Cape Peninsula
University of Technology

POTENTIAL FOR ENERGY RECOVERY AND ITS ECONOMIC EVALUATION FROM A MUNICIPAL SOLID WASTES LANDFILL IN CAPE TOWN

by

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DECLARATION

I, BokhabaneTlotliso Violet Serutla, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed Date

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ABSTRACT

Landfill gases, principally methane, CH_4 are produced from the decomposition of the municipal solid wastes deposited on landfill sites. These gases can be captured and converted into usable energy or electricity which will assist in addressing energy needs of South Africa. Its capture also reduces the problems associated with greenhouse gases. The aim of this study is to estimate gases that can be produced from the Bellville landfill site in Cape Town. The landfill gas capacity was estimated using Intergovernmental Panel on Climate Change (IPCC) model. The IPCC model showed that 48 447m^3/year of landfill gas capacity was determined only in 2013. The LFGTE process plant is designed in a manner of purifying landfill gas, which at the end methane gets up being the only gas combusted. As a matter of fact 14 544kg/year of gases which consists mainly methane gets combusted. The average energy that can be produced based on the generated landfill gas capacity (methane gas) is 1,004MWh/year. This translates to R1. 05million per year at Eskom's current tariff of R2.86 /kWh) including sales from CO_2 which is a by-product from the designed process plant. A LFGTE process plant has been developed from the gathered information on landfill gas capacity and the amount of energy that can be generated from the gas. In order, to start-up this project the total fixed capital costs of this project required amounted up to R2.5 million. On the other hand, the project made a profit amounted to R3.9million, the Net profit summed up to R1. 3million and the payback time of Landfill Gas ToEnergy (LFGTE) project is 4years.The break-even of the project is on second year of the plant's operation. The maximum profit that this project can generate is around R1. 1million. The life span of the plant is nine years. Aspen plus indicated that about 87% of pure methane was separated from CO_2 and H_2S for combustion at theabsorption gas outletstream. I would suggest this project to be done because it is profitable when by-products such as CO_2 sales add to the project's revenues.

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CHAPTER 1

1.1 Background to the research problem

The months of rolling blackouts which took place in 2008 were a powerful reminder of the importance of keeping the lights on. Though much has changed since 2008, South Africa’s power system remains constrained and will be for some years, until Eskom’s large new power stations, Medupi and Kusile, deliver the capacity needed to relieve the shortage of supply. Keeping the lights on is therefore, arguably, the most immediate and pressing challenge for South Africa’s electricity supply industry now and for the next few years. It is also key to the longer term prospects for the economy. A secure supply of electricity, at a cost which South Africans can afford, is essential if the economy is to sustain faster rates of investment and growth as well as to provide access to electricity for all (Joffe et al., 2008).

At the same time, an industry which has been dominated by coal-fired power and by a single player Eskom must make the transition to a more diverse source of supply, and more diverse players. Diversifying the energy mix is important if the industry is to address the challenges of climate change. Bringing in new players will bring in new funding, technology and skills. But those transitions will take time and will have to be carefully managed (Joffe et al., 2008).

Bringing in other alternatives of energy sources such as the electricity generated from LFGTE can be used to overcome electricity shortages in South Africa by working together with Eskom. Landfill is one of the most commonly adopted technologies for Municipal Solid Waste (MSW) disposal as alternatives to waste incineration and composting. The sanitary landfill method is a call for the isolation of the landfilled wastes from the environment until the wastes are rendered innocuous through the biological, chemical and physical processes (Srang-iam et al., 2014). It continues to be widely used in different countries for the final disposal of solid waste material due to its economic advantages. Anaerobic decomposition of biodegradable fraction namely kitchen and yard waste in the MSW, which is disposed in the landfills results in the production of landfill gas (Surroop et al., 2011). Besides conversion of landfill gas to electricity, landfill gas can be flared, converted into heat, methyl alcohol can be produced from methane which constitutes 41% in landfill gas (Mohee et al., 2011). Usage of landfill gas to produce energy will also contribute towards green technology by reducing emission of greenhouse gases into the atmosphere, which results in the climatic changes.

The economic evaluation of LFGTE is essential before the establishment of energy projects, besides the environmental impact which is well known (Surroop et al., 2011).In addition, LFGTE projects will help in the facilitation of electricity by aiding Eskom supplies, especially during rolling blackouts when the capacity is inadequate. Countries such as USA, Brasil and Mauritius are already practicing LFGTE and the projects turned out to be economically viable (Surroop et al., 2011).

1.2 Research problem statement

South Africa has been experiencing electricity shortages in its cities, especially in the central business districts (CBD). The CBD is where the economic backbone of the country lies. If the utilities such as electricity become insufficient then, there will be problem on the performance of the country’s economy. Landfill gas in this case can be a source of energy in reducing power-cuts if Eskom is not coping. Landfill gas is hazardous because it consists of greenhouse gases, which are unfriendly to the environment. Green house gas emission contributes to global warming, so by capturing the greenhouse gases emitted from the landfill site, the global warming problem will be reduced. It is of great importance to analyse the viability of landfill gas to energy (LFGTE) economically, so that LFGTE projects can be implemented. In addition to that, this research is to overcome decrease in the growth of economy due to facility shortages and capturing of greenhouse gas in South Africa to reduce GHG’s emission. Secondly, the collected landfill gases could be used to generate electricity.

1.3 Research motivation

The motivation of this research is to reduce the amount of greenhouse gases emitted from landfill sites into the atmosphere by utilizing it. For instance, addressing the issue of LFGTE process plant in some other countries like Brazil and United States of America. They have LFGTE process plants. It is discovered that levels of disposable incomes are rapidly growing and urbanization. The households are found to be the producing wastes at a higher scale. In addition, low-income countries spend almost all of their SWM budgets on waste collection and a small amount towards disposal (Horizonte et al,. 2012). Solid waste is a huge source of methane, a dominant greenhouse gas and if let free to the atmosphere results in natural man-made disasters such as floods, air pollution and public health impacts (Horizonte et al,. 2012). These problems can be dealt with by utilizing methane gas. The reason why I am motivated to do this research is to reinforce in many alternatives that can be used in the future for capturing and conversion of methane gas to energy such as LFGTE process plant. On top of that, it was agreed at the Conference of Parties 21 (2015) (COP 21 (2015)) to explore the increasing role of renewable energy technologies on low carbon development and how new technologies and grid infrastructure can increase climate change resilience and to examine the impact of the evolving carbon pricing and market matrix on business behavior and low carbon project development (Burston et al., 2015). This agreement is important to my study because it encourages GHG mitigation, which will be looked at the landfill site, in this research.

1.4 Research question

The research question if can, the amount of landfill gas produced from Bellville landfill site be used to produce electricity? If it is possible, then would it be possible to design a LFGTE process plant? Will the project be feasible economically?

1.5 Research aim and objectives

The overall aim of this research is to evaluate the potential of electricity generation from capturing landfill gas from the Bellville South Landfill Site.In this regard, the objectives of this study are limited to:

- Estimate the amount of landfill gas that can be produced from the Bellville landfill site.
- Design of an LFGTE process plant.
- Economic analysis of the process composition and quantity

1.6 Significance

The field of this research is chemical engineering based, due to the kind of objectives that will be dealt with, as the research progresses. It is of great importance that this research is carried out because the project is going to overcome more than one problem. The first problem is the emission of greenhouse gases into the environment, which is going to be prevented by capturing the gases, purifying of methane so that it can be combusted and converted into electricity. Secondly the South Africans specifically people in Bellville, Cape Town will benefit from the project because there will be a power station in their area which could provide some employment.

1.7 Delineation

There are other important issues regarding this research that are not considered in this study.Theseinclude environmental benefits and leachate evaporation of landfill gases.

CHAPTER 2

2. Introduction

Chapter two is going to deal with the following issues; the historical waste disposal estimates at Bellville landfill site thus; waste volume estimates based on records of incoming waste delivery vehicle counts and capacities, site opening year and annual growth in disposal, estimated amount of waste in place and future waste disposal estimates. Literature review is also present in this chapter and things covered under it are; municipal solid waste sources and characterization in Cape Town, municipal solid waste management vision in Cape Town, waste disposal practices and attended problems of the Bellville landfill, its capacity, practices at the landfill site, problems and factors that affect landfill gas formation. Again the how part of LFGTE process is going to be viewed thus, landfill gas recovery process, economic evaluation of LFGTE project, investment costs in landfill gas (L FG) recovery system, revenue from landfill gas recovery and another case study on the economic evaluation of LFG at the Wildcat wastewater treatment plant Cinder lake landfill Flagstaff, Arizona. Landfill gas generation; the steps in generation of landfill gas, typical uncertainties in variables affecting methane generation and its modeling.Landfill gas production tonnages and energy production estimations and types of landfill gas production models, their application, pros and cons and conclusion towards the model that is found to be applicable for estimation of landfill gas at Bellville landfill site.

2.1 Historical Waste Disposal Estimates at Bellville landfill site

In this section the following are discussed; waste volume estimates based on records of incoming waste delivery vehicle counts and capacities, site opening year and annual growth in disposal and estimated amount of waste in place at Bellville landfill site. This information was attained from City of Cape Town municipality documents (C.C.T. et al., 2014). The information to be discussed is relevant to this research because it guides in getting waste data and its contents before landfill gas produced can be determined.

2.1.1 Waste volume estimates based on records of incoming waste delivery vehicle counts and capacities

The incoming waste volume estimates require conversion to weights based on the estimate of “as received” waste density. Variation in waste loads will not have insignificant difference in densities, depending on the waste category (forinstance, construction waste will have a higher density than regular MSW), so some records of the sources of waste also may be required.

2.1.2 Site opening year and annual growth in disposal

The models require assigning a start year, so the actual or estimated site opening date is an essential data that must be obtained, because disposal growth rates are related to population growth, they can be estimated or checked using population growth data. At a minimum, the opening year and growth rates need to be coupled with one more piece of information, either the amount of waste in place, or at least one year's disposal estimate, to develop a disposal history.

2.1.3 Estimated amount of waste in place

Waste in place can be roughly calculated using a scaled site drawing showing the size of the waste disposal area and estimate of the average waste depth. Topographic maps of the site can be used to develop more detailed estimates of waste depth and volume, but a drawing showing base contours are shown on the map of Bellville landfill site. Once a waste volume is calculated, it needs to be converted to mass using an appropriate "in-place" density factor. This conversion can create error because densities can vary widely depending on site conditions and waste composition, as well as on soil cover volumes (and whether soil is included in the density calculations). Waste density for sites in developing countries is about 0.6 to 0.8Mg/m^3, but densities outside of this range commonly occur based on varying site conditions.

2.2 Future Waste Disposal Estimates

Future solid waste disposal waste disposal estimates require, at a minimum, an estimated growth rate and either a site closure date or a total (which is remaining) site capacity with a density conversion factor. Another recommendation is that independent calculations to project the year that the site reaches capacity to validate a site closure date must be completed. On the contrary, the closure year can be due to a permit expiration date or other matters that can stop the site from being filled to capacity.

2.3 Literature Review

2.3.1 Municipal solid waste sources and characterization in Cape Town

There are six general sources of waste generation, namely; domestic, commercial, industrial, agricultural, institutional and natural (Nkala et al., 2012).

Households are the highest producers of domestic waste. Domestic waste includes, among others, paper and cartons, plastics, glass, leftover food and cans.

- The main agents of commercial waste producers are stores, business premises, markets and restaurants.
- Industrial waste refers to wastes such as construction and demolition debris and from food processing plants outlets.
- Agricultural wastes refer to the waste from dairy and poultry farms, livestock and other agricultural activities like vegetation cultivation. Most of the agricultural wastes contain biodegradable components.
- In case of institutional wastes, major producers are schools, offices and banks. This type of waste contains mostly paper and cartons.
- Natural waste consists of leaves, tree branches, seeds and carcasses of animals.

The characterizations for the various districts in Western Cape are shown on the figure below. The Central Karoo data is still uncertain at the moment and it is required that it should be verified further (Mbebe et al., 2013).

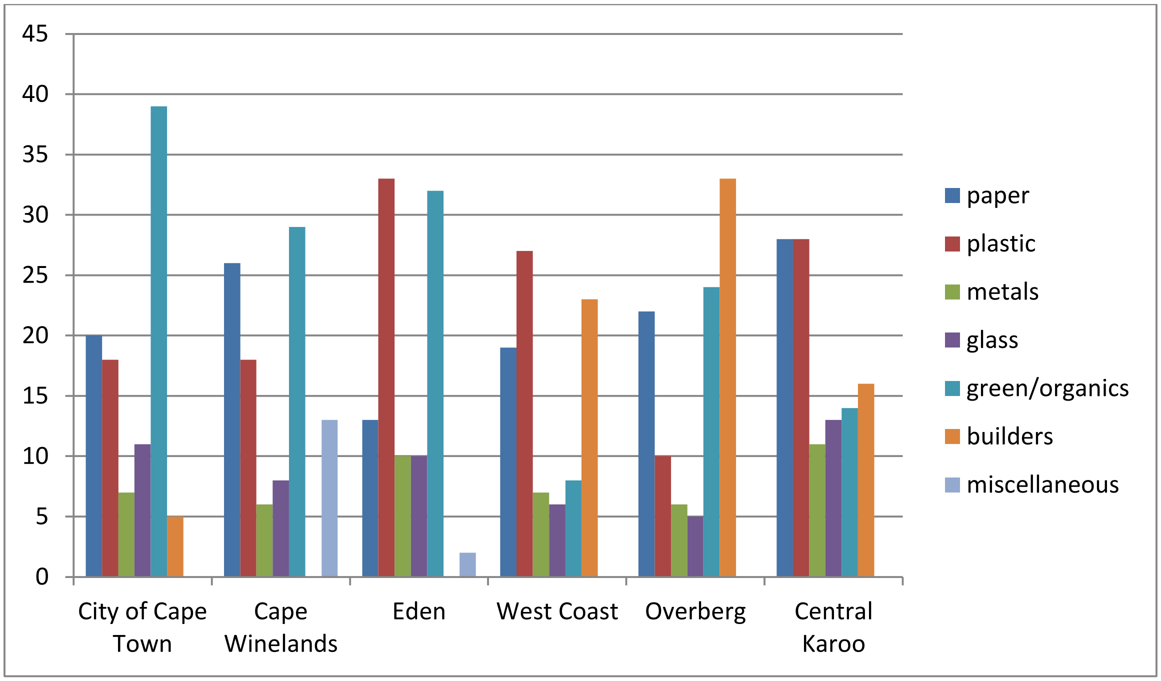

Figure 2.1: Waste stream analysis for the Western Cape (DEADP 2012a) (Mbebe et al., 2013)

The main observations from the characterization study data include (Collins et al., 2013)

(DEADP):

- The Central Karoo District showed a high paper and plastics percentage but is low in green waste.
- Paper, plastics, metals and glass percentages in the waste stream were higher in the city of Cape Town than what is found in Johannesburg.
- Builder’s rubble figures, although in most cases not reported, were noticeably high for the Overberg District.

- The city of Cape Town has a significant green waste component, as does Eden and the Cape Wine-lands.
- Eden, Central Karoo and West Coast Districts have significantly high plastic waste percentages.

The information on figure 1 portrays that City of Cape Town has the highest amount of greens/organic wastes, which are biodegradable. According to this facts, it is assumed that Bellville landfill site has got high landfill gas emissions because it is situated within the City of Cape Town (Scheutz et al.,2009). Again the reason why the green/organic waste is high in the City of Cape Town, it is because the area is densely populated.

2.3.2 Municipal solid waste management vision in Cape Town

The long-term vision for the city of Cape Town's waste management services, is to integrate waste management services in such a way that they are able to not only provide basic services, but to augment economic activity and minimize the effects of waste on human and environmental health (Meyer et al., 2012). Much national support and development is necessary, as waste minimization and recycling activities are not limited to Cape Town and involve the processing and manufacturing sectors on a national scale.

The new legislation provides for the formulation of Industry Waste Management Plans, the declaration of "priority waste", the submission of waste information and regulations and policies within the powers of the Minister of Department of Environment Affairs. It is apparent that this will not be an easy or a quick process. These are the key influence on achieving the long terms waste management vision and objectives set by the Department (SWM et al., 2013).

The long-term vision for the Cape Town waste management sector is(SWM et al., 2013):

- To improve access to basic services for all residents (formal, informal and backyarders) to as close to 100% as possible within the constraints of available funds and planned growth.
- To develop multiple integrated initiatives that will reduce waste and the associated impacts substantially as well as contribute to and support economic development.
- To generate other sources of funding for integrated waste management through Public-Private Partnerships within the Cape Town municipal area.
- To improve the income generated by the Council's waste services.

- To optimize the utilization of the Council’s resources and capital.
- To regulate waste and the associated services to ensure sustainability and prevent impact or harm to people and the environment.

The MSA S.78(3) assessment of alternate service delivery mechanisms findings and recommendations as considered and adopted by Council in March 2011 gives effect to the long-term vision, as part of the integrated strategy to achieve large volume waste diversion from landfills. This is driven by the need to comply with the provisions of NEMWA (SWM et al., 2013).

Waste minimization is also prioritized in municipal solid waste management vision in Cape Town, for instance, to facilitate the act a number of processes, mechanisms and stakeholders in the production, marketing, packaging, selling and consumption of goods that produce waste. Therefore, it will demand a conscious, comprehensive and intentional decision and effort by all stakeholders to ensure that waste and secondary effects of poor waste management can be reduced through waste minimization to increase landfill site lifecycles and the environment (Maree et al., 2012). This may involve additional mechanisms and process that include the below(Maree et al., 2012):

- Improving product and packaging designs to reduce resource consumption
- Changing marketing and sales approaches to influence consumer perceptions and behavior.
- Extended producer responsibilities (EPR) of producer of products, which may require producers to accept their used products back for recycling.
- Changing procurement policies and practices in large organizations that should encourage environmentally-friendly production and manufacturing.
- Encouraging waste separation, streaming and diversion practices.
- Creating infrastructure to enable waste to be diverted from landfill sites.
- Developing infrastructure for processing waste for reuse/recycling.
- Developing markets for recycled materials and products.
- Applying Clean Development Mechanisms (CDM) to reduce, amongst other effects, the global warming effects of landfill gas to the benefit of all stakeholders including the environment.
- Conducting awareness and education campaigns to disseminate information regarding waste diversion, minimization and recycling.

2.3.3 Waste disposal practices and attended problems at the Bellville landfill

This section is going to show waste disposal practices and attended problems at the Bellville landfill site.

2.3.3.1 Capacity

The Bellville South landfill site, which is found in the Cape Town's southern suburbs at Sacks circle, Bellville Industrial, is approximately 60 hectares in size (C.C.T et al.,2014). Thirty hectares are occupied by the waste already. It is said that the remaining airspace is quickly filling up. Currently the landfill's height is about 35m above ground level (C.C.T et al.,2014).

2.3.3.2 Practices at the landfill site

The importance of this section is to familiarize the researcher to the essential activities at the landfill site, which facilitates the gathering of data for the purpose of work to be carried out (EPA et al.,2011).

Designing and Installing a cover system:

Design that mimic rather than alter the site's natural setting, to improve the covers long-term performance and protect ecosystem services such as potable water, wildlife habitat and carbon storage. Design a cover accounting for potential effects of climate change, which could involve changes in onsite soil development or increased vulnerability to flooding. Uncontaminated soil, sand, gravel and rocks can be used for drainage; covers frost prevention and erosion control layers rather than imported soil. Application of low impact development strategies, for example installing earthen berms to manage storm water. Selection of geotextile fabric or drainage tubing consisting of 100% recycled materials rather than virgin materials for lining, erosion control and drainage. Choosing materials with bio-based content for daily activities during cover construction, including those designated for procurement by federal agencies. Use of clean fuel and emission control technologies for routine field vehicles and machinery such as backhoes and bulldozers to reduce fuel consumption and emission of air pollutants such as GHG's and particulate matter.

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2.3.3.3 Problems

The problems encountered at the landfill site are important to be known before establishing any project on site. For instance, if the infrastructure still needs to be developed, it must be developed first before commencing huge projects like LFGTE process plant. The problems addressed below are according to (Gaasboll et al., 2011).

When waste collection service is disrupted, waste can end up being illegally dumped. This is especially the case in situations where drop-off centres are considered too far away or where drop-off centres do not accept general waste. The public is also not keen to incur additional cost over and above the collection service already paid for.

Transport on the other hand is said to be expensive in providing the waste management services. Several municipalities encounter difficulties in meeting their legal mandate of giving more than a weekly waste collection service to all households because of limited budgets. Inadequatewaste generation volume during particular seasons (tourist destinations during holiday periods) or events (sporting events, concerts).

Largest waste backlogs in South Africa happen in rural areas and informal settlements. Problems in supplying sustainable waste collection service involve: limited road access and infrastructure. In some areas, road infrastructure is limited and the collection vehicles cannot reach all the households. Where road infrastructure exists, the streets maybe in accessible to conventional waste collection vehicles due to more gradient slopes and narrow roads with sharp curves, deep potholes and dongas. Extensive travel distances: Transportation expenses around rural area result in rampant illegal dumping because of households which are sparsely spread over wide distances.

Irregular landfill road surfaces, steep slopes, loose sand, dust and the nature of the material disposed at landfill sites add to the rate of wear and tear on vehicles operating on those sites.

2.3.3.4 Factors that affect landfill gas formation

Methane generation is due to biological reactions occurring. This is a result of bacterial action for methane production from organic substrates. This is further proven by the following equation:

$$nC_6H_{10}O_5 + nH_2O \xrightarrow{\text{Carbonic anhydrase}} 3nCH_4 + 3nCO_2$$

Below is the list of operational and relevant variables that influence generation of methane and the uncertainties that can exist. The reason for doing this is to assess if the landfill site is capable of producing enough landfill gas that can be utilized (Vedrenne et al., 2005).

- The actions that facilitate the rate of methane production are baling, shredding, crushing and material separation, which increase the surface area of the waste for production of methane.
- Waste composition variables are organic/ inorganic, proportion yard/food/paper/other organic residues, proportion of readily/moderately/slowly decomposable material and whether co-disposal has been done (namely sewage biological solids as well as refuse). Organic matter is said to decompose faster than other waste composition variables and thus directly proportional to the production rate of methane (k).
- The pH between 6.7 and 7.4 is discovered to be suitable for the function of methanogenic bacteria, and then from 7 to 7.2 is the optimal point for survival of the enzymes. In addition, methane production may decrease if the pH is lower than 6.3 or higher than 7.8.
- The physical properties such as design play a major role in the capability of production of landfill gas; the dimensions (area, depth), gas containment (base, sides, top cover) and gas extraction system and its effectiveness or efficiency.

2.4 Landfill gas recovery process

According to figure 2.2 landfill gas is extracted from the landfill site using landfill gas extraction blowers to facilitate its transportation to the LFGTE process plant. The landfill is then filtered in order, to remove any large pieces of debris and liquids mixed with the gas. Due to the presence of toxic gases that make part of the landfill gas, pre-treatment is done on the landfill gas, to remove carbon dioxide, sulphides and siloxanes, so that they do not cause any damage to the equipment. At the end of pre-treatment methane concentration is high. The methane gas is compressed causing pressure and temperature of the gas to be high enough for the gas to be compressed for easy transportation. Then the gas is cooled so that moisture within the gas condenses. The gas flows into the filter in order, to remove some moisture. The gas is reheated before it enters an internal combustion engine, where themethane gas is combusted and converted into electricity in a generator. The electricity then gets distributed, but before it is distributed there is a transformer which divides the energy to low and high voltage. The low voltage is used to run the energy process plant and high voltage is fed to the grids and transported to businesses and homes (Vedrenneet al., 2000).

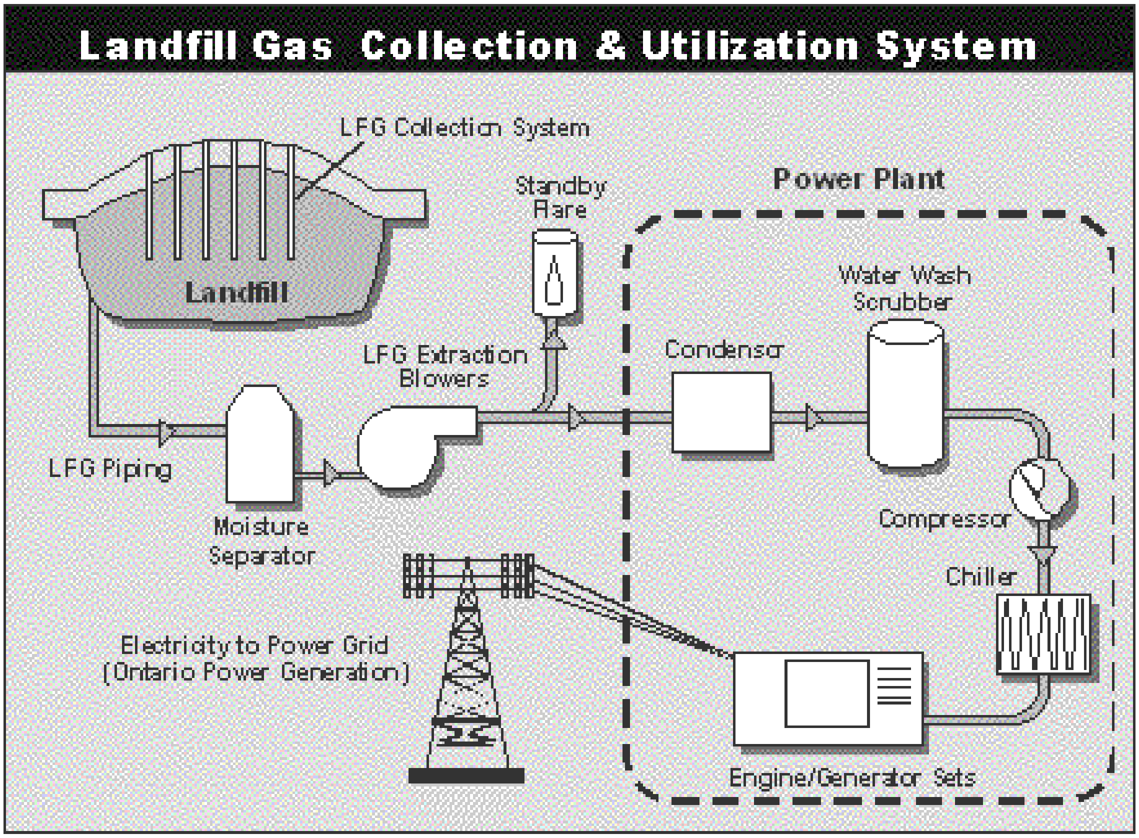

Figure 2.2: landfill gas to energy diagram (Vedrenneet al., 2000)

2.5 Economic evaluation of LFGTE project

It is important to look at the economic aspects of this research at the literature review, so that after designing the LFGTE process plant it can be known if the plant will be economically feasible. Furthermore, it will guide in the necessary parts to look at when costing the entire project.When looking at different projects full detailed design of the plants is not shown, so in this research it will be shown before the economic analysis of the project (Vedrenneet al., 2000).

2.5.1 Investment costs in LFG recovery system

The Stearns Conrad and Schmidt Engineers (SCS Engineers) made a case study of the construction of Loma de Los Cocos Landfill Cartagena de Indias, Colombia.

First of all, the team of engineers made an estimate of the construction costs of the landfill and discovered that LFG collection to be R 11. 7million.The importance of table 2.1 shows the total estimated cost for LFG Collection and control system. These costs include proposed gas collection system, which consists of extraction wells, header and lateral piping, condensate management, installation of blower and enclosed flaring station.

Table 2.1: Budgetary Costs for initial LFG Collection and Control system

Item	Total Estimated Cost (ZAR)
Mobilization and project management	R 630 180
Vertical extraction wells and wellheads (24 wells, 20m average depth)	R 2 240 640
Leachate pumping equipment (assumed required for 25% of the wells)	R 350 100
Main gas header collection piping (assume about 1300m of 350mm diameter) and header valve	R 1 598 790
Lateral piping (assume about 800m of 110mm diameter)	R 373 440
Condensate management	R 700 200
Road crossings	R 175 050
Blower and flaring equipment (enclosed 2 500cfm flare)	R 4 376 250
Engineering/ contingency and up-front (pre-operational) costs	R 1 342 050
Total Estimated Cost	R 11 786 700

Furthermore, the team estimated the annual collection system expansions for 2009 to 2027 to be R 2 million. This was calculated by using the annual cash flow analysis prior to the assumption that annual system expansions would happen in order to maximize well-field coverage and LFG recovery.

The annual cost for operation and maintenance of the gas collection system was estimated to be seven percent of the initial construction costs, which amounted to R 825 069 for 2009 which was the first year of operation.

There are costs encountered in the process of fulfilling the climate Act such as, obtaining emission reductions, monitoring, verification and registration of the emission reductions.These costs amount to R 350 100 before inflation adjustments.

Electrical Generation Project Costs

These are the capital and annualized costs for developing an LFG-fueled IC engine power plant. These costs are as follows;

Initial Power Plant Costs

It was estimated by the team of engineers that the initial capital cost for implementing an LFG-fired 1, 600kW (gross) IC engine power plant to be roughly R 37.4 million.The LFG collection and flaring system costs are included, except costs for local import taxes (Rogoff et al., 2008).

Annual Power Plant Operation and Maintenance Costs

The budgetary cost for annual operation and maintenance of the power plant was precisely R26.26 cents per kilowatt-hour of electricity output and annually it amounted to R3.3 million, before any facility expansions (based on a 1 600kW plant capacity and prior to inflation adjustments). These costs are in additional to those for operation and maintenance of the power plant such as labour, testing equipment and parts, routine maintenance and repairs and minor equipment replacement.

The LFG-fired 1 600kW (gross) IC engine power plant project concept and capital cost is based on the following assumptions:

- The LFG fired generator sets can be interconnected to the local distribution network at relatively low kW. The interconnection can be made at the local distribution line (without major re-conducting of cables) or at a nearby substation with access to these lower voltages.

The results obtained from the LFG models, encouraged the team to draw the conclusion that the plant could be expanded by installing additional 1 600kW units in 2012 and 2018 because of increasing gas flows. Capital investments are estimated to be R23 million in each of these years. The importance of table 2.2 shows the total estimated cost for IC Engine Power Plant.

Table 2.2: Budgetary Costs for IC Engine Power Plant

Item	Total Estimated Cost
Mobilization and project management	R1 867 200
Plant construction/sitework (incl. piping)	R 1 400 400
LFG measuring and recording equipment	R 408 450
LFG-fired 1 600kW Gen-set	R 22 406 400
Plant substation (main breaker, step-up transformer)	R 3 209 250
Electrical Interconnection (2km)	R 2 917 500
Source Test	R 291 750
Engineering/ Contingency (~15% of other costs)	R 4 901 400
Total Estimated Cost	R 37 402 350

Direct Use Project Costs

Initial Direct Use Plant Cost and Ongoing Costs

The pipeline system was estimated to be R 15.9 million. This cost includes the LFG collection and flaring system. The project concept allows all the current and future LFG to be sold to Ladrillera in Colombia or another user. The project concept and costs are based on the following assumptions:

- Ladrillera (or other end user) is within 2 kilometers
- The pipeline is buried and can be excavated without directional drilling or jack and bore under roadways.
- Any right of way required can be obtained at a relatively low cost.

- Delivery pressure to the end user's facility is low (under 5 psi)
- Costs of modifications to the existing Ladrillera natural gas infrastructure, including the control system, were included in the investment costs. This cost is typically not included in the project developer's cost and is incurred by the end user, however these costs were included in this analysis to show the total cost of such a project.

A 15 percent contingency cost is included to account for conditions in Colombia

Table 2.3: Budgetary Costs for Direct Use Project

Item	Total Estimated Cost
Engineering Design, Permits, Surveying, Mobilization	R 1 167 000
Skid-mounted filter, Compressor and Dehydration Unit	R 6 325 140
2km (1.24-mile) 10 inch HDPE Pipeline to Convey LFG to Project Site	R 3 828 927
Construction Management, Technical Assistance	R 933 600
Modification to Ladrillera NG infrastructure and Control System	R 1 633 800
Engineering/ Contingency (15% of other costs)	R 2 083 095
Total Estimated Cost	R 15 971 562

In this case yearly operating and maintenance costs include pipeline and compressor station maintenance and electricity costs for operating the compressor station. The first year of commencement of operation (2009), the costs were estimated as follows R 383 710 and R 350 100 and altogether amounted to be R 733 810.

2.5.2 Revenue from landfill gas recovery

In order to evaluate the project economythe following were assumed by SCS Engineers:

- Two capital structures were considered, one with financing of capital expenditures (i.e. 100% initial application of capital expenditures) and the other with financing of 75 percent of initial capital expenditures (25% equity investment).

- Two prices of emissions reductions were considered, with sales prices of $8.31 (R117) and $8.52 (R120) per ton of CO_2-equivalent (CO_2e) emission reductions (Bennett et al., 2014). Two scenarios for the period over which these prices are received were evaluated. Scenario 1 assumed revenues from 2009 through 2012 and Scenario 2 assumed revenues from 2009 through 2018.

- The economic evaluation of Option 1, LFGE electric generation project, covered a 15 year period (FY 2008-2022), with one year of construction and 14 years of operation. The economic evaluation of Option 2, LFGE direct use project, also covered a 15-year period (FY 2008-2022), with one year of construction and 14 years of operation. The economic evaluation of Option 3, the flaring only project, considered shorter time periods based on the reasoning that the project would not likely continue when there was no longer any source of revenue from emission reductions. The time periods considered for the flaring only project were therefore FY 2008-2012 (5 years) under scenario 1 and FY 2008-2018 (11 years) under scenario 2.A capitalcostof 14 percent was used for the NPV analysis.An interest rate (cost of borrowing) of 10 percent was used for the loan financing.

- Initial investment for the LFG collection and flaring system and power plant was assumed to occur in fiscal year (July 2008-June 2009). Loan term was assumed to be 10 years for option 1 (power project), 10 years for option 2 (direct use project), four years for option 3 (flaring only project) under scenario 1 and 10 years for option 3 under scenario2.

- For purpose of this analysis, payment of approximately 20 percent of the emission reduction revenues to the LFG rights owner for use of LFG was considered (represented by a rate of R 7.84/MMBtu ($0.56/MMBtu) under R92.82 ($6.63) per ton emission reduction price scenario and R116.34/MMBtu ($8.31/MMBtu) under the R119.28 ($8.52) per ton emission reduction price scenario). This is based on international experience that payment to the landfill owner for LFG under carbon credit projects can typically range between 5 and 30 percent of the emission reduction revenue. However, there are many variations on this pricing structure. If the landfill owner were to self-develop the project (which is not typical) this value could be assumed to be zero.

- For the purpose of this analysis, the project developer was assumed to be a private entity with the resources to provide all of the capital for making the project investments or any needed modifications to the end user equipment under the direct use project scenario.Future LFG collection system O&M and system expansion expenditures escalate at an annual rate of 3 percent.The impact of local taxes (including import taxes, VAT and income taxes) for the importation of capital equipment, as well as any tax obligations from operations, were not included as part of this analysis in order, to support growth and reduce costs and risks.

- Under the option 1 (power project) the following assumptions were applied:

- The initial power plant will consist of one 1 600kW LFG-fired IC engine that will be operational for a period of 14 years, from 2009 through 2022. A second 1 600kW engine will be added in 2011 and be operational from 2012 through 2022. A third 1 600kW engine will be added in 2017 and be operational from 2018 through 2022.

- A seven percent reduction in electricity output by the plant was assumed to account for parasitic load and a plant capacity factor of 92 percent was assumed to account for routine and non-routine plant downtime. LFG collected during plant downtime will be routed to the flare for combustion.

- All electricity generated by the project is assumed to be sold to the interconnected grid at a wholesale market rate of R0.502 per kWh.

- In addition to the electricity revenues, the facility will sell GHG credits for the destruction of LFG (methane) as well as displacing dirtier electric generation technologies on the grid. The plant will sell GHG credits for a period of 4 years (2009-2012) under scenario 1 and 10 years (2009-2018) under scenario 2.

● The LFG collection system and flare will be operational at the end of Fiscal year 2008 through the end of the project period. The flare will be used not only under option 3 (flaring only) but also under option 1 and 2 to combust excess LFG not utilized. Under option 3, no capital or operating costs are incurred for an energy facility and no revenues from electricity or LFG sales are received.

For the economic evaluation, the following project revenues were considered under power plant:

- The power plant produces a total of 11 992MWh/year from 2009 through 2011, which is sold to the power grid at a rate of R0.502/kWh (2008). The power output gets increased by another 11 992MWh/year in 2012 and again in 2018 when new generation capacity is included.
- The sale of emission reductions is considered for the years 2009 through 2012 under scenario 1 and 2009 through 2018 under scenario 2.
- LFG collected in excess of the power plant capacity, along with LFG collected during plant downtime is assumed to be combusted in the flare.

Project Expenditures

The following project expenditures were considered under option 1, the LFG-fired electric generation project:

● Initial capital investment for the LFG collection and flaring systems (R 11 786 700) and power plant (R 37 402 350) occurs in FY 2008.

● Purchase of LFG from the gas rights owner at a rate of R7.82/MMBtu under the R93.36 per tonne emission reduction price scenario and R9.80/MMBtu the R117 per tonne emissions reduction price scenario.

● Capital investments for the annual LFG collection system expansions and periodic power plant expansions (in 2011 and 2017). The cost of the power plant expansions are assumed to be financed under the financing options outlined above.

● Annual cost for operation and maintenance of the LFG collection and flaring system (about 7% of LFG collection system capital investment) and the power plant (R0.263/kWh).

The following project expenditures were considered under option 2, the LFG-fired electric generation project:

- Purchase of LFG from gas rights owner at a rate of R7.82/MMBtu under the R93.36 per ton emission reduction price scenario and R9.80/MMBtu under the R117 per ton emission reduction price scenario.
- Annual cost for operation and maintenance of the LFG collection and flaring system (7% of LFG collection system capital investment) and compressor station and pipeline.

For the economic evaluation, the following project revenues were considered under direct use:

- The direct use project produces a maximum of 154 969 MMBtu/year of LFG in 2009 through 2022. The LFG is sold to the end-user (assumed to be Ladrillera) at a rate of R47.85/MMBtu. This price is estimated based on approximately 50 percent of the average reported natural gas sales price for industry in Cartagena in October 2007. This is a very conservative sale price for LFG, given that the project developer under this option is assumed to be providing all the capital for the project and modifications to the end user equipment. No energy pricing information has yet been provided by the potential industrial end-users, which are located in the Mamonal Industrial Zone within about 2km of the landfill.
- GHG emission reductions are sold at a rate of R93.40 or R117 per ton CO_{2e}. The sale of emission reductions was considered for the years 2009 through 2012 under power plant and 2009 through 2018 under direct use.
- LFG collected in excess of the amount delivered to the end user, along with LFG collected during facility downtime was assumed to be combusted in the flare.

The following project expenditures were considered under option 3, the flaring only scenario:

- Initial capital investment for LFG collection and flaring system (R 11 786 700) occurs in FY 2008.

- Purchase of LFG from gas rights owner for a rate of R 7.82/MMBtu under the R93.36 per ton emission reduction price scenario and R 9.80/MMBtu under the R 117 per ton emission reduction price scenario.
- Capital investments for the annual LFG collection system expansions.
- Annual cost for operation and maintenance of the LFG collection and flaring system (7% of LFG collection system capital investment).

2.5.3 Another case study on the economic evaluation of LFG at the Wildcat Wastewater treatment plant Cinder lake Landfill Flagstaff, Arizona

In this case study a summary of economic evaluation of landfill gas to energy for direct use of LFG at the Wildcat Wastewater treatment plant Cinder Lake Landfill Flagstaff, Arizona is described by Geosyntec Consultants (Geosyntec et al., 2013).

