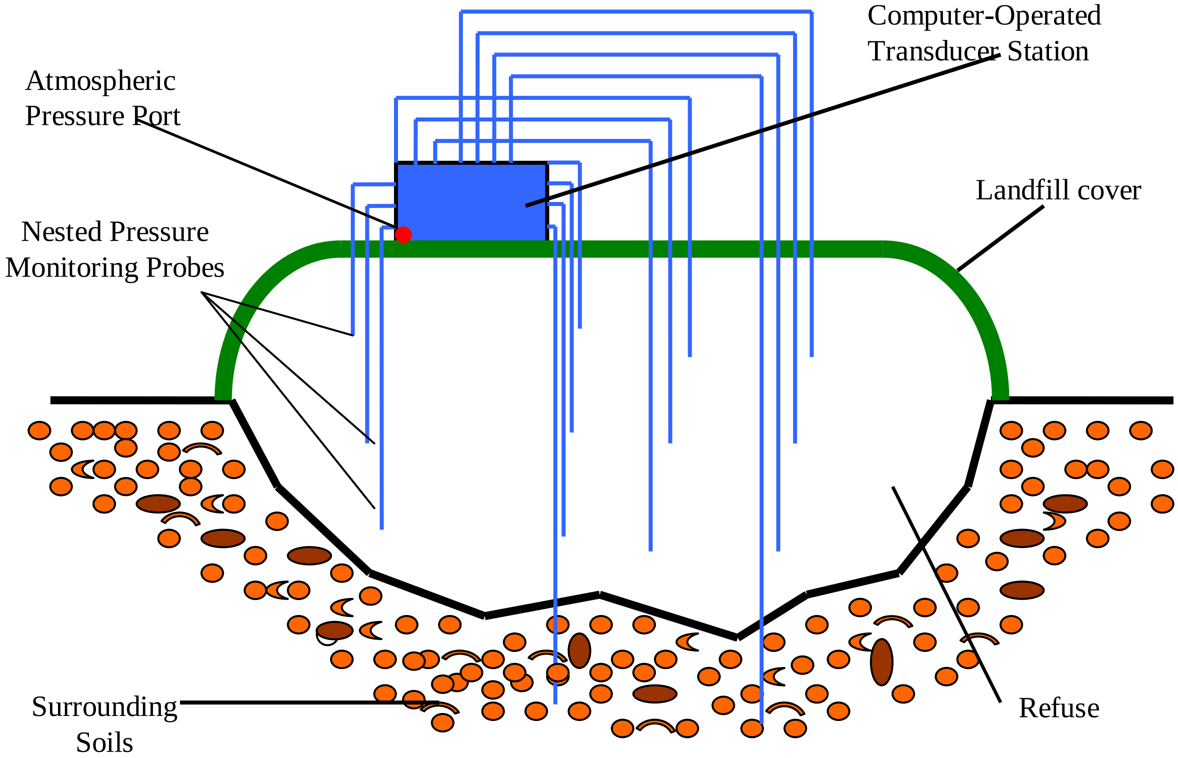

Figure 5: Baro-Pneumatic Monitoring System **[40]**

3.3.3 Description and Formulation

Let us assume the Darcy's law which gives the empirical relation between pressure gradient and gas velocity for a slow flow as:

$$\vec{u}\,\varphi = -\frac{\bar{\bar{k}}}{\mu}(\nabla P + \rho g\,\vec{n}) \qquad (4.2)$$

Where $\vec{u}$ is the Darcy fluid velocity that is the volume of fluid passing through unit area per unit time; μ is the gas dynamic viscosity; φ represents the gas filed-porosity or simply the porosity; $\bar{\bar{k}}$ is the effective gas permeability tensor; ∇ stands for the gradient operator; P is the pressure at the point in the landfill; g is the gravitational acceleration; ρ the gas density; and $\vec{n}$ the unit normal vector downward to the surface. The gas parameters such as: permeability, viscosity and density are assumed to be constant. For a given value of $\overline{\overline{k}}$, the computation of the difference between the barometric pressure and pressure in the landfill yields the LFG rate of production. However, the complexity of such route resides on the constant changes in the atmospheric pressure, which in turn causes the gas pressure to fluctuate from it average value. To account for actual conditions such as soil barrier, geometry of the landfill and, the location of pressure measurements points; the mathematical model combines Darcy's law and the continuity slow flow equation for single species that is

$$\frac{\partial}{\partial t}(\rho\varphi) + div(\rho.\vec{u}\varphi) = Q \qquad (4.2)$$

It therefore follows from equations (4.2) and (4.3) that:

$$\nabla \bullet \frac{-\overline{\overline{k}}\rho}{\mu}(\nabla P + \rho g \vec{n}) = \varphi \frac{\partial \rho}{\partial t} + \rho \dot{Q} \qquad (4.3)$$

Where $\dot{Q}$ is the volumetric rate of the gas generation per unit volume of porous material; and t is the time. Solving equation (4.3) provides the foundation for estimating the LFG generation rate. Also the combination of the barometric pressure data makes possible the parameter identification of model.

4 LFG extraction and treatment technologies

4.1 Rational and Scope

The process by which methane formed inside the landfill is captured represents another major step in GHGs sequestration. It is of paramount importance to cut-off the direct emission from landfill after the rate of gas generation has been estimated. Meeting methane sequestration can be achieved with the help of an optimum design of the LFG extraction system connected with a flare station. The rationale of the following part is to characterize the technologies used for gas collection, treatment and/or destruction. An example of technique used for methane capture is the oxidization of generated methane by methanotrophic microorganism in cover soil. Experimentations at the laboratory scale achieved by the landfill cover soils presented the results of 150-250 g CH_4/m^2/day oxidation [**41**] and [**42**]. Passive or active methanotrophic biofilters for methane emission reduction is another opportunity for its capture, [**43**] and [**44**].

In the quest of meeting reliable and effective capture of methane and, other unwanted gases, an optimum combination of extraction and oxidization techniques should be sought. For project development sake, extraction and collection gain an edge over other techniques whenever the gas amount is important and planned to be utilized. From this perspective, the significant question to be addressed is how much LFG generated can be extracted or collected. The answer to such question highlights the degree of significance for gas extraction systems optimization.

In the same way, the gas treatment systems are regarded with concern since the collected gas has to be treated before its utilization. Flaring the LFG should also be done after treatment in accordance with environmental regulations, since emissions from flare systems contribute to the deterioration of the air quality surrounding the landfill site.

4.2 LFG Collection Technologies

Different technologies for LFG extraction system exist; these techniques are closely connected to site specifics parameters such as: the landfill geometry, the amount of wastes and their density distribution inside the landfill. Gas extraction systems generally consist of wells dug at a certain distance inside the landfill and connected to a suction pump. In general the design of the network is based on the notion of radius of influence (ROI). This notion is a parameter which expresses the interaction effects caused amongst gas wells, due to their positioning throughout the landfill site. It is obvious that any gas sucked by one well evidently reduces the amount available for the others, this effect will respectively increase or decrease with the distance amongst gas wells. The concept of ROI is an important constraint for the optimization of networks installation.

Two types of extractions systems prevail within the available technologies for landfill gas recovery: (1) passive venting system and (2) active venting system. The second system is further subdivided into horizontal gas collectors and vertical gas extraction wells.

4.2.1 Passive Gas Collection Method

Passive venting is used whenever the amount of gas generated from the landfill reactor is projected to be small. In such system the gas flows freely from the inner part of the landfill to outside. The system only relies on pressure or concentration gradient difference. This type of venting is usually applied in vertical configuration. **Figure 6** presents a schematic description of the vertical vents. Atmospheric conditions will influence the efficiency of the passive venting system. The amount of gas collected will be regulated by the variation of barometric pressure. It is important that the transient pressure remains lower than the soil gas pressure otherwise it will coerce the gas to flow horizontally or will tend to balance the soil gas pressure. Failing to extract the gas can lead to flow of air inside the landfill which can jeopardize the landfill site.

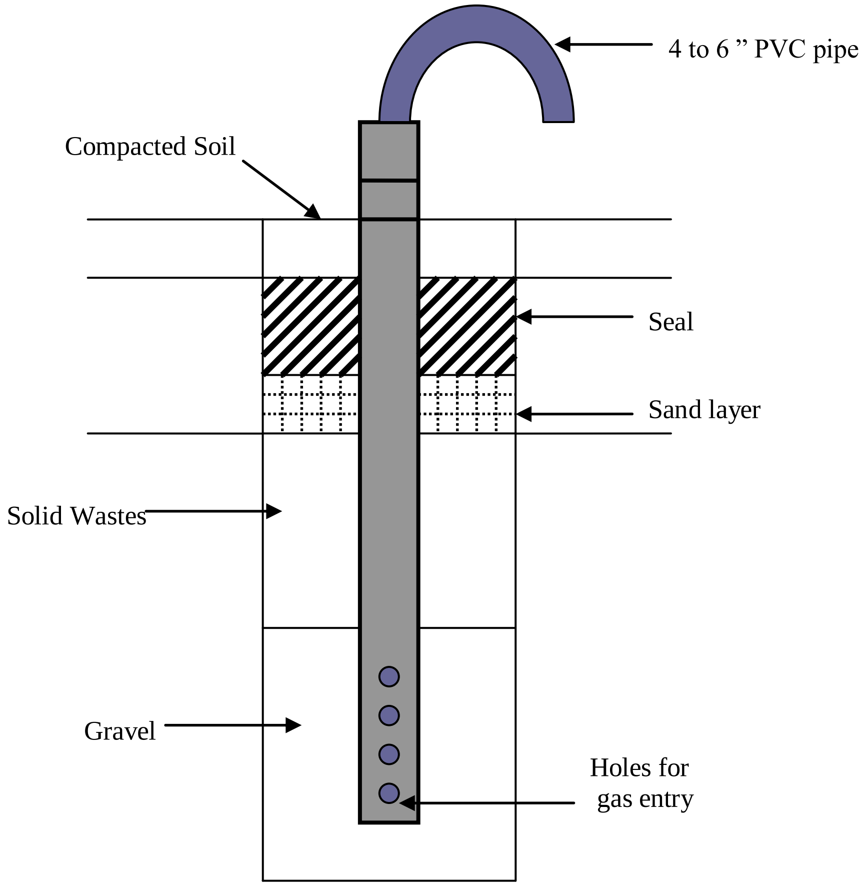

Figure 6: Passive Gas Collection System in Landfill [**45**]

4.2.2 Active Gas Collection Method

Active venting or forced flow system uses generally prime movers that produced a vacuum inside the landfill. Prime movers in this case can be a centrifugal blowers or other types of suction pump utilized to force the gas to flow out. Active extraction is utilized whenever the amount of gas is forecast to be important and can be converted into energy; the system is more effective than natural flow. As mentioned earlier, the venting system is divided into horizontal and vertical gas collection wells. The choice of the vertical extraction well or horizontal collector system is primarily determined by the geometry of the landfill.

4.2.2.1 Vertical Extractions Wells

In such system, vertical wells are drilled into the waste mass and connected to horizontal high density polyethylene (HDPE) pipe. Vertical wells extraction permit greater flexibility in the process and such system provides better LFG quality [**46a**]. The potential threat of such system is the reduction of the effective length of the well, since this latter is limited to the depth of unsaturated zone beneath the landfill.

4.2.2.2 Horizontal Collectors

In comparison to vertical piping, horizontal collectors are sensitive to leachate flooding and differential settlement [**46a**]. Such a system should incorporate valves, pressure gauge, condenser and sampling port at each collection well. The significant advantage in the utilization of vertical system is the reduction of the number of well required and its larger zone of influence.

4.2.3 Measurement of Collection Efficiency

There is limited discussion in the literature describing the efficiency of LFG collection system. Therefore, some default values are utilized according to different criteria. For instance 75% efficiency is used as standard by the US EPA [**47a**]. In general LFG extraction efficiency values reported so far for actual projects vary from 10 to 85% [**48**]. Higher gas extraction efficiency combined with final cover at cell greater than 90% have also been achieved [**49**]. A comprehensive and simple method to compute collection efficiency is to balance the actual gas recovered, the amount oxidized and released with the model outcomes.

4.2.3.1 Definition of Collection Efficiency

Gauging the effectiveness of LFG collection system is an important tool for engineering and environmental policy, as a consequence different definitions are used according to each purpose. At a glance, the collection efficiency would be the ratio of the collected to generated gas during a period of time. It is mathematically expressed by the following expression (3.1)

$$E = \frac{Q_{CH4collected}}{Q_{CH4generated}} \qquad (3.1)$$

Where: $Q_{CH4collected}$ is the quantity of LFG collected in mass per time; and $Q_{CH4generated}$ is the quantity of methane generated in mass per time. In the computation of expression (3.1) the numerator is well defined since the measured values are reported whereas the understanding of the denominator varies somewhat. The divergence in the collection efficiency calculation resides in the interpretation of the gas generation rate distribution. The **Figure 7** below depicts the general distribution pattern of gases generated within the landfill also known as methane mass balance [**23b**].