Project Data:

Design LFG Methane Content=50%

Annual Capacity Factor=95%

Capital Costs in their design:

Gas collection system= R 31 134 589.6

Pipeline Installation= R 50 405 032.8

Initial Capital Costs –hard= R 81 539 622.4

Total capital costs- soft= R 5 633 704.4

Initial capital cost= R 87 173 326.8

The below table shows the summary on the economic evaluation of LFGTE project in Arizon, which is used as a case study in order, to understand the strengths and weaknesses of the LFGTE project regarding the project’s economics

Table 2.4: Summary of economic evaluation of LFGTE project at Cinder Lake Landfill Flagstaff, Arizona (Geosyntec et al., 2013)

Project year	**Calendar year**	**Revenue (USD) (ZAR)**	**Capital costs (USD) (ZAR)**	**(Revenue-Costs) (USD) (ZAR)**	**Net Present Value (USD) (ZAR)**
0	2013	0	5 974 868.6 (87 173 332.6)	-5 974 868.2 (-87173 326.8)	-5 974 868.6 (-87 173 326.8)
1	2014	750 218.7 (10 945 690.8)	0	707 043.9 (10 315 770.8)	-5 271 119.3 (-76 905 630.8)
2	2015	764 966.1 (11 160 855.6)	0	721 791.0 (10 530 935.6)	-4 556 040.5 (-66 472 630.4)
3	2016	780 459.7 (11 386 907.6)	0	737 285.0 (10 756 987.6)	-3 829 015.5 (-55 865 335.6)
4	2017	796 716.6 (11 624 094.8)	0	753 541.8 (10 994 174.8)	-3 089 422.2 (-45 074 669.6)
5	2018	813 754.5 (11 872 677.6)	0	770 579.7 (11 242 757.6)	-2 336 630.8 (-34 091 444.0)
6	2019	831 589.6 (12 132 891.6)	0	788 414.8 (11 502 971.6)	-1 570 005.7 (-22 906 383.6)
7	2020	850 241.4 (12 405 022.0)	0	807 066.2 (11 775 102.0)	-788 901.8 (-11 510 076.8)
8	2021	869 727.8 (12 689 329.2)	0	826 553.1 (12 059 409.2)	7 334.6 (107 012.0)
9	2022	890 069.3 (12 986 110.8)	0	846 894.5 (12 356 190.8)	819 363.8 (11 954 517.6)
10	2023	911 286.1 (13 295 664.4)	0	868 111.3 (12 665 744.4)	1 647 857.2 (24 042 236.0)

11	2024	933 398.7 (13 618 287.6)	0	890 224.0 (12 988 367.8)	2 493 495.5 (36 380 099.6)
12	2025	956 428.4 (13 954 290.4)	0	913 253.6 (13 324 370.4)	3 356 966.4 (48 978 140.0)
13	2026	980 398.9 (14 304 020.0)	0	937 224.1 (13 674 100.0)	4 238 972.7 (61 846 612.0)
14	2027	1 005 333.2 (14 667 811.2)	0	962 158.4 (14 037 891.2)	5 140 224.1 (74 995 869.6)
15	2028	1 633 544.9 (23 833 420.0)	0	1 590 270.1 (23 203 500.0)	6 622 976.8 (96 629 232.0)

2.6 Landfill gas generation

2.6.1 The steps in generation of landfill gas

This section previews the process on how landfill gas is generated. The information to be discussed will cover the following; steps in landfill gas formation due to bacteria decompose landfill waste in five phases. Gas composition changes with each phase and waste in a landfill may be undergoing several phases of decomposition at once. The time after placement scale (total time and phase duration) varies with landfill conditions (Staley et al., 2009), chemical reactions associated with microbial degradation (Scheutz et al., 2009)(Kjeldsen et al., 2009) and landfill gas formation.

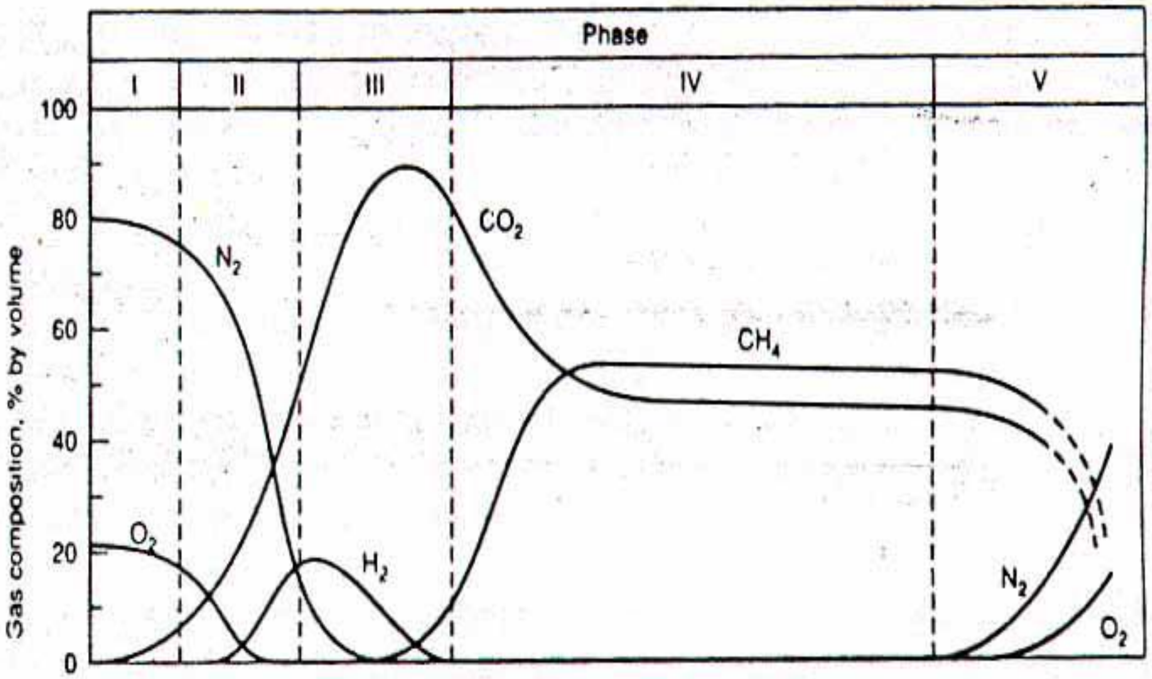

Figure 2.3: Generalized Phases in the Generation of Gases (Palananthakumar et al., 1999)

Source: (Tchobanoglous et al., 1993)

I. Initial adjustment

It is the first phase, in which the organic matter and biological decomposable elements in the wastes degrades aerobically due to the activities of the micro-organisms.

II. Transition phase

This phase is where there is oxygen depletion and anaerobic reaction starts occurring.

III. Acid phase

At this level, hydrolysis of high mass compound takes place and it produces compounds suitable for microorganism to use as energy or carbon sources.

IV. Methane fermentation phase

CH_4 and CO_2 are formed due to methanogen bacteria which converts acetic acid and hydrogen.

V. Maturation phase

It is the last stage whereby gas production rate ceases, due to that most of the nutrients have been removed during the past levels and substrates that are still remaining in landfill are slowly biodegradable.

(Palananthakumar et al., 1999)

Landfill gas (LFG) is generated through the degradation of municipal solid waste (MSW) by microorganisms. The quality (higher percent methane gases signify higher qualities) of the gas is dependent on the composition of the waste, presence of oxygen, temperature, physical geometry and time that elapsed since waste disposal. Aerobic conditions, presence of oxygen, leads to predominately CO_2 emissions. In anaerobic conditions, as is typical of landfills, methane and CO_2 are produced in equal amounts. Methane (CH_4) is the important component of landfill gas with a calorific value of 33.95 MJ/Nm^3. The amount of methane that is produced varies significantly based on composition of the waste. They also stated that most of the methane produced in MSW landfills is derived from food waste, composite paper, and corrugated cardboard which comprise 19.4 ± 5.5%, 21.9 ± 5.2%, and 20.9 ± 7.1% respectively on the average for MSW landfills in the United States. The rate of landfill gas production varies with the age of the landfill (Palananthakumar et al., 1999)

.

Respiration: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

$$C_6H_{12}O_6 + 4.5O_2 \rightarrow 3(COOH)_2 + 3H_2O$$

Decomposition of waste commence after the depletion of oxygen, under anaerobic process. Bacteria are responsible for converting organic compounds into acetic, lactic and formic acids and alcohols such as methanol and ethanol. The first step of landfill gas formation involves aerobic respiration. What happens is that aerobic bacteria make use of oxygen present to break down long molecular chains of complex carbohydrates, proteins and lipids that are contained in the organic waste. At this stage carbon dioxide is a primary by-product. In the beginning of the process nitrogen content is high but reduces as methane starts to form. The first phase continues until oxygen is depleted.

Oxalic Acid

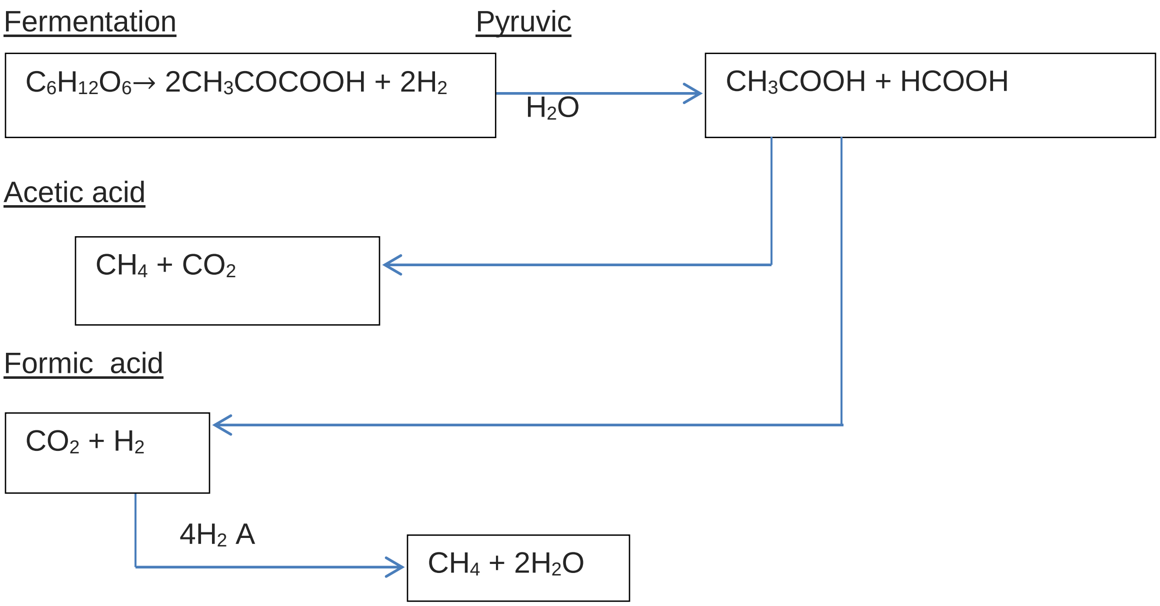

Figure 2.4: Simplified reaction sequence for decomposition of glucose under oxidizing and anoxic conditions (Baedecker et al., 1979)

After the depletion of oxygen decomposition commences. Bacteria at this stage are responsible for conversion of compounds into acetic, lactic and formic acids as indicated by figure 4(Bogner et al., 2009). At this phase the landfill is highly acidic and when acid mix with the moisture or leachate, some nutrients dissolve, causing nitrogen and phosphorus available to the increasingly diverse species of bacteria in the landfill (De Visscher et al., 2009). Carbon dioxide and hydrogen are byproducts of the second phase.

After the acid forming stage, particular types of anaerobic bacteria (methanogenic bacteria) use the organic acids created in the previous phase and form acetate; an organic acid (Bogner et al., 2009). The formation of acetate makes the landfill environment to become neutral in which methane producing bacteria begin to develop themselves while forming acetate (Gebert et al., 2009).   Furthermore, it is discovered that there is mutual beneficial, relationship between methane and acid producing bacteria (Kjeldsen et al., 2009). Acid producing bacteria create compounds for methanogenic bacteria to consume. Methanogenic bacteria use the carbon dioxide and acetate, too much of which would be toxic to the acid producing bacteria (Hilger et al., 2009).

The last stage where methane is produced occurs when both the composition and production rates of landfill gas stay relatively constant (De Visscher et al., 2009). In phase four landfill gas has approximately 45% to 60% methane, 40% to 60% carbon dioxide and 2% to 9% other gases, such as sulfides by volume (Gebert et al., 2009). All of the gases are harmful to human health at high doses (Staley et al., 2009).The gas production is stable at this level for about 20 years. However, the gas can be emitted continually for 50 or more years after the waste is placed in the landfill. Gas production can be pro-longed if greater amounts of organics are present in the waste, such as at a landfill receiving higher than average amounts of domestic animal waste (Hilger et al., 2009).

The landfill gas production rate will reach a maximum 60% by volume at around 5 years and start to decline (Staley et al., 2009). Landfill gas follows first-order kinetic decay after decline begins with a k-value ranging 0.02 $yr^{-1}$for arid conditions and 0.065 yr^{-1} for wet conditions (Staley et al., 2009). Landfill Methane Outreach Program (LMOP) provides first order decay model to aid in the determination of landfill gas production named LandGEM (Landfill Gas Emissions Model) (Staley et al., 2009). Typically, gas extraction rates from a municipal solid waste (MSW) landfill range from 25 to 10 000 m^3/h where Landfill sites typically range from 100,000 to 10 million m^3 (Staley et al., 2009).

Landfill Gas Formation Mechanisms

When waste is disposed at the landfill site, the presence of oxygen causes biodegradable organic materials to react aerobically, forming carbon dioxide, water and other by-products (e.g. bacterial cells). As the reaction continues, carbon dioxide gets closer to molar equivalents of oxygen consumed. When oxygen starts to deplete then that is the beginning of anaerobic decomposition phase (Staszwsk et al., 2011). Anaerobic reaction is the dominant phase in comparison to aerobic reaction. The assumption is that anaerobic occurrences in landfills originate from the art of anaerobic digesters (Staszwsk et al., 2011). The same types of micro-organisms are active in both digesters and landfill site. On the contrary, the main variations is that the substrates may differ in their relative content of fat, protein and carbohydrates and conversely to landfills, the conditions in an anaerobic digesters is well controlled and often under optimal conditions (Staszwsk et al., 2011).

2.6.1.1 Mechanism of Biogas formation

The following diagram shows anaerobic fermentation, happening for example in peat bogs, on sea bottom, in manure and at landfills. Organic matter is converted into biogas. (Staszwsk, et:al 2011)

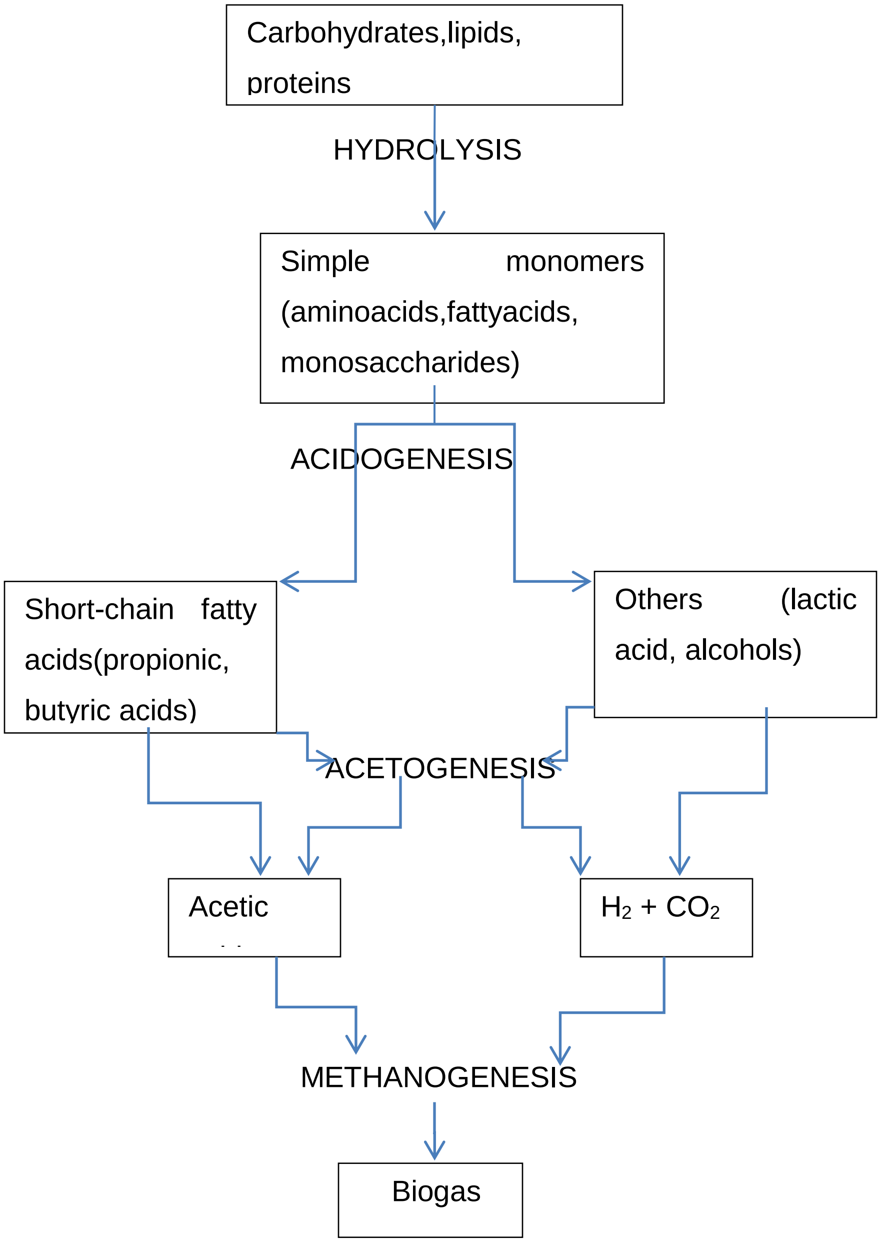

Figure 2.5: Mechanism of Biogas formation (Staszwsk et al., 2011)

2.6.2 Typical uncertainties in variables affecting methane generation and its modeling

Below are listed kinds of uncertainties that are likely to occur in data for creating a model. These differ from uncertainties in wastes placement history, location, composition, to the serious uncertainties regarding extraction efficiency. The importance of a number of factors such as pH, nutrient level, free aqueous phase and temperature are well established (Vedrenne et al., 2005).

- Waste placement history/location/composition may be difficult to trace, especially for older landfills.
- Biological parameters; nutrients, temperature and pH. They are difficult to measure and they are likely to differ spatially, over time through the landfill.
- Moisture content; it is not easy to measure or estimate, moisture content is likely to differ spatially over time at the landfill site. Its essential effect on methane generation and its influenced by capping and rainfall.

2.7 Landfill gas production tonnages and energy production estimations

Figure 2.6 shows the type of wastes deposited at Bellville landfill site in 2013. The reason for doing this is to verify if there is a possibility of methane production at the landfill site.Figure 2.6 focuses on the types of waste and their capacity. According to the information onFigure 2.6, it shows that there is a high percentage of organic waste, to produce landfill gas.

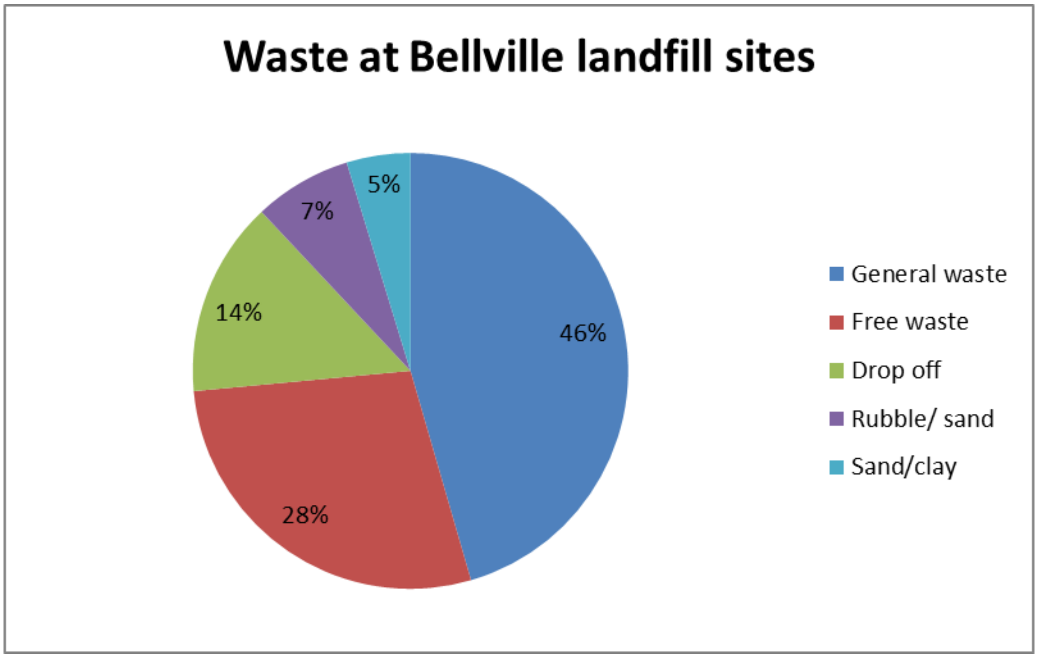

Figure 2.6: Waste percentages at Bellville landfill site in 2013 (Kula et al., 2014)

Figure 2.7 shows the type of wastes deposited at Bellville landfill site in the beginning to mid of 2014

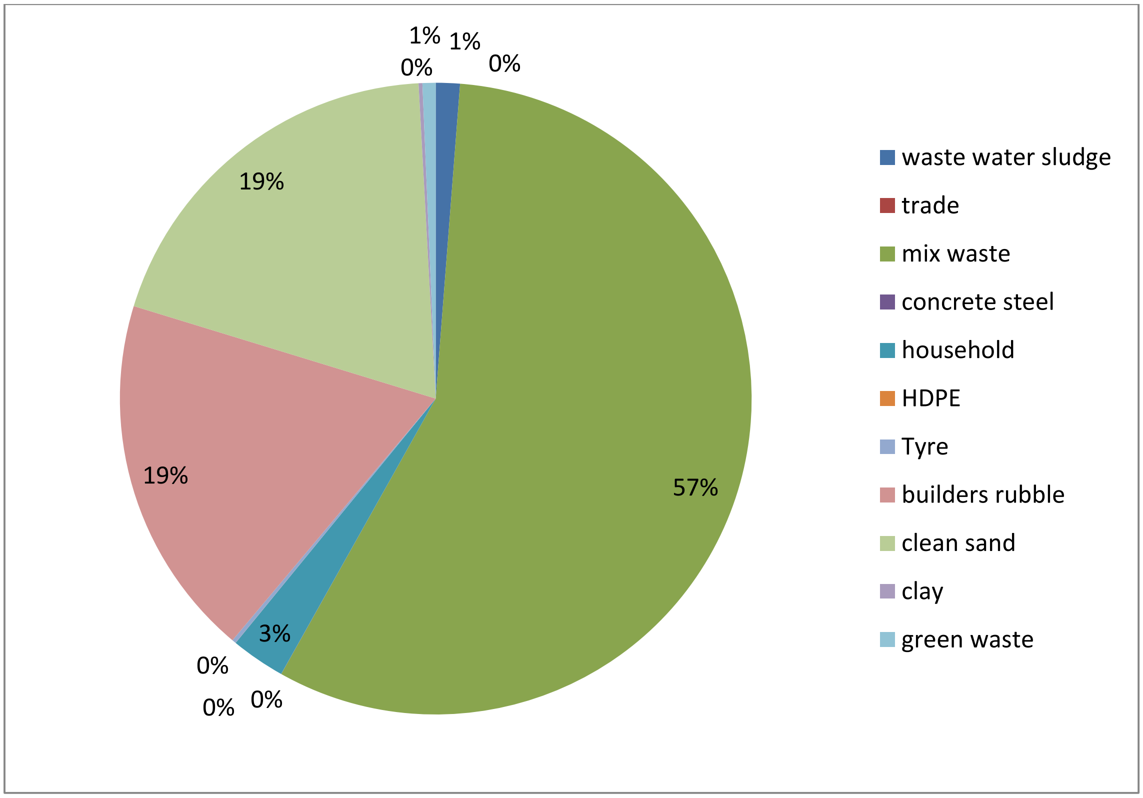

Figure 2.7: Waste percentages at Bellville landfill site from 01/01/2014 to 30/07/2014(Kula et al., 2014)

According to (Chowdhury et al., 2012) for the past years the tonnages at Cape Town landfills were as follows:

Table 2.5: Tonnages from Cape Town's landfills (Chowdhury et al., 2012)

Year	LF1(×10^3 ton/year)	LF2 (×10^3ton/year)	LF3(×10^3ton/year)
97/98	328	222	329
98/99	289	235	392
99/00	269	298	290
00/01	273	338	309
01/02	302	359	300
02/03	317	377	315
03/04	287	383	414
04/05	112	414	386
05/06	420	455	542

The above data on table 5will be used to check the feasibility of developing a landfill gas extraction system at this landfill. Two models are discussed here; (a) Mass balance method and (b) First order decay equation method because these two models are suitable for estimation of landfill gas emissions in Cape Town. When these two methods were reviewed, they portrayed that the mass balance equation does not include a time factor. Also mass balance method assumes that methane is produced on the same of year of deposition of waste (Chowdhury et al., 2012).

The constraints of these two methods are that, the mass balance equation is only applicable for sites that have a constant waste composition. In practice the parameters are difficult to achieve. On the other hand, the first order decay equation includes the variable in the form of opening and closing years of the landfill. Hence, the first order decay method for assessing the electricity generation potential of the Cape Town landfill is as follows:

$$LFG = L_oR(e^{-kc} - e^{-kt})$$

Whereby:

LFG= landfill gas generation rate

L_o = potential methane generation capacity and varies from 6.2-270 m^3/ton. The value for L_o depends almost entirely on the type of waste present in the landfill(Chowdhury et al., 2012)

R = annual quantity of waste disposal

k= methane generation rate per year

c= year when landfill closed

t= year when landfill opened

Calculation of electricity generation potential of Coastal Park landfill in Cape Town by Staffell

The estimated amount of usable landfill gas that can be turned into electricity is found to range between 75-85% of the produced methane in a landfill by the EPA. The calorific value of methane (CH_4) is 50.84±4.38MJ/kg (Staffell et al.,2011).

$$Electricity\ per\ year = CH_4/year \times 75\% \times 50.84 \pm 4.38MJ/kg$$

Possible amount of electricity generation from LF1 is calculated using LandGem and presented in Table 6. It is assumed that only 75% of the methane produced is converted to electricity. The average age of a landfill gas to energy project is approximately 20 years (Chowdhury et al., 2012).

Table 2.6:Shows the predictions of landfill gas produced and energy generated from it at one of the landfill site in Cape Town (Chowdhury et al., 2012).

Year	Landfill produced (m^3/year)	Recuperated landfill gas (m^3/year)	Electric power generation (MWh/year)
2013	121 990.22	91 492.67	411.72
2014	127 677.13	95 757.85	430.91
2015	133 086.68	99 815.01	449.17
2016	138 232.41	103 674.31	466.53
2017	131 490.73	98 618.05	443.78
2018	125 077.86	93 808.39	422.14
2019	118 977.74	89 233.30	401.55
2020	113 175.12	84 881.34	381.97
2021	107 655.51	80 741.63	363.34
2022	102 405.09	76 803.82	345.62
2023	97 410. 73	73 058.05	328.76
2024	92 659.95	69 494.97	312.73
2025	88 140.88	66 105.66	297.48
2026	83 842.19	62 881.65	282.97
2027	79 753.16	59 814.87	269.17
2028	75 863.55	56 897.67	256.04
2029	72 163.65	54 122.73	243.55
2030	68 644.18	51 483.14	231.67
2031	65 296.37	48 972.27	220.38
2032	62 111.82	46 583.87	209.63
2033	59 082.60	44 311.95	199.40

2.8 Types of landfill gas production models and their pros and cons

Table 2.7 shows the mathematical models, main parameters and their references. These mathematical models are used for estimating the amount landfill gas on a particular region.Their abilities are going to be discussed and analyzed, so that a conclusion can be drawn which model will be used for estimation of landfill gas at Bellville landfill site.

Table 2.7: Empirical models for modeling LFG generation (Reinhart et al., 2010)

Model	Order / Main Parameters	Reference
LandGEM, E-Plus	Atmospheric Pollution Prevention Division, Energy Project Landfill Gas Utilization Software (E-PLUS) Version 1.0	US EPA (1997); EPA-430-B-97-006
IPCC Model	First order model/Decomposable degradable organic carbon ($DDOC_m$) and k	Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (2006)
Triangular Model	Zero order model / Methane generation potential (L_0) and peak rate of methane generation	Tchobanglous et al. (1993)
Scholl Canyon Model	First order model / Volume of methane remaining to be generated (G) and gas generation rate constant for submass (k)	EMCON 1980
Palos Verdes Model	First-Order Kinetic Gas Generation Model Parameters for Wet Landfills	US EPA (2005); EPA-600/R-05/072

GASSFILL	Two phase model / Methane generation rate (Q) and peak methane generation rate (Q_p)	Findikakis et al. (1988)
GasSim	First order multi-phase model / Waste input carbon content and degradation rate constant (k)	Gregory et al. (2003)
AMPM	First order multi-phase model / Disposed waste type	Fredenslund et al. (2007)
ADEME	First order model / Methane generation potential (FE) and degradation rate fraction (k)	French Agency for the Environment and Energy Management

2.8.1 LandGEM

The landfill Gas Emissions Model is a simulation tool with a Microsoft excel interface that can be used for estimating rates for total landfill gas, methane, carbon dioxide, non-methane organic compounds and individual air pollutants from municipal solid waste landfills (U.S.EPA et al., 2005).

LandGEM is a first order decay model, this assumes that landfill methane generation is at its maximum immediately after the initial waste placement ‘after a short time lag during which anaerobic conditions are established in the landfill”. Another assumption is that the generation of landfill methane then decreases exponentially (i.e. first order decay) due to the depletion of organic material in the waste, as it is degraded by bacteria in the landfill (U.S.EPA et al., 2010). The LandGEM model was designed for U.S. regulatory applications;however, it was used for modeling LFG capture in the U.S and the rest of the world. (U.S.EPA et al., 2010) The mathematical equation for, estimation of methane generation is as follows:

$$Q = \sum_{t=1}^{n} \sum_{j=0.1}^{1} kL_o \left[\frac{M_i}{10}\right] \left(e^{-kt_{ij}}\right)$$

Where: Q= maximum expected methane generation flow rate (m^3/yr)

i= 1 year time increment

n= (year of the calculation)-(initial year of waste acceptance)

j= 0.1 year time increment

k= methane generation rate (1/yr)

L_o= potential methane generation capacity (m^3/Mg)

M_i= mass of solid waste disposal in the i^{th}year (Mg)

t_{ij}= age of the j^{th} section of waste mass M_i disposed in the i^{th} year (decimal years)

The LandGEM mathematical equation is used to determine precise methane generation for a specific or chosen year, from cumulative waste disposed throughout that year. The sum of the LFG generation is the same as the methane generation rate divided by the percentage of methane assumed in the LFG (U.S.EPA et al., 2010).

Besides the disposal rates, the other considerable variables in the first order decay equation are (k) which is the methane generation rate constant and L_o which is the potential methane generation capacity. In the next two paragraphs these two variables will be explained in order to see their importance.

The methane generation rate constant (k):

The k value is the rate of waste decay, which is proportional to the production of methane. It is in relation to the half-life of waste based on the following equation: half-life=ln(2)/k. When the k value is low, generation of methane is not enough due to small fraction of the deposited waste decay, producing LFG. Higher k results from, high amount of waste decays and produces methane at higher rates. Again high k values are due to quick increase in LFG generation for a period of time as long as the landfill site is getting replenished. When the site closes up, the waste is no longer dumped on it. Hence, the k value lowers as the methane production decreases because the decaying occurs rapidly without being replaced. There are also other factors that influence the k value and there are waste type (organic waste degradability) and moisture content (the estimations are based on the mean annual precipitation). (U.S.EPA et al., 2005)

Potential Methane Generation Capacity (L_o):

The Potential Methane Generation Capacity depends significantly on the kind and contents of the waste from the landfill site. When the cellulose content is high, the potential methane generation gets higher too (Z.W.S. et al., 2012). The shortfall of this variable is that, it is unreachable in extreme dry climates. Therefore, it is discovered to be independent of moisture above a specific minimum threshold (U.S.EPA et al., 2010).

The shortfall of LandGEM model:

The modeling of LFG is done in the U.S. using the EPA's landfill Gas Emissions Model (LandGEM) with inadequate number of model input assumptions known as "Clean Air Act" or "inventory" values which are selected by the EPA for regulation of LFG emissions at landfills of the U.S. Due to limited input values needed by the EPA,LandGEM do not allow for accurate estimates of LFG recovery from a number of U.S. landfills containing various waste composition, landfill condition, and collection system design and operations (Scharff et al., 2010). The effect of this limitation is spotted clearly when LandGEM was applied using U.S. regulatory values to landfills in developing countries with huge different waste characteristics and site conditions(Scharff et al.,2010). When using LandGEM an average value for refuse decay rates ("k value"), is said to be unaccountable for differences in waste decay rates over time. 50 percent of wastes in the developing countries are from food wastes which happen to decay much rapidly than other organic materials in the wastes. Immediately, when the landfill closes and disposal ceases the mean decay rate declines rapidly, leading to very low LFG generation rates within a few years, due to all of this LandGEMtends to over-predict methane generation at closed sites. This type of shortfall becomes obvious in wet climates with large amounts of waste decay rates (Stege et al., 2010).

LandGEM is applied using parameters like (L_o) that are very high for the wastes contents at the landfill site; because of over-projection of methane generation during the methane production. The reason why L_o turns out to be high is due to the application of a U.S. EPA regulatory default value ($170m^3/Mg$) and a failure to adjust it for the high moisture content of disposed waste (since water does not contribute to methane generation). In developing countries L_o ranges from 60-85m^3 per ton of waste this is due to 50 percent of waste being food with a moisture content of about 70 percent. Last but not least application of LandGEMassumes optimistic estimates of collection efficiency, driving to methane recovery being over-estimated for the entire duration of the project. Estimates of collection efficiency often cite U.S. EPA estimates for sanitary landfills in the U.S. as a guide and fail to account for site conditions in developing countries and operation of the collection system. The level at which U.S. landfills methane is collected will never be approached by those of developing countries due to obstacles faced at their landfill sites. These are high leachate levels and the failure to install wells in active disposal areas because of security concerns (Stege et al., 2010).

2.8.2 IPCC Model

Besides LandGEM there is Intergovernmental Panel on Climate Change (IPCC) model which was proposed in 2006, is said to be more useful than LandGEM model because of its numerous features. These features are mainly used for examining SWD sites throughout the globe. IPCC model also has the ability to apply different first order decay calculation, on various organic waste categories with different decay rates. The objectives of the model were to estimate methane emissions from waste disposal with the aid of regional per capita waste generation rates and population estimates, deducting fugitive gases. Another advantage of IPCC model is that it can be used for estimating generation of methane from SWD sites, inmost countries. The IPCC model made it possible to design the standard GHG emissions reduction methodology landfill gas projects, by using similar variables and calculations (U.S.EPA et al., 2010). Similar to landGEM, the IPCC Model applies the first-order decay equation that considers annual waste disposal rates and a waste decay rate variable (k value). Although, L_o variable is not included, but the rest of other variables are included. When these other variables are mixed together, it ends with a variable equivalent to L_o, including the fraction of degradable organic carbon (DOC), the fraction of degradable organic carbon (DOC_f) that decomposes and a methane correction factor (MCF) (U.S.EPA et al., 2010).

Comparing LandGEM to IPCC Model it is found that:

1. With IPCC Model it is possible to divide waste composition data as follows; food waste, garden, paper, wood and straw, textiles, disposal diapers, sewage sludge and industrial waste. In the absence of waste composition data, the IPCC model gives out default values. It also assigns various DOC values for each and every waste type based on the amount of degradable organic carbon.
2. The IPCC Model assumes various k values for different kinds of wastes and groups thus into four categories depending on their decay rates, e.g. food waste and sewage sludge fall under the first category due to their k value which is said to be the highest value. Then, follows garden waste, disposable diapers and industrial waste under category two

while paper and textile are in category three and category four include wood and straw with the slowest decay rates.

3. The option of four various climates based on mean annual temperature, precipitation and (for temperate climates) potential evaporation (PET).The climate categories are as follows; wet tropical, wet temperate, dry tropical and dry temperate. The k values are selected based on the climatic conditions and the waste decay rate, for each waste category.
4. The model also involves an MCF discount to accommodate for aerobic (non-methane generating) waste decay at disposal sites that not managed at all.

According to the features mentioned above the IPCC Model is considered to be the best facilitator when it comes to estimation of LFG production from SWD sites in most countries. On the contrary, it is found not to be precise when it comes to conditions in each country, especially precipitation and its impacts on LFG generation, due to the consideration of two categories. (U.S.EPA et al., 2010)

Furthermore, the IPCC Model's four climate categories which represent an improvement over LandGEM's two climate category approach, limitations exist, including the fact that temperature effect is significantly small on LFG generation than precipitation. Therefore, it should not be equally weighted in choosing climate categories. There is also scarcity of potential evapotranspiration data for most locations it should not be first priority in assigning climate in temperate regions even though scientifically is valid. The 1000mm/year precipitation threshold for separating tropical climates into dry versus wet categories is better than the LandGEM threshold of 635mm/year (25inches/year) but is likely too loose to account for the effects of precipitation across the wide range of values encountered e.g. most areas in Colombia experience more than 1000mm/year of precipitation and many areas get more than 2000mm/year. Landfills in these areas would be treated the same (identical k values) in the IPCC Model, which implies that there are no noticeable effects from increasing precipitation above 1000mm/year (Svardal et al., 2006).

2.8.3 Methodological issues when using the IPCC Model

The method of estimating methane emissions from solid waste disposal sites is based on the First Order Decay method. Although, it can be used worldwide there are assumptions made in order to make use of it, thus the degradable organic component (degradable organic carbon, DOC) in waste perish quite slowly throughout the decades, during which methane and carbon dioxide are formed (Svardal et al., 2006). If the conditions of the landfill site are constant, methane production rate depends on the carbon remaining in the waste. As a result emissions from waste deposited in a disposal site are at their maximum in the first few years after deposition, it then changes slowly as the degradable carbon in the waste is consumed by the bacteria responsible for the decay (Svardal et al., 2006). The conversion of degradable material in the solid waste to methane and carbon dioxide is by a series of reactions. On the contrary, laboratory and field work have proven that methane generation data and overall decomposition can be processed by the first order decay (FOD) kinetics through approximations. FOD model has been adopted and accepted by IPCC as a basis for the estimations of methane emissions from SWDS (Svardal et al., 2006).

Half-lives for various kinds of waste differ from a few years to several decades or longer. In order, for FOD to work accurately it needs data to be estimated for historical disposals of waste over a time period of 3 to 5 half-lives. Therefore it is suggested to prolong the time frame for disposal data for roughly fifty years in order, to get accurate results. Otherwise, the inventory compiler should show insignificancy in underestimation of the emissions (Oonk et al., 2010).

Below are the steps followed in using FOD model in a simple spread sheet to guide countries in using the FOD method: (three tiers to estimate the methane emissions from SWDS)

1. The estimations of tier 1 methods are based on the IPCC FOD method using mainly default activity data and default parameters.
2. Tier 2 methods use the IPCC FOD method and some default parameters, but require good quality country-specific activity data on current and historical waste disposal at SWDS. Historical waste disposal data for 10 years or more should be based on country-specific statistics, survey or other similar sources. Data is needed on amounts disposed at the SWDS.
3. Tiers 3 methods are based on the use of good quality country-specific data (tier 2) and the use of either the FOD method with (1) nationally developed key parameters, or (2) derived country-specific parameters. The inventory compiler may use country-specific methods that are of equal or higher quality to the above defined FOD-based tier 3 methods. Key parameters should include the half-life and either methane generation potential (L_o) or DOC content in waste and the fraction of DOC which decomposes

(DOC_f). These parameters can be based on measurements as described in the equation for methane emissions from SWDS (Svardal et al., 2006).

A spreadsheet model developed by the IPCC to assist countries in implementing the FOD (IPCC spreadsheet for estimating methane emissions from solid waste disposal sites):

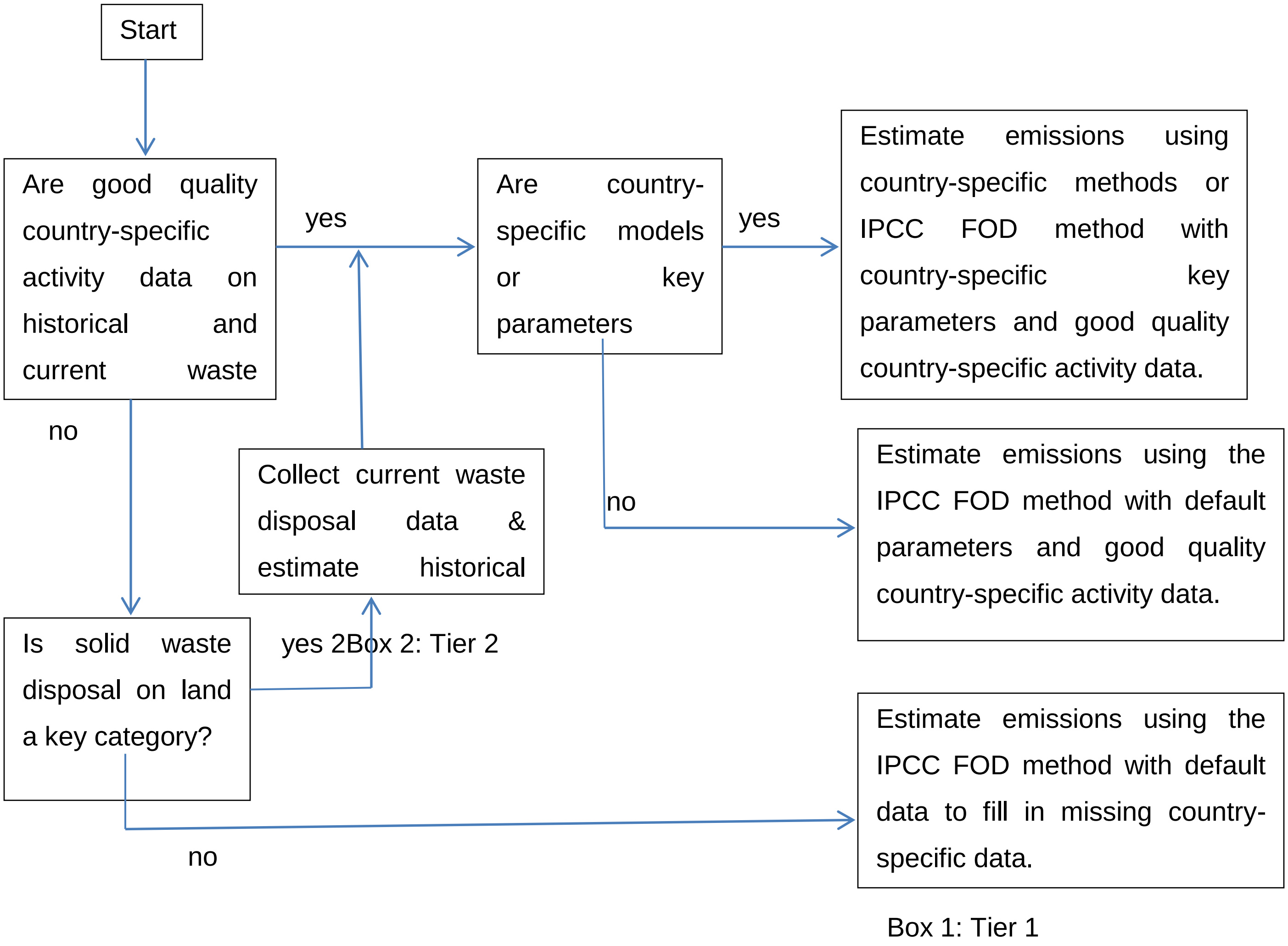

Figure 2.8: Decision Tree for methane emissions from solid waste disposal sites (Svardal et al., 2006)

First order decay (FOD)

Emissions from the disposal site can be estimated from the below equation, and the equation is accommodating emissions annually.

CH_4 Emissions from SWDS

$$CH_4 = \left[\sum_x CH_4\, generated_{x,T} - R_T\right].(1 - OX_T)$$

Where:

CH_4 Emissions =CH_4 emitted in year T, Gg

T= inventory year

x= waste category or type/ material

R_T= recovered CH_4 in year T, Gg

OX_T= oxidation factor in year T, (fraction)

The CH_4 recovered must be subtracted from the amount CH_4 generated. Only the fraction of CH_4 that is not recovered will be subjected to oxidation in the SWDS cover layer (Jigar et al., 2014).

The potential production of CH_4 slowly decreases throughout the number of years. As a result CH_4 released decreases gradually from a given amount of wastes. In order, to account for the CH_4 the FOD model designs exponential factor, that gives the amount of the fraction of degradable matter which is degraded into CH_4 and CO_2 yearly (Jigar et al., 2014).

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The leading input in the FOD model is the amount of degradable organic matter (DOC_m) in waste disposed into SWDS. This is determined on the basis of data on various waste categories thus sludge, industrial and other waste and variety of waste material (food, paper, wood, textiles, etc.) are added in these categories, or rather as mean DOC in bulk waste disposed. In addition to this, concrete evidence is required on the kinds of SWDS in the country and the parameters as mentioned earlier. For instance, Tier 1 needs default regional activity data and default IPCC parameters for usage and are added in the spreadsheet model. Tier 2 and 3 need country-specific parameters (Svardal et al., 2006).

The equations for estimating the CH_4 generation are given below. As the equations are the same for estimating the CH_4 emissions from all waste categories, no indexing referring to the different categories in the equations below.

Decomposable DOC from waste disposal data

$$DDOC_m = W.DOC.DOC_f.MCF$$

Where:

$DDOC_m$= mass of decomposable DOC deposited, Gg

W = mass of waste deposited, Gg

DOC = degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste

DOC_f = fraction of DOC that can decompose

MCF= methane correction factor for aerobic decomposition in the year of decomposition fraction

Although methane generation potential $(L_o)^2$ is not used explicitly in this equations, it equals the product of $DDOC_m$, the CH_4 concentration in the gas (F) and the molecular weight ratio of CH_4 and C (16/12).

Methane potential that is produced throughout the years can be determined on the basis of the amounts and composition of the waste disposed into SWDS and the waste management practices at the disposal sites. The reason for calculation is to get, the amount of Decomposable Degradable Organic Carbon ($DDOC_m$) as described by the equation below. $DDOC_m$ is the certain percentage of organic carbon that degrades under the anaerobic conditions in SWDS. It is applied in the equations and spreadsheet models. The subscript m stands for mass and another thing is that $DDOC_m$ is equivalent to the product of the waste amount (W), the fraction of degradable organic carbon in the waste (DOC), the fraction of the degradable organic carbon that decomposes under anaerobic conditions (DOC_f) and the part of the waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic) in the SWDS, which is interpreted with the methane correction factor (MCF) (Oonk et al., 2010).

Transformation from $DDOC_m$ to L_o

$$L_o = DDOC_m . F . 16/12$$

Where:

L_o=CH_4 generation potential, Gg CH_4

$DDOC_m$= mass of decomposable DOC, Gg

F= fraction of CH_4 in generated landfill gas (volume fraction)

$16/12$= molecular weight ratio CH_4/C (ratio)

$DDOC_{ma}$ ($DDOC_m$ accumulated in the SWDS) it can be used to determine the total CH_4 generated potential of the waste remaining in the SWDS.

(Oonk et al., 2010)

First order decay basics

With a first order reaction, the amount of product is directly proportional to the amount of reactive material. This means that the year in which the waste material was deposited in the SWDS is irrelevant to the amount of CH_4 generated each year. It is only the total mass of decomposing material currently in the site that matters.

This also means that when the amount of decomposed material is known in the SWDS at the beginning of the year, each and every single year can be considered as year one in the estimation method, and the basics first order calculations can be performed by the two below equations, with the decay reaction occurring on 1st of January, after the year of deposition. (Oonk et al., 2010)

$DDOC_m$ Accumulated in the SWDS at the end of year T

$$DDOCma_T = DDOCmd_T + (DDOCma_{T-1} . e^{-k})$$

$DDOC_m$ decomposed at the end of year T

$DDOCm\ \ decomop_T = DDOCma_{T-1}.(1 - e^{-k})$

Where:

T=inventory year

DDOCma_T=$DDOC_m$ accumulated in the SWDS at the end of year T, Gg

DDOCma_{T-1}= $DDOC_m$ accumulated in the SWDS at the end of year (T-1),Gg

DDOCmd_T= $DDOC_m$ deposited into the SWDS in year T, Gg

DDOC$m\ decomp_T$= $DDOC_m$ decomposed in the SWDS in year T, Gg

k= reaction, k=In (2)/$t_{1/2}$ (y^{-1})

$t_{1/2}$=half-life time (y)

CH_4 generated from decomposable $DDOC_m$

The amount of CH_4 formed from decomposable material is found by multiplying the CH_4 fraction in generated landfill gas and the CH_4/C molecular weight ratio.

CH_4 generated from decayed $DDOC_m$

$$CH_4generated_T = DDOCm\ decomp_T.F.16/12$$

Where:

$CH_4generated_T$ =Amount of CH_4 generated from decomposable material

DDOC$m\ decomp_T$= $DDOC_m$ decomposed in year T, Gg

F =fraction of CH_4, by volume in generated landfill gas (fraction)from gas meter

$16/12$ =Molecular weight ratio CH_4/C (ratio)

(Oonk et al., 2010) (Park et al., 2011)

According to (IPCC,1996) L_o can be determined from the following equation:

$L_o(m^3\ of\ methane\ per\ tonne\ \ of\ waste) = MCF \times DOC \times DOC_F \times 16/12 \times F$ (Tanapat et al., 2004)

Where:

MCF= methane correction factor (1=well managed landfill);

DOC= degradable organic carbon (fraction);

DOC_F= fraction DOC dissimilated, and

F= fraction of CH_4 in landfill gas (measurement at landfill has indicated a value of 56% CH_4 in biogas)(Tanapat et al., 2004)

The equation is used to estimate the DOC:

$\%\ DOC(by\ weight) = 0.4(A) + 0.17(B) + 0.15(C) + 0.3(D)$ (Tanapat et al., 2004)

Where municipal solid waste consists of:

A=% paper and textiles

B=% garden waste, park waste or other non-food organic putrescible

C=% food waste, and

D=% wood or straw

The equation below is used to estimate the DOC_F:

$DOC_F = 0.83 - 0.028LC$ (Tanapat et al., 2004)

0.83= empirical constant

0.028=empirical constant, and

LC = lignin content of the volatile solid (VS) expressed as a percent of dry weight from leachate sample

2.8.4 Triangular Model

In triangular model the organic matters, in the landfill site are divided into two groups: materials that decompose fast (from 3months to 5 years) and materials that degrade gradually (up to 25 years). The decomposition rate normally reaches the peak within the first two years and then slowly reduces. The yearly rates of degradation for fast and slow biodegradable material are based on a triangular model. The peak is reached in between first and fifth year from the beginning of production for the fast and slow degradable materials (Lazaridis et al., 2010).

(Halvadakis et al.,1983 and Tchobanoglouset al., 1993)once used the triangular model. They discovered that following the model assumes a linearly rising first phase then, a linearly decreasing second phase of generation rates follows. In addition, to this one year lag prior to starting of methane production and separate triangular curves for fast and gradually decomposable wastes. The total rate is determined by adding the rates from each component at a provided period. The volume of methane generated for the triangular function takes the following form: (Dr. Chaudhary et al., 2014)

$$L_o=1/2\times t_f\times Q_{sp} \rightarrow Q_{sp}=\frac{2L_o}{t_f}$$

Where:

Q_{sp}=specific peak rate of methane generation, in volume per mass-time

t_f = time to complete degradation

The assumption is that the production of biogas starts at the end of the first complete year of the landfill operation. The total quantity of biogas produced can be determined from the following equation straight away from the municipal solid waste (Lazaridis et al., 2010).

Total biogas produced ($m^3\ kg^{-1}$) =1/2(years of gas production) × (peak biogas production rate ($m^3\ kg^{-1} yr^{-1}$))

The limitation factor to this model is the moisture content. Normally, the moisture content at the landfill site is not enough. Therefore, it is unable to perform complete conversion of biodegradable organic materials into municipal solid waste. The moisture content which suits the conversion of biodegradable organic fraction is in between 50-60% (Chalvatzak et al., 2010). The biogas production curve becomes more linear and stretching to longer time periods, is due to the uneven distribution of moisture (Chalvatzak et al., 2010).

2.8.5 GasSim2.5 Model

GasSim2.5 is an up-grade of the previous version, GasSim2, by Gobler in collaboration with Environment Agency. The main reason for the development of this model is to facilitate site-specific risk assessment and management of landfill gas for regulators and operators (Davies et al., 2011). The feature of GasSim series is the manner in which errors or uncertainties are demonstrated in input parameters by the use of Monte Carlo probabilistic approach to simulations (Davies et al., 2011).

The 5 key parts of the GasSim 2 conceptual model have not been able to be differentiated between GasSim2 and GasSim2.5. As for HPM4, only the source term module has been utilized as it determines the production of landfill gas for an individual cell, depending on the mass of waste deposited and composition of the waste streams (Stalleicken et al., 2011). GasSim2.5 contents are built (but user adjustable) data on the moisture content, the cellulose and hemi-cellulose content of waste components (Stalleicken et al., 2011). The information is converted to carbon available for degradation by assuming that 99% of waste is degraded methanogenically and 1% by acetogenic decay. Decomposable organic carbon is divided into three separate fractions and thosethatare rapidly degrading, moderately degrading and slowly degrading with a different degradation rate constant for each fraction which is then aggregated (Stalleicken et al., 2011).

$C_t = C_o - (C_{0.1}e^{-k_1 t} + C_{0.2}e^{-k_2 t} + C_{0.3}e^{-k_3 t})$ (Stalleicken et al., 2011)

Where:

t= time between waste emplacement and LFG generation (years)

C_t=mass of degradable carbon degraded up to time t (tons)

C_o= mass of degradable carbon at time t=0 (tons)

$C_{o,n}$= mass of degradable carbon at time t=0 in each fraction (n=1,2 and 3i.e. rapidly, moderately and slowly degradable fractions respectively) (tons)

k_n= degradation rate constant for each fraction (n=1,2 and 3) of degradable carbon (per year)

$$C_x = C_t - C_{t-1}$$

C_x= mass of carbon degraded in year x (tons) (Stalleicken et al., 2011)

GasSim was mainly created for the U.K. Environmental Agency. This proves that it might have limitations when trying to estimate the landfill gas emissions from other parts of the globe besides the U.K. Although, it is made to be conceptual by considering landfills individually with their own engineering and waste composition. It also applies bits of both multiphase model and LandGEM to determine estimates of methane production (Bhailall et al., 2010).

Here is the equation based upon a multi-phase model described by van ZantenenScheepers (1994)

$\alpha_t = \varsigma c \sum_{j=0}^{m} \sum_{i=1}^{n} A_j\, k_i C_{o,i,j} e^{-k_i(t-j)}$ (Jacobs et al., 2010)

Where:

α_t= landfill gas production at a given time (m^{3}LFG.y^{-1})

ς= formation factor (-)

c=conversion factor (m^{3}LFG.kgOM$_{degrade}^{-1}$)

m= number of years of landfilling (-)

j= year of landfilling amount A_j (y)

n= number of fractions I (-)

i= waste fraction with degradation rate k_i (kg$_i$.kg$_{waste}^{-1}$)

(Jacobs et al., 2010)

2.8.6 Scholl Canyon Model

Scholl Canyon model does not require different parameters which are specific for each landfill, it is a kinetic model based on the qualities of substrate-limited bacterial growth. The gas production rate is assumed to reach its peak after a negligible time session during which anaerobic conditions are developed and the biomass build up. Then, after the gas production rate is said to decrease gradually by assuming that, methane production rate is directly proportional to remaining methane potential to be produced (Palananthakumar et al., 1999).

This model is easy and convenient in estimating the amount of landfill gas emission for LFG engineering. The model is based on the following; the maximum is reached within a short period of time (not longer than one year) after the replenishment of waste in landfill comparative with the entire period (several decades) of anaerobic process in the waste. The emission rate decreases exponentially (Song et al., 2010).

Scholl Canyon model is as follows:

$L_t = kL_o e^{-kt}$ (Xiang et al., 2010)

Where:

L_t=LFG emission rate (m^3/t.a)

k=constant (1/year)

t= time years

L_o= max quantity of LFG generated in the whole period of anaerobic process of waste (Xiang et al., 2010)

Utilization of LFG model to estimate LFG emission rate in a landfill

As anaerobic processes waste will last for a long time, the LFG emission rate reaches the peak only several months, so the time before emission rate peak can be ignored. It is very convenient to get the curve of the LFG emission rate with time. The reason for collection of LFG volume annually is for engineering design. The LFG volume in some year is summation of LFG volume emitted in this year from the waste deposited in each year before (Thompson et al., 2005). The LFG volume in the year can be expressed as follows;

$L_t = kL_o \sum_{t=1}^{n} R_t \, e^{-kT_t}$ (BCME et al., 2010) or $Q_{CH_{4i}} = k \times L_o \times m_i \times e^{-kt}$ (World Bank et al., 2003)

Where:

L_t-Total LFG emission volume in year t (m^3/a)

k- LFG emission rate constant (1/year)

T_t- time (years)

L_o- Max quantity of LFG generated in the whole period of anaerobic (m^3/t)

R_t- The waste quantity is filled in year t from landfill start of operation

(Tanapat et al., 2005)

Estimated L_t is determined with the aid of maximum quantity of LFG generated for the entire duration of anaerobic and LFG emission rate constant (Xiang Xin et al., 2005). L_o becomes a huge value when organic waste portions are high and otherwise when the waste with lower organic portion (Xiang Xin et al., 2005). kisrelated to waste component, landfill condition and local weather etc. Therefore there are various L_o and k valuesfor different landfill, it is needed to get L_o and k value according to waste component and site test before project design, then the L_t can be calculated by the expression above with waste quantity filled in landfill in each year (Xiang Xin et al., 2005).

Estimation of L_o

L_o is the total LFG volume attained by organic element during the anaerobic process at the landfill site. The reason being that the presence of CO_2 and CH_4 is greater than 95% (Song et al., 2010). Therefore L_o is considered to constitute of CH_4 and CO_2 from decomposed organic waste (Song et al., 2010). Furthermore L_o can be expressed as:

$$L_o = {}^{1}/_{2}\, V_{oc}.\, 22.4/M_1 + {}^{1}/_{2}\, V_{oc}.22.4/M_2 = 11.2 V_{oc}\left({}^{1}/_{M_1} + {}^{1}/_{M_2}\right) \text{ m}^3/\text{t}$$

There into:V_{oc}- organic carbon quantity of waste

M_1- The molecular weight of CH_4

M_2- The molecular weight of CO_2

NB: Organic carbon quantity of waste can be obtained through elemental analysis of waste.

The U.S. EPA assigns default values for the following parameters of LFG generation, thus the rate constant (k) and the methane generation potential (L_o) for a conservative preliminary site assessment (World Bank et al., 2003). On the contrary, the mentioned parameters must be chosen with knowledge of the specific site conditions and geographic location (World Bank et al., 2003). The increase in potential for LFG generation is due to variations in organic content of the waste, the moisture presence, or the level to which the waste is compacted will differ (World Bank et al., 2003). However, the Scholl Canyon model is enough for serving the intended purpose. In addition, to that it is simple to understand and apply.

2.8.7 ADEME model

The ADEME model is suitable for estimating the methane emissions when the landfill gas is in a multi-phase state.

$FE_{CH_4} = \sum_x FE_o \left(\sum_{1,2,3} A_i \times p_i \times k_i \times e^{-k_i t}\right)$ (Jacobs et al., 2010)

Where:

FE_{CH4}= annual methane production ($m^3CH_4.y^{-1}$)

FE_o= methane generation potential ($m^3CH_4.Mgwaste^{-1}$)

p_i= waste fraction with degradation rate k_i ($kg_i.kgwaste^{-1}$)

k_i= degradation rate of fraction i (y^{-1})

t= age of waste (y)

A_i= normalization factor (-)

The model gives a description of three categories of waste with its specific methane generation capacity per Mg of waste. This model determines three fractions and three k values for each waste category (Scharff et al., 2010). The distribution of the fractions is the same for category 1 and 2. As a result the k value ends-up being the same and for category 3, k value is zero. Hence, French EPER multi-phase model can now be referred to be a single-phase model.

Furthermore, it assumes that oxidation capacity of the top cover is 10%. The total methane emission is determined by the following equation (Scharff et al., 2010).

$$CH_4 emission = P(1-\boldsymbol{\eta}) \times 0.9 + FE_{\boldsymbol{CH_4}} \times \mathbf{0.9}$$

Where:

$\boldsymbol{\eta}$=extraction efficiency

2.8.8 AMPM (Afvalzorg) Multi-phase model

Various kinds of waste contain different fractions of organic matter that dispose at various rates. The multi-phase mode is essential because the typical waste content can be taken into account. In this model eight waste categories and three fractions are determined (Jacobs et al., 2010). LFG emission rate is calculated separately for each fraction. It can be expressed mathematically: (Jacobs et al., 2010)

$$\alpha_t = \varsigma \sum_{i=1}^{3} cAC_{o,i}\, k_{1,i} e^{-k_{1,i} t}$$

Where:

α_t=landfill gas production at a given time (m^3LFG.y^{-1})

ς= dissimilation factor (-)

i= waste fraction with degradation rate $k_{1,I}$ ($kg_i.kg_{waste}^{-1}$)

c= conversion factor (m^3LFG.$kgOM_{degraded}^{-1}$)

A= amount of waste in place (Mg)

C_O=amount of organic matter in waste (kgOM.Mg $waste^{-1}$)

$k_{1,I}$ = degradation rate constant of fraction i (y^{-1})

t= time elapsed since depositing (y)

Only rapidly, moderately and slowly degradable organic matter has been taken into consideration (Jacobs et al., 2010). The total organic matter content is higher than the sum of these three categories due to the presence of organic matter that is not considered biodegradable under anaerobic conditions (Jacobs et al., 2010). e.g.humic substances, lignin and plastics. Minimum and maximum value of 0.7 and 0.74 $m^3LFG.kgOM_{degraded}^{-1}$ were used (Jacobs et al., 2010).

2.8.9 Palos Verdes

For Palos Verdes model to be used the following details must be known:

- The design capacity of the landfill
- The amount of refuse in place in the landfill or the annual refuse acceptance rate for the landfill
- The methane generation rate (k)
- The methane generation capacity (L_o)
- The concentration of total non-methane organic compounds and special NMOC found in the landfill gas
- The years the landfill has been in operation
- Whether the landfill has been used for disposal of hazardous waste (co-disposal) (Tsave et al., 2010)

The equation below is used when estimating the biogas production:

$$LFG = L_oR(e^{-kc} - e^{-kt})$$

Where:

LFG= total landfill gas generation rate

L_o = methane generation capacity (m^3/ton)

R = annual quantity of waste disposal (ton)

k = methane generation rate (y^{-1})

c and t, are the numbers of years since the landfill closed and opened. The most important variables of the above equation are L_o(potential methane generation capacity) and k (methane generation rate) (Karapidakis et al., 2010).

It should be well known that the above model is meant for estimation of LFG generation and not LFG emissions to the atmosphere. (U.S. EPA et al., 1992) On the contrary, the difficulty that is being faced when using the Palos Verdes model is in making a decision on values for L_o (the potential methane generation capacity of the refuse) and k (the methane generation rate constant) (DAPT et al., 2005).

2.9 Conclusion

According to the information gathered on the different types of landfill models. The IPCC will be the one suitable for estimation of landfill gas emission at Bellville landfill site in Cape Town. Besides for modeling U.S. and the rest of the world, IPCC has the following characteristics, its ability to examine solid waste disposal sites and apply separate first order decay calculation, on various organic waste categories with different decay rates. It divides waste composition data, including arrangement of various k values for different kinds of groups into four categories depending on their decay rates. The option of four various climates based on mean annual temperature, precipitation and potential evaporation and the model also involves an MCF discount to accommodate for aerobic waste decay at disposal sites that are not properly managed (U.S.EPA et al., 2010).

IPCC model is the best model to be used for estimation of landfill gas from the rest of the discussed models. The short falls of these models are as follows; poor quality disposal data which is a significant model error, waste composition data is seldom provided to determine if unusual waste composition is a cause of model inaccuracy and inaccurate assumptions this is about variables such as future disposal rates, site closure dates, expansion schedules or collection efficiencies resulting in huge errors in the prediction of future recovery of landfill gas (U.S.EPA et al., 2010).

Set up of landfill gas to energy plant according to (EPA et al., 2000) shows that the project is feasible and the community can benefit from it. Another thing is that it pre-treats methane before its combustions. This proves that when doing the detailed design environmental matters were taken into consideration. The economics of the LFGTE project is said to cost only R11 786 700 (SCS Engineers et al., 2008), this shows exactly that the project will be fundable because South Africa is willing to invest R9.4 billion in this kind of project (Mudzuli et al., 2015). Chowdhury carried out a study on gathering data on tonnages from three anonymous Cape Town’s landfills and determined landfill gas produced (m^3/year), recuperated landfill gas (m^3/year) and electric power generation (MWh/year) from 2013 to 2033 hence, show high feasibility of LFGTE project in Cape Town. The next chapter will be dealing with various types of technologies applied in the purification of methane and drawing a conclusion on which technology to be used, based on the efficiency and economic factors. Then a process flow will be done prior to the kind of technology chosen.

CHAPTER 3

3. Introduction

Chapter 3 looks at the feasibility study of LFGTE process plant and the importance of advanced treatment of landfill gas.It also includes discussion of purification and selection of technologies for landfill gas as well as economics of the technologies.

3.1 Feasibility study

LFG is one source of energy that can be utilized to provide electricity and a suitable feed to internal combustion generators, turbines, micro-turbines, fuel cells and other power producing facilities. The production of electricity with LFG is done with internal combustion engines,withflow rates of methane at 50% volume ranging from 30-2000 m^3/h (Aquilar-Virgen et al., 2014). LFG generates 1MW of electricity when its flow rate is between 500 and 540 m^3/h at 50% volume. In addition, if generation of electricity is required to increaseup to 3 MW, this could be achieved by adding more than one engine in the process. When operated on LFG, engine power ratings are commonly reduced by 5-15 % compared to operation on natural gas. The good impact of using LFG is that there are low capital costs, high efficiency and the engine can quickly accept different LFG output rates (Taboada- Gonzalez et al., 2014).

Instead of using internal combustion engines, turbines could be used to convert LFG to electricity. If 1 784m^3/h of LFG enters the turbine, it is guaranteed that at least 3MW electricity could be generated (Ojeda-Benitez et al., 2014). The capacities of LFG-fired turbines can exceed 5 MW if turbines and engines are used. For instance, in the United States most LFG projects which make use of turbines have capacities in the range of 3-5 MW requiring 2 000m^3/h of LFG flow rate. Advantages of turbine technology in comparison to internal combustion engines include a greater resistance to corrosion damage, relatively compact size, and lower operation and maintenance costs (Cruz-Sotelo et al., 2014. Turbines need additional power to run its compression system and they are larger than internal combustion engines. Furthermore, they have different capacities from 1MW to more than 10MW (Cruz-Sotelo et al., 2014).

3.2 Process Description

Some waste can be recycled and a portion taken into a waste disposal site. Once inside the land, waste decomposes and produce methane. The landfill gas which constitutes fifty percent methane goes through a network of pipes and wells. The gas is drawn into a pre-treatment system where the gas is dried, pressurised and filtered to make it clean. When landfill gas enters the system it is filtered, to remove any large pieces of debris and some liquids which may have become mixed with the gas. It enters the compressor to increase its pressure, so that the gas can be used as a fuel. During compression the temperature of the gas rises and then sent to the cooler where the temperature of the gas drops, allowing the remaining moisture in the gas to condense. The gas is filtered for the second time, to remove the condensed moisture, at this stage the gas is re-heated to prevent further condensation and it is then ready to be used as a renewable fuel. The whole process from start to finish takes seconds (Dudek et al., 2010).

Either IC engine or turbine engine can be used to produce energy, because they both follow the same principle to produce electricity. The engine used is similar to that of a car engine. Landfill gas enters the engine and it is combusted, causing the piston to turn the drive shaft, then the drive shaft is connected to a generator which converts the power to electricity. The controls systems direct electricity to transformers on site of the plant, which either increases or lowers the voltage. Low voltage electricity (480 V) is used to power equipment within the renewable energy plant. High voltage electricity (12 000V) is exported to the utility grid to supply energy for communities and businesses. However, before getting to the final stage of converting landfill gas to energy, there is the second stage (advance treatment) which is in between the first filter and compressor. It deals with the desulphurisation, removal of organic silicon compounds and removal of other gaseous contaminants, such as hydrocarbons and ammonia (Dudek et al., 2010).

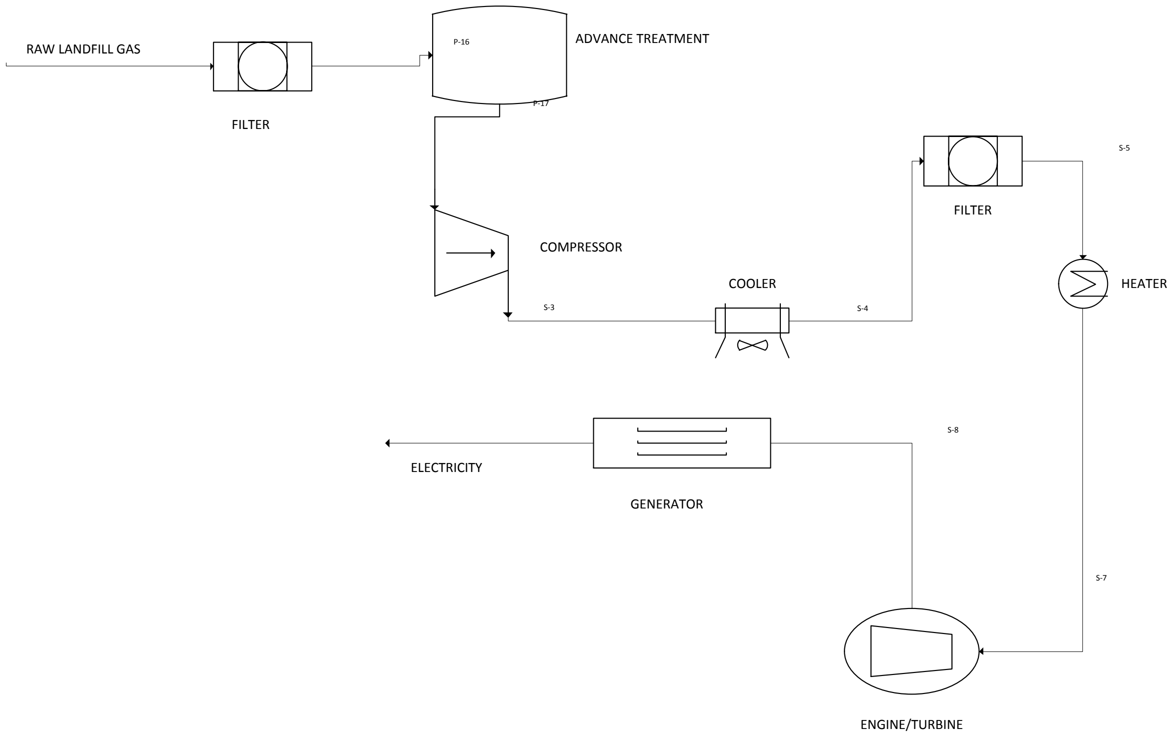

Figure 3.1: Process flow diagramof LFGTE process plant (Dudek et al., 2010)

3.3 The Main Reason of advance treatment of landfill gas

Methane is a greenhouse gas if exposed into the atmosphere. Landfill gas can be utilised directly to generate power, but the large volume of CO_2 content decreases the heating value of the gas, increasing compression and transportation costs and reducing its economic viability. Hence, when landfill gas gets purified it accommodates for broader range of its application, either for heat and electricity or as fuels forvehicles.Contaminants must be removed from the landfill gas, because H_2S can corrode vital mechanical components within the engine (Zhao et al., 2010).

Purified landfill gas provides reduction in GHG emissions as well as many other environmental benefits when utilised as a vehicle fuel.Less environmental risks are encountered when refuelling with landfill gas than with gasoline or diesel, because it can be carried out at small units in homes or business. Disadvantages are that it is costly to upgrade the biogas, reduced driving range for vehicles depending on specialty fuel and less cargo space due to biogas storage (Zhao et al., 2010).

3.4 Purification Technologies for purifying the LFGs

3.4.1 Water Scrubbing

Water is used for removal of CO_2 and H_2S from biogas because these gases are discovered to be more soluble in water than methane. The process is operated counter-currently because the gas is fed at high pressure at the bottom of the column and water enters at the top section of the unit (Zhao et al., 2010). Water scrubbing is used for the removal of H_2S, because it is found to be highly soluble in water than carbon dioxide. For instance; water scrubbing technology was used at the biogas plant in Appolonia, Ghana as a case study carried out by (Ofori-Boateng et al., 2009). The system was designed in a packed bed form for a feasibility study on the Appolonia biogas plant to remove about 92% of CO_2 present in the raw biogas. The system operates as follows; the water which is used for the removal of carbon dioxide and hydrogen sulphide is then regenerated and re-circulated back to the absorption column unit. In order, to achievethe desorption, the process is de-pressurised with air. The reason being that when high levels of hydrogen sulphide and carbon dioxide are stripped, the water becomes rapidly contaminated with sulphur which causes operational problems. When cheap water can be used, e.g. outlet water from a sewage treatment plant, the most cost efficient method is not to re-circulate the water (Zhao et al., 2010).

The table below shows a summary of feasibility study on water scrubber design for Appolonia biogas plant(Ofori-Boateng et al., 2009).

Table 3.1: Summary of feasibility study on water scrubber design

Design parameters	**Specifications**
Plant capacity (m^3)	300
Plant efficiency (%)	70
Biogas produced (m^3/day)	210
% of methane in biogas	55-65
% of methane in scrubbed gas	75-95
Calorific value of biogas	20MJ/m^3
Calorific value of scrubbed gas	28.7MJ/m^3
Total energy required per day	1082MJ
Total energy available from the biogas plant	4283.13MJ
Diameter of scrubber (mm)	300
Height of scrubber (mm)	9 800
Number of ideal stages	18
Pressure of biogas(kPa)	1000
Pressure of water used for scrubbing (kPa)	1 300

In this case study, three common methods of purifying biogas were compared economically. Cost benefit analysis on the design of the scrubbing units were carried out based on the size of the biogas plant at the Appolonia and accessibility of water. In regard to the design parameters provided in the feasibility study summary, the capital, annual operational and maintenance cost of water scrubber were compared to that of the chemical absorption and biological technologies of purifying biogas(Ofori-Boateng et al., 2009). The results were based on the design parameters compared with their corresponding price of the packed bed absorber on the international market and the Ghanaian manufacturers.

Table 3.2: Comparative cost analysis of three types of biogas purification methods (Ofori-Boateng et al., 2009)

Type of purification method	Cost of biogas purification unit, USD		
	Capital	Operational	Maintenance
Water Scrubbing	28 050	2 995	595
Chemical absorption	28 055	3 719	779
Biological method	22 251	3 277	648

Water scrubbing is considered the best when comparing it to chemical absorption. It is able to remove 93% v/v of carbon dioxide present in raw biogas while chemical absorption releases some dangerous gases into environment and contributing to greenhouse effect(Ofori-Boateng et al., 2009)

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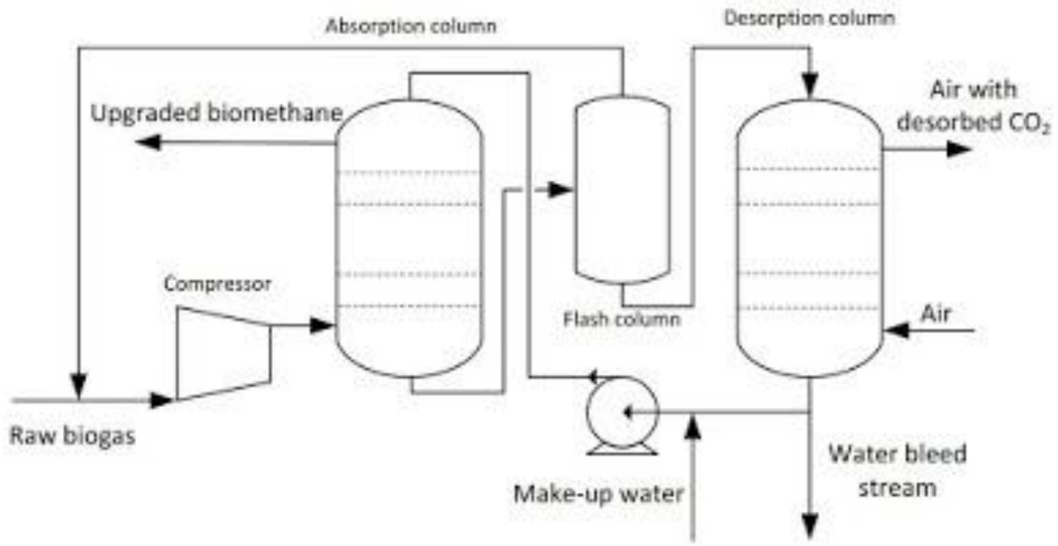

Figure 3.3: Flow chart of water scrubbing technology (Zhao et al., 2010).

On the contrary, water scrubbing requires much water besides its regeneration along the process, as well as limitations on H_2S removal, due to CO_2 reducing pH of the solution and corrosion to the equipment caused by H_2S. The cost of water scrubbing procedure is R 1.85/Nm^3 biogas (Zhao et al., 2010).

3.4.2 Biological Treatment

Biological treatment of landfill gas is done by oxidising H_2S by micro organisms of the species Thiobacillus and Sulfolobus. When these micro organisms produce oxygen, that oxygen reacts with H_2S and gets it desulphurized. This can take place inside the digester and can be facilitated by immobilizing the microorganisms occurring naturally in the digestate (Petersson et al., 2009). In the trickling filter the micro organisms grow on a packing material. Landfill gas meets a counter flow of water containing nutrients. The sulphur containing solution is removed and replaced when the pH drops below a certain stage. Unfortunately, landfill gas biological treatment is not found suitable if the gas is to be used as vehicle fuel or for grid injection because of the remaining traces of oxygen (Wellinger et al., 2009).