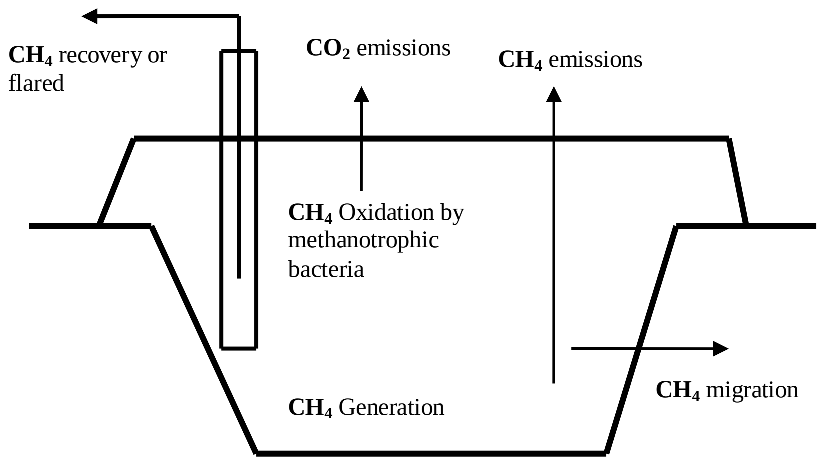

Figure 7: Methane mass balance, [**23b**]

The simplest model considers the LFG generated to be distributed into three streams, that is, the gas generated is split between the gas emitted, the gas recovered and the proportion oxidized [**50a**]. The expression of the denominator in (3.1) will thus take the form:

$$Q_{CH4generated} = Q_{CH4emitted} + Q_{CH4collected} + Q_{CH4oxidized} \qquad (3.2)$$

Where: $Q_{CH4emitted}$ is the quantity of methane emitted into the atmosphere in unit of mass per time; and $Q_{CH4oxidized}$ is the amount of methane oxidized at the surface of the cover soil in unit of mass per time.

A more complex approach takes into account all the streams illustrated in the figure above [**23c**]. Therefore the amount which migrated and which is stored must be included in the approximations. From this standpoint, the denominator of expression (3.1) will be rewritten as follow:

$$Q_{CH4generated} = Q_{CH4emitted} + Q_{CH4oxidized} + Q_{CH4collected} + Q_{CH4migrated} + \Delta Q_{CH4stored} \quad (3.3)$$

Where: $Q_{CH4migrated}$ is the amount of methane which migrates horizontally in unit of mass per time; and $\Delta Q_{CH4stored}$ is the variation of methane which is stored in the landfill over period of time in unit of mass per time.

Obviously, using expression (3.3) will require precise field measurements over a longer period. The results obtained from static flux chambers measurements have corroborated the gas distribution presented by equation (3.2) [**47b**]. Therefore, the LFG stored is insignificant and does not affect greatly the collection efficiency. Furthermore, default values ranging from 0 to 10% are used to quantify the methane oxidized [**50b**].

Instead of using equation (3.1) and (3.2), the US EPA has developed a model whereby it takes into account the monitoring of the area source. The resulting expression is directly related to the integrated surface measurement.

$$E = \frac{ISM_{collected}}{ISM_{collected} + ISM_{emitted}} \quad (3.4)$$

Where: $ISM_{collected}$ is the Integrate Surface Monitoring due to collection, or integrated surface methane recovered; and $ISM_{emitted}$ is the Integrate Surface Monitoring due to emissions, or integrated surface emitted.

4.2.3.2 Factors limiting the Collection Efficiency

The LFG extraction is hindered by natural conditions of the landfill itself. The first and main hurdle for the thorough recovery is the soil barriers which is present inside the landfill. Another factor of great importance is the lag time barrier; this factor is almost impossible to be surmounted. It is obvious that after the waste deposition, some rapidly degradable wastes will start to degrade, thus the gas produced prior to the gas extraction installation will not be captured. Further issues which alter the collection efficiency are: the decrease in gas amount inside the landfill over the time and, the effect of ROI will diminish the amount of gas recovery.

4.3 LFG Flare and Treatment Systems

The aim of this part is to describe another option used in landfill gas management to meet pollution regulations. Although direct combustion process is important for GHG emissions mitigation; it remains an alternative solution when CH_4 collected is not used for other end. Nowadays, most landfills incorporate flare systems as backup option to manage the excess gas produced.

4.3.1 Flare system

Flaring is the process by which the collected gas after be to some extent treated is combusted under environmental regulations [**51**]. Owing to the variations in the gas production rate and overhaul of the energy system systems, flare station should be used to handle the gas produced. Additionally, flare systems have the function to establish an effective gas control, with the basic objectives that they can be used for unexpected large flow of incoming gas. In general two categories of flared systems exist, enclosed flare and open flare. Each system is applicable depending on the environmental regulations, the settlement cost, the way it is utilized and the gas content presents in the landfill.

4.3.1.1 Open Flares

Often called elevated flares, they are mainly characterized by the elevated open flame which burns freely in open air. The system helps to prevent dangerous conditions at the ground level; however important heat is dissipated outside. A significant inconvenient of open flare is the poor combustion leading to side effects which can quench the combustion. **Figure 8** highlights a schematic of open flare system connected to the gas flow.

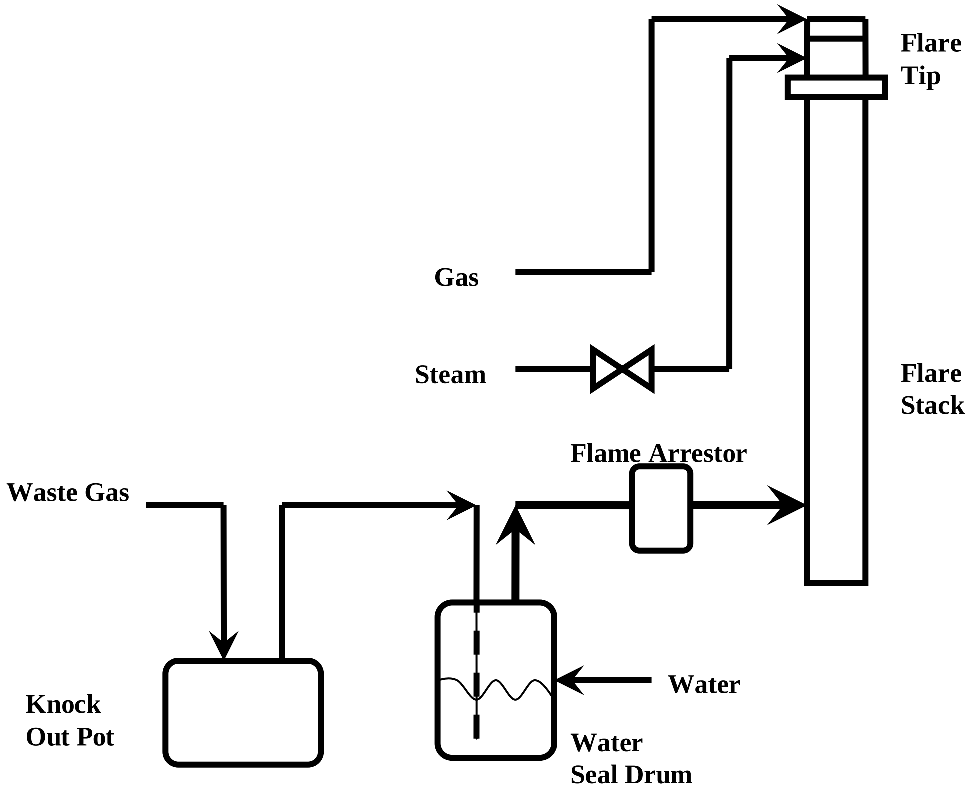

Figure 8: Simplified Open Flare schematic, [**51**]

4.3.1.2 Enclosed Flares

In enclosed flares system the burners are enclosed within the cylindrical shroud boundary. The shroud is designed as to determine the residence time in advance. Such systems prevent quenching and improve combustion quality. Monitoring emissions standard and, temperature control is easily achieved through enclosed flares. Enclosed flares are subdivided into sub-category such as fully enclosed and semi enclosed flare, or according to the air inlet, diffusion aeration and pre-aerated mode. The figure below describes the picture of a semi enclosed candlestick flare.

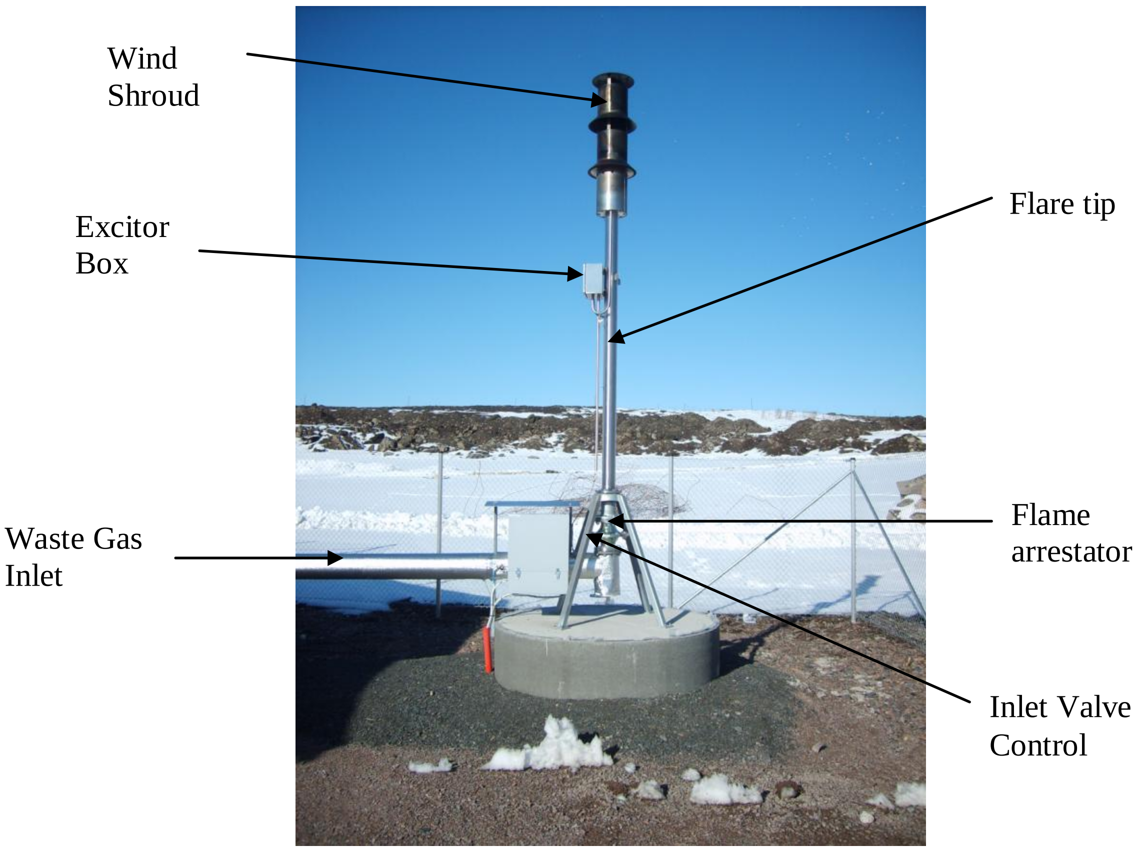

Figure 9: Semi Enclosed Flare [Ylivieska landfill]

4.3.2 Landfill gas Treatment Systems

Treatment of the raw LFG is of paramount importance for environmental and financial implications in case the gas is intended to be used for power generation. Gas clean up processes can be summarized as primary and advanced treatment. Advanced LFG treatment is more specific, that is, the LFG is cleaned in order to fulfill specific criteria.

For instance, utilizing LFG as alternative fuel for power generation will require different treatment than if the LFG is intended to be injected in the gas grid. Other possibilities are the utilization for steam boiler or hydrogen recovery. This section aims to present primary and advanced gas cleaning methods with a focus on the LFG as fuel to meet microturbine requirements.

4.3.2.1 Primary treatment of raw LFG

At this stage of the process, the main constituents of concern are water or condensate and, with low concern particulates. Thus the clean up process at this stage will mainly consist of gas drying. Drying the raw LFG is achieved by different means depending of the cost and the effectiveness of the technology.

Knockout drums which role is to slow the gas velocity constitute more often the first unit in the gas clean up process flow sheet. After this stage, vapor reduction is achieved by different means such as refrigeration drying or glycol stripping.

In refrigeration drying the gas is abruptly cooled to around 2^0C, this cause part of the water to condense. But the gas needs to be reheated to approximately $10\text{-}15^0$C, leading to excess energy utilized.