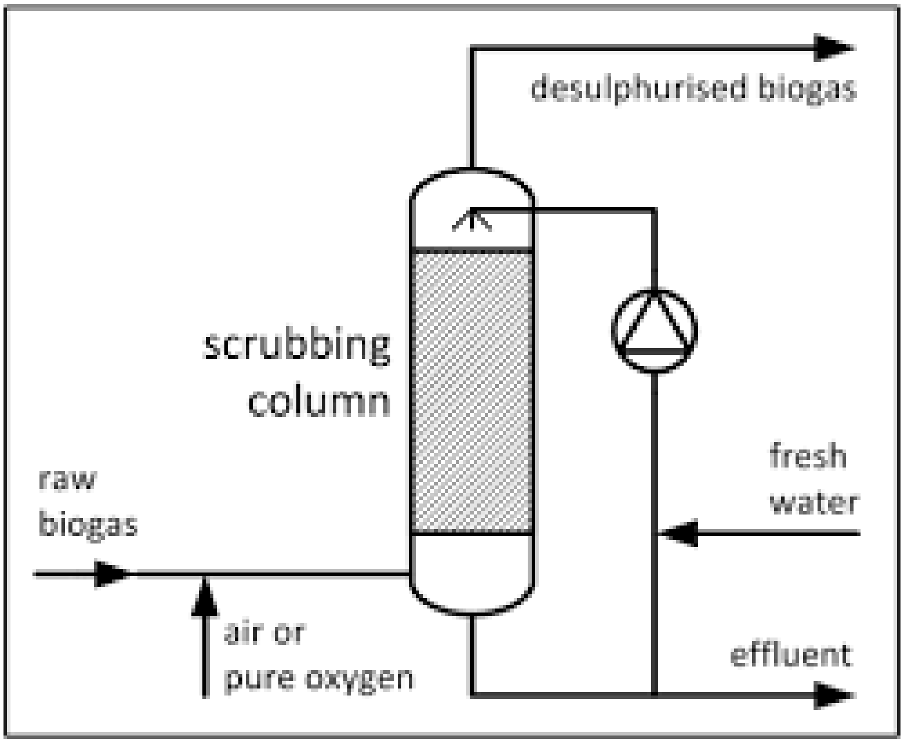

Figure 3.4: Flowchart of Biological treatment technology (Serfass et al., 2013)

3.4.3 Chemical Absorption

Zorn describes chemical absorption as follows; in chemical absorption solvents have to be regenerated at low pressure with the aid of steam, formed by heating the desorption column. He says by so doing results in high efficiencies of methane yield and calorific value (Zorn et al., 2005). Alkanol-amines and potassium carbonate solutions are groups of chemicals used inindustries for removal of CO_2 and H_2S from CH_4 (Medigo et al., 2014).Theyobserved that the recovery of both the compounds was close to 100%, leaving almost pure CH_4.Mono-ethanol-amine (MEA) is said to be the most feasible chemical absorbent (Zorn et al., 2014). It was again observed that MEA has high efficiency in removing CO_2, its costs are moderate at R2.42/Nm^3 biogas (Zhao et al., 2010).With low methane losses.On the contrary, usage of chemicals (MEA) in absorption can lead to high capital costs and additional measures such as corrosion inhibitors and foaming.Furthermore, MEA cannot remove water, halogenated hydrocarbons or ammonia from the process system (Zorn et al., 2014). Below is the flow chart of the chemical absorption process.

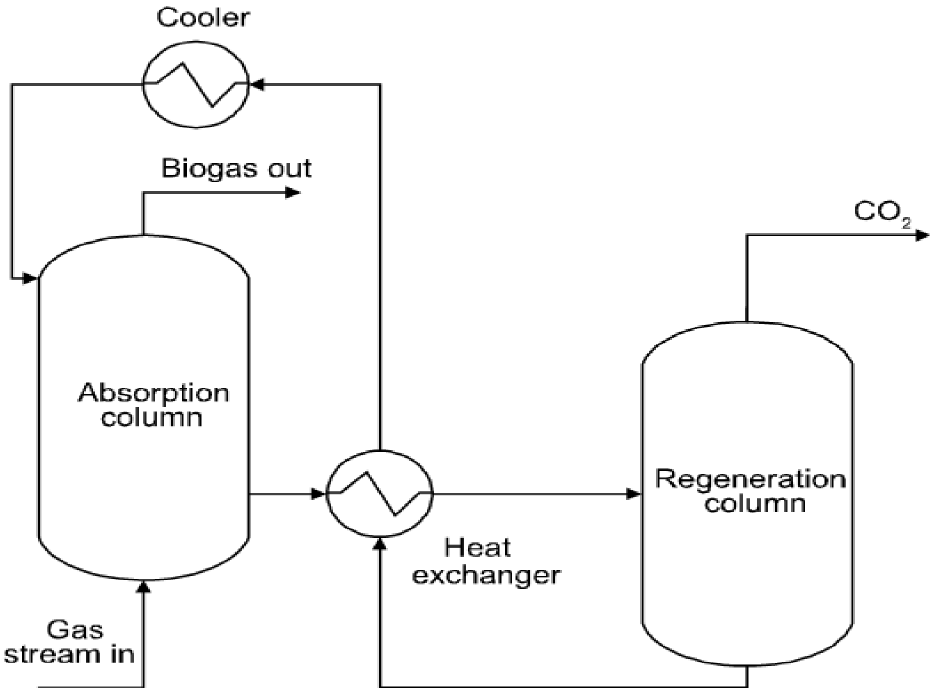

Figure 3.5: Flow chart of chemical absorption process (Zhao et al., 2010)

3.4.4 Pressure Swing Adsorption (PSA)

It is applied by separating some gas species from a mixture of gases under pressure in the presence of an adsorbent. The conditions for its operation are as follows; temperature is close to ambient and so varies from cryogenic distillation techniques of gas separation. Some adsorbents such as zeolites and active carbon can be applied as molecular sieves, adsorbing the desired gas species at high pressure. The desired gas can be released in the next unit by operating at low pressure (Zhao et al., 2010). Developed countries practice this type of biogas treatment. For instance, in Sweden there are about 55 biogas upgrading unit and 8 of them use PSA technology. When the biogas has been treated it is used as vehicle fuelor domestic gas for cooking (Bauer et al., 2013).

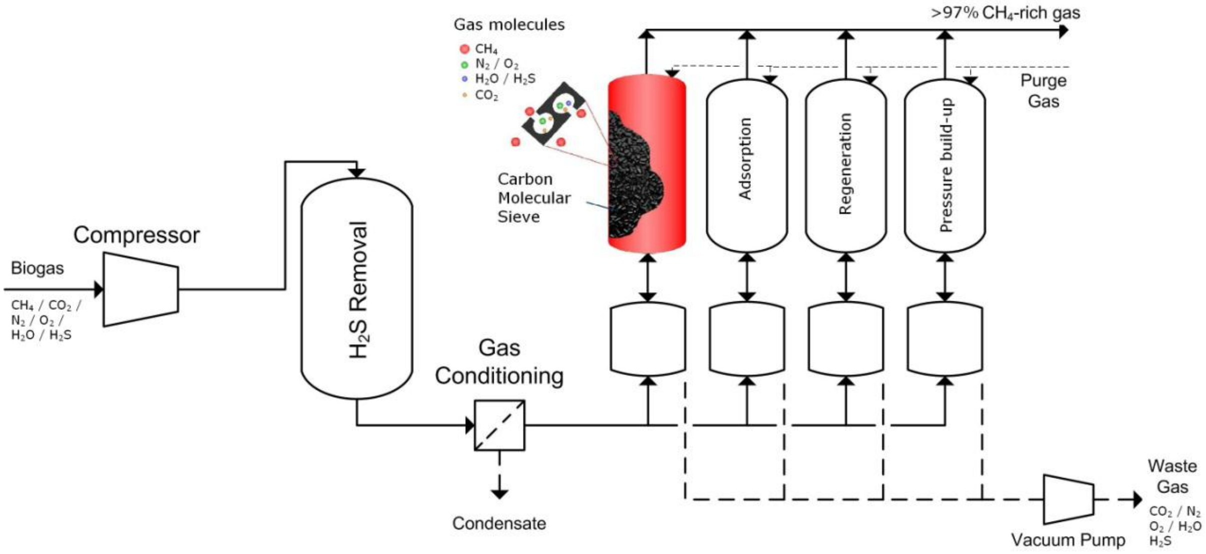

Figure 3.6: Pressure-swing adsorption schematic (Zhao et al., 2010)

The PSA process relies on the fact that under pressure, gases tend to be adsorbed. As pressure increases, more gas is attracted to the solid surface of the adsorbent, and when the pressure is decreased the gas is desorbed. The ability of PSA system is that gas separation in a mixture can happen due, to the fact that different gases favour adsorbent surfaces more or less strongly. For instance, if pressurised gas mixture passes through a column consisting of an adsorbent bed, that attracts nitrogen vigorously than it does oxygen, a portion or all of nitrogen gas will remain in the bed and the product stream of the column will have high percentage of oxygen (Zhao et al., 2010).

This method of PSA is efficient, when applying zeolites or activated carbon at different pressure for the separation of CO_2 from methane. Potassium iodide when added to activated carbon, it catalytically reacts with oxygen and H_2S forming sulphur and water. For successful occurrence of this reaction, the operational conditions must range from 7 to 8 bars and 50 to 70°C. In order, for the system to remain effective, activated carbon beds require replacement, when they reach saturation. The effectiveness of PSA method is that it retains 97% of methane in the mixture, the demand of energy is low and emissions are said to be low and there is the removal of nitrogen and oxygen. The shortfall of this process it is that an additional H_2S removal step is required before PSA because the adsorption of H_2S is normally irreversible in the adsorbents (Grande et al., 2013). PSA is highly expensive than some other processes because it requires more energy to produce high pressure. The cost of PSA is at least R 5.73/Nm^3 biogas (Zhao et al., 2010).

3.4.5 Membrane

Membranes were constructed with less selective membranes and a lower recovery demand for methane. In European market most applications require above 98% methane recovery.Except for countries like the Netherlands and Germany, where liquid gas grids exist with lower Wobbe index limitations (which is an indicator of the interchangeability of fuel gases) (Hulteberg et al., 2013).The most efficient membrane was constructed in Bruck, Austria in the year 2007 and the following years many more units with similar properties to the first one were built in Germany and France (Persson et al., 2013). They simply operate as follows; it separates gases, some components of raw gas go through a thin membrane while others are captured. The permeability of the membrane is directly proportional to chemical solubility of the desired component in the membrane. Solid membranes can be constructed as hollow fibre modules or other structures which give a large membrane surface per volume and thus very compact units. The system operational pressure range from 25-40 bars. The membrane separation principle develops a trade-off between high methane purity in the enriched gas and high methane production. The upgraded gas purity can be improved by broadening the surface area of membrane or adding more of the membrane modules. Although, more of the methane will penetrate through the membranes and be lost (Zhao et al., 2010).

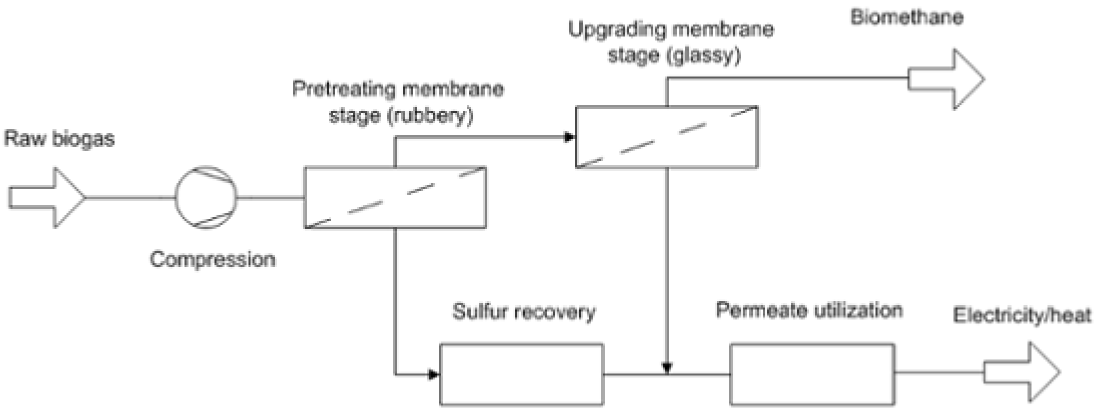

Figure 3.7: Flow chart of membrane biogas purificationprocess (Zhao et al., 2010)

There are two ways of membrane separation methods; high pressure gas separation and gas-liquid adsorption. The former method selectively separates H_2S and CO_2 from CH_4. The separation process occurs in three stages and 96% pure CH_4 is produced. The latter process is a newly created technique that uses micro-porous hydrophobic membranes as an interface between gas and liquids. CO_2 and H_2S are dissolved into the liquid while methane gets liberated and are collected for use. Membrane process is advantageous in that it is compact, light in weight, has low energy and maintenance requirements and easy processing. Low CH_4 and high membrane cost are shortfalls of membrane separation. The membrane method cost is found to be at least R1.71/Nm^3 biogas. Although it was discovered that membrane separation has lower cost in comparison to other methods discussed, its downfall is that the yield of gas is small and the gas purity is not satisfying because there are contaminants remaining, which leads to fouling of the membranes during the operation. Hence, the operating costs increase and impacts project economics (Zhao et al., 2010).

3.4.6 Cryogenic Separation

One of the research students Nina Johansson in Sweden discovered that cryogenic technology is based on differences in condensation temperature for various compounds. She found out that methane can be recovered from biogas impurities by chilling biogas. It turned out that this technology liquefies CO_2 making it a by-product, which can be used in other applications(Johansson et al., 2008).As result she observed that cryogenic process consumes between 0.8- 1.8kWh/Nm^{3}clean biogas to form LBG. The net energy required is influenced by disposal of waste heat and use of liquid CO_2 in external processes while CH_4 losses have a small influence (Johansson et al., 2008). She finally stated that formation of LBG is highly energy intensive than the production of compressed biogas but in some situations the product is more valuable since the biogas becomes available for more customers (Johansson et al., 2008).

Cryogenic process works as follows; this process involves purification of CH_4 at low temperatures, close to -100°C and pressures are high at 40 bars. The units used are in series and they consist of compressors, heat exchangers as shown in the Figure 15 (Zhao et al., 2010).

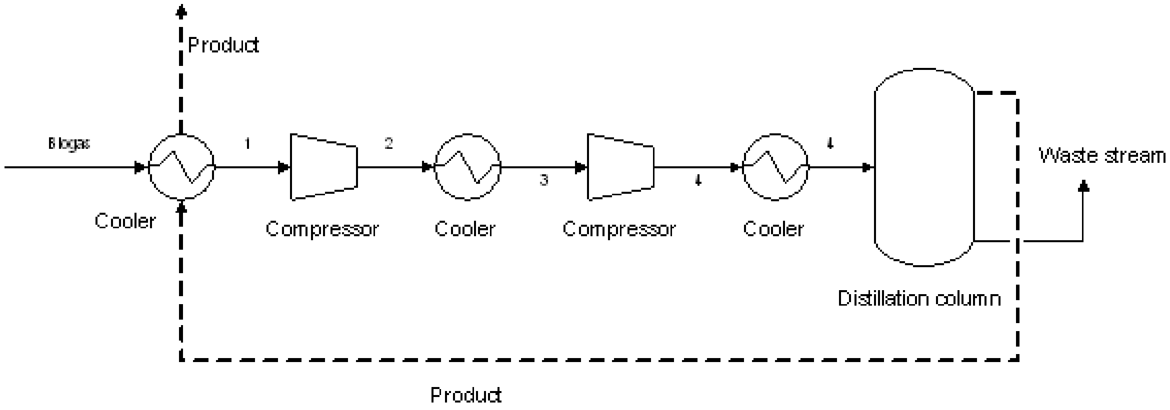

Figure 3.8: Schematic of cryogenic separation (Zhao et al., 2010)

In this process what happens is that crude biogas firstly enters heat exchanger in order to lower temperature of the gas to 70°C. The same unit is for preheating of pure biogas before exiting the plant. The heat exchanger is followed by compressors and heat exchangers which keep down the inlet gas at -100°C, under a pressure of 40 bars before its entrance to the distillation column. In the distillation column methane is separated from the contaminants, such as H_2S and CO_2 (Zhao et al., 2010).

It is suggested that 99% of CH_4 can be obtained from this process, including huge amount of by-products that can be processed further. In addition to that cryogenic technology does not require any water or absorbent to operate, but it needs cooling equipment such as a refrigeration cycle or liquid nitrogen (Jonsson et al., 2011). The disadvantage of cryogenic separation is that the units used for separation increase capital and operating costs, in comparison to other technologies. The final price of upgraded biogas is R6.23/Nm^3 biogas (Zhao et al., 2010).

3.4.7 Methods for siloxane (VOC's) removal from biogas

3.4.7.1 Why are siloxanes a problem?

Siloxanes are volatile compounds that evaporate together with landfill gases to be combusted inside internal combustion equipment (Xebec et al., 2007). During their combustion a crystalline substance forms on the surfaces of the heads of the engine pistons due to the burning of siloxanes. When this occurrs continuously this white coating becomes a thick, hard, abrasive layer that covers the interior surfaces, preventing proper heat transfer in the gas engine (Xebec et al., 2007).This can severely affect the maintenance intervals of the internal combustion equipment. There will be much more downtime and several more parts to replace (Xebec et al., 2007).

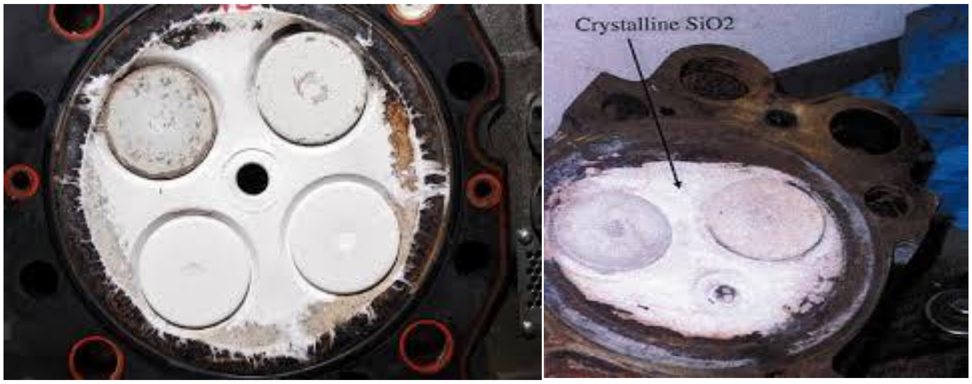

Figure 3.9: Silica build-up on heads and scrapped pistons of Caterpillar and Jenbancher engines

3.4.7.2 Solid adsorption (activated carbon, zeolites, molecular sieves, silica gel etc.)

Solid adsorption can be done both at the laboratory and full (industrial) scale. The efficiency of this method is found to range from 90-99% and the running costs are moderate. Solid adsorption systemhavehigh adsorption capacity, degree of regeneration is said to be high, usage of multiple columns connected in parallel can increase the performance of this system, biogas can be dried and operating costs are found to be low-medium costs (Soreanu et al., 2011).

On the contrary, significant quantity of adsorbent are lost along the process during its regeneration; a minimum of two units could be used, the reason being that when one is in usethe second one undergoes regeneration. There is a high risk of pressure drop and activatedcarbon is not suitable for humid gases (Beland et al., 2011). Experiments were carried out at two landfill sites, Calabasas and Waukesha, on the application of solid adsorption forsiloxanes removal. It was discovered that when siloxane concentration is low in the landfill gas the cost of removal is acceptable, but then the costs tend to be excessive when high siloxane concentration is being treated (Pierce et al., 2009).

Table 3.3: shows how concentration of siloxane affects the solid costs of adsorption process at the landfill sites (Pierce et al., 2009)

Parameters	Calabasas landfill site	Waukesha landfill site
Concentration, mg/m^3	2	34
Carbon Cost, cents/kWh	0.3	1.5

3.4.7.3Liquid absorption (methanol, selexol, etc.)

Liquid absorption can be done on a full scale, the removal efficiency of this process is from 97-99% and the efficiency increases by contact phase between the liquid and the gas. Although, the estimated operating cost is high, the solvent for the functioning of this process is highly toxic, the energy needed for regeneration (heating or distillation) is very high and the solvents are highly flammable (Falletta et al., 2011). The Mountain Gate landfill in California uses liquid absorption for removal of siloxanesand it is said to remove about 99% of siloxanes from the landfill gas (Wheless et al., 2009). In this process selexol is used as an absorbent, it is continuously regenerated and the flow pattern in the absorber is counter current (Pierce et al., 2009).

3.4.7.4Degradation (sulphuric acid 97%)

The constraints of this method are that it can be done at the laboratory scale, it is corrosive because 97% of sulphuric acid concentration is used, it is not easy to regenerate the solvent and hazardous to handle and transport. In addition, the efficiency of this method at room temperature is 56-70% but at 60 °C the removal ofsiloxane ranges from 95-99%. The costs of operation are medium in comparison to the liquid absorption (Soreanu et al., 2011).

3.4.7.5 Refrigeration/ Condensation

Refrigeration is simple to use, the reagent for this method is low as well as being non-toxic, it can be used as a drying agent for biogas and it does not require media for disposal. But itsoperating costs is highly expensive because of the amount of energy needed to reach temperatures below 0°C, per $m^3.h^{-1}$ of treated gas. The efficiency of this method happens to be 15-50% at 35-40°F and 95% at -20°F (Edmonson et al., 2011).

3.4.7.6Biotrickling filtration

The estimated operating cost ($\$/m^3.h^{-1}$) treated gas is low. Furthermore, the method is simple, economical and regenerative. But the efficiency is very low, from 10-20% and 10-43%, when regeneration occurs loss of material is encountered, fouling within the process unit is high and there is also high risk of pressure drop (Al-Jamal et al., 2011).

3.4.7.7 Membrane

The risks of using membrane are that pressure drop along the system is very high; membrane can be destroyed by chemicals, rapid variation in pH, excess pressure and fouling of the membrane. Besides all of the above mentioned short falls, membrane is simple to use, its large surface area facilitates its efficiency (Beland et al., 2011).

3.5 Choice of process plant route and chemical selection for removal of H_2S, CO_2 and siloxane and equipment list (Conclusion)

The above technologies of removal of H_2S, CO_2 and siloxane from methane, have their advantages and disadvantages. Therefore, when developing a process route, economic and environmental impacts are considered in this scenario. The reason why environment must be taken into consideration when designing the system is because the pollutants that are eliminated from biogas during its development are discharged into the atmosphere (Zhao et al., 2010), the contamination of the environment will run in parallel to the objective of creating an environmentally-friendly fuel to replace non-renewable fuels.

Of all the five technologies for removal of H_2S and CO_2 discussed above. High pressure water scrubbing is the one that seems not to emit CO_2 and H_2S to the atmosphere, the reason being that, they get absorbed in the stripper during the gas phase, so that the purge stream does not have to be treated (Zhao et al., 2010). Whereas, in the rest of technologies the purge streams must further be treated, so that these toxic gases do not get discharged into the environment. Although, chemical absorption needs further treatment, the system of treatment will be suitable for removal of CO_2 and H_2S because these two gases are by-products of the process. They can be stored and utilised in other industries. For instance, CO_2 can be further treated and used in food industries while H_2S can be in contact process. Besides the environmental issue, economically chemical absorption is said to have low cost per Nm^3 of biogas produced. Water scrubbing is lower than chemical absorption, when it comes to cost of biogas per Nm^3 but it is again expensive because of high consumption of water which increases utility costs (Zhao et al., 2010). That is why chemical absorption is preferred in this project for removal of CO_2 and H_2S. As for the rest of the technologies, theyare quite expensive, cryogenic separations taking the lead.

On the other hand siloxanes are supposed to be removed from methane because if not removed, they harm the combustion units of LFGTE process. There are about six processes or technologies that can be used for the removal of siloxanes. According to the above discussed technologies solid adsorption will be the best alternative. The reason being that 90-99% of siloxanes can be removed and the adsorbent can be created from cheap and available material such as activated ashes of wood, banana peels, carbon etc. These results in having low-medium operating costs. In addition, it is a simple system, the adsorbent is highly regenerated and the adsorption capacity is high. It is environmentally-friendly because there are no toxic gases emitted to the atmosphere, when removing siloxanes except for methane which is utilized for electricity.Although carbon adsorption can be expensive to operate especially when the concentration of siloxane is high (Wheless et al., 2009). The case will be different when treating Bellville landfill site gases; siloxane concentration is quite low in (ppm). Therefore, the operating costs of carbon adsorption would be low when applied at Bellville landfill site.

To add up to this information below is a table which the relative adsorption rate of siloxanes (VOC's)

Table 3.4: Relative Adsorption Rate (Sherpherd et al., 2001)

VOC's	Molecular weight (g/mol)	Boiling Point (°C)	Carbon Capacity %
Nitrobenzene	123	211	51
Tetra-chloroethane	166	147	50
Tetra-chloroethylene	165	121	35
Styrene	104	145	25
Xylene	106	138	21
Napathylene	128	217	20
Toluene	92	111	20
Benzene	78	80	12
MTBE	88	55	12
Hexane	86	68	7
Ethyl acrilate	100	57	5
Dichloro ethane	99	99	7
Methyl ethyl ketone	72	80	4
Methylenechloride	84	40	2
Acrylonitrile	53	74	2
Acetone	58	56	0.8
Vinylchloride	62	-14	0.7
Chloro ethane	64	12	0.5
Bromotrifloromethane	149	-58	0.13
Methane	16	-161	0.0003

Chemical compounds with a molecular weight of over 50 and a boiling point which is above 50 degrees Celsius are perfect candidates for adsorption (Sherpherd et al., 2001). Table 3.4 contains of list of organic compounds and their relative adsorption strength (Sherpherd et al., 2001). The manner in which organic adsorption is rated is weak, moderate and strong. For instance, nitrobenzene because it has a molecular weight of 123 and a boiling point of 211°C is said to be a very strong adsorber (Sherpherd et al., 2001). On the contrary, methane as demonstrated on the table appears to be the last compound and classified as a weak adsorber, because of its molecular weight of 16 and a boiling point of -161°C (Sherpherd et al., 2001). This is why the LFGTE process plant will have an adsorption system because of its ability of capturing less percentage (0.0003%) (Sherpherd et al., 2001) of methane to the rest of other VOC's. Therefore the rest of methane will be passed to the next stage of its conversion to electricity.

3.6 Sample of landfill gas constitutes at Bellville landfill site

- Methane
- Carbon dioxide
- Oxygen
- Hydrogen sulphides
- VOC's: Benzene
  Toluene
  Mercaptans
  Xylene
  Aldehydes
  Ketones
  Ethers
  Aliphatic Fatty acids and Volatile Fatty Acids

3.7 Equipment List

According to the feasibilty study of this project is successful. The equipment that is going to be used for this task will be listed. The listed equipment and the process flow are adopted from literature, published articles and from existing technologies. The following equipment list has been compiled from researching of possible process flow diagrams for LFGTE process plant. It is also essential to be aware that some equipment was included to the process.

Equipment List

1. Two storage tank for (solvents)
2. Combustion Engine
3. Two Heat exchanger
4. Dehumidifier
5. Two Compressor
6. Absorber column

7. Stripper
8. Two adsorption units
9. Pump
10. Flush Drum
11. Furnace
12. Water tank
13. Air Cooler
14. Filter

3.8 Process Route of landfill gas to energy plant

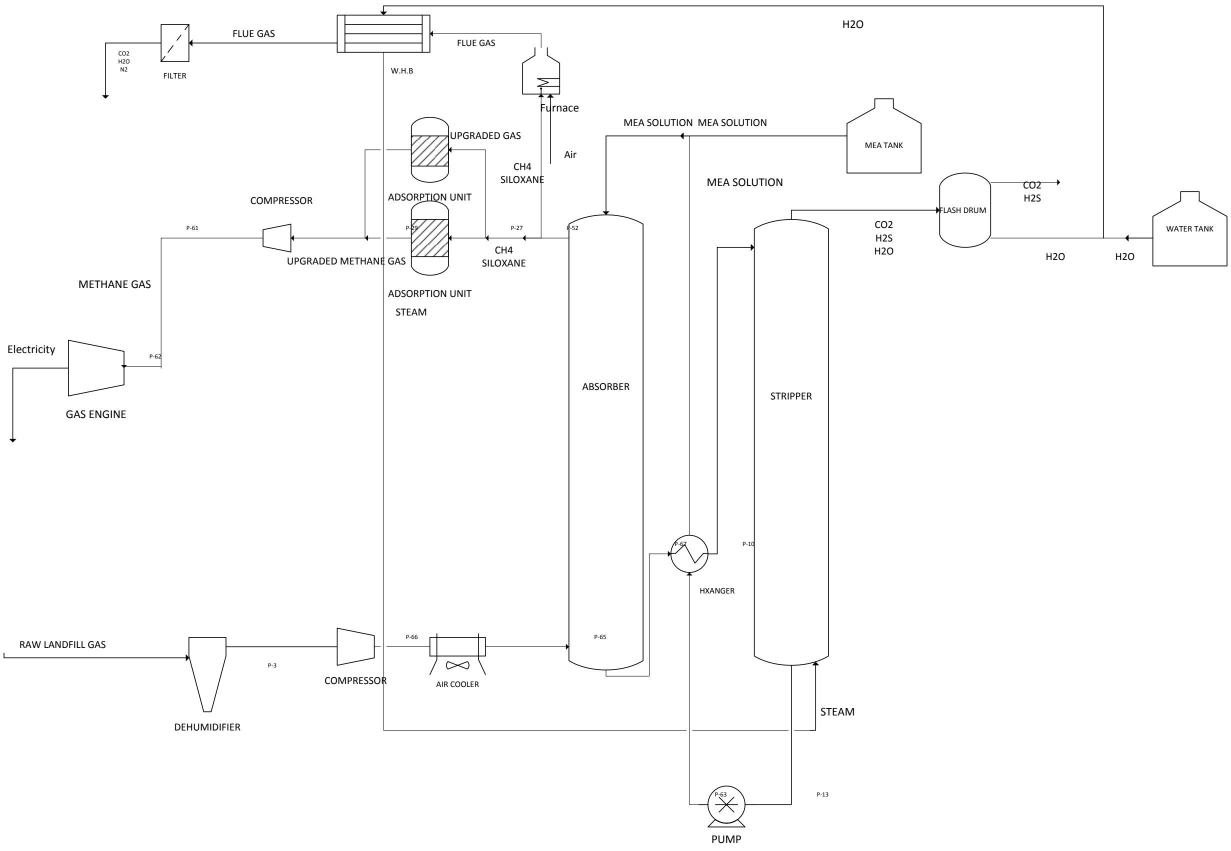

Figure 3.10: Process Route of landfill gas to energy plant

Process Description of landfill-gas-to-energy plant

After discussing the various technologies for removal of H_2S, CO_2 and siloxane. Figure 3.10 was developed based on the economic and environmental factors that are supposed to be evaluated when designing a process plant. At the landfill site there would be wells to channel the landfill gas to the energy plant (LFGTE). The first unit is the dehumidifier, which separates the water from the landfill gas. The landfill gas exits at the dehumidifier outlet into a compressor and then to an air cooler. In the compressor the gas is pressurized raising its temperature, the MEA solution from the absorber cools the gas down in a heat exchanger in order, to prepare it for absorption. The operating conditions of the absorber are at 1.7MPa and temperature ranges from 32 to 38 °C. The reason for these operating conditions is to enable CO_2 and H_2S to dissolve in the MEA solution. 10% of upgraded gas is liberated and lead to the furnace. In the furnace it is combusted, forming flue gases which are used for producing steam. This steam is used as a stripping agent.

The rest of methane and VOC's is taken into an adsorption system whereby activated carbon is used as an adsorbent and the operational conditions of both the adsorption units range from 7 to 8 bars and 50 to 70 °C. There is only one adsorption unit working at a time (the adsorption units are connected in parallel for standby purposes). When one reaches saturation the control system switches it off and put the parallel unit on. The purpose of having these units is for the removal of siloxane from the methane gas, to facilitate a good combustion process and ensure the proper engine functioning. About 97% of the gas leaving the adsorption system is methane;the compressor maintains high pressure of methane gas because in the adsorber, there is high pressure drop.

After the compression of the gas, it is sent to an engine which is connected to a generator to convert the gas into electricity at 461°C and 87.46 psia. In the stripper CO_2 and H_2S gases are separated from MEA solution. The operating conditions of the stripper are as follows 107 to 112 °C and 2-4 bars. The purpose of operating under such conditions is to facilitate CO_2 and H_2S removal from MEA solution. The MEA solution is recycled back to the absorber and gets mixed with the fresh one from the storage tank, after CO_2 and H_2S have been released from the stripper. The purpose of this is to strengthen the weak MEA solution from stripper. On its way back to the absorber the MEA solution temperature is reduced to 38 °C in a heat exchanger so that, it can be used for absorption of the toxic gases except for methane gas and VOC's.

The H_2S, CO_2 and water are separated in a flush drum. In the flush drum the methane and H_2S are then, compressed and stored for other industrial purposes. The water coming out of the flush drum bottom is mixed with fresh water from the water tank and gets heated in the heat exchanger by the flue gases which are produced in a furnace, for combusting the methane. The ashes from the flue gas are filtered after heating the water up and from there air (CO_2, O_2 and N_2) is released into the atmosphere. On the other hand, in the USA process designers prefer the following route, which occurs to be slightly different to the one explained in this passage, depending on the composition of landfill gas. Landfill goes into the dehumidification, particulate filtration and compression and hydrogen sulphide removal using adsorption beds, biological scrubbers and other available technologies after the dehumidification step (U. S. EPA et al., 2014). Methane can be combusted by internal combustion engines or gas turbine can be applied for conversion of methane to electricity (U. S. EPA et al., 2014).

3.9 Discussion

It is important to expect changes as the design is in progress. Technological changes and improvements, due to the economics and environmental factors which may lead to equipment being added and removed from the flow diagram. The following chapter will show the amount of landfill gas estimation for 2013 and 2014 and the material and energy balance around the major units.

CHAPTER 4

4. Introduction

This chapter involves the estimation of mass and energy balances around major equipment that are going to be used for treatment of landfill gas.In chapter two it was concluded that IPCC model will be used to estimate landfill gas emissions.

4.1Landfill gas emissions estimation using IPCC model:

The equations for estimating the CH_4 generation are given below using IPCC model. As the methods are the same for estimating the CH_4 emissions from all waste categories, no indexing referring to the different categories are used in the equations.

Methane potential that is produced throughout the years can be determined on the basis of the amounts and composition of the waste deposited into SWDS and the waste management practices at the disposal sites. The reason for calculation is to get, the amount of Decomposable Degradable Organic Carbon ($DDOC_m$) as described by the equation. $DDOC_m$ is the organic carbon that degrades under the anaerobic conditions in SWDS. It is applied in the equations and spreadsheet models. The subscript m stands for mass and another thing is that $DDOC_m$ is equivalent to the product of the waste amount (W), the fraction of degradable organic carbon in the waste (DOC), the fraction of the degradable organic carbon that decomposes under anaerobic conditions (DOC_f) and the part of the waste that will decompose under aerobic conditions (prior to the conditions becoming anaerobic) in the SWDS, which is interpreted with the methane correction factor (MCF) (Oonk et al., 2010).

Decomposable DOC from waste disposal data

$$DDOC_m = W.DOC.DOC_f.MCF$$

Where:

$DDOC_m$= mass of decomposable DOC deposited, Gg

W = mass of waste deposited, Gg

DOC = degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste

DOC_f = fraction of DOC that can decompose

MCF= methane correction factor for aerobic decomposition in the year of decomposition fr. It is 1 for Bellville landfill site because it is considered to be well managed, according to the city of Cape Town municipality.

CH_4 generated from decomposable $DDOC_m$

The amount of CH_4 formed from decomposable material is found by multiplying the CH_4 fraction in generated landfill gas and the CH_4/C molecular weight ratio.

CH_4 generated from decayed $DDOC_m$ as given by Park et al (2011) is

$$CH_4 generated_T = DDOCm\ decomp_T . F . 16/12$$

Where:

$CH_4 generated_T$ =Amount of CH_4 generated from decomposable material

$DDOCm\ decomp_T$= $DDOC_m$ decomposed in year T, Gg

F =fraction of CH_4, by volume in generated landfill gas (fraction)

$16/12$ =Molecular weight ratio CH_4/C (ratio)

<u>The amount of methane calculated in 2013 and 2014</u>:

These are the amounts of landfill gas emitted from Bellville landfill sites in 2013 and 2014

<u>48 447m^3/year for 2013</u> or 132m^3CH_4/ton MSW in a day

<u>And</u>

<u>49 416m^3/year for 2014</u> or 135m^3CH_4/ton MSW in a day

The rest of the calculations are done in Appendix B

In a landfill site, Mare Chicose in Mauritius, methane emissions were estimated using similar IPCC model, usedfor determining the Bellville landfill site emissions. The amount of methane emissions in Mare Chicose were found to be 119.8m^3 CH_4/ton MSW (Surroop et al., 2011) while the Bellville landfill site emissions were found to be 132m^3 CH_4/ton MSW. Thisbecause Mare Chicose has up to 40% putrescible wastes (Mohee et al., 2006) while Bellvile has 46% (CCT et al., 2014). Mare Chicoselandfill site is twenty hectares (Surroop et al., 2011) while Bellville landfill site is sixty hectares (C.C.T et al., 2014).In addition, the literature states that the amount of methane that is produced varies significantly based on composition of the waste. It also states that most of the methane produced in MSW landfills is derived from food waste, composite paper and corrugated cardboard percentages (Palananthakumar et al., 1999). It turned out that for Bellville the percentages of these composites are quite high when compared them to that of Mare Chicose, which is why methane emissions are higher than that of Mare Chicose.

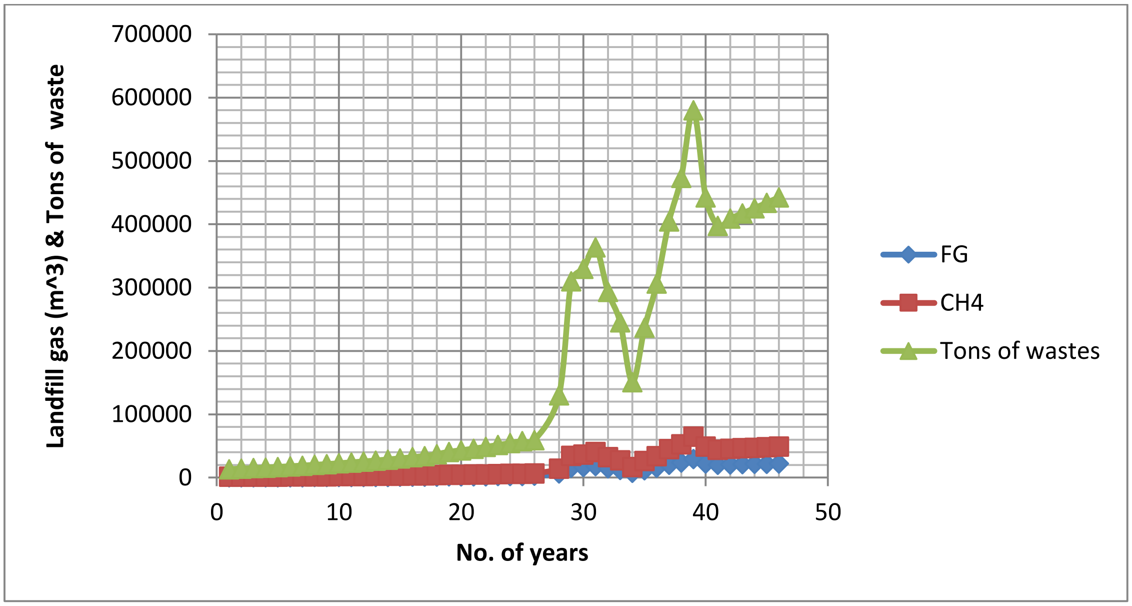

Figure 4.1: Landfill gas rates from Bellville landfill site since it was established

The IPCC model was used to determine the datainFigure4.1. The figure simply proves that landfill gas is produced at Bellville landfill site. The gas has two categories which are methane and fugitive gases. Fugitive gases are those gases that escape utilization while methane gas, in this case is determined as a gas to be utilized after accounting for fugitive gases. Hence, the landfill gas to energy process plant can be established at the site according to what is portrayed by the figure. The figure shows that landfill gas production increases, with time as the increasedamount of waste is deposited at the site. One of the reasons why the amount of waste increased over these years is because of rapid urbanisation and industrialisation. This isshownin Appendix B which gives the amount of tonnages from 1970 to 2014. The amount of gas produced is directly proportional to the amount of wastes deposited at the landfill site as shown in figure 4.1. For instance, the peaks on the graph indicate highest amount of gas produced in the past years, which corresponds to the highest amount of tonnages that were deposited at the site.

Material and Energy Balances

4.2 Introduction on material and energy balance around the major units

Material and energy balances are fundamentals for process design. The material balance determines the amount of raw material to supply to the system and products. Individual material balances will be performed around each units, the stream flow composition offers knowledge of equipment sizing and material of construction. The physical and chemical state of any stream helps to develop plant safety tips to prevent loss of life or equipment (Towler&Sinnot et al., 2008). The material and energy balance will be performed in this chapter, the material and energy requirements are needed in order to size the units and each material and energy balance is presented in S.I units.

4.2.1 Compressor Material and Energy balance

The objective of compressing the landfill gas is to make it ready for being absorbed in the absorber column. The compressor is operating at 1.7MPa and 256°C. There is no reaction occurring in a compressor. Therefore,

$$\sum_{inputs} F_i = \sum_{outputs} F_o$$

Figure 4.2: Compressor

According to the calculations that were performed using the models, IPCC model showed that 48 447.5m^3/year of landfill gas was generated in 2013 which translates to5.52m^3/hr gas produced while in 2014.IPCC model suggested that 49 416m^3/year of landfill gas was produced, which is 5.63m^3/hr of landfill gas generated from the site. The value that was calculated for 2013 with the IPCC model will be the one used to size or design the entire landfill gas to energy plant because data on wastes deposited in that year for each and every month was available.IPCCmodel is said to be the most suitable for estimating the amount of landfill gas emissions, no matter where the place is situated (U.S.EPA et al., 2010). 5.63m^3/hr is the amount of feed into the LFGTE process plant.

Table 4.1: The landfill gas composition from Bellville landfill site(C.C.T et al., 2014)

Gas components	Composition	Flow rate (0.226kmol/hr) in total
CH_4	0.45	0.101
O_2	0.10	0.0226
CO_2	0.35	0.0792
N_2	0.04	0.0091
H_2S	0.06	0.0136
VOCs	3.52 (v/v)	-

Energy Balances

To evaluate the energy balance around the compressor unit, the heat of reaction method will be used.

The reference states of landfill gas components are at 25^{0}C and 1atm and at the outlet of a compressor they are at 1.7MPa and 32-38 °C.

$$\dot{Q} - \dot{W}_S = \Delta\dot{H} + \Delta\dot{E}_K + \Delta\dot{E}_P$$

We can simplify the equation by making the following assumptions

- No shaft work is done.
- No reaction takes place.
- Insignificant changes in potential and kinetic energy.

$$\sum Q = \dot{m} \times c_p \times \Delta T$$

$$
\begin{aligned}
\sum Q = \Bigg(&\left(\frac{101mol}{hr}\times\frac{1}{3600s}\times\frac{0.0358kJ}{mol}.K\times 13K\right)\\
&+\left(\frac{22.6mol}{hr}\times\frac{1}{3600s}\times\frac{0.0294kJ}{mol}.K\times 13K\right)\\
&+\left(\frac{79.2mol}{hr}\times\frac{1}{3600s}\times\frac{0.0374kJ}{mol}.K+13K\right)\\
&+\left(\frac{9.1mol}{hr}\times\frac{1}{3600s}\times\frac{0.0292kJ}{mol}.K\times 13K\right)\\
&+\left(\frac{13.6mol}{hr}\times\frac{1}{3600s}\times\frac{0.0346kJ}{mol}.K\times 13K\right)\Bigg)
\end{aligned}
$$

$$\sum Q = 28.8\times 10^{-3}kW$$

$$\sum Q = 28.81W$$

4.2.2 Absorber-Stripper system Material and Energy balance

The absorber is used to absorb carbon dioxide and hydrogen sulphide using MEA as solvent at temperature around 32-38^{0}C. The carbon dioxide and hydrogen sulphidehasan affinity for MEA and enabling carbon dioxide from the landfill gas to get absorbed into the liquid stream, (Sherrick et al., 2009). The outlet streams from the absorber are $CO_2$and H_2S-lean landfill gas and $CO_2$and H_2S-rich MEA. The $CO_2$and H_2S-lean landfill gas with at least 90% of the CO_2 and H_2S removed is then vented to the adsorption system altogether with CH_4 and VOC's after possible additional treatment with water to remove any MEA that might have escaped in the absorber.

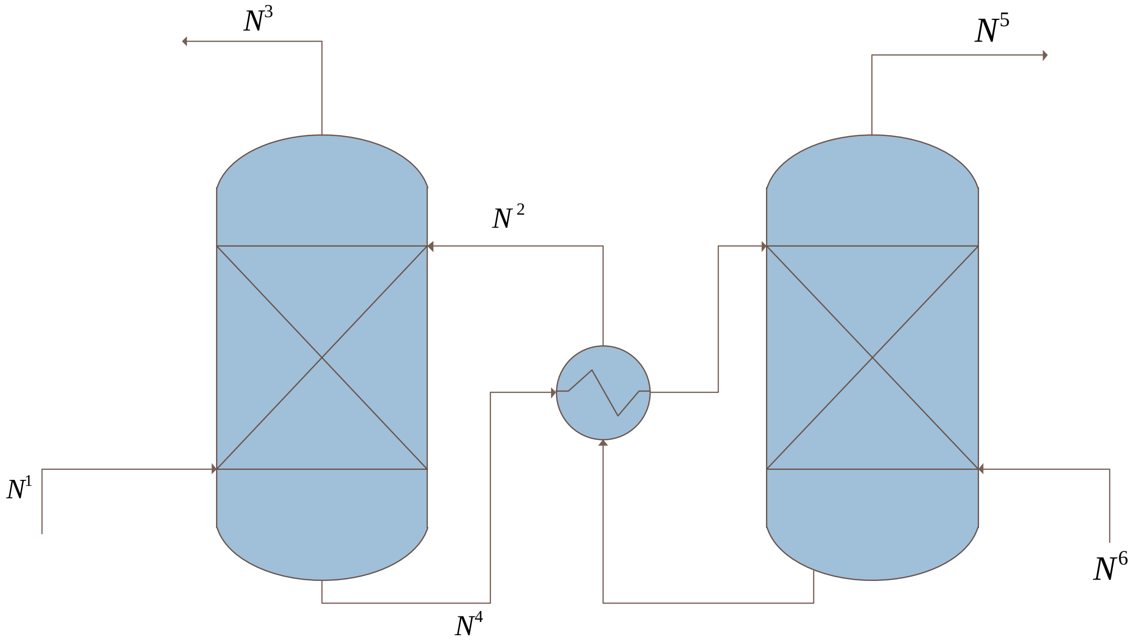

Figure 4.3: Absorber and stripper units

<u>Chemistry of the MEA system</u>:

When MEA reacts with CO_2 in liquid phase, it solubilizes in a carbamate, carbonator or bicarbonate form. The following reversible reactions occur in the MEA system.

$2H_2O \leftrightarrow H_3O^+ + OH^-$ …………………………… (4-3)

$CO_2 + 2H_2O \leftrightarrow HCO_3^- + H_3O^+$…………………….. (4-4)

$MEA + HCO_3^- \leftrightarrow MEACOO^- + H_2O$……………… (4-5)

$MEA + H_3O^+ \leftrightarrow MEA^+ + H_2O$…………………….. (4-6)

$HCO_3^- + H_2O \leftrightarrow CO_3^{2-} + H_3O^+$…………………… (4-7)

The equilibrium constants for the reaction are temperature dependent and follow the dependence given in (4-8)

$$InK_x = A + \frac{B}{T} + CInT + DT$$

In this case, T is the temperature in °K. The constants A, B, C, D for the different reactions are presented in Table 4.2 and are referenced from Augsten's work.

Table 4.2: Values of temperature dependent parameters for equilibrium constant in MEA system:

Reaction	A	B	C	D
(4-3)	132.89	-13445.9	-22.47	0
(4-4)	231.46	-12092.1	-36.78	0
(4-5)	-0.52	-2545.53	0	0
(4-6)	-3.038	-7008.3	0	-0.00313
(4-7)	216.05	-12431.7	-35.48	0

Material Balance

Determining the total mass of solvent:

The loading rate of landfill gas should be 0.25-0.35mol CO_2/mol of solvent

We know that the flow rate of carbon dioxide is 0.0792kmol/h=3.485kg/h

We take loading rate as 0,3

H_2S loading rate should be 0.06mol H_2S/mol of solvent

We take loading rate as 0,06

The flow rate of hydrogen sulphide is 0.0136kmol/h=0.462kg/h

$$\frac{n_{CO_2}}{n_{MEA}} = 0.3 \Leftrightarrow n_{MEA} = \frac{n_{CO_2}}{0.3} \Leftrightarrow n_{MEA} = \frac{0.0792}{0.3} = 0.264 kmol/h$$

$$\frac{n_{H_2S}}{n_{MEA}} = 0.06 \Leftrightarrow n_{MEA} = \frac{n_{H_2S}}{0.06} \rightarrow n_{MEA} = \frac{0.0136}{0.06} = 0.227 kmol/h$$

The mass flow rate of MEA will then be: $m = (0.264 kmol/h + 0.227 kmol/h) \times (61 kg/kmol) = 29.93 kg/h$

According to (Kothandaraman et al., 2010); the solvent solution is made of 30% MEA and 70% water.

Mass of water= $\frac{0.7}{0.3} \times 29.93 kg/h$=69.84kg/h

Mass of solution=mass MEA+ mass Water

Mass of solution=29.93+69.84= 99.77kg/h

Carbon dioxide balance:

Let's assume that 0.1% of carbon dioxide escape to the atmosphere

Thus $N^3{}_{CO_2} \rightarrow 0.1\% N^1{}_{CO_2} = 0.001 \times 0.0792 = 0.0000792 kmol/h$

$$M^3{}_{CO_2} = 0.00348 kg/h$$

$$N^1{}_{CO_2} + N^2{}_{CO_2} \rightarrow N^3{}_{CO_2} + N^4{}_{CO_2}$$

$$0.0792 + 0 \rightarrow 0.0000792 + N^4{}_{CO_2}$$

$$N^4{}_{CO_2} = 0.0792 - 0.0000792 = 0.0791 kmol/h$$

We assume that 100% recovery in the absorber, thus $N^5{}_{CO_2} = 99\% N^4{}_{CO_2}$

$N^5{}_{CO_2} = N^4{}_{CO_2} = 0.0791 kmol/h$

$M^5{}_{co_2} = 3.481 kg/h$

Hydrogen Sulphide balance

Again let's assume that 0.1% of hydrogen sulphide escape to the atmosphere

Thus $N^3{}_{H2S} \rightarrow 0.1\% N^1{}_{H2S} = 0.001 \times 0.0136 = 0.0000136 kmol/h$

$N^3{}_{H2S} = 0.0004624 kg/h$

$N^1{}_{H_2S} + N^2{}_{H_2S} \rightarrow N^3{}_{H_2S} + N^4{}_{H_2S}$

$0.0136 + 0 \rightarrow 0.0000136 + N^4{}_{H_2S}$

$N^4{}_{H_2S} = 0.0136 - 0.0000136 = 0.0135 kmol/h$

We assume that 99% recovery in the absorber, thus $N^5{}_{H_2S} = 100\% N^4{}_{H_2S}$

$N^5{}_{H_2S} = N^4{}_{H_2S} = 0.0135 kmol/h \times 34 kg/kmol$

$M^5{}_{H_2S} = 0.462 kg/h$

Methane balance

The composition of Bellville landfill site contains about45% of methane. Assume none of methane gas is going to get absorbed by MEA. Therefore, the amount of methane that entered the absorber is the same amount that will get liberated and get into the adsorption system, together with the VOC's.

NB: **3.62kg/h** is the amount of feed to the LFGTE process plant from the landfill site.

3.947kg/h= flow rate of carbon dioxide and hydrogen sulphide.

Therefore, to get the flow rate of N^3which has 2% of CO_2 and H_2S in total? We assume that 1% of methane is absorbed by MEA solution and the rest is to be combusted by gas engine. Thus:

F^1= 1.01kmol/h×16kg/kmol= 16.16kg/h

F^4= 1.616kg/h×0.01= 0.01616kg/h

F^1-F^4 =F^3

F^3=16.16kg/h- 0.01616kg/h=15.998kg/h

$F^3_{CH_4}$ =16.0kg/h

Nitrogen balance

Nitrogen it is also not absorbed in the absorption unit. Therefore, the composition that entered the absorber is the same as that liberated at the top of the absorber system. That is 4% according to the Bellville landfill site data analysis.

$$N^3_{N_2} = 0.04 \times 0.226kmol/h = 0.0091kmol/h$$

$M^3_{N_2}$=0.255kg/h

Oxygen balance

The landfill gas contains 10% of oxygen, which is also not absorbed by MEA. It leaves by stream 3.

$$N^3_{O_2} = 0.10 \times 0.226kmol/h$$

$$N^3_{O_2} = 0.0226kmol/h$$

Energy Balance around the absorber-stripper

The equation below will enable us to get the change in enthalpy for each stream:

Change of enthalpy with reaction:

$$\Delta H = \sum r\Delta H_{reaction} + \sum n_{out}H_{out} - \sum n_{in}H_{in}$$

Change of enthalpy without reaction:

$$\Delta H = \sum n_{out} H_{out} - \sum n_{in} H_{in}$$

$\Delta H = \sum n_{out} H_{out} - \sum n_{in} H_{in}$

$$Q - W_S = \Delta H + \Delta KE + \Delta PE$$

Reaction in an absorber

$$CO_2 + H_2O + C_2H_7NO \rightarrow C_2H_7NOCOO^- + H_2O$$

Calculations of moles consumed and moles generated:

Table 4.3: Moles and Enthalpy around the Absorber- Stripper

Component	n_{in} (kmol/h)	H_{in} (kJ/kmol)	n_{out}(kmol/h)	H_{out} (kJ/kmol)
CH_4	0.101	23.94	0.0999	11.01
O_2	0.0226	604.2	0.0226	604.2
CO_2	0.0792	27 540	0.0791	26 895
N_2	0.0091	0.89	0.0091	1.96
H_2S	0.0136	4.00	0.0135	3.998
C_2H_7NO	1.263	180.21	1.263	31.61
$C_2H_7NOCOO^-$	-	-	1.342	4 925 444

$\Delta H = \sum n_{out} H_{out} - \sum n_{in} H_{in}$

$$\begin{aligned}\Delta H = \Big(\big((0.0999 \times 11.01) + (0.0226 \times 604.2) + (0.0791 \times 26\,895) + (0.0135 \times 3.998) \\ + (1.263 \times 31.61) + (1.342 \times 4\,925\,444)\big) \\ - \big((0.101 \times 23.94) + (0.0226 \times 604.2) + (0.0792 \times 27\,540) + (0.0091 \times 0.89) \\ + (0.0136 \times 4.00) + (1.263 \times 180.21)\big)\Big)\end{aligned}$$

$\Delta H = \frac{6\,609\,703 kJ/h}{3600 s} = 1\,836 kW$= 1 836kJ/kg

4.2.3 Furnace material and energy balance

The objective of the furnace is for the combustion of natural gas mainly made of methane gas from the absorbing unit. The reaction is carried out at 227^{0}C, an excess air of 5-10% is supplied in the furnace for complete combustion of fuel.

$$\sum_{\text{inputs}} \mathrm{M_i} + \mathrm{G_i} = \sum_{\text{outputs}} \mathrm{M_o} + \mathrm{G_o}$$

Reaction: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

There is 1.60kg/hof methane liberated from absorber to the adsorption system of which 10% (thus 0.16kg/h) of methane is channelled for combustion into a furnace.

Calculating the percentage excess air required

$$\%excess.air = \frac{molO_2\,fed - molOreq}{molO_2req} \times 100\%$$

$$10\% = \frac{molO_2fed - 32}{32} \times 100\%$$

10% of excess air is required

$molO_2fed=35.2kmol/h$

$molN_2$ fed=30.8kmol/h

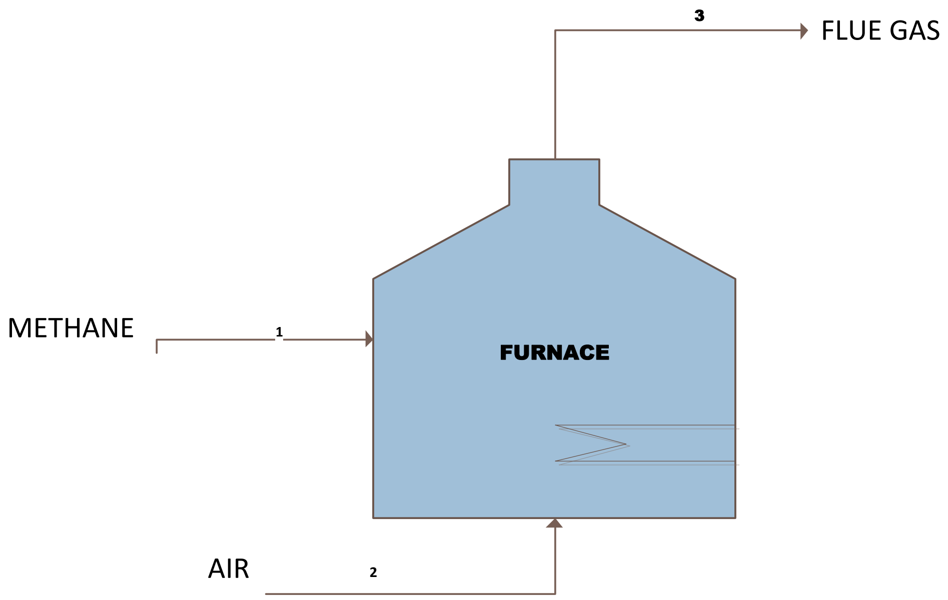

Figure 4.4: Furnace

Table 4.4: Methane gas composition

STREAM 1: METHANE GAS		
T=38 ^{0}C,P=1atm	Mass (kg/h)	Mass %
CH_4	0.16	100
Total	0.16	100

Table 4.5: Air composition

STREAM 2: AIR		
T=25 ^{0}C, P=1atm	Mass (kg/h)	Mass %
O_2	1 126.4	56.64
N_2	862.4	43.36
Total	1 988.8	100

Table 4.6: Flue-gas composition

STREAM 3: FLUE GAS		
T=25 ^{0}C, P=1atm	Mass (kg/h)	Mass %
CO_2	0.16	0.008
H_2O	1 126.4	56.63
N_2	862.4	43.362
Total	1 988.96	100

Energy balance

To evaluate the energy balance around the combustion unit, the heat of reaction method will be used.

The reference states are reactant and product species at 25^{0}C and 1atm.

The extent of reaction assuming complete combustion of methane:

$$CH_{4(g)} + 2O_{2(g)} + N_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)} + N_{2(g)}$$

$$N^1{}_{CH_4} + 0 = N^3{}_{CH_4} + vr$$

$$2.56 + 0 = 0 + vr \Leftrightarrow vr = 2.56 kmol/h$$

References: O_2, N_2, CO_2, H_2O at 25^{0}C and 1atm

Table 4.7: Molar flow and Enthalpies of flue gas and the moles were determined from the flue gas streams on a molecular mass.

Components	(kmol/h) P=1.013bar, T=25°C	Enthalpy in (kJ/mol)	(kmol/h) P=1.013bar, T=25°C	Enthalpy out (kJ/mol)
CH_4	2.56		-	-
O_2	35.2		3.52	
N_2	30.8		30.8	
CO_2	-	-	2.56	
H_2O	-	-	4.206	

$\hat{H}_1$ =0 because methane is at its reference state

The specific enthalpies of selected gases were taken from (Felder et al., 2000)

$\hat{H}_2 = \Delta\hat{H}$ for O_2 (25^0C) $\longrightarrow$ O_2 (25^0C) =0

$\hat{H}_3 = \Delta\hat{H}$ for N_2 (25^0C) $\longrightarrow$ N_2 (25^0C) =0

$\hat{H}_4 = \Delta\hat{H}$ for O_2 (25^0C) $\longrightarrow$ O_2 (227^0C in a furnace) =6,163.2kJ/kmol

$\hat{H}_5 = \Delta\hat{H}$ for N_2 (25^0C) $\longrightarrow$ N_2 (227^0C in a furnace) =5,937.3kJ/kmol

$\hat{H}_6 = \Delta\hat{H}$ for CO_2 (227^0C) $\longrightarrow$ 8 295kJ/kmol

$\hat{H}_7 = \Delta\hat{H}$ for H_2O (227^0C) $\longrightarrow$ 6,971.2kJ/kmol

Determination of $\Delta\hat{H}_R{}^0$ for $CH_{4(g)} + 2O_{2(g)} + N_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)} + N_{2(g)}$

$\Delta\hat{H}_R{}^0$ = ?

$$\sum_{products} v_i \Delta H_f{}^0 - \sum_{\mathrm{Re}actan\,ts} v_i \Delta_{fi}{}^0$$

$\Delta\hat{H}_R{}^0 =$ $1\left(\Delta\hat{H}_f\right)CO_{2(g)} + 2\left(\Delta\hat{H}_f\right)H_2O_{(g)} - \left(\Delta H_f\right)CH_{4(g)}$

$\Delta\hat{H}_R{}^0 =$ $1(-393{,}5) + 2(-241.83) - 1(-74{,}85)$

$\Delta\hat{H}_R{}^0$ =-802,3kJ/mol and theoretically the value is found to be -891 kJ/mol (Bini et al., 1997)

Calculation of $\Delta\dot{H}$ the reaction

$$\sum \dot{n}_{out}\hat{H}_{out} = (2.56kmol/h)\times(8295kJ/kmol) + (30.8kmol/h)\times(5937.3kJ/kmol) + (3.52kmol/h \times 6163.2kJ/kmol) + (4.206kmol/h)\times(6971.2kJ/kmol) = 450369.5472kJ/h \times \frac{1}{3600s} = 125.1kJ/s$$

$$\Delta\dot{H} = \varepsilon\Delta\hat{H}_r{}^0 + \sum \dot{n}_{out}\hat{H}_{out} - \sum \dot{n}_{in}\hat{H}_{in}$$

$$\Delta\dot{H} = (2.56kmol/h)\times\frac{1}{3600s}\times(-802300kJ/kmol) + (125.1kJ/s) - 0$$

$$\Delta\dot{H} = -445.4kW$$

Energy balance

$$\dot{Q} - \dot{W}_S = \Delta\dot{H} + \Delta\dot{E}_K + \Delta\dot{E}_P$$

Assumptions:

- Negligible kinetic and potential energies, constant Temperatures
- No shaft work performed by or on the system
- Combustion reaction in furnace is occurring in 10% excess air

$$\dot{Q} \approx \Delta\dot{H} = -445.4kW$$

4.2.4 Gas Turbine

The gas turbine combusts air internally; it uses air as the working fluid. It extracts chemical energy from fuel, then converts it into mechanical energy makes use of gaseous energy of the working fluid to move the engine and propeller.

There are four basic steps for any internal combustion engine:

- The inlet section
- The compressor section
- The combustion section (the combustor)
- The turbine (and exhaust) section

The turbine section of the gas turbine engine has the task of producing usable output shaft power to drive the propeller. In addition, it must also provide power to drive the compressor and all engine accessories. It does this by expanding the high temperature, pressure and velocity of the gas and converting the gaseous energy to mechanical energy in the form of shaft power (Waumans et al., 2006).

A large mass of air must be supplied to the turbine in order to produce the necessary power. This mass of air is supplied by the compressor, which draws the air into the engine and squeezes it to provide high-pressure air to the turbine. The compressor does this by converting mechanical energy from the turbine to gaseous energy in the form of pressure and temperature (Reynauts et al., 2006).

Therefore, to size the entire plant it is necessary to know the amount of fuel to be combusted in order, to try to find the amount of energy that can be possibly produced at the Bellville landfill site. A gas turbine that is going to be used on this project has a free turbine in parallel with the turbine which drives the compressor. The heat transfer rate to the combustion chamber is 80-120kW. The gas leaves the combustion chamber at 1100°C. The fuel is drawn into the compressor at 1 bar and 461°C. The pressure after compression is 7.2 bars. The adiabatic index is 1.313 for CH_4 and 1.401 for gas produced by combustion. The specific heat c_p is 2.22kJ/kg.K for CH_4 and 1.005kJ/kg.K for the air (Pathirathna et al., 2013). In order, to size the entire plant the following must be calculated:

- The mass flow rate in each turbine
- The net power output

Calculations of mass flow rate in each turbine

T_1=734K

$T_2=734(7.2)^{(1.313-1}/_{1.313)}$=1 175K

T_3=1373K

$T_4=1373\ (\frac{1}{7.2})^{(\frac{2-1}{1.401})}$=780.3K

<u>Compressor</u>

According to literature thermal ratio

$$\eta_i = 0.8 = (1175 - 734)/(T_2 - 734)$$

$$T_2 = 1285K$$

<u>Turbine</u>

$\eta_i = 0.85 = (1373 - T_5)/(1373 - 780.3)$Hence T_5=869K

<u>Heat Exchanger</u>

Thermal ratio=0.8=$2.22(T_3 - 1285)/1.005(869 - 1285)$ hence T_3=1134K

<u>Combustion Chamber</u>

1.44kg/h of methane is fed into the gas turbine, which is 0.0004kg/s

Φ (in) =$mc_p(T_4-T_3)$=120kW

= (0.0004)(2.22)(1373-1134) hence m=0.0004kg/s is the flow rate required to get 0.212kW the same power as the power input.

<u>Compressor</u>

P(in)=$mc_p(T_2-T_1)$=0.0004kg/s(1.005)(1285-734)

= 0.222kW

<u>Turbine</u>

P(out)=$m_A c_p(T_4-T_5)$

=0.0004kg/s(2.22)(1373-869)

$P_{(OUT)}$= 0.448kW

Hence the efficiency of gas turbine:

$\varepsilon = \frac{0.448kW}{0.222kW}$

ε=2.01

The figure below defines of the processes that are occurring in the gas turbine.

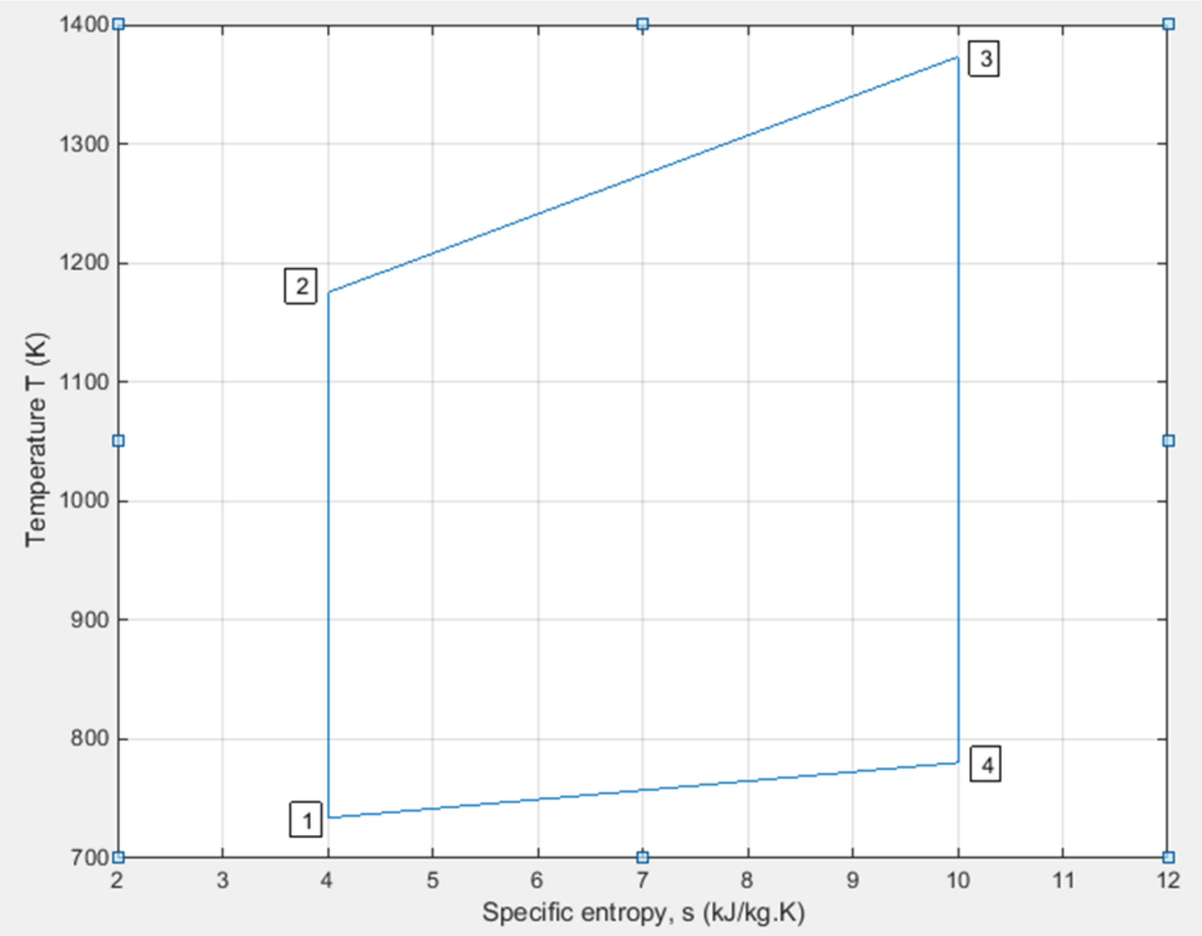

Figure 4.5: A thermal cycle diagram of a gas turbine

Description of processes occurring in the gas turbine (Smith et al., 2005)

Process 1-2: Isentropic compression

In this process, the piston moves from bottom dead centre (BDC) to top dead centre (TDC) position. Methane undergoes reversible adiabatic (isentropic) compression. Hence, in this process, volume of methane decreases from V_1 to V_2 and pressure increases from p_1 and p_2. Temperature increases from T_1 and T_2. As this an isentropic process, entropy remains constant.

Process 2-3: Constant volume heat addition

Process 2-3 is isochoric (constant volume) heat addition process. Here, piston remains at top dead centre for a moment. Heat is added at constant volume ($V_2=V_3$) from an external heat source. Temperature increases from T_2 to T_3, pressure increases from p_2 to $p_3$and entropy increases from s_2 to s_3.

Process 3-4: Isentropic expansion

In this process, methane undergoes isentropic (reversible adiabatic) expansion. The piston is pushed from top dead centre (TDC) to bottom dead centre (BDC) piston. Here, pressure decreases from p_3 and p_4. Volume rises from V_3 to V_4, temperature falls from T_3 and T_4 and entropy remains constant.

Process 4-1: Constant volume heat rejection

The piston rests at BDC for a moment and heat is rejected at constant volume ($V_4=V_1$). In this process, pressure falls from p_4 to p_1, temperature decreases from T_4 to T_1 and entropy falls from s_4 and s_1.

The sizing of major units will be dealt with in chapter five.

CHAPTER 5

5.1 Introduction

This chapter is going to show how single units involved in purification of methane are sized. This is done based on the amount of estimated landfill gas produced in 2013. The following should be expected to be seen; sizing up of the major units, their capital costs from their manufacturers based on the capacity of the unit.

5.1.1 Air cooler heat exchanger

The air-cooled heat exchanger is a unit used for transferring heat from a fluid directly to ambient air.The fact about air cooler is that water is not needed for cooling the fluids and it is not necessary to place the cooling system next to a supply of cooling water. Furthermore, the issues associated with water treatment and disposals have become expensive with government regulations and environmental concerns (Amercool et al., 2011).

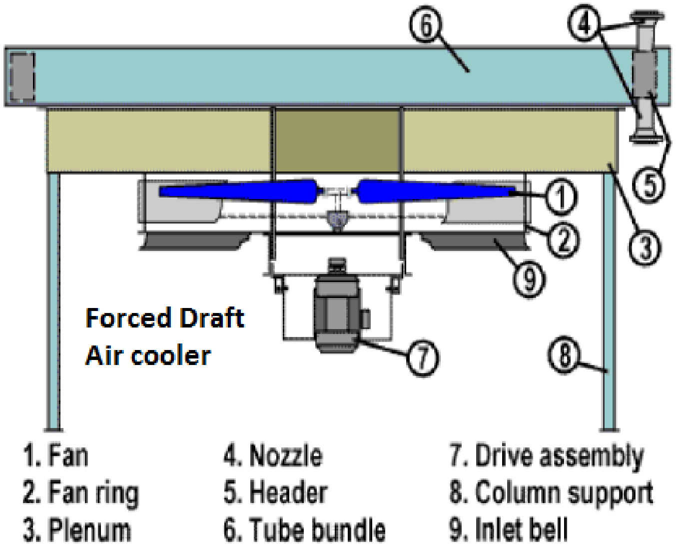

Figure 5.1: Air force air cooler heat exchanger (Amercool et al., 2011)

Basic Heat Transfer principles

The principles that are applied when designing a heat exchanger are also considered in the process of air-cooled heat exchanger. Although, there are more variables to bear in mind in the design of an air-cooled exchanger (Amercool et al., 2011). There is an obstacle in controlling of air cooler temperature due to changing climatic conditions. A proper decision must be made as to what the actual ambient air temperature to be used for the design (Amercool et al., 2011).

Some of the governing factors in the design of the air cooler are as follows:

- Tube diameter
- Tube length
- Fin height
- Number of tube rows
- Number of passes
- Transfer area
- Horsepower availability
- Plot area

Basic heat Transfer Equations:

$$Q = m\Delta H_{hot} \cong mC_p(T_{in}^{hot} - T_{out}^{hot})$$

$Q = m\Delta H_{cold} \cong mC_p\left(T_{out}^{cold} - T_{in}^{cold}\right)$ (Sinnot et al., 2005)

Furthermore, the overall heat transfer equation for the exchanger must be solved simultaneously:

$Q = UA\Delta T_{LM}$(Sinnot et al., 2005)

U- Being the overall heat transfer coefficient

A-the heat transfer area

ΔT_{LM} – The log-mean temperature difference

The above equation is used in simple counter or co-current flows. When the flow pattern is more complex (such as the case with most shell and tube heat exchangers), then a correction factor (F) is applied. Therefore, the equation becomes:

$Q = UAF\Delta T_{LM}$ (Sinnot et al., 2005)

The equation may differ from approximate calculation based on the exchanger geometry, depending on how complex the chosen model is.

The data below shows typical heat transfer coefficients for air-cooled heat exchangers.

Overall heat transfer coefficient is:

Typical Heat Transfer Coefficients for Air-Cooled Heat Exchangers

Condensing service	**U**
Amine reactivator	100 - 120
Ammonia	105 - 125
Refrigerant 12	75 - 90
Heavy naphtha	70 - 90
Light gasoline	95
Light hydrocarbons	95 - 105
Light naphtha	80 -100
Reactor effluent Platformers, Hydroformers, Rexformers	80-100
Steam (0 - 20 psig)	135 - 200
Gas cooling service	
Air or flue gas @ 50 psig (DP = 1 psi)	10
Air or flue gas @ 100 psig (DP = 2 psi)	20
Air or flue gas @ 100 psig (DP = 5 psi)	30
Ammonia reactor stream	90 - 110
Hydrocarbon gasses @ 15 - 50 psig (DP = 1 psi)	30 - 40
Hydrocarbon gasses @ 50 - 250 psig (DP = 3 psi)	50 - 60
Hydrocarbon gasses @ 250 - 1500 psig (DP = 5 psi)	70 - 90
Liquid cooling service	
Engine jacket water	130 - 155
Fuel oil	20 - 30
Hydroformer and Platformer liquids	85
Light gas oil	70 - 90
Light hydrocarbons	90 -120
Light naphtha	90
Process water	120 -145
Residuum	10 - 20
Tar	5 - 10

(Hudson Products Corporation)

The geometry of the heat exchanger is required to calculate the heat transfer area. In order, to determine the surface area specifications of the dimensions of process streams contact area are necessary (Yunus et al., 2002). For example, in a shell and tube exchanger, the pipe diameter and length are used for this purpose (Yunus et al., 2002).

The reason why correction factor is used in conjunction with the LMTD is toaccountfor the deviation from the ideal counter-current flow pattern (Sinnot et al., 2005). e.g. Shell and tube exchangers where the tubes make more than one pass or when two or more shells are available (Sinnot et al., 2005). The LMTD represents the driving force between process streams and is given by:

$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{In(\frac{\Delta T_1}{\Delta T_2})}$(Sinnot et al., 2005)

Whereby:

$\Delta T_1$and ΔT_2 are the temperature differences between the two fluids at the two ends (inlet and outlet). The use of the LMTD stands for an average driving force since the temperature variance between the two streams changes as it flows through the exchanger. In the counter-current flow, the driving force is stable, whereas in the co-current flow it declines as the fluids exchange heat (Sinnot et al., 2005). It is essential to bear in mind that it is pointless if the two temperature curves cross or reach a pinch point when trying to transfer heat to another fluid. If it does occurthenheat transfer will switch direction which is practically not possible (preferably what can happen is for both streams to reach the same temperature) (Sinnot et al., 2005).

5.1.2 Design of an air cooler heat exchanger

Given fluids are:

LANDFILL GAS:

Inlet temperature = 50 ^{0}C

Outlet temperature = 32 ^{0}C

Air:

Inlet temperature = 25 ^{0}C

Outlet temperature = 43 ^{0}C

$Q = m\Delta H_{hot} \cong mC_p(T_{in}^{hot} - T_{out}^{hot})$ (Sinnot et al., 2005)

<u>Routing</u>

Shell Side = air

Tube Side = landfill gas

Heated mass flow= 3.62kg/h =0.00101kg/s

Heat capacity of landfill gas=1 241J/kg.K

$$Q = \frac{3.62kg/h}{3600s} \times 1\ 241J/kg.K \times (323 - 305)K$$

$Q = 22.46W$Which is the amount of heat energy transferred by the heat exchanger?

The overall heat transfer equation for the exchanger

$Q = UA\Delta T_{LM}$(Sinnot et al., 2005)

$22.46W = UA\Delta T_{LM}$then, the following parameters U and ΔT_{LM} must be calculated in order to get the area of the heat exchanger.