Glycol stripping is achieved by passing the wet gas through countercurrent contact tower with triethylene glycol (TEG). This technology is better suited for large flow stream. An example of a primary clean up unit using TEG is shown in **Figure 10.**

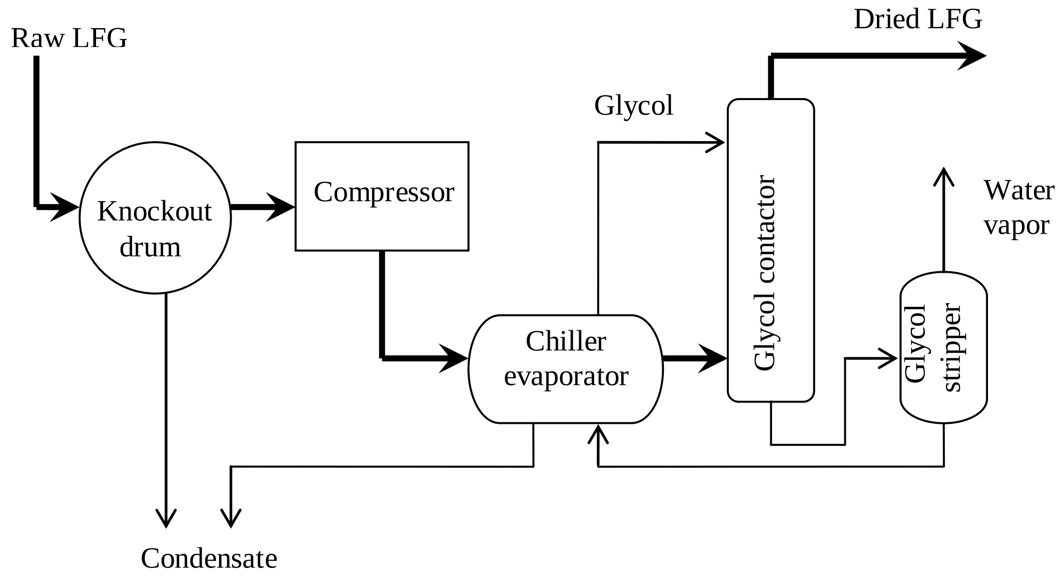

Figure 10: Simplified gas drying process using glycol (TEG) [**52**]

4.3.2.2 Advanced LFG clean up technologies

The main objective of advanced treatment is to upgrade the gas for further exploitation; doing so will help to mitigate the negative impact of certain constituents in power engine. Moreover advanced treatment improves the LFG quality and energy content, achieving this is done chiefly by the removal of CO_2. Besides that, sulfur and halogenated removal is significant in the LFG upgrading process. CO_2 which is the major constituents after CH_4 can be reduced by several proven technologies such as membrane process, molecular sieve and solvent absorption. In LFGTE project, siloxanes removal is of paramount concern.

Molecular sieve also known as pressure swing is a process by which a media adsorbs specific molecules whenever it is put in contact with a gas stream which is at lower pressure. The mechanism is identified as adsorption. In general the molecular sieve is tailored for CO_2, and the media should be regenerated when its adsorption capacity is exhausted. The choice of the technology will depend on the capital cost and the project scale.

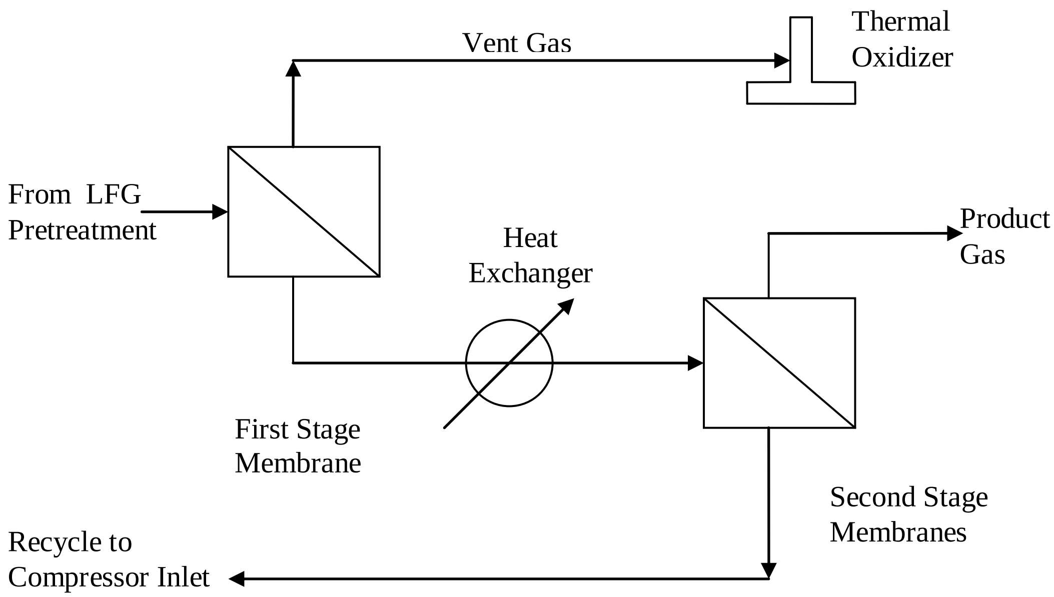

Figure 11: Membrane Process for LFG [**46b**]

5 LFGTE and Distributed Generation

5.1 Rational and Objectives

The foremost aim of this chapter is to present an insight of two different distributed generation systems often used in Landfills to produce energy. Distributed generation system also known as distributed energy resource, are defined as the application of small scale power generator developed to provide energy closer to end users.

As mentioned in the previous chapter, the gas produced from the landfill should after collection be either flared or utilized in environmental friendly way. In the specific case of landfill, on-site power generation or combine heat and power appears as an effective option to use the methane recovered in comparison to mere flaring.

With the breakthrough in conversion power technologies, distributed generations are now fuelled by a wide range of unconventional fuels such as biofuels. These facts have made distributed generation technologies attractive for projects development, whose purposes are to reduce methane emissions by converting it into an asset.

5.2 Distributed Generation Technologies

Existing LFG recovery plants was estimated to be approximately 950 in the world during the year 2001 [**53**]. Recovered LFG have been implemented successfully for purposes such as: Chemical energy storage, Gas purification, upgrade and introduction to natural gas grid, and direct utilization. Notwithstanding, LFG to energy remains an attractive solution because of it effectiveness. Current distributed generation technologies used are:

- Internal Combustion Reciprocating Engines (Otto cycle)
- Gas Microturbine
- Organic Rankine Cycle (ORC)
- Stirling Engine
- Fuel Cell (Molten Carbonate fuel cell, Solid Oxide fuel cell)

More often, the choice of the technology to be put into operation is dictated by the fuel quality and availability. However, it must be pointed out that financial aspect (Capital and maintenance cost) combined with technical expertise of the energy system are other hidden aspects of great importance for project viability.

Within the scope of the paper, focus is paid toward the Internal Combustion Reciprocating Engine (ICRE) and Gas Microturbines technologies. This is justified by the fact that, ICREs and gas microturbines are so far the most used distributed generation systems for LFG to energy project [**54**]. Below, the main points of interest for each technology are evaluated.

5.2.1 Internal Combustion Reciprocating Engine (ICRE)

Reciprocating engines used in distributed generation systems appear as the main technology applied for power generation in LFGTE project. More than 200 reciprocating engines fuelled by LFG in service in the world have been reported [**55**]. The combine effect of good heat rate at lower capacities and their good availability (80-90%) have consolidated their share as reliable distributed energy systems for small scale applications [**56]**.

5.2.1.1 Description of ICREs

In order to operate with gaseous biofuels, reciprocating engines should be of spark ignition (SI). Four-stroke ICRE operates in four cycles (Intake, Compression, Combustion and Exhaust). The lean gas-air mixture is induced to the cylinder in the bottom dead center, compressed and ignited by the spark plug. The disadvantage of using gas Diesel engine with gaseous biofuel is due to the fact that gaseous fuel must be compressed into around 200 bar pressure, which is high. **Figure 11** shows the block schematic of an internal combustion reciprocating engine used for distributed generation application. The presented system is for cogeneration purpose.

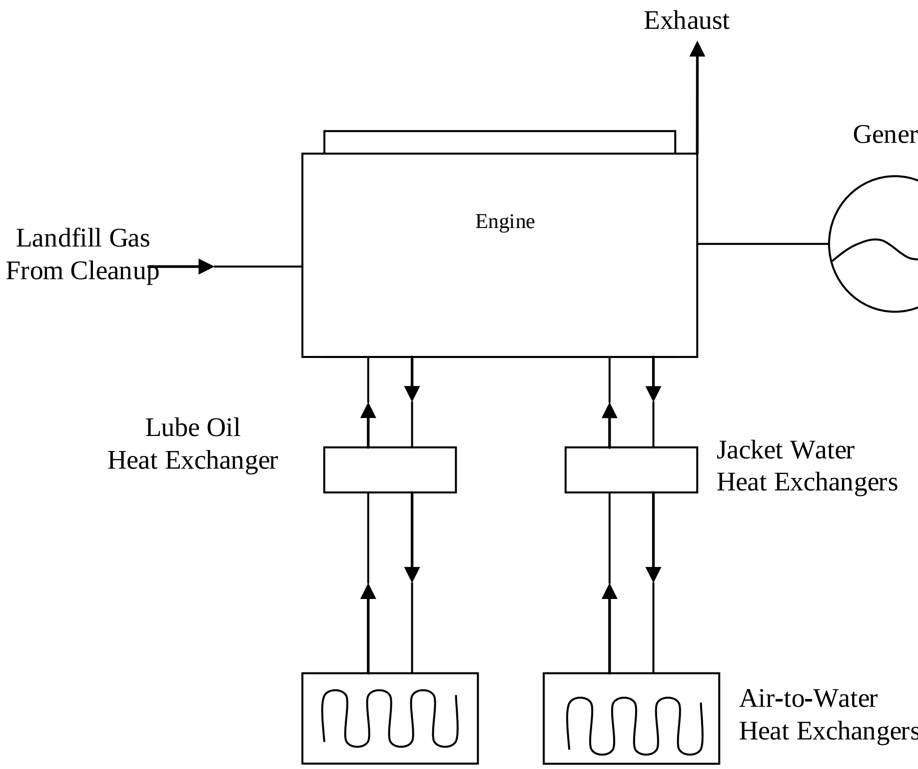

Figure 12: Power generation with Reciprocating Engines [**46b**]

5.2.1.2 Fuel Characteristics for ICREs

LFG makes a good fuel to power reciprocating engines, because of the knock-resistant methane and its high content of carbon dioxide **[57]**. ICREs powered by LFG require undemanding pretreatment process as compare to other distributed generation systems. Meeting fuel requirements is done mainly by compression and removal of moisture. Furthermore, the pressure by which the fuel is supplied is an important requirement to meet the rated power. Actually, the LFG needs to be pressurized at around 3 to 60 psig at ISO conditions before be fuelled in the engine.

5.2.1.3 ICRE performances assessment

An important performance feature of ICREs is the high efficiency they highlight from size ranging within 75KW to 50MW. As an example, small and medium size engines have efficiency varying from 70-85% in combined heat and power (CHP) application, and an electric efficiency ranging between 35-45% [**58**]. High power output can be achieved by increasing the mass of air inside the cylinder and the air temperature at the exhaust valves should be cooled. However, high temperature of exhaust air can be preferable for cogeneration which increases the overall efficiency. The ambient conditions are not of concern, since their impacts on engine performances are slight. The main impact is the decline in power output of 1% per 5.5^{0}C increase in ambient temperature. In **table 6**, it is shown a comparison of reciprocating engine performances fuelled by natural gas and LFG or anaerobic digestion gas (ADG).

Table 6: Reciprocating engine performance

Fuel	Electric Efficiency	Power output
ADG/LFG	29-38%	90-95%
Natural Gas	30-40%	100%

Adapted from **[57]**

5.2.1.4 Emissions from ICRE

An important drawback of the reciprocating engine technology is their higher emissions of nitric oxides (NO_x), carbon monoxide (CO), and other VOCs. The primary reason is related to the fact that ICREs combust gas under high pressure, an alternative reason is the low gas clean-up. Adding clean-up units can facilitate to minimize the impurities and achieve low emissions level, however inserting these units will increase the capital cost. The following table provides typical reciprocating engine emissions.

Table 7: Air emissions for a Reciprocating Engine in LFG

Emitted Agent	Ibs/MMBtu*
NO_x	0.200
CO	0.790
NMOCs	0.490
SO_x	0.008
Particulates	0.160

*lbs/MMBtu = pounds per millions of British thermal unit, NO_x = Nitric oxide;

CO = carbon monoxide; NMOCs = Non methane organic compounds; SO_x = Sulfur oxide, adapted from: [**46b]**

5.2.2 Gas Microturbine

Microturbines technologies are prime movers currently used for power generation or combined heat and power (CHP) to supply small scale unit. The growing attraction toward microturbine is partly due to the insertion of advances electronic technologies to handle the synchronization of the generator with power grid. They are used for many purposes, with emphasize for back up or stand alone applications. Furthermore, they are set in commercial-sized system ranging from less than one kilowatt to tens of kilowatt [**55**].

5.2.2.1 Microturbine Components and Thermodynamic

Microturbines arrangements are different from simple gas turbine. The basic parts are compressor, turbine generator, and recuperator. In order to handle small volumetric flows and maintaining high efficiency, their turbomachinery are set on single-stage radial flow compressor and turbine. The recuperator main role is to preheat the compressed air; consequently it can boost the efficiency of the microturbine according to the operating parameters. However, the recuperator reduces the effectiveness of the microturbine in CHP since it lower the exhaust gas temperature. **Figure 12** shows the energy flows for microturbine application in CHP.