Then let's solve for LMTD which is the driving force between process streams:

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{In(\frac{\Delta T_1}{\Delta T_2})}$$

$$\Delta T_1 = 323K - 298K$$

$$\Delta T_1 = 25K$$

$$\Delta T_2 = 316K - 305K$$

$$\Delta T_2 = 11K$$

Therefore, $\Delta T_{LM} = \frac{25K - 11K}{In(\frac{25}{11})}$

ΔT_{LM} =9.87K

One shell, 2 tubes passes

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{50 - 43}{32 - 25} = 1$$

$$S = \frac{t_2 - t_1}{T_1 - t_1} = \frac{32 - 25}{50 - 25} = 0.28$$

From the graph of FT against S at various R, we have

$F_t = 0.98$

$U = 1.80 - 5.70 W/m^{2\,0}C$ for typical heat transfer coefficients for landfill gases(Megalla et al., 2015).

Then, Area can be calculated as,

$$Q = F_t U A \Delta T_{lm}$$

$$A = \frac{Q}{F_t U \Delta T_{lm}} = \frac{22.46}{0.98 \times 1.80 \times 9.87} = 1.29 m^2$$

The area of an air cooler heat exchanger that is calculated above is quite small when compared to what manufacturers such as Hudson Products Corporation are producing. Hudson Products Corporation produce air cooler heat exchangers of **263m^2** in area. The one that is required by the LFGTE process plant is quite small. It is only **1.29m^2** and this due to the amount of landfill gas that is harvested per hour at Bellville landfill site. Again the flow rate of the fluid treated by the air cooler heat exchanger is one of the factors that affect the sizing of the unit. To prove it, the equation $Q = mC_p\Delta T$ and Q can be used to determine the transfer area of the air cooler heat exchanger. The equation $A = \frac{Q}{F_t U \Delta T_{lm}}$ shows that the higher the flow rate the larger the transfer area of the air cooler heat exchanger. The air cooler heat exchangers cost prices range from R 1 435- R 143 539, the cost price is again affected by material of construction and size of the unit according to Alibaba manufacturers. Material selection of the air cooler heat exchanger is previewed in chapter 6 under material of construction.

5.2 Absorber-stripper design

Introduction

Absorption in chemical engineering is the second main operation. In this unit it is either one or more component gets removed, from a mixture of gases by using a suitable absorption solvent. The removal occurs on interphase mass transfer controlled widely by rates of diffusion. The absorption solvent can be recovered from absorption liquid-air mixture by passing the gas stream into water in which the absorption liquid gets trapped while the gas escapes. The absorption process is considered to be physically dominant than chemical process. Absorption processes are in two groups and those are chemical and physical occurrences. For gas absorption to be achieved, the gas must be intimately in contact with the absorbent (Harker et al., 2002).

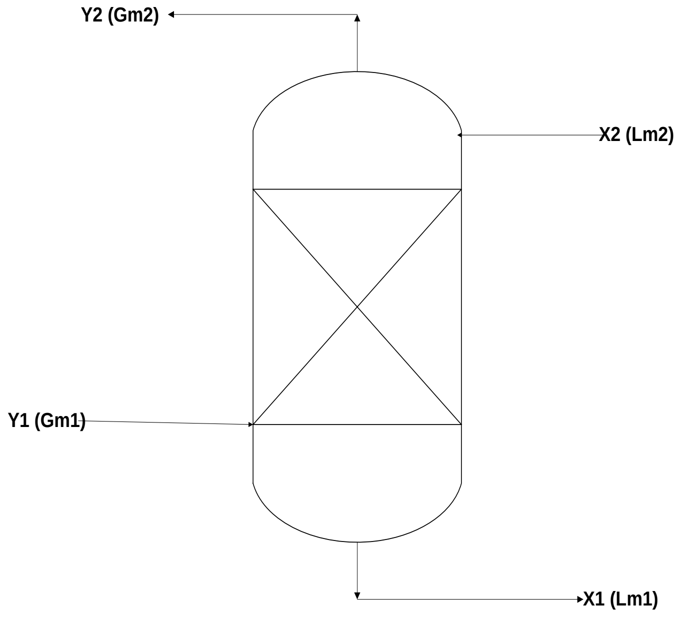

Figure 5.2: Absorber design

Design Procedure

The design of counter-current absorbers involves the following steps: developed by (Kohl et al., 1960).

- Selection of contactor including types of trays or packing based on process requirements and expected services conditions
- Calculation of material and energy balances
- Estimation of required column height (number of trays or height of packing) based on mass transfer analysis
- Calculation of the required column diameter and tray or packing parameters based on gas and liquids flowrates and hydraulic conditions
- Mechanical design of the hardware.

The key data required for the design of absorbers are the physical, thermal, and transport properties of the gases and liquids involved, vapour/liquid equilibrium data and reaction rate data (Kohl et al., 1960).

Solvent Selection

The key advantage of the primary and secondary alkanolamines such as MEA and DEA is their fast reactivity due to the formation of stable carbamates. Conversely, this will lead to very high solvent regeneration costs. The alkanolamines have proved to be the principal commercial interest for gas purification (Aschenbrenner et al., 2010). Monoethanolamine (MEA), diethanolamine (DEA) and methyl-diethanolamine (MDEA) are the main solvents used because of their absorption capacity, reaction kinetics, and regenerative potential and facility. Triethanolamine has been displaced because of its low reactivity (as tertiary amine), and its poor stability (Styring et al., 2010). MDEA was described by Kohl and co-workers as a selective absorbent (Aschenbrenner et al., 2010). Different types of alkanolamine are also used 2-(2-aminoethoxy ethanol commercially known as diglycoamine (DGA) was proposed by Blohlm and Riesenfield, this compound couple with the stability and reactivity of monoethanolamine and its low vapour pressure can also be used in more concentrated solutions than monoethanolamine (Aschenbrenner et al., 2010).

The ideal chemical solvent possesses according to Aschenbrenner et al., (2010):

- High reactivity with respect to CO_2 – which would reduce height requirements for the absorber and/or reduce solvent circulation flow rates.
- Low regeneration cost requirements –based on a low heat of reaction with CO_2
- High absorption capacity – which directly influences solvent circulation flow rate requirements.
- High thermal stability and reduced solvent degradation – reduced solvent waste due to thermal and chemical degradation
- Low environmental impact
- Low solvent costs – should be easy and cheap to produce

Table 5.1: Choice of plate or packing (Sinnott et al., 2005)

Plate columns	✓ **Packed columns**
Can handle a wider range of liquid and gas flow rates.	Suitable for corrosive liquids, it will generally be cheaper compared to plate column.
Suitable for low liquids flow rates.	Suitable for small diameter columns.
Good liquid distribution maintained over the plate column.	The liquid hold up is appreciably lower in a packed column than in a plate column.
Easier to make provision for cooling in a plate and withdrawal of side streams from the plate.	Suitable for handling foaming systems.
Can be designed with more assurance than packed column.	The pressure drop can be lower for packing than for plate columns.

Table 5.2: Landfill gas composition

Component	Amount (kmol/h)	Mole fraction
CH_4	0.101	0.45
O_2	0.0226	0.10
CO_2	0.0792	0.35
N_2	0.0091	0.04
H_2S	0.0136	0.06

The average molecular weight of incoming gas:

$$M_{avg} = (0,45 \times 16) + (0.10 \times 32) + (0,35 \times 44) + (0.04 \times 28) + (0.06 \times 34) = 28.96 kg/kmol$$

Inlet temperature $T = 32^0 C = 305K$

The density of the gas: $\rho_g = \dfrac{28.96 \times 273}{22.4 \times 305} = 1.157 kg/m^3$

Carbon dioxide and Hydrogen sulphide are absorbed in MEA solution, after absorption the exit concentration of MEA is assumed to be (3% free CO_2).

Assuming negligible absorption of other gases at the temperature T=32^{0}C

Calculating the density of liquid (solvent mixture at 32^{0}C), by interpolation we have the densities as follow:

$\rho_{MEA@50^0C} = 1016 kg/m^3$ and $\rho_{MEA@20^0C} = 990 kg/m^3$

Thus: $\dfrac{50-32}{50-20} = \dfrac{1016-x}{1016-990} \Rightarrow \rho_{MEA@32^0C} = 1000 kg/m^3$

The density of water at 32^{0}C will be: $\dfrac{43.3-32}{43.3-37.8} = \dfrac{990.6-x}{990.6-993}$

$\rho_{H2O@40^0C} = 992 kg/m^3$

We know that from the material balance calculation the mass flow rate needed for the liquid streams around the absorber: $m_{MEA} = 29.93 kg/h$

$m_{H2O} = 69.84 kg/h$

Then $V_{MEA} = \frac{m}{\rho} = \frac{29.93}{992} = 0.0302 m^3/h$ and $V_{H2O} = \frac{m}{\rho} = \frac{69.84}{992} = 0.0704 m^3/h$

The total volumetric flow rate is then: $V_T = 0.101 m^3/h$ and the density should be evaluated as follows: $\rho_{L@40^0 C} = \frac{99.77 kg/h}{0.101 m^3/h} = 988 kg/m^3$

a. Calculating number of transfer units (N_{OG})

   Before calculating height of the absorber column, we must find theoretical number of stages.

   From process plant conditions:

   Partial pressure CO_2 feed into the absorber= 1 700kPa

   Partial pressure CO_2 out of the absorber= 176kPa

   We can get theoretical stage from (Sinnot et al., 2005) with use of figure A.4. Colburn (1939) has suggested that the optimum value for the term mG_m/L_m will lie between 0.7 to 0.8.

   $\frac{y_1}{y_2} = \frac{P_1}{P_2} = \frac{1700}{176} = 9.659 \approx 10$

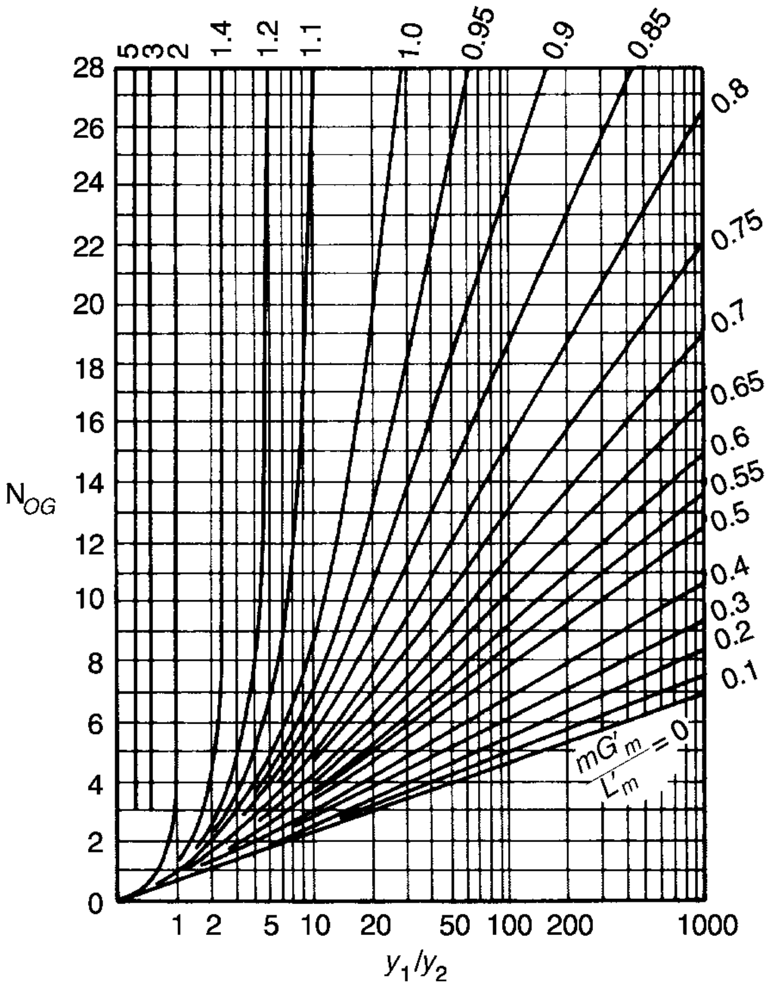

Figure 5.3: Number of transfer units N_{OG} as a function of y_1, y_2 with mG_m/L_mas a parameter (Sinnot et al., 2005)

With $mG_m/L_m = 0.1$, N_{OG} from figure 5.3 is 4.

b. Calculating of a column diameter

$$Y = \frac{G^2 F \mu^{0.1}}{\rho_g(\rho_l - \rho_g)}$$

$$X = (L/G)(\rho_g/\rho_l)^{0.5}$$

Where:

L=liquid mass velocity, kg/m^2.s

G= gas mass velocity, kg/m^2.s

$\rho_l =$ Liquid density, kg/m^3

ρ_g= gas density, kg/m^3

μ= liquid (MEA) viscosity, centistokes

F= packing factor

Table 5.3: Nominal Packing size (Sinnotet al., 2005)

Packing type	Material	5/8" or #15	1" or #25	1.5" or #15 or #40	2" or #2 or #50	3" or #70	3.5" or #3
IMTP	Metal	51	41	24	18	12	
Hy-Pak	Metal		45	29	26		16
Pall rings	Metal	70	56	40	27		18
Pall rings	Plastic	75	55	40	26		17
Super Intalox saddles	Plastic		40		28		18
Super intalox saddles	Ceramic		60		30		
Intalox saddles	Ceramic		92	52	40	22	
Radchig rings	1/16" metal	300	144	93	62	43	

For this absorber column, we use intalox saddles ceramic 1.5 inch with packing factor 52.

Calculate X, to get Y value.

$$X = (m_l/m_g)(\rho_g/\rho_l)^{0.5}$$

From material balance:

m_l=mass flow rate of the liquid= 99.77kg/h=0.611lb$_m$/s

m_g= mass flow rate of the gas= 3.62kg/h=0.00223lb$_m$/s

ρ_l= mass density liquid= 988kg/m^3= 61.68lb$_m$/ft^3

ρ_g= mass density gas = 1.157kg/m^3=0.07223lb$_m$/ft^3

μ= 2.588 centistokes

$$X = (\frac{L}{G})(\frac{\rho_G}{\rho_L})^{0.5}$$

$X = (\frac{0.0611}{0.00223})(\frac{0.07223}{61.68})^{0.5}$=0.938

Pressure drop is determined by using parametric lines (inches of water per foot of packing)

So, Y value from (Sinnotet al., 2005) is 0.7

Table 5.4: Pressure drop parametric lines (inches of water per foot of packing)

Service	ΔP, in H_2O/ ft packing
Absorber / Regenerator Liquids with foaming tendency Light hydrocarbon distillation	0.25-0.50
Atmospheric and H.P. distillation Non-foaming fluids	0.5-1.0
Minimum ΔP	0.05
Maximum ΔP	1.0

With the help of this information we determine that Y=0.24

$$Y = \frac{G^2 F \mu^{0.1}}{\rho_G(\rho_L - \rho_G)}$$

$$0.24 = \frac{G^2(52)(2.588)^{0.1}}{0.07223(61.68 - 0.07223)}$$

G^2= 0.0187

G= 0.137lb_m/ft^2.s

$d = (4m/\pi G)^{0.5}$ = $(\frac{4\times 0.611}{\pi\times 0.137})^{0.5}$=2.383ft= **0.726m**

c. Calculating column height

H= (HETP) (N_{OG}) where HETP is height equivalent to a theoretical plate

The data on table below shows correspondence between packing size and HETP

Table 5.5: Packing size and HETP data (Sinnot et al., 2005)

Packing Size	**HETP**
2.54cm (1 in.)	0.46m (18in)
3.81 cm (1.5in.)	0.66m (26in)
5.08 cm (2 in)	0.89m (1 in)

So, absorber column height: 0.89m×4=**3.56m**

The height of the absorber that is calculated is 3.56m and the heights of absorber sizes that AceChemPack Tower Packing Co., Ltd manufactured are as follows; 7.96m,11m,17.16m and 37m. The height of the absorber depends on the amount of gas that is treated per hour. If the amount of gas flow rate is high the height of the absorber is also is supposed to increase in order to increase the surface area or contact time for liquid to gas interphase to facilitate good absorption process. The reason why the height of absorber for this LFGTE process plant turned out to be 3.56m is because only 3.62kg/h of landfill gas is to be treated in this unitwhile the 37m absorber was used to treat 7 000kg/h of gas. As for the cost price of these units it ranges from R143 499-R14 349 900 and the cost prices are also affected by sizes (height) as confirmed by (Alibaba Manufacturers 2016)

Stripper design

Table5.6: stripper operating conditions (Sinnot et al., 2005)

Specifications	conditions
Inlet gas temperature	104,5^{0}C
Inlet gas pressure	2bar
Lean amine temperature	40^{0}C
lean amine pressure	1.1bar
Rich amine pump pressure	2 bar
Heated rich amine temperature	104,5^{0}C
Reflux ratio in stripper	0.3
Reboiler temperature	112^{0}C
Lean amine pump pressure	2 bar
Stripper column temperature	107-112^{0}C
Stripper column pressure	2-4bar

From the material balance around the absorber and stripper column:

We know that $N^5{}_{CO_2} = 0.0791 kmol/h.$ the recovery of CO_2 in the stripper is 85% according to (Yang et al 2005).

Thus: $0.85 = \dfrac{m_{CO_2} out}{m_{CO_2} in} = \dfrac{3.48 kg/h}{m_{CO_2}} \Leftrightarrow m_{CO_2} in = \dfrac{3.48}{0.85} = 4.095 kg/h$

And also that $N^5{}_{H_2S} = 0.0136 kmol/h$ the recovery of H_2S in the stripper is 85%.

Thus: $0.85 = \dfrac{m_{H_2S} out}{m_{H_2S} in} = \dfrac{0.435 kg/h}{m_{H_2S}} \Leftrightarrow m_{H_2S} in = \dfrac{0.435}{0.85} = 0.512 kg/h$

The mass of $MEAH_2S$ at the bottom of the column is: $0.512 - 0.435 = 0.077 kg/h$

85% MEA is recovered; the amount of unreacted MEA is 0.605kg/h from the absorber outlet

$$\frac{0.435-x}{0.435}=39\%\Leftrightarrow 0.435-x=0.1697\Leftrightarrow x=0.605kg/h$$

The mass of MEACO$_3$ at the bottom of the column is: $0.605-0.435=0.169kg/h$

$$\frac{0.435-x}{0.435}=39\%\Leftrightarrow 0.435-x=0.1697\Leftrightarrow x=0.605kg/h$$

Mass of MEA in the bottom stream=0.435+0.605=1.04kg/h

Stream ID	RICH IN MEA	RICH IN MEA	LEAN MEA OUT	LEAN MEA OUT	CO$_2$	CO$_2$	H$_2$S	H$_2$S
	Mass flow kg/h	Mole flow kmol/h	Mass flow kg/h	Mole flow kmol/h	Mass flow kg/h	Mole flow kmol/h	Mass flow kg/h	Mole flow kmol/h
CO$_2$	-	-	-	-	3.481	0.0791	-	-
H$_2$S	-	-	-	-	-	-	0.462	0.0144
MEA	0.605	0.00992	1.04	0.017	-	-	-	-
MEACO$_3$	3.481	0.0288	0.163	0.00135	-	-	-	-
MEAH$_2$S	0.462	0.00497	0.077	0.000828	-	-	-	-
H$_2$O	918	51	899.6	49.98	9.18	0.51	9.18	0.51

The average molecular weight of the rich leanMEA at 104.5 ^{0}C:

$$M_{mean}=(0.0686\times 61)+(0.0566\times 105,04)+(0.0875\times 18)=2,67832kg/kmol$$

Rich in flow rate: $M^4=L^4=0.00434kg/s$

The density of the liquid mixture at 104^{0}C

$$\rho_m=\rho_L=987,3kg/m^3$$

Mass flow rate of gas in the column=3.943kg/h

$G = 0.001095 kg/s$

The gas average molecular weight:

$$M_{avg} = (61{,}08 \times 0{,}171) + (105{,}04 \times 0{,}00282) + (0{,}8261 \times 18) = 25{,}61 kg/kmol$$

$$\rho_G = \frac{M_{avg}}{V_m} \times \frac{273}{T} \Leftrightarrow \rho_G = \frac{25{,}61}{22{,}4} \times \frac{273}{383} = 0{,}815 kg/m^3$$

$$\rho_m = \rho_G = 0{,}815 kg/m^3$$

Calculation of the diameter and height

Stripper diameter calculation

We first determine the vapour flow factor (Coulson & Richardson et al., 2005).

$$F_{LV} = \frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}} \Leftrightarrow F_{LV} = \frac{0.0434}{0.01095}\left(\frac{0{,}815}{987{,}3}\right)^{0{,}5} = 0{,}1139$$

it is the range therefore with a pressure drop of 21mm water/m of packed height (Coulson & Richardson et al., 2005).

From the plot of K_4 vs $\frac{L}{G}\sqrt{\frac{\rho_G}{\rho_L}}$, we design for a pressure drop of 21mm H_2O per metre of packing.

To determine percentage flooding the below data is given:

$K_4 = 0{,}8$

at flooding we have K_4=5

The percentage loading = [K_4 at designed pressure/ K_4 at flooding]$^{1/2}$

Percentage flooding= $\sqrt{\frac{0,8}{5}} \times 100\% = 40\%$

Selecting 38mm ceramic INTALOX saddles, $F_P = 170m^{-1}$ this packing material has the following characteristics; high mechanical strength, high chemical stability and excellent heat endurance. Furthermore, ceramic super intalox saddles ring can ensure that interspace will be increased a lot when saddles are stacked in the column randomly. Therefore, the resistance to vapour-liquid is decreased and it facilitates flow and distribution of vapour-liquid through the packing bed. As a result, pressure drop is low and mass transfer efficiency is high (Matsui et al., 2011).

Size (mm)	Bulk density (kg/m^3)	Surface area a (m^2/m^3)	Packing factor (m^{-1})
38	625	194	170

$$K_4 = \frac{13{,}1 \times \left(G^*\right)^2 \times F_P \times \left(\frac{\mu_L}{\rho_L}\right)^{0,1}}{\rho_G(\rho_L - \rho_G)}$$

$$G* = \left[\frac{0{,}8 \times 0{,}815(987{,}3 - 0{,}815)}{13{,}1 \times 170\left(\frac{1 \times 10^{-3}}{987{,}3}\right)^{0,1}}\right]^{1/2} = 0.139 kg/m^2 s$$

Therefore $G* = 0{,}4 \times 0.139 = 0{,}0558 kg/m^2 s$

Column area required: $A = \frac{m}{G^*} = \frac{0{,}01095 kg/s}{0{,}0558 kg/m^2 s} = 0{,}196 m^2$

Diameter required: $D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4 \times 0{,}196}{\pi}} = 0.50m$

Column area = $\frac{\pi(0.50)^2}{4} = 0{,}196 m^2$

Packing size to diameter ratio= $\frac{0.50}{38^{-3}} = 27{,}436$ thus a larger packing size may be considered because it increases the contact time of fluid, allowing almost complete stripping.

Calculation of the height of the stripper

Cornell's method will be used to evaluate the height of the stripper: the objective of the stripper column is to achieve a desire outlet liquid concentration, thus liquid phase transfer unit is more customary to work with.

$$H_L = 0{,}305\phi_h (Sc)_L^{0,5} K_3 \left(\frac{Z}{3{,}05}\right)^{0,15}$$

$$H_L = \frac{L_m}{k_L a_w C_t} \text{ Thus } \frac{L_m}{k_L a_w C_t} = 0{,}305\phi_h (Sc)_L^{0,5} K_3 \left(\frac{Z}{3{,}05}\right)^{0,15}$$

The material for the stripper will be INTALOX saddles ceramic: (Coulson & Richardson et al., 2005).

size	Bulk density (kg/m^3)	Surface area (m^2/m^3)	Packing factor (m^{-1})
38	625	194	170

Determination of H_L:

$$H_L = \frac{L_m}{k_L a_w C_t}$$

k_L was calculated from

$$k_L \left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0{,}0051 \left(\frac{L_w^{\ *}}{a_w \mu_L}\right)^{2/3} \left(\frac{\mu_L}{\rho_L D_L}\right)^{-1/2} (a d_P)^{0,4}$$

The diffusivity of the liquid was predicted using Wilke and Chang correlation (1955)

Structural contributions to molar volumes, (Bretsznajder et al., 1971)

$V_m(H_2O) = 0{,}0189 m^3/kmol$ and $V_m(MEA) = 0{,}0785 m^3/kmol$

$$D_L = \frac{1{,}173\times10^{-13}T}{\mu V_m{}^{0,6}} = \frac{1{,}173\times10^{-13}(373)}{1.67.10^{-3}\times(0{,}2055)^{0.6}} = 1{,}014\times10^{-8}\,m^2\,/\,s$$

The actual area of packing is 194m^2/m^3(Coulson & Richardson et al., 2005), it was found that the effective interfacial area a$_w$ per unit volume is: $a_w = 0{,}71\times194 = 138m^2\,/\,m^3$

$$k_L\left(\frac{987{,}3}{1{,}67.10^{-3}\times9{,}81}\right)^{1/3} = 0{,}0051\left(\frac{0{,}457}{138\times1{,}67.10^{-3}}\right)^{2/3}\left(\frac{1{,}67.10^{-3}}{987{,}3\times1{,}04\times10^{-8}}\right)^{-1/2}(194\times0{,}038)^{0,4}$$

$$39k_L = 0{,}0051\times1{,}578\times0{,}0784\times2{,}22$$

$$k_L = 3{,}57\times10^{-5}\,m/s$$

Determination of the total concentration C$_t$:

$$C_t = \frac{\rho_L}{M_{solvent}} = \frac{987{,}3kg/m^3}{2{,}678kg/kmol} = 368{,}6kmol/m^3$$

Thus $H_L = \dfrac{L_m}{k_L a_w C_t} = \dfrac{0{,}017}{3{,}57\times10^{-5}\times138\times368{,}6} = 0{,}00936m$ acceptable

$$H_L = 0{,}305\phi_h\,(Sc)_L{}^{0,5}\,K_3 \quad \sqrt[0.15]{\frac{Z}{3.05}}$$

Schmidt number $(Sc)_L = \dfrac{\mu_L}{\rho_L\times D_L} = \dfrac{1{,}67.10^{-3}}{987{,}3\times1{,}014\times10^{-8}} = 166{,}8$

$K_3 = 1$ The percentage flooding correction factor in (Sinnot et al., 2005)

.

From figure 11.53, a value of ϕ_h=1

Therefore: $0{,}0094 = 0{,}305\times0{,}55\times(2.98)^{0,5}\times1\times\sqrt[0.15]{\frac{Z}{3.05}}$

$$(0.5980032977)^{0.15} = \frac{Z}{3.05} \Leftrightarrow Z = 1.82m$$

Theoretical height of the stripper column is **1.82m**

According to (Zygula et al., 2007) the height of the stripper is determined by the amount of flow rate that is being treated.The higher the flow rates per hour the bigger the height of the stripper. He had 40 823kg/hr of trichloroethylene and 1 361kg/hr of steam entering the stripping column and the height of the stripper was 5m while for this LFGTE process plant the stripper height was 1.82m and its feed flow rate is 3.943kg/h. As for the cost price of the unit ranges at the same cost to that of the absorber and the material of construction also is one of the factors that influence the cost price of the unit.

Pressure drops at flooding in stripper

$\Delta P_{flooding} = 0.115 F_p^{\ 0.7}$ (Bretsznajder et al., 1971)

F_P :The packing factor for INTALOX saddles ceramic

Hence the pressure drops: $\Delta p = 0.115(170)^{0.7} = 4{,}18Pa$

5.3 Design of a heat exchanger between an absorber and a stripperusing Kern's method

Kern's method is restricted to a fixed baffle cut of 25% and is inadequate when it accounts for baffle-to-shell and tube-to-baffle leakages.Kern's method is not accurate but it allows quite simple and rapid calculations of shell-side coefficients and pressure drop to be carried out and has been successfully used since its inception (Kara et al., 2004).

5.3.1 Tube side coefficient

Given fluids are:

Rich MEA:

Outlet temperature = 104 ^{0}C

Inlet temperature = 40 ^{0}C

This MEA is rich in CO_2 and H_2S meaning that the solution is highly concentrated with these compounds;asthe solution is the product from the absorber. The reason why we have to raise the temperature of the solution is to get it ready for stripping process. This solution is to be located in the shell of a heat exchanger.

Lean MEA:

Inlet temperature = 112 ^{0}C

Outlet temperature = 34 ^{0}C

This MEA is low in CO_2 and H_2S meaning that the solution has low concentration of these compounds; the MEA solution is from the stripper to absorber. The reason why MEA solution's temperature is lowered, it is to get it suitable for absorption of H_2S and CO_2. This solution will be flowing on the tube side of a heat exchanger. The equation to be used for determining the amount of energy to be transferred:

$Q = m\Delta H_{hot} \cong mC_p(T_{in}^{hot} - T_{out}^{hot})$ (Sinnot et al., 2005)

<u>Routing</u>

Shell Side = Rich MEA is allocated in the shell because it is cold solution. Therefore, it cannot cause thermal stress on the shell which is quite expensive to maintain should it become faulty.

Tube Side = Lean MEA the reason why it is allocated in the tubes is because it is a hot solution. Therefore, it can cause thermal stress inside a shell if it was to be allocated in the shell. It is quite cheaper in terms of operating cost when replacing tubes instead of a shell of a heat exchanger.

The type of flow pattern in the heat exchanger is counter flow. The reason of choosing this pattern is to minimise thermal stresses that could cause damage to the tubes which also leads to lower maintenance costs of the unit.

Mass flow rate of the MEA solution to the absorber= 99.77kg/h= 0.0277kg/s

Heat capacity of MEA =684.9J/kg.K

$$Q = 0.0277kg/s \times 684.9J/kg.K \times (385 - 307)K$$

$Q = 1\ 480W$This is the amount of heat energy transferred by the heat exchanger

The overall heat transfer equation for the exchanger

$Q = UA\Delta T_{LM}$(Sinnot et al., 2005)

$1\,480W = UA\Delta T_{LM}$then the following parameters U and ΔT_{LM} must be calculated in order to get the area of the heat exchanger.

Then let's solve for LMTD which is the heat transfer driving force between process streams:

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{In(\frac{\Delta T_1}{\Delta T_2})}$$

$\Delta T_1 = 385K - 377K$

$$\Delta T_1 = 8K$$

$$\Delta T_2 = 313K - 307K$$

$$\Delta T_2 = 6K$$

Therefore, $\Delta T_{LM} = \frac{8K - 6K}{In(\frac{8}{6})}$

ΔT_{LM} =6.95K

One shell, 2 tubes passes to increase the surface area of heat energy transfer

$$R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{112 - 104}{40 - 34} = 1.33$$

$$S = \frac{t_2 - t_1}{T_1 - t_1} = \frac{40 - 34}{112 - 34} = 0{,}10$$

From the graph of FT against S at various R, we have

$F_t = 1.0$

We obtained $U = 100 - 300W/m^{2\,0}C$ from typical heat transfer coefficients for shell and tube heat exchangers for amine solutions (Sinnot et al., 2005).

Then, Area can be calculated as,

$Q = F_t UA\Delta T_{lm}$

$$A = \frac{Q}{F_t U \Delta T_{lm}} = \frac{1480}{1.0 \times 100 \times 6.95} = 2.129m^2 \approx 2.13m^2$$

Comparison of heat surface area to what manufacturers have in stores. The sizes of shell and tube heat exchangers that they have range from 300-344m^2 in size. The reason why they are this big is due to the amount of fluid flow rate that is treated in this unit. For instance, the flow rate in a tube is 129 085kg/h while in a shell it is 23 100kg/h (Mukherjee et al., 1998). In case there is a need to order the sized shell and tube heat exchanger of 2.13m^2, the manufacturers will have to be supplied with the flow rates of fluid in both the shell and tube, so thatthey can be able to design the heat exchanger and it is not surprising to have calculated this small size of heat exchanger because it is influenced by the amount of fluid flow rate in its tubes which is 99.77kg/h and as for the shell side it is 3.62kg/h. According to (Alibaba Manufacturers 2016) the cost prices of shell and tube heat exchangers are from R1 420- R142 000, the cost price of the shell and tube heat exchanger of size 2.13m^2 might also be within the mentioned range.

Pressure Drop calculations

From the tubing characteristics as given in (Perry et al., 2005),The following dimensions were chosen for the tube,

1 inch outer diameter tubes with 1.25 inch Triangular Pitch, 16BWG

Do = 1.0 inch

= 25 mm

Di = 0.87 inch

= 22.1 mm

P = 31.75 mm

Let us assume the tube to be 4.88m.

Area of one tube= $\pi dL = \pi \times 0.025 \times 4.88 = 0.383m^2$

Number of tubes= $\frac{0.710}{\pi \times 0,025 \times 4.88} = 1.853$≈2 tube

Equivalent diameter

$$d_e = \frac{4\left(\frac{p_t}{2}\times 0.87\,p_t - \frac{1}{2}\pi\frac{d_0{}^2}{4}\right)}{\frac{\pi d_0}{2}} = \frac{1.10}{d_0}\left(p_t{}^2 - 0{,}917 d_0{}^2\right)$$

$$d_e == \frac{1.10}{d_0}\left(p_t{}^2 - 0{,}917 d_0{}^2\right) = \frac{1.10}{0.025}\left(1{,}008\times 10^{-3} - 0.917\times 6.25\times 10^{-4}\right)$$

$$d_e = 0{,}0191 m$$

Shell side Reynolds number

$$\mathrm{Re} = \frac{G_S d_e}{\mu} = \frac{402.2\times 0{,}0191}{8.16\times 10^{-6}} = 9.43\times 10^{5}$$

From (Sinnot et al., 2005) the value of the heat transfer factor is 1×10^{-2} and heat capacity of MEA.

$$\mathrm{Pr} = \frac{Cp\mu}{k} = \frac{125\times 0{,}0000816}{0{,}22} = 0.0464$$

$$\Delta P_S = 8 j_f \left(\frac{D_S}{d_e}\right)\left(\frac{L}{L_B}\right)\frac{\rho u_s{}^2}{2}\left(\frac{\mu}{\mu_m}\right)^{-0{,}14}$$

$$\Delta P_S = 8 j_f \left(\frac{D_S}{d_e}\right)\left(\frac{L}{L_B}\right)\frac{\rho u_s{}^2}{2}$$

$$\Delta P_S = 8\times 1\times 10^{-2}\left(\frac{223.6}{19.1}\right)\left(\frac{6\times 10^{-3}}{80}\right)\frac{1010\times 0.398^2}{2}$$

$$\Delta P_S = 8\times 1\times 10^{-2}\left(\frac{0{,}2236}{0{,}0191}\right)\left(\frac{10}{0{,}08}\right)\frac{1010\times 0.398^2}{2}$$

$$\Delta P_S = 9.364 kPa$$

5.4 Pump Design

5.4.1. Introduction

In process industries, the transporting of fluids from different points for processing is one of the major concerns. Poor pump and piping design results in loss of money when overrated and when underrated, no processing will take place (Karassik et al., 2001). As part of the piping and instrumentation diagram, the valves and piping concerned with fluid transport ought to be carefully designed and sized. In order to displace a fluid from a point to another one, the use of a pump is required. A pump is a mechanical device using suction or pressure to raise or move a liquid from one point to the other (Karassik et al., 2001). A large range of pumps are available and appropriate for different types of duties. This implies that the selection of a pump might require certain criteria. This section of this report is to size the pump for transporting water from a storage tank to the heat exchanger. To achieve that, different calculations will be performed such as pressure drop due to frictions, static head, total head (Sinnot et al., 2005).

5.4.2. Literature review

5.4.2.1. Definitions

5.4.2.1.1. Miscellaneous pressure losses

Miscellaneous pressure losses are contributed by interconnections such as fittings and pieces like valves. So when a fluid flows through a pipe, these pipe fittings, reduce pressure along the piping system (Sinnot et al., 2005).

5.4.2.1.2. Pump power required

When a fluid is flowing the system offers resistances for different reasons. So in order to transport the fluid from one point to another, the pump has to overcome such resistances due to friction by using energy to produce a desired flow rate (Karassik et al., 2001).

5.4.2.1.3. Static head and dynamic head

The static head is independent of the fluid flow whereas the dynamic head is a function of flow rate. They represent the head which must be supplied by the pump in the piping system (Sinnot et al., 2005).

5.4.2.1.4. Characteristic curve and system demand curve

The selection of a pump is driven by the volumetric flow rate and the head developed. The characteristic curve which is drawn by the manufacturer shows the performance of the pump selected (Sinnot et al., 2005).

The system head is the plot of the total system resistance variable. Static head is plotted against dynamic head of the pump. When this two parameters are plotted against one another they converge and where they do, thus said to be the operating point of the pump (Karassik et al., 2001).

5.4.3. Net Positive Suction Head (NPSH)

The net positive suction head describes the excess head which must be available so that cavitation (formation of bubbles of vapour, air inside the pump casing) in the pump would be avoided (Sinnot et al., 2005).

5.4.4. Calculation of pressure drop due to friction

To be able to calculate the pressure drop due to frictions and fittings, the number of bends, valves are suppose to be considered. Using the velocity heads method, two pressure drops were calculated, at the suction respectively and at the discharge and after added up to give the total pressure drop of the system. The total pressure head ΔP_f will help in determining the impeller size and the efficiency of the pump.

$$\boxed{\Delta P_f = 8f\left(\frac{L}{d_i}\right)\times\left(\frac{\rho u^2}{2}\right)}$$

(Sinnot et al., 2005)

Table5.7: pipe fitting and K values assumptions (Sinnot et al., 2005)

Miscellaneous losses			
Fitting/valve	**Number of velocity heads,K**	**Equivalent pipe diameters**	**Description**
Elbows	2.4	120	3 x 90° standard radius elbow
Entry	0.5	25	Storage tank inlet
Exit	1	50	Pump 1 outlet
1x Gate valve, fully open	0.15	7.5	V-11
1x Gate valve, half open	4	200	V-3
2x Globe valve, half open	17	900	V-41,V-4
Total	25.05	1302.5	

The goal of pump sizing is to get the size of the impeller required to transport a mixture of MEA solution containing CO_2 and H_2S. The pump is connecting an absorber and stripper, the pipeline contains a gate valve half open and plug valve fully open. The line is commercial steel pipe, 25mm internal diameter, length 10m.

The properties of the mixture are:

Viscosity: 2.501×10^{-4} Poise

Density: 997kg/m^3(Amundsen et al., 2008)

Then the total pressure drop will be determined so that, the efficiency and size of the centrifugal pump could be determined. The flow rate is 103.717kg/h.

Calculations

Cross-sectional area of pipe= $\frac{\pi}{4}(25\times 10^{-3})^2=4.91\times10^{-4}$ m^2

MEA solution velocity, u=$\frac{103.717}{3600}\times\frac{1}{4.91\times10^{-4}}\times\frac{1}{997}$= 0.0589m/s

Reynolds number, Re= (997 ×0.0589×25×10^{-3})/(2.501×10^{-4}) =5 865≈ 5870

Absolute roughness commercial steel pipe, Table 5.2 (Sinnot et al., 2005)= 0.046mm

Relative roughness= 0.046/(25×10^{-3})= 0.0018 ≈ 0.002

Friction factor chart, figure 5.7 (Sinnot et al., 2005), f= 0.0030

Friction loss in pipe:

$\Delta P_f = 8\times0.0030\times\frac{10}{25\times10^{-3}}\times997\times\frac{0.0589^2}{2}$

= 16.6kN/m^2

Therefore the total pressure head; ρgh= 16.6kN/m^2

$h=\frac{16.6}{997\times9.8}$

h=1.7 ×10^{-3}m

The manufacturers of the centrifugal pumps have a range of sizes from 150-250mm (Sinnot et al., 2005). The pump designed above seems to be on the range because its impeller size is 225mm and efficiency of the pump was found to be 55%. Again the efficiencies of the pumps is between 30-80% and the one designed for LFGTE process plant is only 55%.