Microturbines follow the ideal Brayton cycle. The gas inlet is pressurized in the compressor increasing its temperature. The heat released from the combustor increases the gas temperature before be expanded through the turbine. In general, the process is characterized by two isentropic phases (compression and expansion) and two phases at constant pressure. Microturbine expander inlet temperatures are set to 1800F (~982.230C) in order to maintain low pressure ratio ranging within (3.5-4.0) [55]. For cogeneration purposes a heat recovery unit (HRU) is introduced, this latter collects the waste heat from the hot exhaust gas and increase the overall efficiency of the distributed generation.

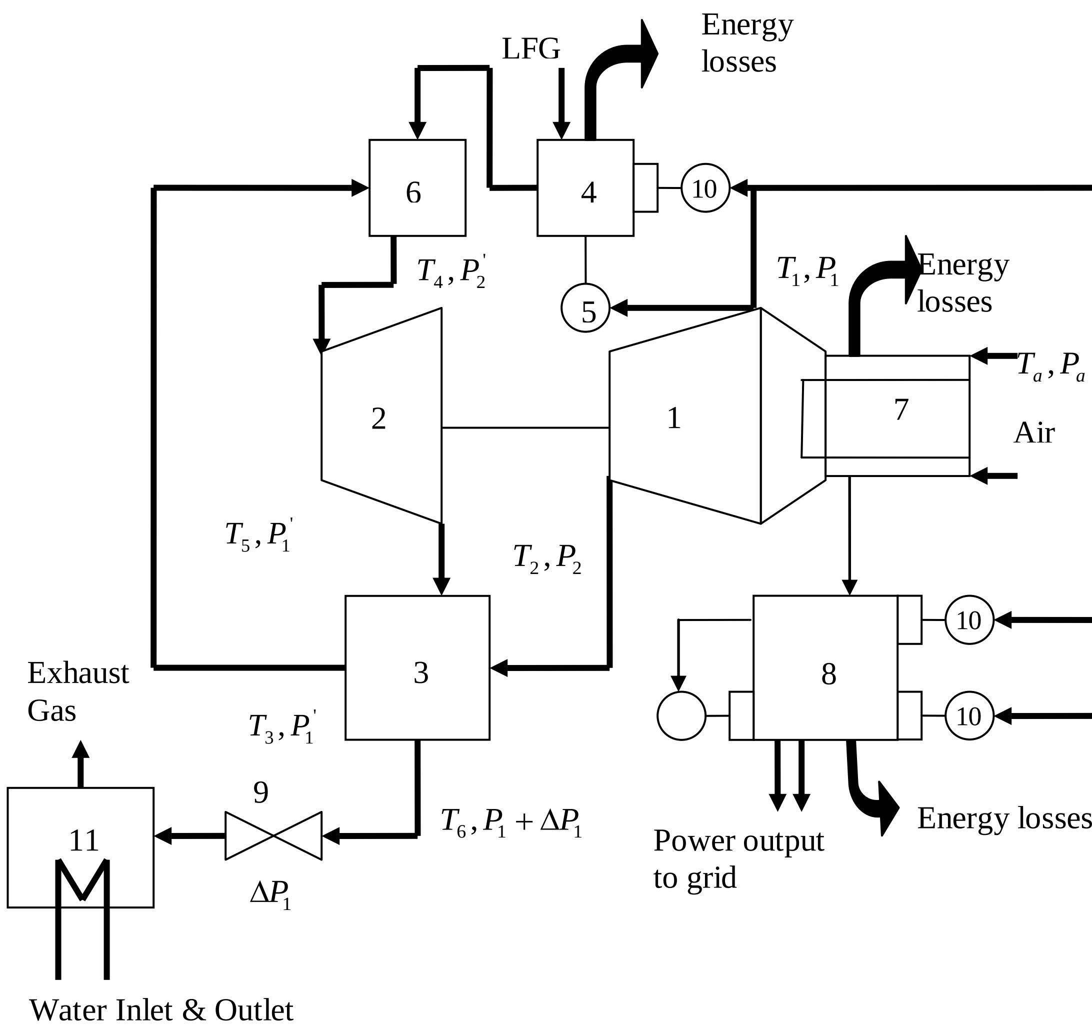

Figure 13: Microturbine Schematic diagram (Single-Shaft), modified from [**59**]

From the figure layout above we have: 1-air compressor; 2- turbine; 3-recuperator; 4-gas compressor; 5-electric motor; 6-combustion chamber; 7-electrical generator; 8-controller; 9-damper (throttle); 10-fans; and 11- heat recovery unit (HRU).

Microturbine energy balance can be analyzed via the mathematical model expressing the variation of thermodynamic quantities. Here will be considered the simple opened Brayton cycle and air-standard analysis, that is, air is the working fluid. Estimation of the theoretical power output is done by considering the power delivered by the turbine, the power developed by the air compressor, the power developed by the fuel compressor and the energy losses. Energy losses can be split into the power consumed to cool the fans and the heat loss [**60**]. The power output (gross electrical power) of the microturbine is broadly given by the following expression

$$W_p = W_T - W_{AC} - W_{FC} - W_{EL} \qquad (2.1)$$

Where: W_P, W_T, W_{AC}, W_{FC} and W_{EL} stand respectively for the gross electrical power out, the turbine power, the air compressor power, the fuel compressor power, and energy losses. Denoting respectively the turbine expansion rate and the compression rate by

$$\varepsilon_T = \frac{p_3}{p_4} \ , \ \varepsilon_C = \frac{p_2}{p_1}$$

Letting respectively the exhaust gas, the air and the fuel heat capacity at constant pressure and the heat capacity at constant volume by

C_P, C_{Pa}, C_F, and C_v

By denoting also the ratio in the turbine, compressor and inside the fuel compressor as follow

$$k_T = \frac{C_p}{C_v}, \ k_C = \frac{C_{Pa}}{C_v}, \ k_F = \frac{C_F}{C_v}$$

The turbine power is then given by the following expression

$$W_T = \frac{k_T}{k_T - 1}\frac{R}{M_T}(\dot{m}_a + \dot{m}_F)T_4\left[1 - \frac{1}{\varepsilon_T^{\frac{k_T - 1}{k_T}}}\right]\eta_T \qquad (2.2)$$

Where $\dot{m}_a$, $\dot{m}_F$ represents the mass flow rate of respectively the air and the fuel in unit of (kg/s); M_T is the molecular weight of the gas mixture inside the turbine in unit of (kg/kmol); and T_4 the turbine inlet temperature in Kelvin (K).

The power of the air compressor is also given by the following expression:

$$W_{AC} = \frac{k_C}{k_C - 1}\frac{R}{M_a}\dot{m}_a T_1\left[\varepsilon_C^{\frac{k_C - 1}{k_C}} - 1\right]\frac{1}{\eta_C} \qquad (2.3)$$

Where M_a is the molecular weight of the air inside the compressor in (kg/kmol); T_1 is the air temperature at the compressor inlet in Kelvin (K).

The power delivered from fuel compressor is given by the expression

$$W_{FC} = \frac{k_F}{k_F - 1}\frac{R}{M_F}\dot{m}_F T_1\left[\varepsilon_F^{\frac{k_F - 1}{k_F}} - 1\right]\frac{1}{\eta_{FC}} \qquad (2.4)$$

In expression (2.4), M_F represents the fuel molecular weight in (kg/kmol).

The mathematical expression of the energy loss is given by the following expression

$$W_{EL} = Q + W_c \qquad (2.5)$$

In expression (2.5) Q is the heat loss and W_c is the power consumed to cool the fans. The power consumed by the cooling fans is estimated by [**60**] as follow:

$$W_c = \frac{k_a}{k_a - 1}\frac{R}{M_a}\dot{m}T_1\left(\varepsilon_f^{\frac{k_f - 1}{k_f}} - 1\right)\frac{1}{\eta_f} \qquad (2.6)$$

Where $\dot{m}$ is the cooling air flow rate (kg/s), ε_f represents the fan head, and η_f represent the fans efficiency. The turbine exit temperature is an important parameter; it determines the amount of recovered heat. To this end it is worth considering the polytropic process which leads to its determination:

$$T_5 = T_4\left[1 - \eta_T\left(1 - \frac{1}{\varepsilon_T^{\frac{k_T - 1}{k_T}}}\right)\right] \qquad (2.7)$$

In expression (2.2)-(2.6) R represents the universal gas constant in (kJ/kmol.K), η_T is the turbine efficiency, η_C the compressor efficiency, and η_{FC} the fuel compressor efficiency

From equation (2.1) it is clear that any increase in expander power will increase the electric power generated. However this latter is constrained by its pressure ratio and the temperature T_4. According to equation (2.1) the parasitic powers should be kept low in order to achieve high efficiency.

5.2.2.2 Fuel Characteristics for Gas microturbine

Microturbines are less sensitive to the variation of fuel quality than internal combustion reciprocating engines [**61**]. This characteristic allows microturbines a wide operating range of fuel, from conventional fuel (natural gas, gasoline) to unconventional fuel such as sour gaseous, LFG and ADG. Whenever the concern is to fuel microturbine with LFG, the level of methane content required is approximately 35% to 38% at minimum. The LFG needs to be pretreated to remove moisture, siloxanes, hydrogen sulfide (H_2S) and other traces elements. Moisture could be removed by desiccant drier or chilling while siloxanes can be removed by activated carbon filter. Further requirement is the compression of the fuel, which should be around 70-80 psig. Table 8 presents the constituent limits for gaseous fuels to be burnt in microturbine.

Table 8: Constituents and impurities limit in Ingersoll Rand microturbine 70 series

Constituent	Limit
Oxygen	3% maximum
Hydrogen	5% maximum
Carbon dioxide	45% maximum
Methane	35% - 38% minimum
Ethane	8% maximum
Propane & Butane	2% maximum
Moisture	150 ppm maximum
Impurity	**Limit**
Hydrogen sulfide	25 ppmv maximum*
Halogenated organic compounds	200 ppmv maximum
Non-methyl organic compounds	1500 ppmv maximum
Particulates	3 μ average size**
Alkali metal sulfide (Na, K, Li)	0.6 ppm by mass maximum
Siloxanes	10 ppbv maximum***

* ppm = part per million, ** μ : micron = 10^{-6}, *** ppbv = part per billion volume
Modified from [**62**]

Economic feasibility for distributed generation installation is linked to fuel supply and the proper characteristics of microturbine design parameters **[63]**. Because microturbine performances and emission limits depend somewhat on the fuel properties, important considerations must be paid to standardize the fuel specifications to avoid under performance of microturbine. For the sake of economical evaluation, turbine efficiency is also assessed from fuel power to the output power; the corrected power of the fuel is given as follow [**62**]:

$$p_{fuel} = HV_s Q \frac{P}{P_s} \frac{T_s}{T} \qquad (2.8)$$

Where: HV_s is the heating value (either higher or lower heating value) of the fuel at standard temperature and pressure (energy/volume), Q is the fuel volume flow rate, P is the gas pressure, P_s is the standard pressure, T is the temperature of the gas, and T_s represents the standard temperature. The efficiency of the microturbine system is then defined as:

$$\eta = \frac{W_T - W_{AC} - W_{FC} - W_{EL}}{P_{fuel}} \qquad (2.9)$$

The utilization of fuel compressor to increase the LFG pressure implies higher power requirement than for natural gas. This fact contributes to decrease the efficiency. Taking into account the thermal power (net heat released) at the exhaust of the distributed system and denoting it W_{th}, it can be seen that the total efficiency is:

$$\eta_{tot} = \frac{W_p + W_{th}}{P_{fuel}} \qquad (2.10)$$

5.2.2.3 Microturbine Performances

In comparison to ICREs which are volumetric machine, microturbine performances are expected to vary with air density. Air inlet temperature is rated at 15^{o}C (59^o F) by ISO at sea level. The rise of temperature affects the power output of the turbine. The irregularities cause by ambient temperature is depicted in **Figure 14 (a)**. Further concern of microturbine performances is the insertion of a recuperator which positive effect is the increase in electrical efficiency by improving fuel economy. However, it also enhances internal pressure losses, leading to a decline in 10% to 15% of the power output from the attainable without recuperator [**55**].

Evaluation of specific power variation is done by differentiating the power output as presented in expression (2.11). This represents a measurable increase amount of power produced by pressure difference between two points in the gas [**65**].

$$d(Power/massflow) = -RTdp/p \qquad (2.11)$$

An attempt to estimate the relative variation of the power provided a result similar to the expression (2.11) [**60**]. The derivation of expression (2.12) was achieved by applying linear analysis to the set of equation (2.1)-(2.6) this yield:

$$\frac{\Delta W_P}{W_P} = -Z\frac{\Delta P}{P_1} \qquad (2.12)$$

In expression (2.12) Z represents the effects of the backpressure of the turbine output power. From (2.11) it can be seen that the output power variation is proportional to the absolute temperature of the gas and to the percent change in pressure. Therefore, achieving high performance is done by minimizing the pressure losses and stabilizing the gas flow at ambient temperature.