5.5 Gas Engine design

Jenbacher gas engines

Technical Specification

JMS 620 GS-N.L

Natural gas 3.048kW el.

Table 5.8: Co-GEN Module data from Jenbacher Manufacturers

Electrical output	kW el.	3.048
Recoverable thermal output (120°C)	kW	3.034
Energy input	kW	7.076
Fuel consumption based on a LHV of 9.5kWh/Nm^3	Nm^3/h	745
Electrical efficiency	%	43.1%
Thermal efficiency	%	42.9%
Total efficiency	%	86.0%
Heat to be dissipated (LT-Circuit)	kW	175
Emission values		NO_x<500mg/Nm^3(5% O_2)

Table 5.9: Specifications of Engine data

Engine type		J 620 GS-E01
Configuration		V 60°
No. of cylinders		20
Bore	mm	190
Stroke	mm	220
Piston displacement	lit	124,75
Nominal speed	rpm	1, 500
Mean piston speed	m/s	11
Mean effe.press.at stand.power&nom.speed	bar	20,00
Compression ratio	Epsilon	11,0
ISO standard fuel stop power ICFN	kW	3 119
Spec. fuel consumption of engine	kWh/kWh	2,27
Spec. lube oil consumption	g/kWh	0,30
Weight dry	kg	12, 000
Filling capacity lube oil	lit	670
Based on methane|min. methane number	MZ	94|80

Table 5.10: Specifications of main dimensions and weights (approximate value)

Length L	mm	8 900
Width B	mm	2 200
Height H	mm	2 800
Weight empty	kg	29 300
Weight filled	kg	30 300

Determination of gas flow in the gas engine at normal conditions

It can be calculated using the following equation:

$$Q = \frac{P}{\eta} . \frac{1}{LHV_{gas}}$$

Whereby:

Q is the gas flow in norm. Conditions

P is the engine power

η is the mechanical efficiency

LHV is the Low Heating Value of the gas

$$Q = \frac{3.048kW}{0.86} . \frac{1}{9.5kWh/Nm^3}$$

$$Q = 0.373Nm^3/h$$

According to the calculation from the material balance Q is 16.0kg/h which will be received and combusted by the gas engine thus 14544kg/year of methane.

The amount of power could be completed using the electrical conversion efficiency using the equation below:

$Electrical\ energy = m_{CH_4} \times LHV_{CH_4} \times \Re \quad \times \eta_{el}$ (Surroop et al., 2011)

Whereby:

- m_{CH_4} is the flow rate of methane to be combusted in an engine
- $LHV_{CH_4}$is the lower heating value of methane (MJ/kg)
- $\boldsymbol{\Re}$is the recovery rate of methane from LFGTE process plant in % (44.2%)
- $\boldsymbol{\eta}$is the electrical efficiency of the gas engine (43.1%)

$$Electricity\ per\ year = 14\ 544 kg/year \times 0.442 \times 0.431 \times 37.5 MJ/kg$$

$$Electricity\ per\ year = 1\ 004\ 021 Wh/year$$

Thus;

$Electricity\ per\ year = 1.004 MWh/year$in 2013

The amount of electricity produced per year is 1.004MWh for the LFGTE process plant while the one that was said to be produced at Mare Chicose in Mauritius is 53.5GWh for 2013. This is unexpected because Mare Chicose is only 20 hectares while Bellville is 60 hectares and fifty per cent of it is said to be filled up. Bellville landfill site has been operating from 1970-2013 while Mare Chicose started operating in 1997-2013. It is well known that methane production at the landfill site depletes with time and the reason why Bellville landfill site produced low methane in comparison to Mare Chicose is because methane production is approaching depletion.TheBellville landfill site LFGTE process plant is designed to purify the gas before combustion while Mare Chicose combusts its gas directly from the landfill site. The reason for pointing out this matter is that the LFGTE process plant designed for Bellville landfill site is only 44.2% efficient, thus the recovery rate of methane available for conversion of electricity after purification.On the contrary, Mare Chicose recovery rate is 75%. Furthermore, the amount of methane for conversion to electricity at Bellville landfill site for 2013 is 14 544kg/yr while Mare Chicose is 14 124 900kg/yr so this is the reason why there could be more electricity produced at Mare Chicose landfill site than at Bellville landfill site. The reason why there is a need to pre-treat the landfill gas from Bellville landfill site is because it contains H_2S and VOC's. These components if they are not removed can cause inefficiency in a gas engine. For instance, VOC's can form a layer which can prevent enough transfer of heat energy. Both landfill sites used IPCC model for estimation of landfill gas.Moreover, the same model was used to estimate the amount of landfill gas from both Bellville and Mare Chicose landfill sites and the values estimated were reasonable.

5.6 Aspen Simulations

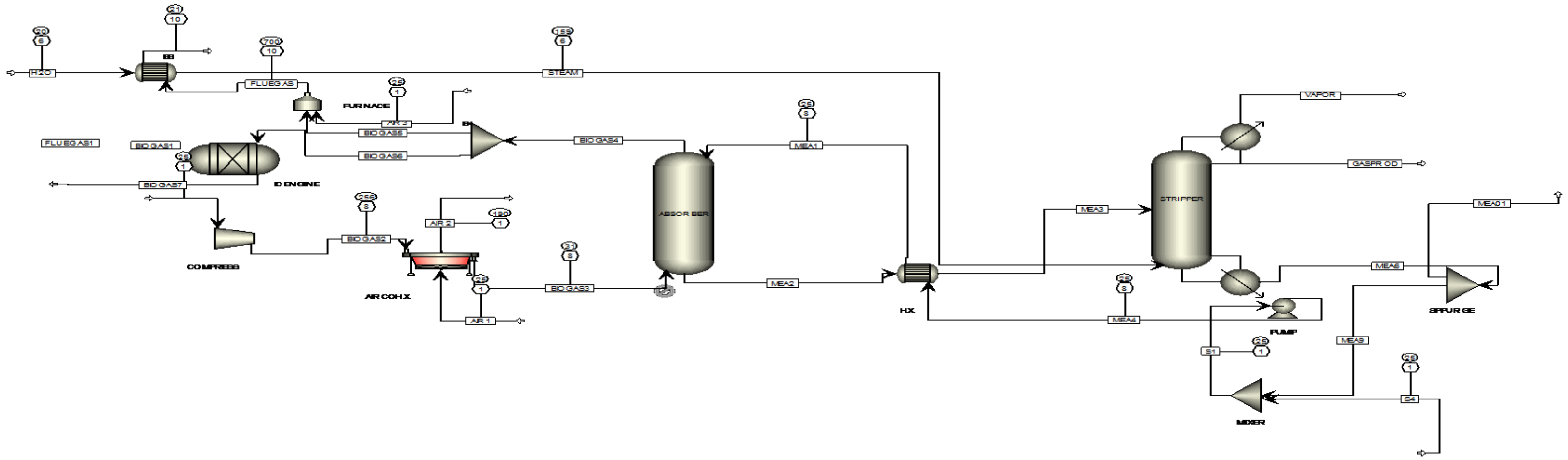

Figure 5.4: Process flow diagram from Aspen Simulation

Objective

The objective is to simulate and optimize the LFGTE plant with Aspen by varying pressure and number of stages in the absorption unit in order, to determine at which conditions will allow maximum yield of methane.

Methodology

Process Simulation

Aspen simulator was used in order, to test whether the designed LFGTE process plant can actually work. All the units used to build up this process are continuous and are at steady state. In this process the landfill gas simulation comprises of a compressor which increases the pressure and temperature of the gas in order, to get it ready for absorption but high temperatures are not suitable for physical and chemical absorption in this process. Therefore, air cooler is placed between the compressor and absorber so that, it can reduce the temperature of the gas. The air cooler uses natural air to lower the temperature of the landfill gas according to the specifications. The absorber unit was used to separate CH_4 from CO_2 and H_2S with the aid of MEA solution. After absorbing CO_2 and H_2S by MEA solution, the MEA solution takes these gases to the stripper. In the stripper, steam is used strip $CO_2$and H_2Swhich then exit the stripper from the top, stored and sold for commercial use. CH_4, VOC's and smaller quantities of CO_2 and H_2S are liberated from the top of the absorber. 10% of CH_4 is combusted in the furnace for generation of steam and 90% goes to the IC engine where CH_4 gets combusted and converted into electricity. The MEA solution in the stripper gets recycled, added to a fresh MEA solution and pumped back to the absorber for absorption of more CO_2 and H_2S.

Data Collection

The process operating conditions were collected from the literaturereview.It was collected from the articles which focused on separation of gases and suitable operating conditions of the units involved in various separation technologies.For instance, articles which were discussing enrichment of methane were used.

Results from Absorption unit:

This table shows how pressure variation would affect the yield of methane

Table 5.11: Pressure variation on the yield of methane

Pressure of column (bars)	Outlet stream of gas (kg/h)	CH_4flowrate in the outlet stream (kg/h)	Yield of CH_4 in (%)
3	1.48	1.27	86.3
4	3.31	2.86	86.4
5	5.37	4.61	85.7
6	7.70	6.53	84.8
7	10.39	8.67	83.4
8	13.61	11.08	81.4

The data in the table above shows that at 4 bars the yield of methane is produced at maximum and as pressure is increased the yield decreases.Below is the exhibition of results in a graphical form, on how the yield of methane appears when the pressure in the absorber was varied during the separation of gases by MEA. The absorber and stripper technology was chosen because it is discovered that it has lower operating cost and its efficiency is quite high comparable to other separation technologies.

The graph below shows the yield of methane and pressure variation in the absorber

Absorber Analysis

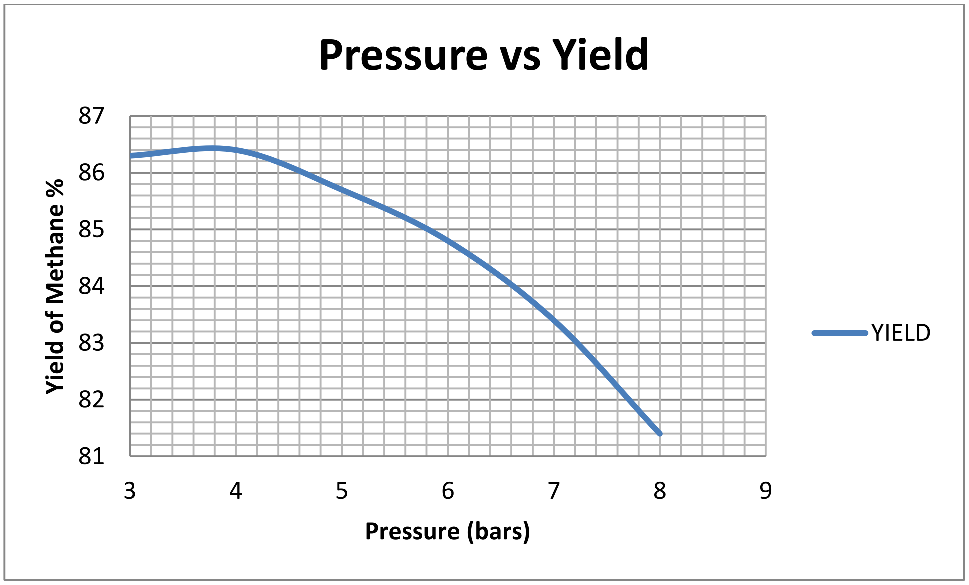

Figure 5.5: Absorber Analysis graph on change of pressure versus yield

The absorber unit portrays that 86.4% of pure $CH_4$is the maximum yield that can be attained at 4 bars. This methane is liberated at the top of the absorber unit to the IC engine where methane is combusted and converted to electricity.This information proves that chemical and physical reactions that were taking place in the absorber were relevant in meeting the desired process separation. Furthermore, it shows that CO_2 and H_2S had been absorbed in the MEA solution because the remaining percentage yield is that of CO_2, H_2S and VOC's which is quite low in comparison to the targeted methane gas.

This table shows how variation of number of stages in the absorber unit would affect the yield of methane

Table 5.12: Number of stages on the yield of methane

Number of stages	Pressure (bars)	Outlet stream of gas (kg/h)	CH_4flowrate in the outlet stream (kg/h)	Yield of CH_4 in (%)
6	4	3.22	2.80	87.0
7	4	3.25	2.81	86.4
8	4	3.26	2.83	86.8
9	4	3.28	2.84	86.6
10	4	3.29	2.84	86.3
11	4	3.30	2.85	86.4
12	4	3.30	2.85	86.4
13	4	3.31	2.86	86.4
14	4	3.31	2.86	86.4
15	4	3.31	2.86	86.4

The data in the table above shows that at stage 6 the yield of methane is produced at maximum at optimum pressure. This is an indication that as number of stages decreases the yield of methane increase.

The graph below shows the yield of methane and the effect of variation on number of stages in the absorber

Absorber Analysis

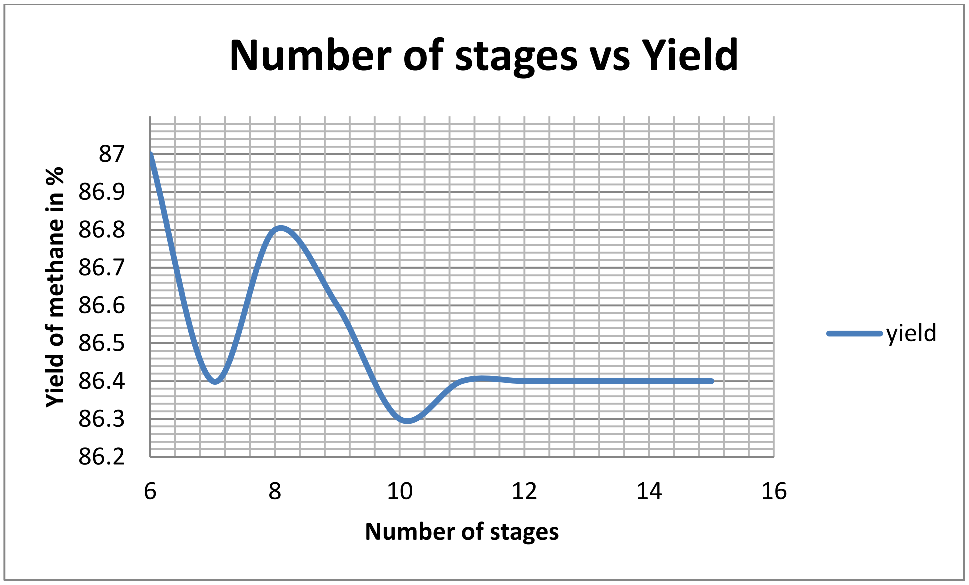

Figure 5.6: Absorber Analysis graph on change of number of stages versus yield

Figure 5.6 shows the when number of stages in the absorber is varied at optimum pressure 87% of pure methane can be produced. Stage six has proven to be the one suitable for this yield. Again the graph indicates that the less are number of stages present in the column results in high yield of methane.

Conclusion:

Other separation technologies were simulated. For instance, membrane technology from ChemCAD 6.5.5 simulator was used to separate methane from contaminants found in biogas upgrading plant and up to 90.69% of methane was recovered while the input to the process plant was 53.93% (Masebinu et al., 2014). While the absorption process simulation by Aspen plus used for running a LFGTE process plant simulation exhibited that 86.4-87% of methane was recovered while the input of methane in the process plant was 45% at optimum conditions of the absorber which are 4 bars and six number of stages in the absorption unitwhile for membrane recovery the optimal condition was 9.9 bars (Masebinu et al., 2014). According to this information the results obtained from the simulations when compared to the literature do not agree. Literature says that absorption system can recover about 100% of methane from one of the experiments which were carried out in Spain (Medigo et al., 2014). Although, the optimal conditions were not mentioned. While membrane can recover 98% of methane (Hulteberg et al., 2013).One of the reasons the results might not agree with literature is that for this project Aspen plus was used to simulate the process while the other author used ChemCAD 6.5.5 to run the methane recovery process. Therefore, it can be suggested that one simulator could be used at a time in order, to verify whether what the literature says is correct about the efficiencies of membrane and absorption technologies.In the next chapter safety and material of construction of the plant will be discussed. Furthermore, the economic evaluation of this project will be conducted.

CHAPTER 6

6. Introduction

This chapter will discuss the following issues in the designed LFGTE process plant; P&ID and HAZOP Analysis, material of construction and the economics and evaluation of LFGTE process plant.

6.1 Introduction to P&ID and HAZOP

During plant operation the instruments are there to monitor the key process variables. They can be used in automatic control loops and for manual monitoring of the process operation (Sinnot et al., 2005). Furthermore, these instruments can be part of an automatic computer data logging system. In plant operation the critical process variables are monitored by placing automatic alarms to notify the operators of critical and hazardous situations (Sinnot et al., 2005). It is preferable that the process variables to be monitored be measured directly, and frequently, however, this is not always so in practice and some dependent variables, whichare easier to measure, are monitored online (Sinnot et al., 2005). For instance, in a distillation column its controls are continuous, on-line, assessing of the overhead product is desirable but not easy and costly to achieve reliably, instead temperature is monitored as an indication of composition most times (Sinnot et al., 2005). The temperature instrument maybe made part of a control loop, for example, reflux; with the composition of the overheads checked often by sampling and laboratory analysis (Sinnot et al., 2005).

6.2 Instrumentation and control objectives

The primary objectives of the designer when specifying instrumentation and control schemes are:

<u>Safe plant operation</u>:

- To keep the process variables within known safe operating limits.

- To detect dangerous situations as they develop and to provide alarms and automatic shut-down systems.
- To provide interlocks and alarms to prevent dangerous operating procedures.

(Sinnot et al., 2005)

Production rate:

- To achieve the design product output. (Sinnot et al., 2005)

Product quality:

- To maintain the product composition within the specified quality standards.

(Sinnot et al., 2005)

Cost:

- To operate at the lowest production cost, commensurate with the other objectives. (Sinnot et al., 2005)

Altogether, these objectives are inseparable and must be taken into consideration. The order in which they are listed is based on safety purposes. Product quality, production rate and the cost of production depends on sales requirements. For instance, is it preferable to make a better-quality product at a higher cost (Sinnot et al., 2005). In a typical chemical processing plant these objectives are achieved by a combination of automatic control, manual monitoring and laboratory analysis.

6.3 Automatic-control schemes

There are specialistswhoare usually responsible for the detailed design and specification of the automatic control schemes for a 250m^2 project. The major step in the specification of control systems for a process will be discussed: This will involve a preliminary scheme of instrumentation and control, developed from the process flow-sheet (Sinnot et al., 2005). The process designer can draw up the process plant facilitated by his critical assessment of the process requirements. In this case, several control loops will be conventional and a detailed analysis of the system behaviour would not be required nor specified (Sinnot et al., 2005). Judgment is done based on experience, on the decision made which systems are critical and need detailed analysis and design. Examples of typical (conventional) control systems used for the control of specific process variables and unit operations are given below and can be utilized as a guide in preparing preliminary instrumentation and control schemes (Sinnot et al., 2005).

Guide rules

To ensure the safety of the designed LFGTE process plant certain control instruments are supposed to be included in the process in order to correct deviations that are likely to occur along the process.

The following proceduresthatcan be used when drawing up preliminary Process Instrumentation and Diagrams are as follows:

1. Identify and draw in those control loops that are obviously needed for steady plant operation, such as:

- level controls
- flow controls
- pressure controls
- temperature controls

2. Identify the key process variables that need to be controlled to achieve the specified product quality. Include control loops using direct measurement of the controlled variable, where possible; if not practicable, select a suitable dependent variable.

3. Identify and include those additional control loops required for safe operation, not already covered in steps 1 and 2.

4. Decide and show those ancillary instruments needed for the monitoring of the plant operation by the operators and for trouble-shooting and plant development. It is well worthwhile including additional connections for instruments which may be needed for future trouble-shooting and development, even if the instruments are not installed permanently. This would include: extra thermo-wells, pressure tapping, orifice flanges and extra sample points.

5. Decide on the location of sample points.

6. Decide on the need for records and the location of the readout points, local or control room. This step would be done in conjunction with steps 1 to 4.

7. Decide on the alarms and interlocks needed, this would be done in conjunction with step 3.

(Sinnot et al., 2005)

6.4 Process & Instrument Design Description

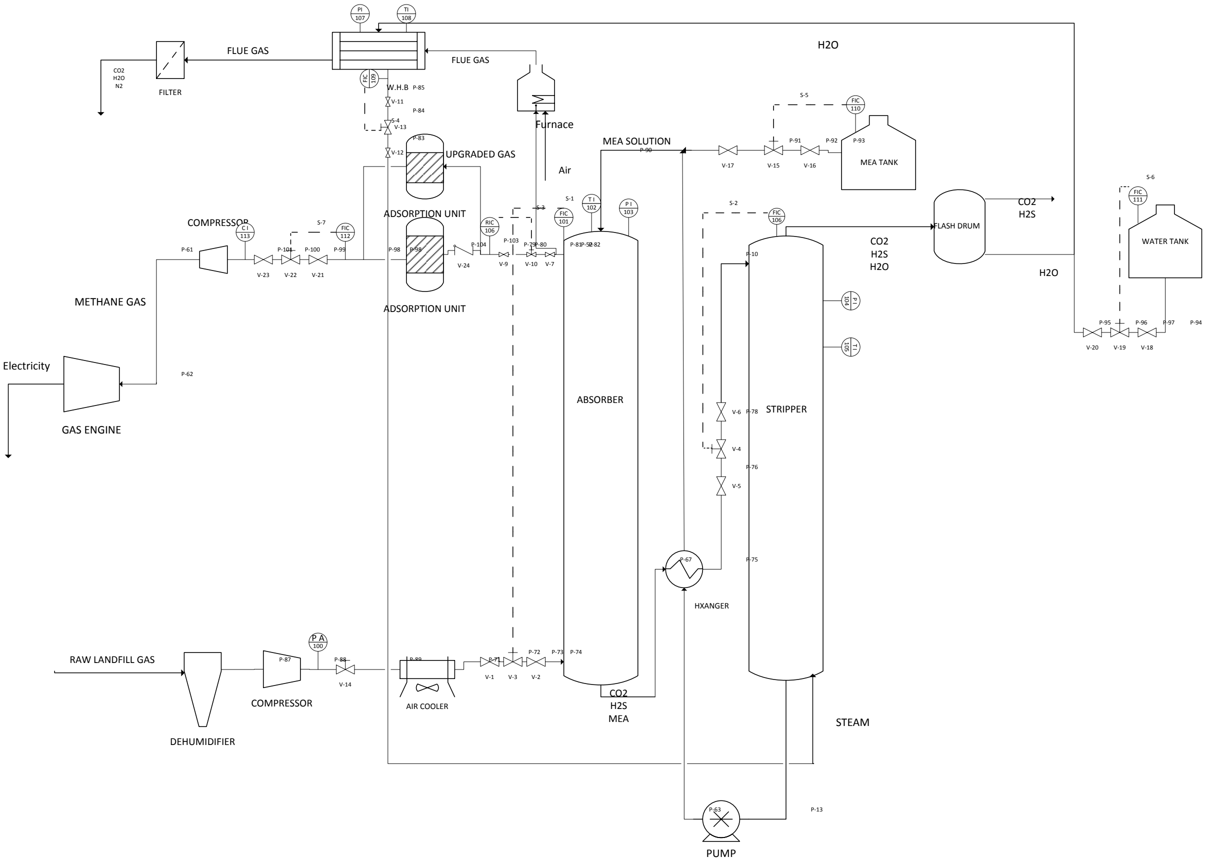

Figure 6.1: Process & Instrument Design Diagram

The raw landfill gas after it has been dehumidified and compressed its temperatures must be decreased by an air cooler before entering the absorber. The absorber has a pressure controller indicator, temperature indicator controller and a flow rate indicator controller. So what happens when temperature and pressure are not within specifications is that the flow rate indicator controller controls the flow rate according to how the variables are supposed to be. For instance, if the temperature and pressure of the landfill gas are high the flow rate of the gas is decreased. If the variables conditions decrease then the flow rate indicator controller must act otherwise. The stripper has the similar instruments and process control, the operation is the same as done by the absorber instruments. At gas outlet of the absorber there is a ratio indicator controller which monitors the flow ratio of the gas to the adsorption system and furnace. If there is a change to a desired ratio, then the ratio indicator controller, automatically adjust the flow rate accurately.

Thewaste heat boiler (WHB) also has temperature, pressure and flow rate indicator and control instruments. The WHB is responsible for generation of steam, which is used as a stripping agent. Whenever the temperature and pressure variables deviate from their set points, the flow rate indicator controller manipulates the flow rate of the steam. The stripping performance relies on the quality of steam. After the adsorption system there is composition detector which is responsible for showing the purity of methane in the stream.

When the traces of VOC's are detected the alarm goes off and the flow rate indicator controller adjusts the flow rate of the gas. There are two reasons why the VOC's can be present in the stream. Firstly, it can be due to high flow rate of the gas preventing prolonged contact time between the gas and the adsorbent. Secondly, the adsorbent can be saturated and no longer adsorb the VOC's. For the adsorption system, there are two adsorption units connected in parallel. They do not operate at the same time, with one on standby. In order to ensure that happens there will be an alarm installed with the system, which will go off and as soon as it goes off a check valve will automatically close completely.

The gas will be channeled into another adsorption unit for treatment. There is a flow rate indicator controller along the water tank system; its duty is to control the flow rate of water for generation of steam. Similarly the MEA tank has a flow rate controller to control the flow rate of MEA in the makeup stream, for strengthening of the lean one, coming from the stripper.

Pictures of some of the P&ID Instruments

The pictures below are of some types of valves and meters used in the process control of the LFGTE plant. All the conditions in the process plant are monitored with digitalmeters.

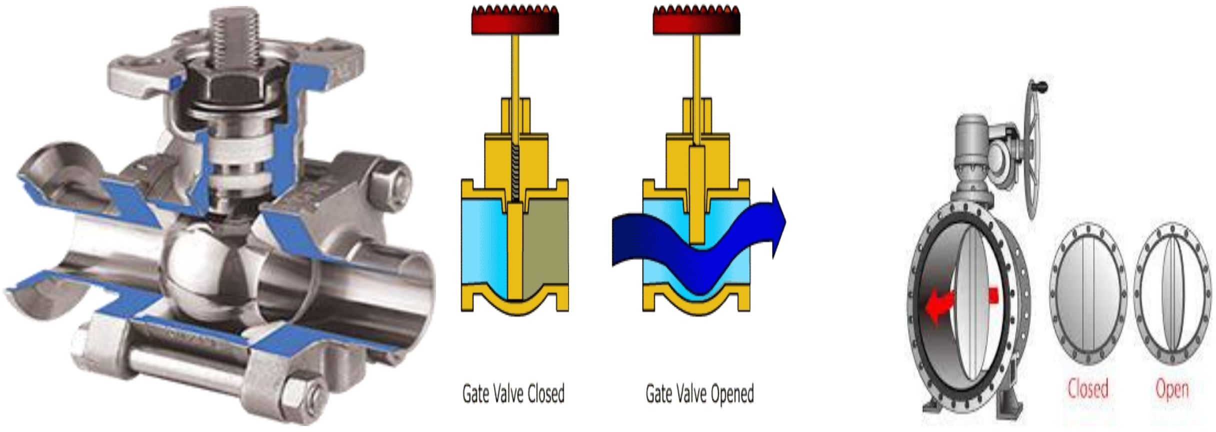

Figure 6.2: Diagrams of ball, gate and butterfly valves

Figure 6.3: Digital flowmeter

Figure 6.4: Digital pressure gauge

Figure 6.5: Digital thermometer

6.5 HAZOP Analysis

6.5.1 Introduction

For systematic process design study, a formal operability study must be done, vessel by vessel, and line by line, with the aid of “guide words” to facilitate in the creation of thought based on how deviations from the set operating conditions could start hazardous situations (Sinnot et al., 2005). There are seven guide words recommended for a formal operability study of a process design and operation:

Intention: the intention explains how the particular part of the process was intended to operate; the intention of the designer.

Deviations: these are departures from the designer’s intention which are detected by the systematic application of the guide words.

Causes: reasons why and how, the deviations could occur. Only if a deviation can be shown to have a realistic cause is it treated as meaningful.

Consequences: the results that follow from the occurrences of a meaningful deviation.

Hazards: consequences that can cause damage (loss) or injury.

(Sinnot et al., 2005)

6.5.2 Introduction to HAZOP Analysis

There are other words like no/not, more and less used for formal operability study of the design. For instance, when manipulating process plant operational parameters for a hazard and operability study (Sinnot et al., 2005).

Below is a procedure that an engineer might use in conducting a hazard and operability study.

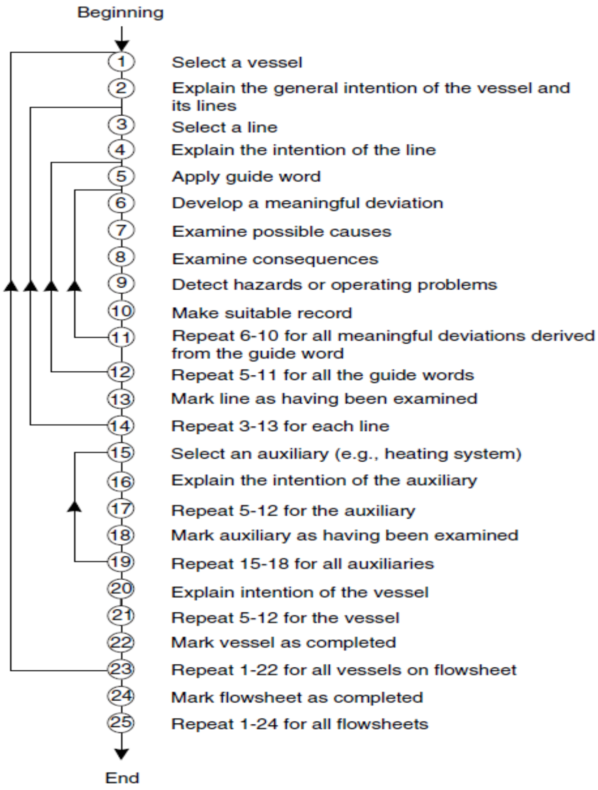

Figure 6.6: Procedure for conducting HAZOP (Sinnot et al., 2005)

Explanation on the guide words used for a hazard and operability study:

As well as: something in addition to the design intention, such as, impurities, side-reactions, ingress of air, extra phases present.

Part of: something missing, only part of the intention realized; such as the change in composition of a stream, a missing component.

Reverse: the reverse of, or opposite to, the design intention. This could mean reverse flow if the intention was to transfer material. For a reaction, it could mean the reverse reaction. In heat transfer, it could mean the transfer of heat in the opposite direction to what was intended.

Other than: an important and far-reaching guide word, but consequently more vague in its application. It covers all conceivable situations other than that intended, such as, start-up, shut-down, maintenance, catalyst regeneration and charging failure of plant services.

When referring to time, the guide words SOONER THAN and LATER THAN can also be used.

(Sinnot et al., 2005)

Table 6.1: List of Guide Words (Sinnot et al., 2005)

Guide words	Meanings	Comments
NO or NOT	The complete negation of these intentions	No part of the intentions is achieved but nothing else happens.
MORE LESS	Quantitative increases or decreases	These refer to quantities and properties such as flow rates and temperatures as well as activities like “HEAT” and “REACT”
AS WELL AS	A qualitative increase	All the design and operating intentions are achieved together with some additional activity
REVERSE	The logical opposite of the intention	This is mostly applicable to activities for example reverse flow or chemical reaction. It can also be applied to substances, e.g. POISON instead of “ANTIDOTE” or “D” instead of “L” optical isomers.
OTHER THAN	Complete substitution	No part of the original intention is achieved. Something quite different happens.

6.5.3 HAZOP Analysis within the LFGTE process plant

Operability Study

Vessel – dehumidifier's outlet stream

Intention – to remove moisture that will foul the compressor

Guide word	**Deviation**	**Cause**	**Consequences and Action**
Less of	The flow rate of the landfill gas is low. Its suppose to be 3.62kg/h ±10% of landfill gas fed into the process plant, but it has deviated below those values.	The cause of the deviation in the flowrate specification could be that the filter is partially blocked. Therefore, the amount of flowrate of landfill gas expected to go through could not.	If the blockage increases the process plant would end up using lots of energy to drive the compressor which will increase the running cost of the plant. The action that should be taken regarding this matter, is to maintain the filter regularly, at least the filter must be monitored every morning for debris.
As well as	Composition: the composition of the landfill gas consists of moisture at the outlet stream of the dehumidifier.	The cause of deviation in the dehumidifier could be due to the wear and tear or wrong installation of some parts within the unit.	If water enters the compressor it will cause fouling in the compressor. The composition indicator controller should be installed on the outlet stream of the dehumidifier, so that when the composition of water is more than

			10% of the set point it should make the alarm go off.

Vessel- compressor’s outlet stream

Intention- to supply gas at 1.78MPa to the absorber

Guide word	**Deviation**	**Cause**	**Consequences and Action**
No/None	The landfill gas is not reaching the absorber at all for its purification.	This is due to the amount of pressure supplied by the compressor that is 10% lower than 1.78MPa, which is the specified pressure for operating the compressor.	When the landfill gas is not entering the absorber this will result in MEA being wasted because it will not be absorbing any CO_2 and H_2S from CH_4. The furnace will not be getting 10% CH_4 which is used for converting water into steam and this steam is used as a stripping agent in the stripper for separating MEA from CO_2 and H_2S. If they are not stripped there will be a build-up of these compounds in the plant. The solution to

			this problem is to install, alarms sensitive to the flowrate of gas.
More	The flow rate of gas is higher than 1.78MPa±10% due to the high pressure from the compressor unit.	The cause of high than 10% of 1.78MPa can be due to the failure of pressure controls.	The amount of pressure for MEA might fail to absorb the necessary gases due to the amount of flowrate and pressure of those gases entering absorption unit. The pressure alarms should be installed.

Vessel- air cooler's outlet stream

Intention- to supply absorber with landfill gas at 32°C

Guide word	**Deviation**	**Cause**	**Consequence and Action**
More	The temperature of the landfill gas is more than 10% of 32°C. ±10% of 32°C is the amount suitable for operating conditions of the absorption column.	The gate valve after the compressor maybe fully opened, which reduces the contact time between the gas and air in the air cooler heat exchanger.	If the temperature of the landfill gas is more than 32°C±10%, it is not suitable for absorption process and CO_2 and H_2S will escape with CH_4 into the IC engine. Therefore, cause corrosion to the parts of the engine. The temperature

			indicator controler should be installed at the air cooler outlet stream.

Vessel- absorber's inlet stream

Intention- to separate methane from carbon dioxide and hydrogen sulphide

Guide word	**Deviation**	**Cause**	**Consequence and Action**
More	The temperature is 32°C±10% high in the absorption column. 32°C is the suitable temperature for absorption conditions.	The flow rate of landfill gas is 3.62kg/h +10% more. This is because of the gate valve which is partially opened located between the compressor and air cooler.	If the temperature is greater than 35°C, absorption of CO_2 and H_2S cannot occur. H_2S can corrode the engine parts if not removed. The flowrate of the gas to the absorber can be controlled with flow rate indicator controller (FIC).
Less	The flow rate of MEA solution is low. It is suppose to be 1.62kmol/h ±10%.	The reason why the flowrate of MEA solution is low its due to the valve that is partially closed and the back flow of MEA solution.	CO_2 and H_2S cannot be fully absorbed by MEA. Therefore, H_2S presence can cause damage to the engine parts. A non-return valve can be installed incase there is a back flow and a flow

			controller can be placed at the MEA stream to the absorber column.

Vessel – stripper's inlet stream

Intention- to liberate carbon dioxide and hydrogen sulphide at 112°C and 0.1MPa

Guide word	**Deviation**	**Cause**	**Consequence and Action**
Low	The temperature of MEA solution with CO_2 and H_2S leaves the heat exchanger at a lower temperature which is 112°C±10%	The reason could be an increase in flow rate of MEA solution in the heat exchanger positioned between the absorber and stripper.	If the temperature of this MEA solution does not meet the stripping specifications, then CO_2 and H_2S will fail to be stripped from solution and end up being recycled. Therefore, cause a build-up in the process plant. The flow rate of MEA solution into the heat exchanger should be manipulated by (FIC).
Low	The temperature of steam is lower than	The steam can loose its energy along due	If the steam looses energy before

	120°C. It should be 120°C+10%.	to partially opened gate valve on its way to the stripper, after leaving W.H.B	reaching the stripper, it will start condensating and fail to strip CO_2 and H_2S in the column. Control the gate valve and the flow of water for steam generation.

Vessel- adsorber's outlet stream

Intention- to remove VOC's from the gas before converting methane into electricity

Guide words	**Deviation**	**Cause**	**Consequence and Action**
More	VOC's concentration in the IC engine	The reason why VOC's concentration is high is due to saturation point reached by activated carbon in the unit.	If VOC's are present in the engine this may lead to damaging of gas engine parts.Install an alarm which will go off when the concentration of VOC's reaches limits as well as composition indicator controller for VOC's at the outlet of the adsorber column.

6.6 Material of Construction

It is important to know the material of construction for the equipment of the process plant. The reason why it is essential to know material used for construction of the equipment is to enable costing of a plant and to avoid the possibilities of rapid corrosiveness along the process plant. For instance, the pipe lines and fittings are made out of stainless steel and carbon steel. The stainless steel pipes are used where there is flow of MEA in a process. The reason why stainless steel pipes are used is because MEA is corrosive. The material of construction for pipes in this process plant is stainless steel and carbon steel. The stainless steel pipes will be used along the process route where MEA solution is present and where its not carbon steel pipes will be used.

Material of construction of the Absorber

The material of construction for an absorber is stainless steel; it is a packed column which is packed with ceramic raschig rings. The reason for opting for a stainless steel absorber unit it is to prevent rapid corrosion that can be due to MEA solution. Again ceramic packing was chosen prior to any other material because it will not be damaged by the corrosive MEA solution.

Figure 6.7: Raschig rings

Figure 6.8: Stainless steel Absorber

Figure 6.9: Stainless steel pipes

Stainless steel pipes are going to be used for any route along the process that will be containing MEA solution. For instance, the inlet pipe to and from the absorber containing MEA solution and other materials will be transported using stainless steel pipes. The heat exchanger which is in between the absorber and stripper, all of its outlet and inlet streams will be made out of stainless steel pipes.

Figure 6.10: Carbon steel pipes

Carbon steel pipes are going to be used to transport fluids that do not contain MEA solutions in them. Thus from the humidifier outlet to the air compressor, the compressor outlet, the outlet of the absorber for the vapour and carbon steel pipes are also used for the inlets and outlets for the following units; adsorption unit, furnace, waste heat boiler, compressor and gas engine. For transportation of landfill gas from the landfill site polyvinyl chloride pipes are used.

Material of construction for a Stripper

The material of construction for a stripper is stainless steel; it is a packed column which is ceramicintalox saddles. The reason of using ceramic intalox saddles is to increase contact time between the steam and MEA solution, so that content of $CO_2$and H_2S can be stripped from the MEA solution. In addition, ceramic saddles have high mechanical strength and their cost price is low (Nieuwoudt et al., 2015).The reason for using stripper unit made out of stainless steel is to prevent rapid corrosion that can be caused by MEA.