Microturbine performances are also evaluated according to their mode of applications. Distributed generation systems are utilized in full-load, part-load and in CHP. In full-load, the microturbine power output is affected by the altitude, while in CHP mode, power and efficiency will be affected by the recuperator effectiveness. Whenever less power than full load is required from a microturbine, the system is said to be in part-load mode. In part-load mode, the efficiency declines with the derating of power according to the part load factor, **Figure 14 (b)** illustrates the efficiency versus the factor in part-load mode.

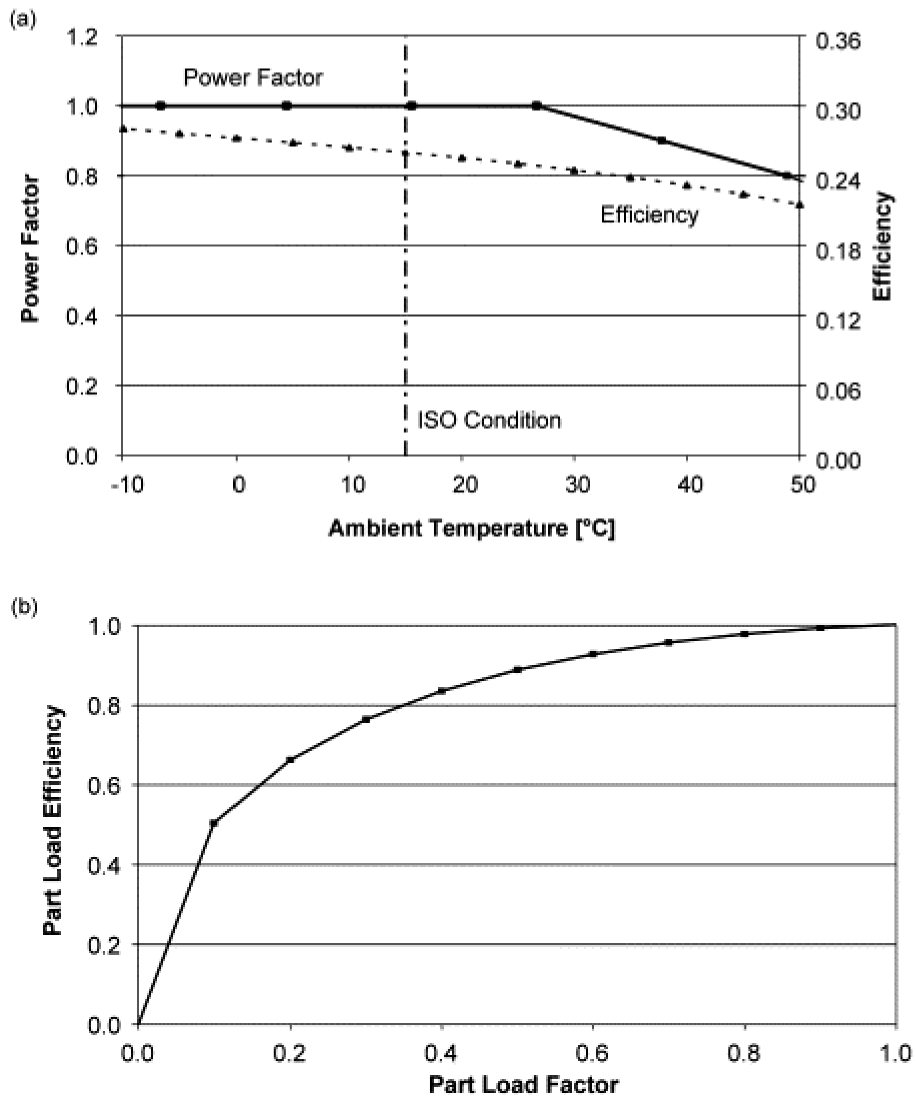

Figure 14: (a) Performance of Microturbine versus Ambient temperature, (b) Part load efficiency Microturbine versus part load factor [**66**]

5.2.2.4 Microturbines Emissions

The most important pollutants observed from microturbines exhaust gas are NO_x, CO and unburned hydrocarbons (THC). Means to control emission from microturbine are achieved by using Lean Premixed Combustion (LPC) or Catalytic Combustion (CC) method. The outstanding advantage that microturbines present is the low level of emissions. Nitric oxide emissions of less than 0.01 lbs/MMBTU for LFG powered microturbines have been reported [**55**]. The table presented beneath describes an example of targeted emissions level by a manufacturer.

From the table below, it appears that there is no significant variation in emissions for unburned hydrocarbons and carbon dioxide according to the power rating. While the lowest CO and SO_2 occur at full power output, the maximum NO_x concentration appears when the power is not at full load. Thus minimizing emissions is also achieved by running close to full power output.

Table 9: Microturbine emission characteristics

Emissions characteristics	System1	System 2	System 3	System 4
Nominal capacity (KW)	30	70	80	100
Electrical efficiency(%)HHV	23	25	24	26
NO_x (ppmv at 15% O_2)	9	9	25	15
NO_x, lb/MWh*	0.51	0.45	1.25	0.72
CO (ppmv)	40	9	50	15
CO (lb/MWh)	1.38	0.27	1.51	0.45
THC (ppmv)	<9	<9	<9	<9
THC (lb/MWh)	0.18	0.16	<0.16	<0.15
CO_2 (lb/MWh)	1765	1585	1650	1535

* Conversion from volumetric emissions rate (15% O_2) to output-based rate (lbs/MWh), for both NO_x and CO, was based on conversion multipliers provided by Catalytica Energy Systems, Source: [**67**]

5.3 Comparative Analysis of Distributed Generation Technologies

Microturbines have proved to be more effective for CHP cogeneration, because it delivers the greatest amount of waste heat compared to other distributed generation systems. The ability to convert waste heat on site into different forms such as hot water, chilled water or steam, increases the overall efficiency of microturbine as distributed generation system. However it is obvious that ICREs are proven technologies and are low capital cost as compare to microturbines. Summarize of the advantages and disadvantages of the two types of prime movers used in distributed generation are presented in the table beneath.

Table 10: Microturbine versus ICREs advantages and disadvantages

Advantages of Reciprocating Engine	Advantages of Microturbine
▪ Higher electrical efficiency ▪ Utilize low pressure fuel gas compressor ▪ Follow electrical and thermal load ▪ Suitable for moderate size landfills ▪ Size to match landfill production capacity ▪ Lowe capital cost and proven technology	▪ Utilization of variety of fuel ▪ Few moving parts and wear points ▪ Simple lubricant system and low operating cost ▪ Low emissions and noise ▪ No cooling water required ▪ Burn low CH_4 content LFG ▪ Installation close to load ▪ Trigeneration opportunity
Disadvantages of Reciprocating Engine	**Disadvantages of Microturbine**
▪ Higher emissions and noise ▪ More complex cooling system ▪ More moving part ▪ Higher maintenance cost ▪ Higher decrease of efficiency for low grade fuel.	▪ Lower efficiency ▪ High pressure gas or high compressor fuel (LFG) ▪ High capital cost ▪ Not suitable for varied LFG supply loads Limited experience ▪ Sensitive to ambient air temperature variation

Modified from **[55]**, **[56]**, **[58]**, **[62]** and **[64]**

6 Case Study: LFGTE Demonstration Project at Ylivieska

6.1 Background

The present case study reports the partial results of the implementation of the microturbine distributed generation fired by LFG in Ylivieska. Ylivieska is located at latitude $64^{0}02^{'}59^{''}N$ and longitude $24^{0}29^{'}50^{''}E$ that is north-east Finland. The landfill site is located at the suburbs of the city and has an area of approximately 7hectares of land filled area. In August 2007 the report from Detes Scandinavia Oy presented the result of gas survey investigations, mainly LFG emissions and risks assessment. Further studies were done by Bionova to assess the CH_4 rate generation according to the amount of waste dumped and the viability to establish a LFGTE project. The designed action was completed in mid September 2008 with the installation of the LFG collection system and a gas microturbine unit.

The field measurements revealed a CH_4 content of about 55% by volume of the LFG and a gas flow rate of about 60-80 m^3/h during the year 2008. The landfill is then used as fuel source to power a Turbec T100 unit delivering 112 kilowatts of electricity. The benefits from such project are threefold because it reduces firstly the direct GHGs emissions; then it provides clean electricity and hot water for the building of Vestia Oy; and finally it contributes to a sustainable development.

6.1.1 Introduction

The project initiated by Vestia Oy undertook the research of microturbine fuelled by LFG and was carried out with the corporation of Vårme-Kollector and Turbec. The waste management company of the city, Vestia Oy, has set a goal to mitigate the environmental impact of the landfill by cutting off the methane emissions from that source. Existing possibilities were the direct flaring of the extracted gas, the oxidization of methane by bacteria via the cover or its utilization as alternative fuel. Achieving this goal with benefits has been done by converting the LFG to useful energy. The project purpose was therefore focused on the design of an appropriate energy system that would embrace the gas collection system network, gas cleaning, and its compression. Furthermore, the piping for the transfer of hot water to the buildings and the connection of the generator to the buildings electrical grid were also achieved during the same period.

In this case study the paramount objectives embrace: (1) The increase in knowledge as regards to the microturbine operation on LFG (evaluation of the limitations to the rated microturbine performances); (2) The understanding of the establishment of distributed energy resource (DER); and (3) The estimation of most favorable requirements for continuous power generation.

6.1.2 Process flow sheet of LFGTE Project

The LFG was extracted from twenty four vertical collection wells drilled in the landfill area; no leachate collection system was constructed. A pipe network within the landfill is used to transport the LFG to the central flaring station. The LFG is dried and cleaned up before being fuelled to the microturbine. An automatic control system regulates the LFG flow rate to the microturbine. A flow sheet layout of the LFGTE system is shown in **Figure 15**.

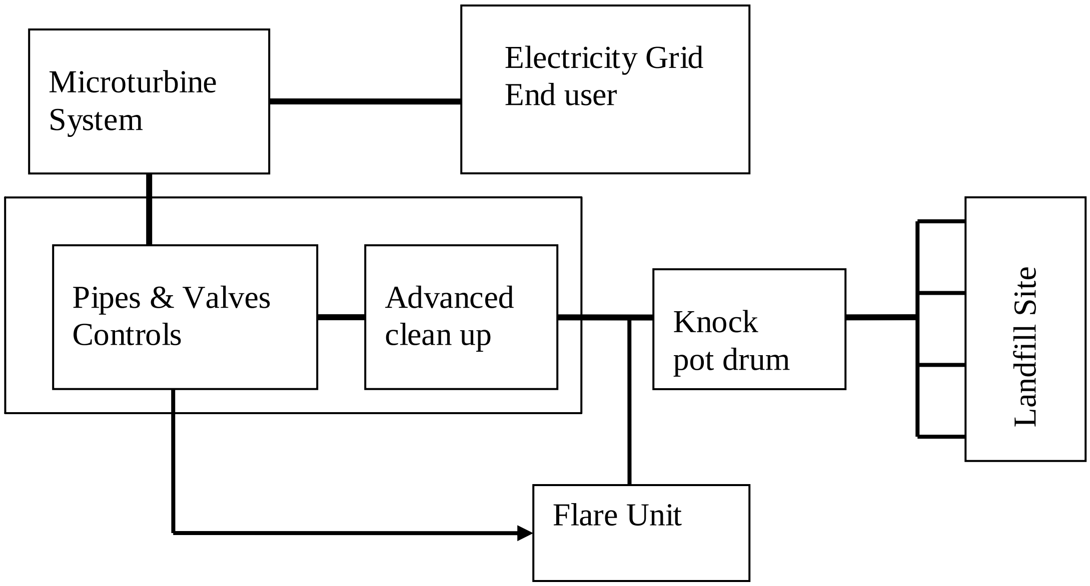

Figure 15: Energy system diagram

6.2 Project Modules

6.2.1 Waste Characterization

The landfill was active from the year 1970 to 2007; therefore it has been difficult to get the accurate amount of wastes land filled in the early years, since no exact record data were available. The first approximation based on historical record revealed 410000 tons, further assessment based on laser scanning weight of the landfill has revealed around 691500 tons of municipal and industrial wastes. From the year 1965 to 2007, the mass of waste disposed in the landfill was estimated by diverse investigations, partial results are presented as bar char in the **Figure16**.

In order to forecast the amount of gas generated from the site and size the energy system, the LFG production and rate generation was computed on the basis of the data between the years 2005-2025. The choice of this period is explained by the fact that, the model input data need to be sufficiently accurate (wastes composition) in order to provide good estimate of the methane generation potential. Owing to the knowledge of waste biodegradability for the period set, the methane content was assumed to be 55% by volume of the LFG. The result from the simulation model yielded a maximum gas flow rate of about 60-80m^3/h during the year 2008, and an average of 350 000 m^3 raw LFG per year until 2017.

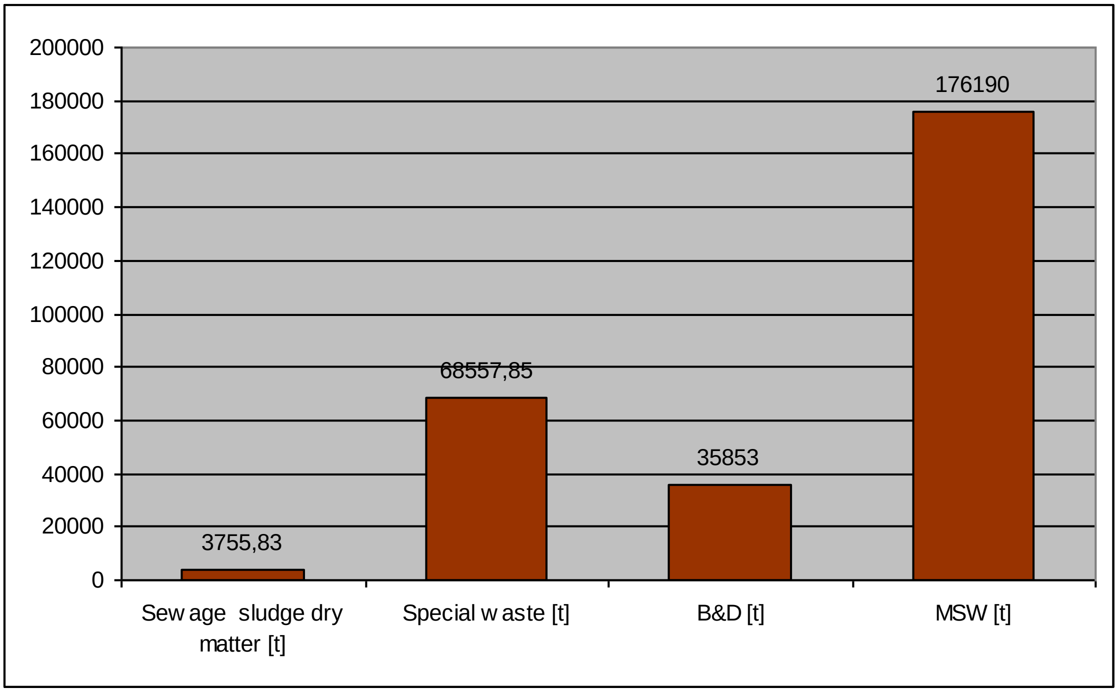

Figure 16: Estimate of waste composition dumped in the landfill (1965-2007)

6.2.2 Gas survey

The gas management survey attempted to quantify the surface and sub-surface emissions from the landfill site. Beyond that, in-situ measurements were achieved to determine the LFG composition. The hidden goal of the gas survey supervision was to improve the erection of the gas collection system. The field measurements have been carried out with a flame ionization detector (FID) and mobile infrared sensor (IR-Sensor). The field measurements were taken over fourteen wells drilled at 1.2m from the surface, with air-pressure conditions around 99600 Pa and 27^{0}C respectively. The results from the measurements are presented in **Figure 17**.

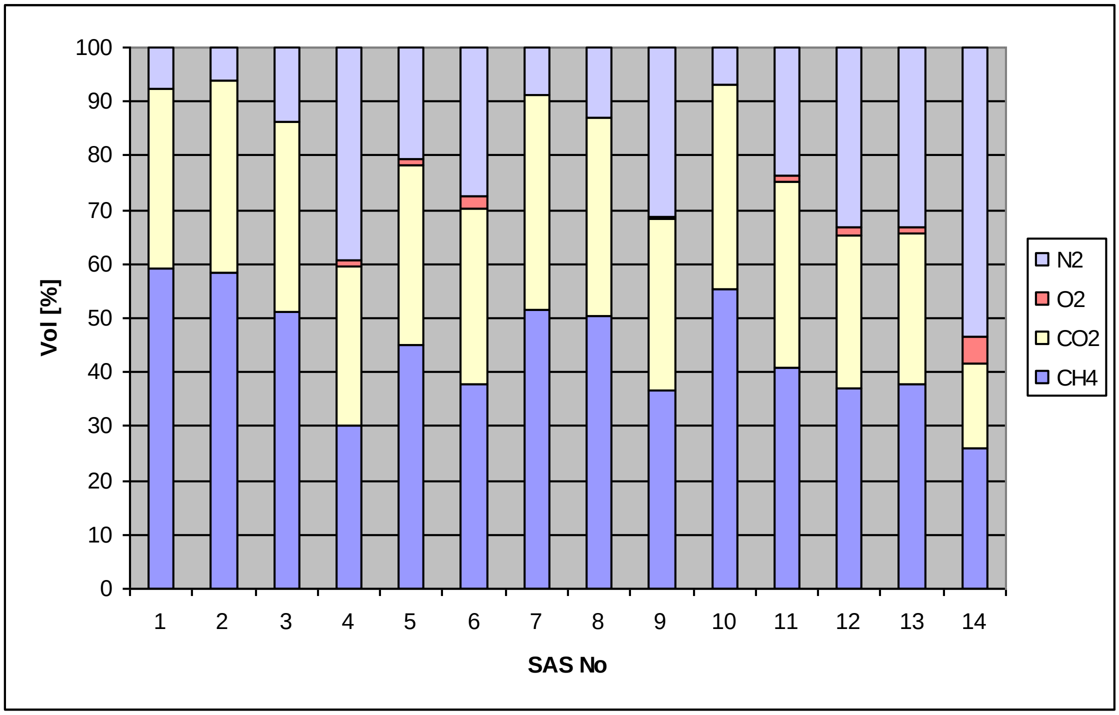

Figure 17: Soil-air measurements

Over the 14 wells the methane to carbon dioxide ratio was noticeably above one. This observation has confirmed the projecting value set to simulate the LFG generation model that is 55% CH_4 content by volume. The presence of nitrogen is explained by the high content of ingress air, since the landfill was not yet covered.

The graph plotted in **Figure 18** depicts the random repartition and the heterogeneity of waste dumped in the landfill, it describes also the availability of organic wastes. The major impact is the inconsistency in fuel quality. The gas survey did not reveal any hazard of LFG migration and, the emissions released were within the frame of the environmental regulations.

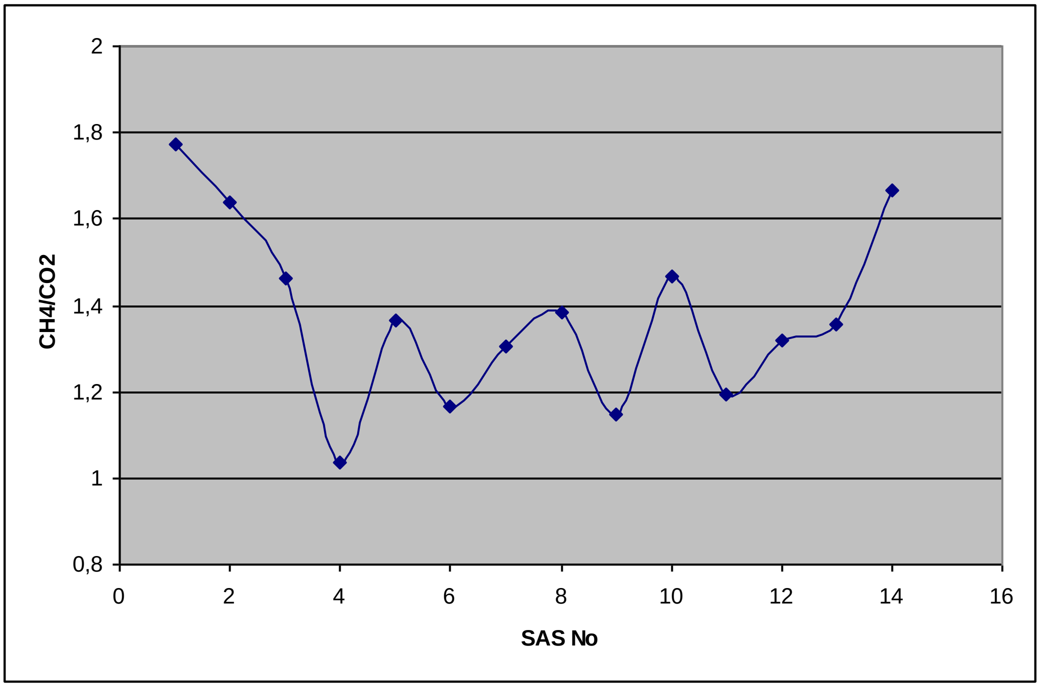

Figure 18: Methane to carbon dioxide ratio at ~1.2 m depth

6.2.3 LFG Collection and Control System

The collection system was established by the company Vårme-Kollector, whose task is also to maintain and screen the progress of the gas recovery system. The implanted 24 vertical gas extraction wells were connected to a blower which creates a vacuum inside the landfill thus, allowing the gas to be sucked out. A flare station was connected to the LFG pipelines to handle any excess of gas production. A treatment unit for impurities removal was added to the overall extraction system. Finally, the LFG was analyzed by two units to check its quality prior to be fuelled in the microturbine.

Figure 19: LFG treatment, conditioning and analyzer

From **figure 19**, each pipe is connected with one of the 24 pipes from the well, where the gross composition of the landfill gas is indicated. The importance of such system is to observe the evolution of a specific region where the gas is sucked. Flow rate, pressure and amount of oxygen present in that zone can be screened over time. The unit is automatically connected to a web based network which is then monitored from remote position. This allows less personal presence on the site and more effective control. Beneath is presented the online monitoring of the physical system during a specific period of time.

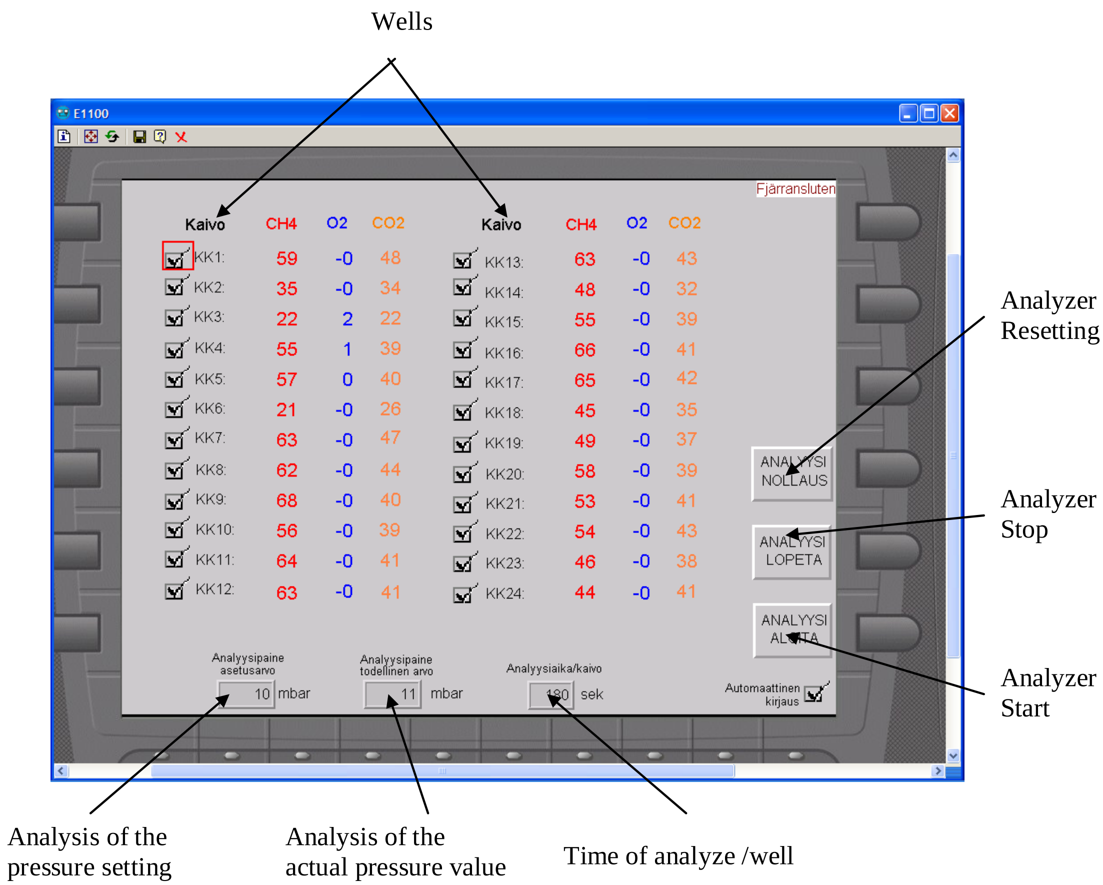

Figure 20: Pipes monitor scream

In **Figure 20**, it is shown the monitoring screen where the overall pipeline system is visualized. The state characterizing each pipe is presented in real time: amount of gas extracted, pressure gauge and gas composition per volume. In addition the cumulative gas recovered is recorded and visualize in over the time. **Figure 21** depicts the flow meter for dynamic observations of the gas pumped. Real time values of the normal volume of the LFG per hour are measured. Although the amount of LFG flared is unknown, the combustion temperature of the flare was estimated to be around 650-800^{0}C.

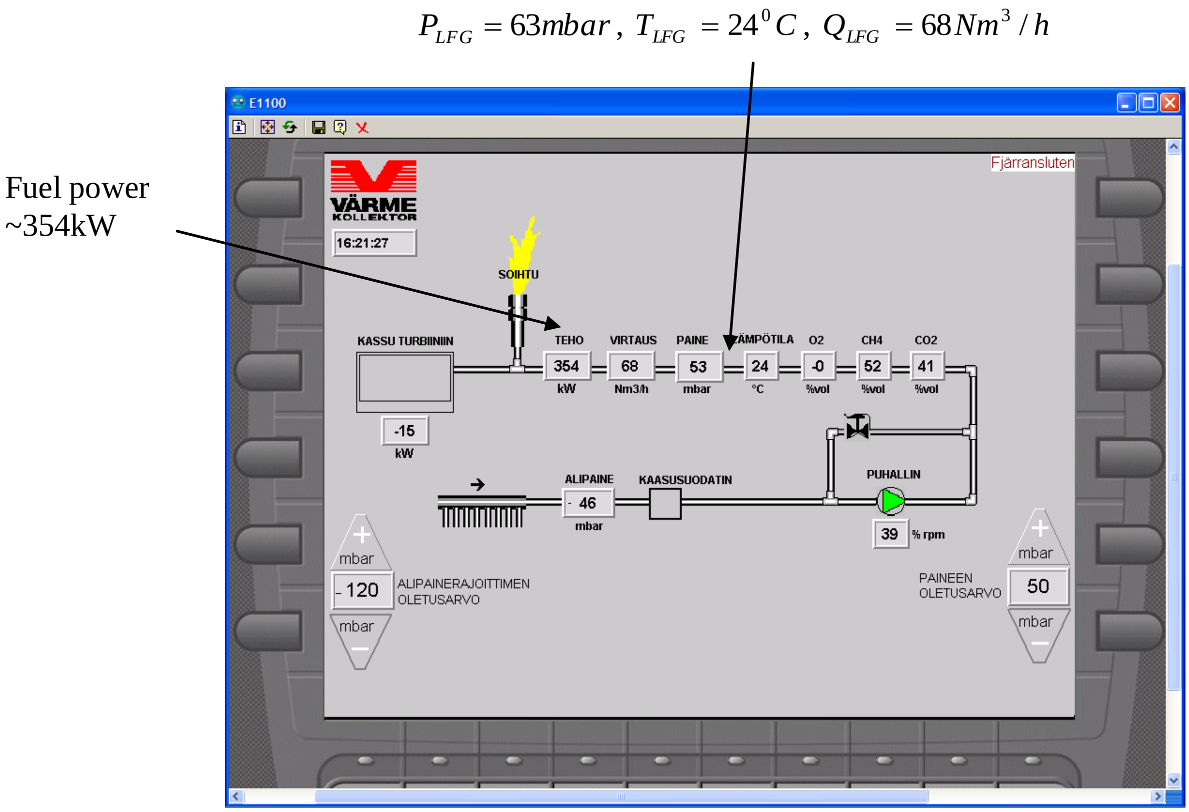

Figure 21: Flow meter monitors showing real time values

The knowledge of real time flow rate, pressure and temperature allow the automatic computation of the fuel power. In the case of **Figure 21**, the extracted LFG after being cleaned reveals the fuel power of about 354kW, flow rate of 68 Nm^3. The knowledge of such values contributes to the adjustment of the fuel demand and the fuel compressor power of microturbine system.

The gas extracted from the landfill undergoes primary and advance treatment. The first step is achieved with glycol stripping and further treatment by activated carbon. The gas was then piped to the gas analyzer where the composition was reevaluated before be pumped in the gas compressor. The observations of the gas recovered made during a long period of time reveals almost regular gas composition and flow rate. Over the 4148 hours of operation time, the total gas extracted was about 734 000Nm^3.

6.3 Design of the Energy system

The distributed generation system is set with a Turbec T100 microturbine unit for CHP purpose. The unit is capable to generate a nominal power output of 112kWe (rated at ISO meaning 2kWe is consumed by the microturbine fans systems) and thermal power of 165 kW in form of delivering hot water. The microturbine is connected to the LFG pipe system and assigned to run at full load whenever the require fuel demand conditions is meet. In the situation of over generation of gas, the valves whose functions are to regulate the incoming flow, directed the excess to the flare station. The external demand is essentially to fulfill the electricity and hot water for Vestia Oy buildings.

Meeting the objectives set earlier entails a close examination of the microturbine performances and how they are affected by the LFG characteristics. The deviations of such performances are of concern when low grade fuel are expected to power microturbine and, should be alleviated. The critical performance indices which are directly or indirectly dependent on LFG fuel characteristics are: the gross electric power output, the total efficiency and the electrical heat rate and/or fuel demand.

6.3.1 LFG fuel characteristics

In order to assess the impact of the LFG fuel, it is essential to limit the domain of our investigation. In this case study, LFG fuel characteristics are divided into: fuel parameter, fuel quality and fuel supply or availability.

6.3.2 Fuel parameters

Fuel parameters are divided in Fuel Inlet Pressure (FIP) and Fuel Flow Rate (FFR). FIP represents the pressure of the LFG at the valve inlet of the combustor. The importance of the FIP is related to the fact that, it directly affects the gross power output. More often, this pressure is greater than the gas supply pressure and slightly greater than the inlet air pressure. This allows better combustion process. The FFR in this study refers to the fuel heat content either higher or lower heating value (HHV or LHV in MJ/m^3) times the LFG volume flow rate (Q_{LFG}, m^3/h or Nm^3/h). The fuel flow rate is computed by the following expression $FFR = LHV * Q_{LFG}$. The FFR can be understood as the fuel power as regard to the dimension analysis. Beneath is summarized the LFG parameters of the project.

Table 11: fuel parameters

Parameters	Units	value
FIP for 112kWe	bar	~6.82
LFG fuel LHV*	MJ/Nm^3	18.54-18.62
LFG FFR	MJ/hr	1210-1300
LFG Fuel power	kW	335-360

*The LHV of the LFG was calculated on the basis of 55% CH_4 to 45% CO_2 content

6.3.3 Fuel quality or chemical composition

The quality of LFG may vary significantly by virtue of the proportion of CH_4 content. Fuel quality will refer in this paper to the chemical composition by volume and heating value of the LFG. The chemical composition of the fuel is estimated to CH_4 55%, CO_2 45%. The composition is useful to quantify the LFG heat content.

6.3.4 Fuel supply or availability

The fuel supply plays an important role because of the status of the LFG which is not determined in advance with accuracy. The combined effect of the variation in LFG rate generation and the limitations in gas recovery will affect the availability or supply of the fuel. **Table 12** beneath presents the summary of the fuel quality and supply.

Table 12: Operating LFG fuel quality and supply

Characteristic	Units	Value range
CH_4 Collection efficiency	%	60-75
CH_4 content in the LFG	%	50-55
CH_4 density	t-CH_4/m^3	0.0007168
LFG supply pressure	mbar	60-65
LFG volume flow rate	Nm^3	65-70

6.4 Analysis of LFG fuel impact on microturbine performances

6.4.1 Fuel demand

The fuel demand which is the amount of fuel consumed by the microturbine is a design parameter to produce the set power output. Fuel demand is affected directly by the chemical composition and indirectly by the FFR. The fuel quality will affect the variation of LFG volume flowing through the combustor for the same power output. The higher the CH_4 content, the higher will be the heat content and the lesser the fuel demand. **Figure 22** shows the combined effect of LFG fuel quality and FFR on the fuel demand variability. For different amount of LFG consumed throughout the combustor, approximately the same power output ~109 kWe is obtained.

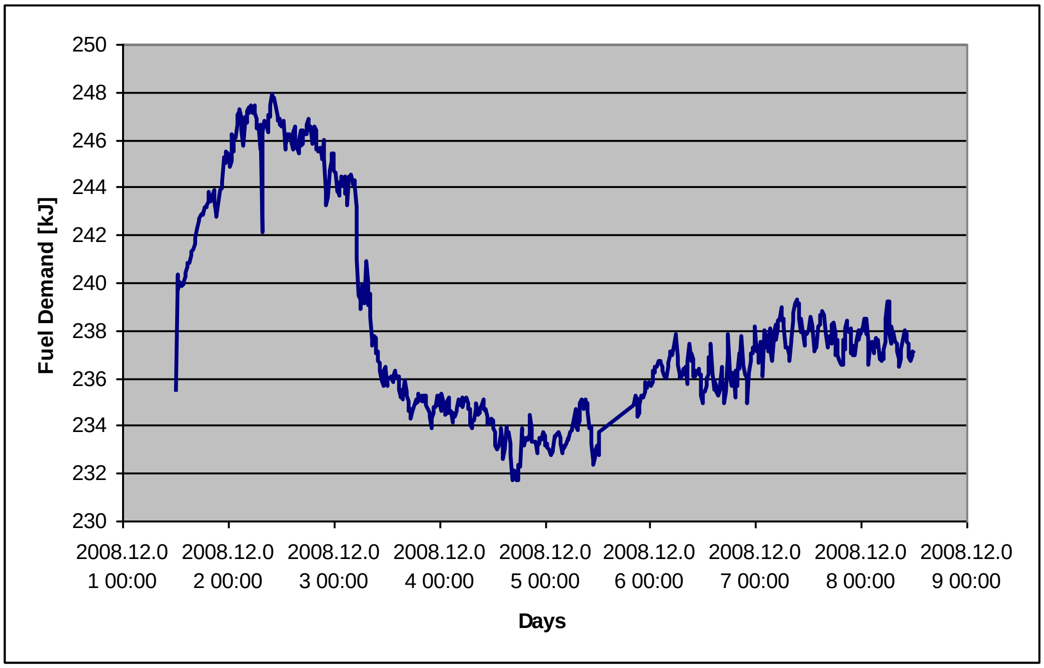

Figure 22: Effects of LFG supply flow rate and quality on fuel demand

The variability in fuel demand will directly impact the power output. The observation in derating of power is due to the inconsistency in LFG fuel quality notably the chemical composition and fuel availability or supply. In **Figure 23** it is shown the effect of variation in the fuel power and availability. The plot highlights mainly the effect of the fuel quality variation combined to LFG rate of generation. At 110.8 kWe, the fuel demand is round 255kJ while at 102 kWe and 95.4 kWe of power the fuel demand is almost equivalent. The probable explanation for the different power output for the same fuel consumed is the variation of the chemical composition of the fuel. Such trend is unpredictable and out of control from the operator.

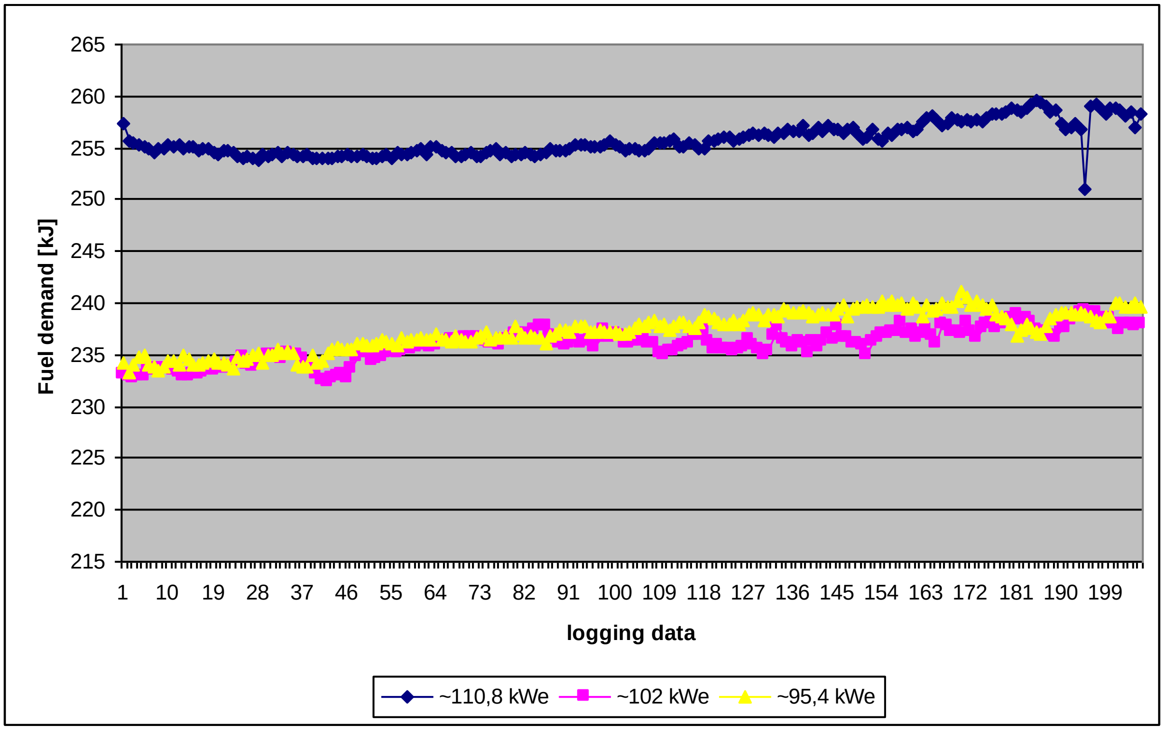

Figure 23: Effect of Fuel quality and variation in fuel supply

The graph presented in figure 23 was plotted with the logging event for a period of continuous functioning of the microturbine without interruption.

6.4.2 Gross electrical power output

The power output is directly affected by the fuel inlet pressure and indirectly by the fuel flow rate. The FIP can increase the expander power at the expense of parasitic powers of the fuel and air compressor as shown in the prior chapter. In the case of the Ylivieska landfill the microturbine minimum FIP was set at about 5.8 bars to 6 bars for power output of 110 kWe. However, data logged highlighted a constant power output (110kWe) within the range of FIP that is around 5.8 bars to 6.6 bars. Beyond this critical value, observations show a decrease of the microturbine power output. This shows that the effects of parasitic power are more important than the increase of the turbine power for certain values of FIP. Therefore, keeping the FIP in the optimum range will enable a stable electrical power output (**Figure 24).**

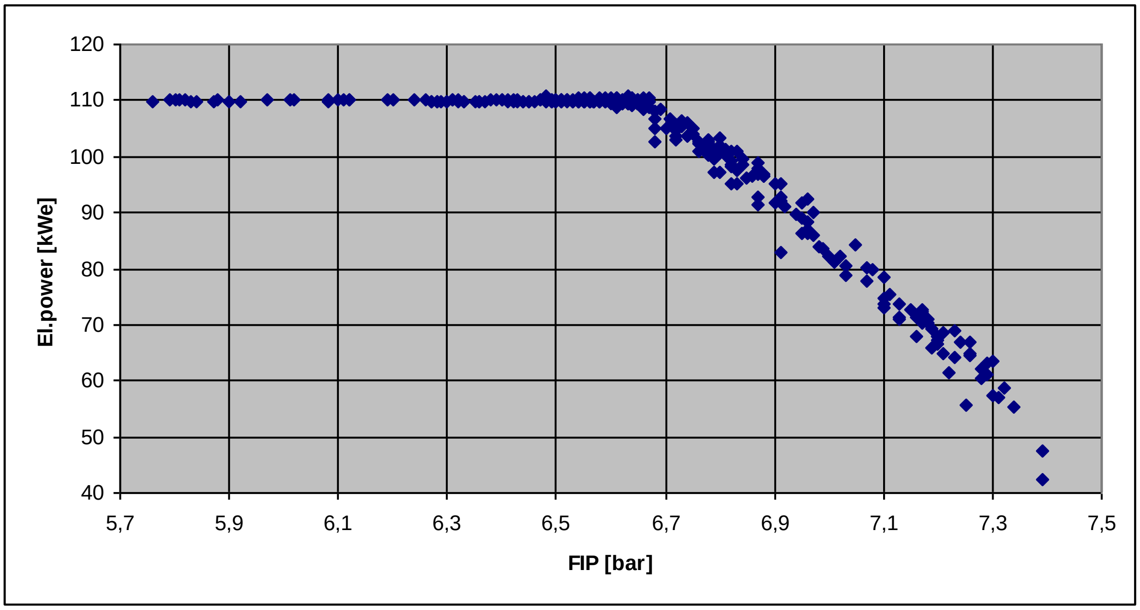

Figure 24: Electrical power output versus FIP

The fuel flow rate which is also understood as the power of the fuel has a secondary effect to the power output, since it is related to the chemical composition. Thus, assuming the CH_4 content constant over a certain period, any increase in fuel flow rate results in power increase, although the trend becomes ill at certain values **Figure 25**.

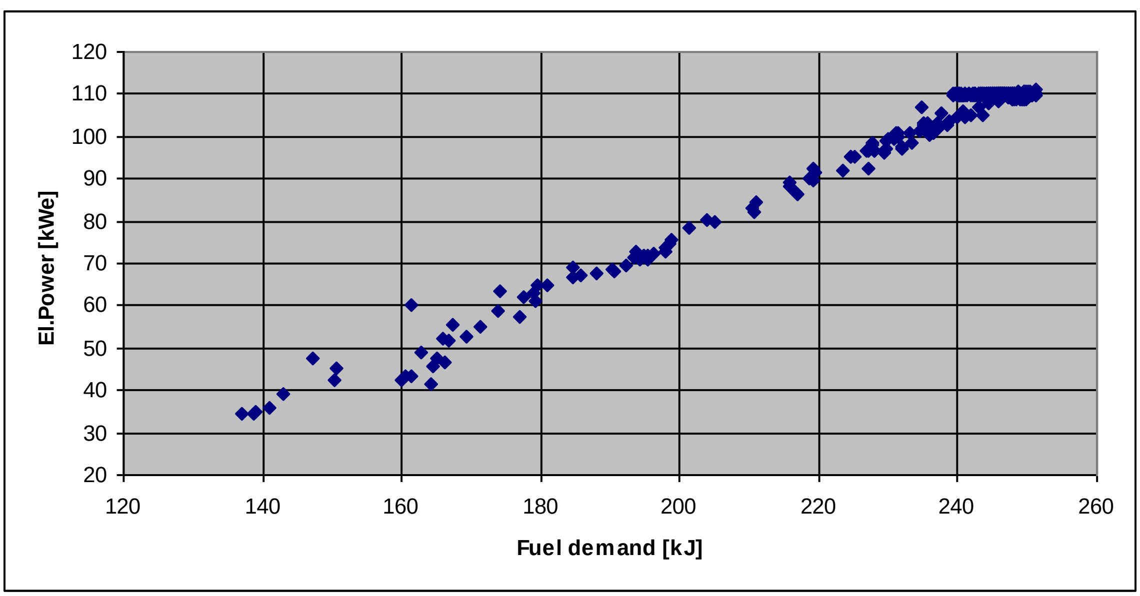

Figure 25: Electric power versus fuel demand

6.4.3 Net Electrical Heat Rate

The electrical heat rate which is defined as the ratio of the fuel power to the electric power output is important for economic considerations. It actually represents the amount of fuel burned to produce a desired electric power. Let us for this purpose consider the theoretical expression of the net electrical heat ratio as: $NEHR = \frac{FD}{EE}$ where FD stands for the fuel demand and EE is the gross electrical energy. From the logged data it was possible to compute the amount of electrical energy produced for the fuel consumed by the microturbine. The graph plotted is presented beneath in **Figure 26**.

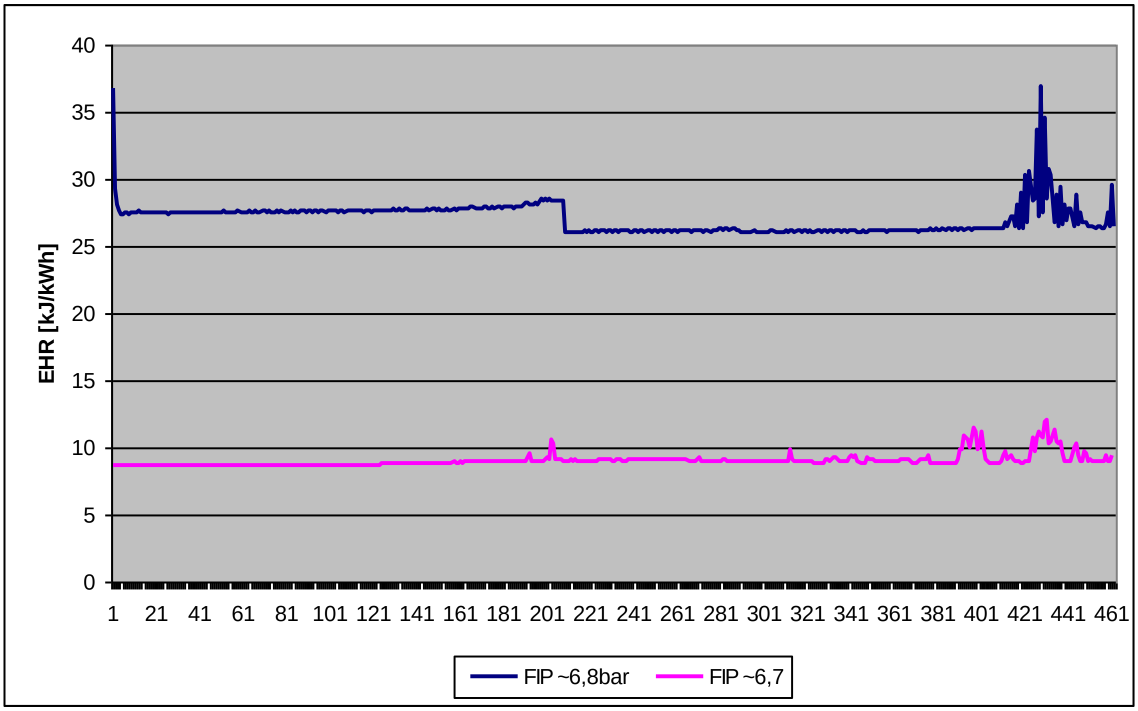

Figure 26: Electrical heat rate

The graph in the figure above highlights two trends, the first which is characterized by higher NEHR ~ 25 kJ/kWh and the second more consistent around ~9 kJ/kWh. The first trend was observed over a period of two weeks while, the second trend which dominates was scrutinized over one month ahead. The first trend can be due to the effect of FIP, since it was shown that too higher FIP decreases the power output. Furthermore, no significant effect of the air inlet temperature was observed.

6.4.4 Heat recovery unit

The microturbine Turbec T100 integrates the heat recovery unit (HRU) for CHP application. The HRU consists of gas-to-liquid cross-flow type (or by-pass type) heat exchanger. The water outlet temperature reference is around 67.5^{o} C; however it strongly depends on the incoming conditions of the water and other parameters such as the microturbine power output, ambient temperature of the HRU and flow rate. The field data observations did not reveals any strong dependence between the water outlet temperature and the ambient temperature of the HRU.

6.4.5 Impact of outdoor Installation

The partial installation of the microturbine system outside has played an important role in the fluctuation of air inlet temperature. This latter is related to the ambient air temperature which varies throughout the day depending on the weather conditions. Therefore it was difficult to investigate the air inlet temperature effect of microturbine.

The direct and significant side effect related to outdoor installation was the interruption of the microturbine system. The combined effects of very low air inlet temperature and relative moisture present in air inlet or the LFG associate with the cold weather have caused condensate water to freeze. This detail has contributed to decrease the availability of the microturbine system.

7 Conclusions and recommendations

The problematic surrounding the usability of the land filling process and the practicability of the LFGTE project is undeniable for environmental and climate change issues. LFG resides at the border between waste management and bioenergy, since environmental burden of land disposal is altered in potential renewable energy source. The contribution of distributed generation technologies such as microturbine capable to burn low grade fuel has enhanced the value of land disposal process. Providing energy from waste is seen as the road to sustainable development.

The prior chapters have helped to streamline the route of energy production from the waste disposal to the gas extraction and energy system sizing. The main findings are summarize and highlighted in this part.

Although waste management policies in many countries encourages higher recycling rate, landfills construction are growing important issue to stakeholders. The findings reveal that the main parameters that influence the anaerobic bacteria activity are temperature and moisture. This is due to the fact that internal heat balance of the landfill is one of the principal factors that regulate its behavior, and fast stabilization is achieved with high moisture content in the landfill reactor. Beyond this limit, current monitoring practices which rely deeply on monitoring gas composition to assess the internal state of the landfill and its safety should be discarded, because gas flux and composition are affected by changes in atmospheric pressure.

The theoretical models presented above are surrounded by inconsistency in their results, due mainly through parameters which are site dependent. Although the broad description of the phenomenon is depicted and follows the real pattern, it comes that the yield of the gas per year varies either slightly or deeply. Furthermore, the implication of the type of model used to illustrate LFG rate of production depends on the software model. While some models will overestimate the gas generated other will underestimate the production.

It is therefore important to complement the theoretical with the direct estimation of the gas rate production. Measurement techniques complement each other, theoretical model provides the ground basis of the biodegradation mechanism and the direct measurements help to improve the calibration of the theoretical results.

The LFGTE project was an opportunity to ascertain the usefulness of unconventional fuel from land filling to power microturbine. The behavior of the microturbine performances fuelled solely by the LFG was carried out through the implementation of distribution generation system. The partial results demonstrated promising results in the way that the system was capable to deliver gross power output close to the rated value and the overall system (extraction system, flare unit and microturbine) shown high availability. Noticeable points were the inconsistency in LFG fuel quality and fuel flow (rate generation) which is closely related to the power output. Continuous power generation requires an accurate knowledge of the waste composition and LFG production in order to allow the microturbine to run at different loads.

Main recommendations are addressed toward the waste segregation, treatment and appropriate landfill construction as the first step before the wastes are entombed. Emission reduction from landfill should be achieved by combining appropriate cover which can oxidize fugitive emission and good extraction system. Thorough knowledge of waste composition and its acceptance rate is a key for better estimation of methane generation potential and gas composition. Finally the utilization of different LFG models to predict the methane generation curve will help improve its reliability. Further research should focus on the optimization of the energy system and the gas flow that is, the distributed generation system can match at any moment the incoming gas flow rate.

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