Figure 6.11: Intalox ceramic saddles

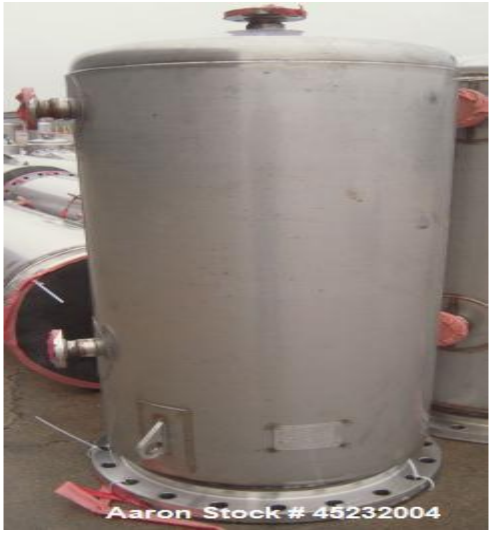

Figure 6.12: Stainless steel stripper

The stripper is made out of stainless steel material because there are two corrosive fluids which are treated in the unit and they are steam and MEA solution. All the inlet and outlet pipes are made out of stainless steel.

Figure 6.13: carbon steel flash drum

The flash drum is made out of carbon steel because it separates CO_2 and H_2S from condensed steam. To prevent corrosiveness that can be caused by water it is coated by water resistant paint.

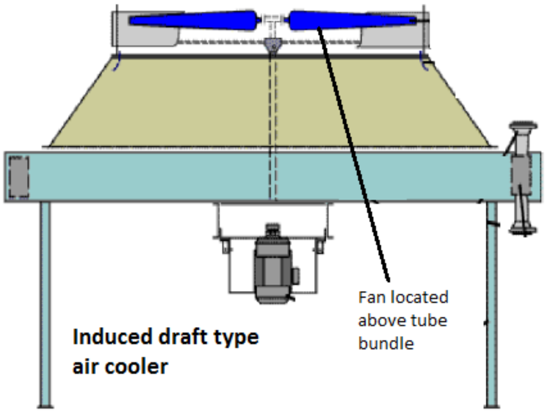

Figure 6.14: Induced air cooler

The air cooler gets the LFG ready for absorption process by lowering the temperatures of LFG, using natural air as a cooling fluid. It works just like a heat exchanger during this process.It is located in between the air compressor and absorber.

Figure6.15: Gas Engine

The gas engine is responsible for internal combustion of purified methane. It converts methane into electricity.

6.7 Economics and Evaluation of LFGTE process plant

6.7.1 Introduction

Cost estimation is a specialised subject and a profession in its own right. The design engineer, however, needs to be able to make quick, rough, cost estimates to decide between alternative designs and for project evaluation. Process plants are built to make a profit, and an estimate of the investment required and the cost of production are needed before the profitability of a project can be assessed.

In this chapter the various components that make up the capital cost of a plant and the components of the operating costs are discussed. Simple costing methods and some cost data are given, which can be used to make preliminary estimates of capital and operating costs at the flow-sheet stage. They can also be used to cost alternative processing schemes and equipment. For a more detailed treatment of the subject the reader should refer to the numerous specialised texts that have been published on cost estimation.

6.7.2 Theoretical Background

There are five ways of estimation of capital costs:

- Order of magnitude estimate
- Study estimate
- Preliminary estimate
- Definitive estimate
- Detailed

Although, we will not be using all of them, in estimating the capital costs for this design. We are just going to explain how we used the first two as this is a feasibility design.

6.7.3 Order-of-magnitude

This estimate is done by taking plants of the previous years for the cost information of the new plant. We use the following equation:

$C_2 = C_1(\frac{S_2}{S_1})^n$……………………………………..(1)

Where C_2 is the capital cost of the project with capacity S_2 and C_1 is the capital cost of the project with capacity S_1. The value of the n is traditionally taken as 0.6.

6.7.4 Study estimate

This estimation is done by sizing the main equipment that are present in the process and determine their approximate cost. The total cost of equipment is then factored in order, to give the estimated capital cost.

Table 6.2: Factors for estimation of project fixed capital cost (Sinnott et al., 2005)

	Process type		
Item	Fluids	Fluids-Solids	Solids
1. Major equipment cost	PCE	PCE	PCE
f_1 Equipment erection	0.40	0.45	0.50
f_2 Piping	0.70	0.45	0.20
f_3 Instrumentation	0.20	0.15	0.10
f_4 Electrical	0.10	0.10	0.10
f_5 Buildings, process	0.15	0.10	0.05
f_6 Utilities	0.50	0.45	0.25
f_7 Storages	0.15	0.20	0.25
f_8 Site development	0.05	0.05	0.05
f_9 Ancillary buildings	0.15	0.20	0.30
2. Physical plant cost (PPC) PPC = PCE(1+f_1+...+f_9)	3.40	3.15	2.80
f_{10} Design and Engineering	0.30	0.25	0.20
f_{11} Contractor's fee	0.05	0.05	0.05
f_{12} Contingency	0.10	0.10	0.10
Fixed capital = PPC(1 + f_{10} + f_{11} + f_{12})	1.45	1.4	1.35

For the determination of Net Present Value of the project the following calculations were done.

- Depreciation
- Gross profit
- Tax
- Net profit
- Cash Flow
- Discounted Cash Flow
- Net Present Value

6.7.5 Depreciation

The depreciation can be calculated by using either straight-line method, sum of the years digits depreciation (SOYD), or Double Declining Balance Depreciation Method (DDB).

Straight line: $d = \frac{C_{fk} - S}{n}$………………………………. (2)

WhereC$_{fk}$-fixed capital investment, d- depreciation amount per year, S is the salvaged value and n is number of years of the equipment.

Straight line method is found to be simplest depreciation method to compute, it can be applied to all long-term assets, the depreciation value for each period of assets service life is the same and it is usable method (Peterson et al., 2002). On the other hand, it does not reflect accurately the difference in usage of an asset from one period to other andit does not match costs with revenues in different types of long-term assets (Peterson et al., 2002).

For sum of the years digits depreciation (SOYD) the equation is as follows:

$d_k^{soyd} = \frac{[n+1-k][C_{fk}-S]}{\frac{n}{2}[n+1]}$…………………………………. (3)

SOYD better matches costs to revenue because it takes more depreciation in the early years of an assets useful life compared to the straight line depreciation method and SOYD reflects more accurately the difference in usage of various assets from one period to the other compared to the straight line depreciation method(Peterson et al., 2002). On the contrary, the method might be confusing and difficult to compute, compared to the straight line method (Peterson et al., 2002).

For Double Declining Balance Depreciation Method (DDB) the equation is as follows:

$d_k^{DDB} = \frac{2}{n}\left[C_{fk} - \sum_{j=0}^{j=k-1} d_j\right]$……………………………….(4)

DDB better matches costs to revenues because it takes more depreciation in early years of an assets useful life compared to the straight line depreciation method and it reflects better the difference in usage of an asset from one period to the other compared to the straight line depreciation method. Although, DDB is found to be harder to compute in comparison to the straight line depreciation method (Peterson et al., 2002).

In conclusion the straight line method will be used for depreciation of this LFGTE process plant. This is because in South Africa the straight line method it is the one used for depreciation of properties.

6.7.6 Gross profit

We obtain gross profit as follows:

$P_{gross} = R - C_{op}$……………………………………(5)

Where R is the sales revenue and C_{op} is the cost of operation or manufacturing.

6.7.7 Tax

To calculate taxwehave;

$T = (R - C_{op} - d)t$…………………………………..(6)

Where *T* is the tax cost/charge, *t* is the income tax rate.

6.7.8 Net profit

We obtain this value by subtracting tax from the gross profit as follows:

$P_{net} = P_{gross} - T = \left(R - C_{op} - d\right)(1 - t) + d$……………………………….(7)

6.7.9 Cash Flow

The cash flow is determined by finding the difference between net profit and fixed capital investment.

$CF_k = P_{net} - C_{fk}$…………………………………………………………….(8)

Where CF_k is the cash flow in year *k*, C_{fk} is the fixed capital investment in year *k*.

6.7.10 Discounted Cash Flow

This is the money earned in any year and can be put to work as soon as it is available and start to earn a return. The money earned in the early years of the project is more valuable than that earned in later years. Discounting the money is bringing it to its present value. This is done by compounding the money to some chosen interest rate.

$DCF_k = \frac{CF_k}{(1+r)^k}$………………………………………..(9)

Where DCF_k is the discounted cash flow in year *k*, *r* is the given *effective interest rate*.

6.7.11 Net Present Value

The Net Present Value (NPV) of a project is the cumulative discounted cash position at the end of the project. Put differently, it is the sum of the discounted cash flows (DCF).

$NPV = \sum_{k=1}^{n} \frac{CF_k}{(1+r)^k}$………………………………………(10)

6.7.12 Cost of plant

The next table will show the results of the costs and the number of P&ID Instruments present along the LFGTE process plant obtained from Alibaba Manufacturer (2016)

Table 6.3: Cost price and the number of P&ID Instruments

Instrument	No. of units along the process flow diagram	Cost price for unit (R)	Total cost price (R)
FIC	5	686	3 430
PA	1	540	540
Control Valves	19	670	12 730
TI	3	910	2 730
PI	3	280	840
RIC	1	700	700
CI	1	860	860
Relief pressure/ Safety valve	6	630	3 780
Total	**39**	**5 276**	**25 610**

Table 6.4: Capital and Operating costs estimates were done with the aid of data form Sinnott et al., (2005)and Alibaba Manufacturers (n.d.). Furthermore, prices for other units were obtained from their manufacturers through the inernet.

Unit	**Diameter (m)**	**Prices**
Absorber	0.72	R 14 650
Stripper	0.50	R 14 621
Pump	0.00	R 4 395
Dehumidifier	0.00	R 4 152
Furnace	0.00	R 20 657
Flash drum	1.00	R 7 500
MEA Storage Tank	2.70	R 3 000
Adsorption column 1	1.00	R 8 790
Compressor 1	0.50	R 6 633
Filter	0.00	R 2 105
Air cooler heat exchanger	0.24	R 7 325
Shell-tube heat exchanger	0.74	R 9 757
Gas engine	0.00	R 29 300
Water Storage Tank	0.79	R 3 000
Adsorption column 2	1.00	R 8 790
Compressor 2	0.50	R 6 633
W.H.B.	1.00	R 36 625
Activated Carbon	0.00 (10 tons)	R 10 988
Raschig rings	Cubic meter	R 11 900
Intalox ceramic saddles	Cubic meter	R 32 340
P&ID Instruments	39 instruments	R 25 610
Plant substation (main breaker, step-up transformer)		R 73 250
Electrical cables (2km)		R 14 650
TOTAL		R 356 671
PIPING		R 14 556

The depreciation of the plant life is done using the straight line method. The life span of Bellville landfill site is 5 to 13 years (CCT et al., 2013).As for this project the life span will be 9 years which is the median of 5-13 years. The salvaged value for each equipment for this project is 10% of the cost price. Inflation rate is 6.25%, as for interest rate is 15% and tax rate is 41%.According to Kanyarusoke et al., (2016) who has several years of experience at the industries said that the maintenance is 4% of total capital cost and this percentage will be used in order, to determine the maintenance cost for this project.For labour three engineers who have obtained their diplomas in chemical engineering will be hired for operation of this pilot plant and each will be paid R15 000 per month.According to (Thopil et al., 2013) the cost of one cubic meter of MEA is R199.6.Thus for a consumption of 12 499 m ^{3} per annum its costs will beR2, 5 million. The designed LFGTE process plant also produces a by-product CO_2. Which can be sold for additional revenue, in some industries it can be used as an extraction agent and again it can be sold to food industries where it can be used as a food preservative. A cubic meter of CO_2 gas is sold for R147per kg and the production of CO_2 per annum from the designed LFGTE process plant is 30 577kg/yr or 57 222m^3/yr which gives R4, 5 million from selling CO_2 per annum. Eskom's average electricity price R 2.86/kWh.Therefore, the total revenues amount to R 4, 7 million for this project which is made from selling of electricity and CO_2.

The tabulated data below shows how annual cost price for each equipment was determined for the period of 9 years of this project. It will be calculated by saying;

$$Annual\ Cost = \frac{C_{fk} - S}{n}$$

Where:

C_{fk}= cost price of the equipment

S= salvage value which is 10% of the cost price per equipment

n= number of years (life span of the plant which is 9 years in this case)

Table 6.5: Annual cost price ofequipment for the life span of LFGTE process plant

Equipment	C_{fk} in (ZAR)	S in (ZAR)	n (years)	Annual Cost price in (ZAR)
Absorber	14 650	1 465.0	9	1 465
Stripper	14 621	1 462.1	9	1 462
Pump	4 395	439.5	9	440
Dehumidifier	4 152	415.2	9	415
Furnace	20 657	2 065.7	9	2 066
Flash drum	7 500	750.0	9	750
MEA Storage tank	3 000	300.0	9	300
Adsorption column 1	8 790	879.0	9	879
Compressor 1	6 633	663.3	9	663
Filter	2 105	210.5	9	211
Air cooler HX	7 325	732.5	9	733
Shell-tube HX	9 757	975.7	9	976
Gas engine	29 300	2 930.0	9	2 930
Water storage tank	3 000	300.0	9	300
Adsorption column 2	8 790	879.0	9	879
Compressor 2	6 633	663.3	9	663
W.H.B	36 625	3 662.5	9	3 663
Raschig rings	11 900	1 190.0	9	1190
Intaloxceramic saddles	32 340	3 234.0	9	3 234
P&ID Instrument	25 610	2 561.0	9	2 561
Transformer	73 250	7 325.0	9	7 325
Electrical cables (2km)	14 650	1 465.0	9	1 465

Piping	14 556	1 455.6	9	1 456
Total equipment cost				**36 026**
Maintenance cost				1 441
Running cost				2 510 988
TotalFixed Capital				**2 548 455**

According toRogoff et al., (2008) the IC Engine power plant project case study of Loma de Los Cocos Landfill Cartagena de Indias, Colombia cost R37, 4 million while Bellville landfill site total costs were estimated at R2, 5million. Bellville landfill site LFGTE process plant costs this much because its size is 250m^2 and itisa pilot plant.Expenses like equipment for material of construction played a major role in the costs because some parts of the process plant is made of stainless steel while the other is made of carbon steel and polyvinyl chloride. The technology used for purification of landfillgas also contributed to the increase in the cost of this project including the reagents used for purification of LFG. While the Colombian case study showed the costs for mobilization and project management, plant construction including piping, LFG measuring and recording equipment, LFG-fired 1 600kW Gen-set, plant sub-station, electrical interconnection, source test and contingency.For Bellville landfill site some of the cost from Colombian case study were included in the material of construction of the equipment, technology for purification of LFG, P&ID instruments and purification agents for absorption process. The capacity of Bellville landfill site is 250m^{2}according to the tabled design and that of Colombia is way greater than it and this is proven by the sizes of equipment used at the Colombia landfill site, though the LFGTE capacity was not specified, sothat is why the total costs for Colombian case study are higher than that of Bellville landfill site study. The reason why Bellville landfill site case study is compared to the Colombian case study when it comes to the total cost is because they are both IC Engine power plants(Rogoff et al., 2008).

6.7.13 Profitability Analysis

The following values contribute in determination of the Net Present Value of this project, the calculations are shown in Appendix E:

6.7.13.1 Gross profit:

R 2 238 689

6.7.13.2 Tax:

R 917 862the taxation was included in this project because it makes profits due to the sales of CO_2.

6.7.13.3 Net Profit:

R 1 320 827

6.7.13.4 Cash flow:

R 1 284 801

6.7.13.5 Payback time:

1.91≈2 years after operations of the plant. In this case design and construction periods are excluded, if included the overall payback time is 4 years

6.7.13.6 Discount Cash Flow:

R 1 209 244

6.7.13.7 Net Present Value: $\sum_{k=1}^{n} \frac{C_k}{(1+r)^k}$

Microsoft excel was used to calculate the net present value

Table 6.6: Net Present Value calculations adapted from Microsoft Excel

C_k	k	r	DCF
−1 284 801	1	1.0625	-1 209 244
−1 284 801	2	1.0625	-1 138 094
1 284 801	3	1.0625	1 071 147
1 284 801	4	1.0625	1 008 138
1 284 801	5	1.0625	948 836
1 284 801	6	1.0625	893 022
1 284 801	7	1.0625	840 491
1 284 801	8	1.0625	791 051
1 284 801	9	1.0625	744 518
NPV			**3 949 865**

Net Present Value =R 3 949 865 and this is a profit for the LFGTE project at Bellville landfill site

6.7.13.9 Cash Flow Diagram

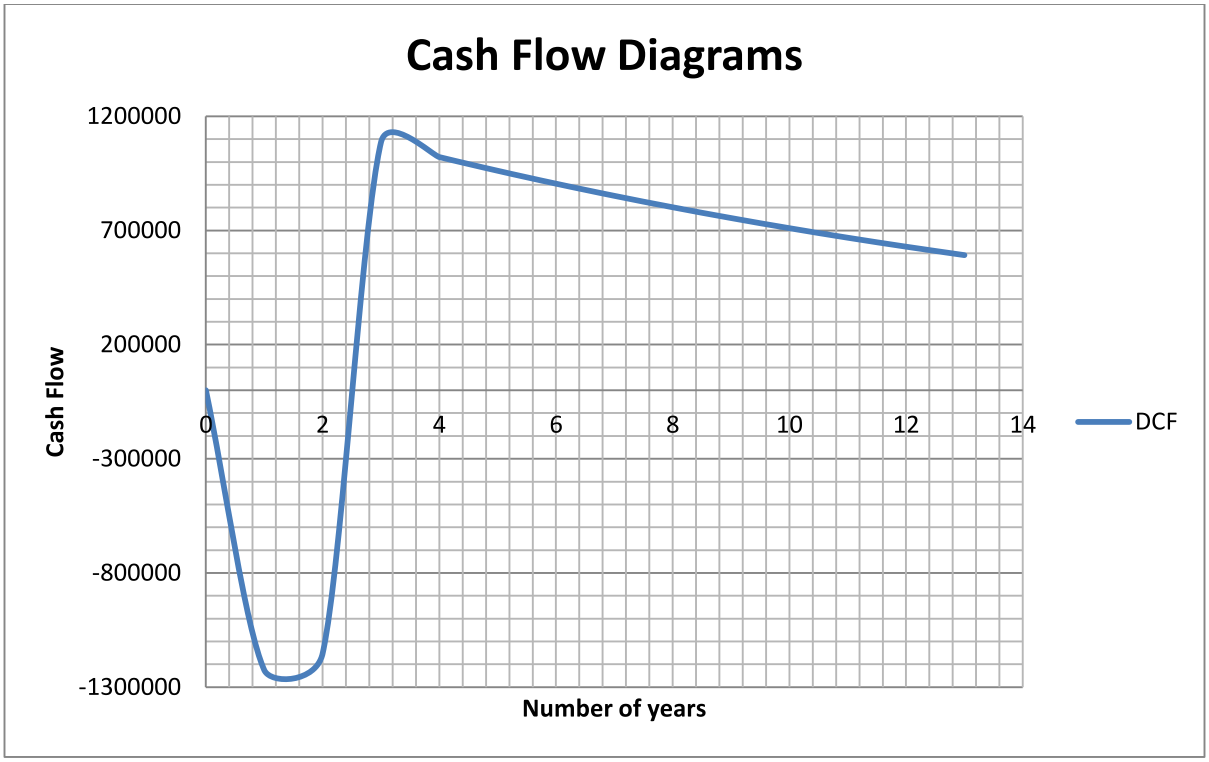

Figure 6.16: Cash Flow Diagram

The graph shows that from 0 to 2 years is the payback timeof this project two years after operation, construction and designing time excluded.On the second year the project broke even, before starting to make up some profits. The maximum profit that this project can generate is around R 1, 1 million and that is at the third year of the project's operation. The graph indicates that this project is making a profit and it shows a decrease when approaching the thirteenth year of the project which is the last year of the plant's operation.

6.8 ECONOMIC FEASIBILITY

According to the Net Present Value, it is determined that the Bellville LFGTE project is feasible because a profit was encountered for the Net Present Value of this project which is R 3, 9 million. On top of that, the payback of the project is 4 years when including the design and construction period because carbon dioxide is also sold in this project which could have been higher if the revenues were only from electricity sales amounting to R4, 7 million. There is another similar project similar to this project in Arizona, U.S.A at Cinder Lake Landfill Flagstaff.

This project was found to be making a loss, the Net Present Value of this project amounted to R45 million losses, as for its payback time is 8 years and the life span of the entire project is only 15 years (Geosyntec et al., 2013) while the Bellville LFGTE process plant life span is 9 years. Another example is that of East Kentucky Power Co-op Green Power Program. The Bavarian landfill located in Boone County Kentucky went from a passive LFG system to an active system producing 3.2MW of power in one year. The East Kentucky Power Cooperative initiated, developed and financed the project at a cost of R60 million from which the cooperative expects a 10 year payback.

7. Conclusion

The objective of this project was to estimate the amount of landfill gas produced at Bellville landfill site with the use of a mathematical model and utilization of landfillgas,in order to generate electricity. Furthermore, South Africa has been experiencing electricity shortages in its major cities, especially in the CBDs. The CBDs is every country's economic backbone. Therefore, if there is insufficient and insecure of electricity in these places then its economy is in trouble. South Africa gets its electricity mainly from nuclear and coal (fired burners). The two sources of energy are non- renewable, thus bringing in other alternatives which are renewable such as landfill gas can be a solution to South Africa's problem because it has several landfill sites across the country. Besides South Africa has a number of landfill sites which can be harnessed for possible electricity generation. Besides this gas is toxic as it contains GHG's since it contains 41% of methane (Mohee et al., 2011). Therefore, the overall objective of this research is to evaluate the potential of generation of electricity and the economic feasibility of the Bellville South Landfill site. In this regard, this research study was limited to; estimate the amount of landfill gas that can be produced from the Bellville landfill site, do a desktop design of LFGTE process plant and economic analysis of the process.

The first objective of this project was to estimate the amount of landfill gas that can be produced from the Bellville landfill site. The objective was achieved by using a model called IPCC. The model was found to be more suitable when compared to other models because it has numerous features which enable its use to estimate the generation of methane from solid wastes disposal sites, in most countries (U.S.EPA et al., 2010). IPCC model was applied to estimate the amount of methane generated at Bellville landfill site, in 2013. In 2013 132m^3 CH_4/ton MSW was produced at the landfill site. This was comparable to the Mare Chicose landfill site in Mauritiuswhichgenerated 119.8m^3 CH_4/ton MSW, the IPCC model was used to estimate the amount of methane produced (Surroop et al., 2011). During the course of this research it was discovered that the amount of wastes deposited at the landfill site is directly proportional to the amount of methane generated.

The second objective was to design a LFGTE process plant. To do so several methods of gas separation were reviewed for separating CH_4 from CO_2 and H_2S. Again CO_2 and H_2S were not the only gases that had to be separated from CH_4; VOC's like benzene, xylene and toluene had to be separated from CH_4 before it could be combusted into the gas engine. Technologies that could be used to purify CH_4 from CO_2 and H_2S such as water scrubbing, chemical absorption, Pressure Swing Adsorption, membrane and cryogenic separation were also reviewed. Analysisof their performance showed that chemical absorption would be the most suitable for removal of CH_4 from CO_2 and H_2S. For this site; CO_2 and H_2S are by-products of the chemical process. They can be stored and utilized in other industries. Moreover the economics analysis of the chosen technology is said to be least expensive when comparing it to the rest of the other technologies. Its costs are said to be R2.42/Nm^3 biogas (Zhao et al., 2010).

The results that were obtained from this project proved that the technology used for separating CH_4 from CO_2 and H_2S is highly effective. Using Aspen plus continuous process simulator. The absorber unit was able to separate 87% of pure CH_4 into the gas stream, which leads to the combustion process for conversion of electricity at optimal condition of 4 bars. The rest of methane was absorbed by MEA solution and the reason why it absorbed that amount is because CO_2 and H_2S were present, lowering methane solubility in the MEA solution (Lawson et al., 1999). The entire LFGTE process plant was simulated. According to Masebinu et al., (2014) effectiveness of purification of CH_4 from biogas can range from 63 to 91%.Although this fact was shown using membrane technology instead of chemical absorption and ChemCAD 6.5.5 was used to simulated the process rather than Aspen plus which was used in this project and the optimal condition was 9.9 bar(Masebinu et al.,2014). This is a prove that membrane technology is more costly to run than chemical absorption because it demands high pressures in order, to improve purity of methane recovery.

The amount of energy obtained from the LFGTE process plant was found to be 1.004MWh while the Mare Chicose in Mauritius said to be producing 53.5GWh (Surroop et al., 2011). Practically the size of the landfill, the amount of the wastes deposited at the landfill site, the amount of landfill gas produced and amount of energy that could be produced were discovered to be directly proportional. The reason being that Bellville landfill site is 43 year old (CCT et al.,

2013) the landfill is at phase five and the anaerobic and methanogenic processes are declining (Palananthakumar et al., 1999) and Mare Chicose is 17 years old (Surroop et al., 2011) the landfill is at phase four and anaerobic and methanogenic processes are steady (Palananthakumar et al., 1999). The literature says the depletion of methane depends on time, especially when the landfill site operation is to be closed very soon and normally when this time approaches the deposition of wastes is reduced at the landfill site and the volume of gas also decreases (Tchobanoglous et al., 1993). That is why Bellville landfill site produced low landfill gas. Hence, producing lower electricity in comparison to Mare Chicose. The Bellville landfill site will be closing in 2018 (CCT et al., 2013).The reason again being that the Bellville landfill site had pre-treatment and advanced treatment of landfill gas before combustion. The analysis of the landfill gas showed that there were VOC's, H_2S and CO_2. It was important to remove VOC's because there were to form silica build-up on the surface of the heads of the engine pistons when burnt. If this occurs continuously it forms a white coating that covers the interior surfaces, preventing proper heat transfer in the gas engine (Xebec et al., 2007). H_2S and CO_2 if not removed they decrease the heating value of the gas, increasing compression and reducing its economic viability. Therefore, the benefit of treating landfill gas allows it to accommodate for broader range of its application, either for electricity or heat generation (Zhao et al., 2010). The Mare Chicose LFGTE process plant did not have any sort of landfill gas treatment. Therefore, that is why the energy produced from it is greater than the Bellville landfill site project because no huge amounts of CH_4 losses could be accounted for along the process plant.

The material of construction was also considered for the units because of MEA solution which is corrosive. Two materials that were considered for material of construction were stainless steel and carbon steel for making the LFGTE process plant. The stainless steel material was considered for the units and pipe lines that MEA solution will pass through. The reason is because stainless steel can withstand the corrosiveness of the MEA solution. The rest of the units and pipelines will be made of carbon steel where MEA solution is absent. HAZOP analysis studies were made around the major units to assess the safety of the LFGTE process plant and quality of the gas treated.

The last objective of this project was to perform the economic analysis of the process. A profit was made in this LFGTE process plant; it is not surprising because CO_2 was sold, which increased the revenue of this project.Eventhough, the literature has shown that this project cannot make a profit no matter its duration (Geosyntec et al., 2013). For instance, the case study on LFGTE process plant that was done at Cinder Lake Landfill Flagstaff has a life span of

15 years, payback time for 8 years, total capital costs of R87 million and losses that were encountered for the entire project amounted to R45 million (Geosyntec et al., 2013) while the results obtained from Bellville landfill project showed that there is profit made from this project, it has a life span of 9 years, payback time of 4 years, total capital costs of R2, 5 million and a Net Present Value of R3, 9 million.

The reason why the LFGTE project is not profitable when electricity is the only product in the revenues of the project is because the case studies were done and it shows that economic factors such as inflation rates, tax rates when they increase, income of the project decreases (Bolinger et al., 2014). Therefore, the project ends up making a loss with time. Another factor could be the types of technologies applied in thetreatment of gases. For Bellville landfill site the technology used for operation of the plant has lower purchase costs but its running costs are very high while the Cinder LFGTE process plant had high purchase cost but low operation cost which is preferable rather than having recurring high operational costs. Material of construction of the units, for treatment of the gas was expensive at Bellville landfill site, about 50% of the process plant is made out of stainless steel. Again process control instrumentscostswhich assist in ensuring the safety of the plant during its operation were considered. Although, for Cinder Lake LFGTE project information on safety control instruments cost prices were not provided.

The recommendation towards exploration of LFGTE process is that the by-products such as CO_2 should be sold, so that they can increase the revenues and this project will become profitable. A model must be created, specifically for estimation of Bellville landfill gas generation, in order to verify whether the amount of landfill gas which is obtained from using IPCC model is close or not. Another recommendation is that various technologies must be applied in the design of LFGTE process plant, in order to evaluate whether the project is not profitable regardless of the types of technologies applied.

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References

- Amercool. 2011. Basics of Air cooled Heat Exchangers. Tulsa, Oklahoma: Amercool Manufacturing Inc.
- Amundsen, T.G. 2008. CO_2 Absorption in Alkaline Solution. Porsgrunn, Norway: Telemark University College
- Andersson, E. 2009. Ethylene Amines. Stenungsund, Sweden: AkzoNobel Functional Chemicals AB
- Aquilar-Virgen, Q. Taboada-Gonzalez, P. Ojeda-Benitez, S. Cruz-Sotelo, S.2014. Power generation with biogas from municipal solid waste: Prediction of gas generation with in situ parameters. Renewable and Sustainable Energy Review, 30:412-419
- Aschenbrenner, O. Styring, P. 2010. Comparative study of solvent properties for carbon dioxide absorption: Energy and Environmental Science, 3:1106-1113
- Bacdecker, M. Back, W. 1979. Ground Water. Hydrological Processes and Chemical Reactions at a Landfill. Virginia:Library of Congress Cataloging
- Backhurst, J.R. Harker, J.H. 2002. Coulson & Richardson Chemical Engineering. London: Butterworth-Heinemann
- Bauer, F. Huleberg, C. Persson, T. Tamm, D. 2013. Catalyzing energy gas development for sustainable solutions. Sweden: SvensktGastekniskt Centre (SGC)
- Bennett, L. 2014. Carbon Trading in South Africa: Trading offsets against the proposal carbon tax, Vol 85:1581
- Bhailall, S. Piketh, S. Smith, N. Bogner, J. 2010. Subsurface Gas Generation at a landfill in Johannesburg. Clean Air Journal, 18(1):10-14
- Bini, R. Pratesi, G. 1997. High-pressure infrared study of a solid methane: Phase diagram up to 30GPa, Vol 55(22):14800-14809
- Bolinger, M. 2014. An analysis of the costs, benefits and implication of different approaches to capturing the value of renewable energy tax incentives. USA: Environmental Energy Technologies Division
- Bretsznajder, S. 1971. Prediction of Transport and other Physical Properties of fluids. New York: Pergamon Press Inc

- British Columbia Ministry of Environment. 2010. Landfill Gas Management Facilities Design Guidelines. British Columbia: Conestoga-Rovers & Associates
- Chalvatzak,E. Lazaridis, M. 2010. Estimation of greenhouse gas emissions from landfills: Application to the Akrotiri landfill site (Chania:Greece), 12(1):108-116
- Chaudhary, R. Garg, R.2014. Comparisons of Two methods for methane emission at proposed Landfill site and their contribution to climate change: Indore City. International Journal of Application or Innovation in Engineering and management, 3:9-16
- Chowdhury, S. 2007. Economic Feasibility Analysis of Electricity Generation from Landfill Gas in South Africa. Washington, DC: IEEE Computer Society
- Chowdhury, S.2012. Economic Feasibility Analysis of Electricity Generation from Landfill Gas in South Africa. Washington, DC: IEEE Computer Society
- Collins, T. Mbebe, A. 2013. State of Environment Outlook Report for the Western Cape Province. South Africa: Environmental Affairs and Development Planning
- CSIR. 2011. Municipal waste management- good practices. Pretoria: CSIR
- Davis, S. Stalleicken, J. Gregory, R.G. 2011. Modelling LFG Generation Using The GasSim2.5 Regulatory Model. UK: GolderAssocites
- Dudek, J. Klimek,P. Kolodziejak, G. Niemczewska,J. Zaleska-Bartosz, J.2010. Biogas as an alternative to natural gas. Landfill Gas Energy Technologies, 67(11):1073-1078
- EPA. 2011. Green Remediation Best Management Practices. US: United States Environmental Protection Agency
- Felder, R.M. Rousseau, R.W. 2000. Elementary Principles of Chemical Process. New York:John Wiley & Sons
- Geosyntec, C. 2013. Final Landfill Gas to energy feasibility report. Arizon, USA: Geosyntec Consultants
- Graasboll, S.2000. How Does Landfill Gas Energy Work. Massachusetts: IEEE Computer Society
- Grande, C.A. 2013. Biogas Upgrading by Pressure Swing Adsorption. Oslo Norway: Intechopen
- Halvadakis, C.P. 1983. Methanogenesis in solid waste landfill bioreactors. USA: Stanford University
- Horizonte, B. 2012. Waste to Energy for more Effective Landfill site Management, Brazil:IRENA

- Jigar, E. Bairu, A. Gesessew, A.2014. Application of IPCC model for estimation of methane from municipal solid waste landfill. Journal of Environmental Science and Water Resources, 3(3):53-59
- Johansson, N. 2008. Production of liquid biogas, LBG, with cryogenic and conventional upgrading technology. Sweden: Lund University
- Jonsson, S. Westman, J. 2011. Cryogenic biogas upgrading using plate heat exchangers. Sweden, Göteborg: Chalmers University of Technology
- Lawson, J.D. Garst, A.W. 1999. Hydrocarbons gas solubility in sweetening solutions: Methane and Ethane in Aqueous Monoethanolamine and Diethanolamine, 21:30-32
- Li-Feng Chiu, Meng-Hui Li. 1999. Heat Capacity of Alkanolamine Aqueous Solution: Journal of Chemical Engineering Data, 44:1396-1401
- Kara, Y. A. Guraras, O. 2004. A computer program for designing of shell-and-tube heat exchangers: Applied Thermal Engineering, 24:1797-1805
- Karapidakis, E.S. Tsave, A.A. Soupious, P.M. Katsigiannis, Y.A. 2010. Energy efficiency and environmental impact of biogas utilization in landfills. International Journal of Environmental Science & Technology, 7(3):599-608
- Karassik, J.I. Messina, P.J. Cooper, P. Heald, C.C. 2001. Pump HandBook. Washington, D.C.:McGraw-Hill
- Kozak, F. Sherrick, B. 2009. Chilled Ammonia Process for CO_2 capture: Energy Procedra, 1:1419-1426
- Kula, M. 2014. Solid Waste Management. Cape Town, South Africa: City of Cape Town
- Maddox, N.R. Mains, J.G. Rahman, A.M. 1987. Reactions of Carbon Dioxide and Hydrogen Sulphide with some Alkanolamines: Ind. Eng. Chem. Res, 26(1):27-31
- Masebinu, S. Aboyade, A. Muzenda, E. 2014. Process simulation and parametric study of a biogas upgrading plant using gas permeation technique for methane enrichment: Process Energy and Environmental Technology, 19(2):18-31
- Matsui, M. 2011. Tower Internals &Towers.Jiangxi, China: Matsui Machine Ltd
- Megalla, D. 2015. Heat Transfer Model for an Engineered Landfill in Sainte-Sophie, Quebec, Canada. Quebec, Canada: Ottawa-Carleton Institute for Environmental Engineering
- Megido, L. Fernandez-Nava, Y. Maranon, E. Castrillon, L. Negral, L. Ormaechea, P. 2014. Optimization of biogas upgrading by absorption of CO_2 into ethanolamine solution. Gijon, Spain: University Institute of Technology of Asturias

- Meyer, C. Maree, G.2012. State of Environment Outlook Report for the Western Cape Province. South Africa: Western Cape Government Environmental Affairs & Development Planning
- Mitri, G. Showman, P.A. Lunine, I.J. Lorenz, D.R. 2006. Hydrocarbon lakes on Titan. USA: Elsevier
- Mohee, R. Rughoonundhun, H. 2006. Solid Wastes as a Potential Energy Source. Mauritius: Mauritius Research Council
- Mudzuli, K. 2015. Tshwane to make gas from trash. South Africa: Daily News
- Mukherjee, R. 1998. Effectively Design Shell-and-Tube Heat Exchangers. India: Engineers India Ltd.
- Nieuwoudt, I. Corio, C. DeGarmo, J. 2015. Improvements in random packing performance. USA: Crambeth Allen Publishing Ltd.
- Nkala, Z.C. 2012. An Analysis of waste minimization initiatives in the city of Cape Town, South Africa. Cape Town: Stellenbosch University
- Ofori-Boateng, C. Kwofie, E.M. 2009. Water Scrubbing: A better Option for Biogas Purification for Effective Storage, 5:122-125
- Oonk, H.2010. Methods to quantify generation, oxidation and emission. Innovations in Environmental Technology, 75:8-11
- Palananthakumar, B.1999.Modelling of Methane Generation, Oxidation and Emission in landfills. Bangkok,Thailand: Asian Institute of Technology
- Park, C.J.2011. The study on the Estimation of Greenhouse Gas Emission from Landfill Facilities. Incheon: IEEE
- Pathirathna, K.A. 2013. Gas Turbine Thermodynamic and Performance Analysis Methods Using available catalogue data. Sweden, Gävle: University of Gävle
- Perry, R.H. Green, D.W. 2007. Chemical Engineering. New York: McGraw-Hill
- Peterson, R. H. 2002. Accounting for Fixed Assets. New York, USA: John Wiley and Sons, Inc.
- Petersson, A. Wellinger, A. 2009. Biogas upgrading technologies-developments and innovations. Aadorf, Switzerland: IEA Bioenergy
- Peyghambarzadeh, S.M. Jamialahmadi, M. AlaviFazel, S.A. Aziz, S. 2009. Experimental and Theoretical study of Pool Boiling heat transfer to Amine solutions: Brazilian Journal of Chemical Engineering, 26(1):33-43

- Pipatti, R. Svardal, P. 2006. Modeling the final phase of landfill gas generation from long-term observations.Solid Waste Disposal, 106(11):62-64
- Reinhart, R.D. Barlaz, A.M. 2010. Landfill Gas Management: A Roadmap for EREF Directed Research. USA: University of Central Florida
- Rogoff, M.J. 2008. Solid Waste Planning Services. Florida: SCS Engineers
- Scharff,H. Jacobs,J. Oonk, H. Hensen, A.2010. Methods to Ascertain methane emission of landfills. Journal of the Air & Waste Management Association, 64:150-159
- Scheutz, C. Kjeldsen, P. Bogner, J.E. De Visscher, A. Gebert, J. Hilger, H.A.&Spokas, K.2009. Microbial methane oxidation processes and technologies for mitigation of landfill gas emissions. Waste Management. 27:409-455
- Serfass, P. 2014. Promoting the Anaerobic Digestion and Biogas Industries. USA: American Biogas Council
- Sherpherd, A. 2001. Activated Carbon Adsorption for treatment of VOC emissions. Boston Massachusetts, USA: CARBTROL Corporation
- Si Ali, B. Aroua, M.K. 2004. Effect of Piperazine on CO_2 loading in Aqueous Solutions of MDEA at Low Pressure: International Journal of Thermophysics, 25(6):1863-1869
- Sinnott, R.K. Coulson, J. M. Richardson, J. F. 2005. Coulson & Richardson’s Chemical Engineering Design. UK: Butterworth-Heinemann
- Smith, J.M. Van Ness, H.C. Abbott, M.M. 2005. Introduction to Chemical Engineering Thermodynaimcs. Canada: McGraw Hill
- Soreanu,G. Beland, M. Falletta, P. Edmonson, K. Svoboda, L. Al-Jamal, M. Seto, P.2011. Approaches concerning siloxane removal from biogas. Canadian Bio-systems Engineering, 53: 8.1-8.18
- Srang-iam, W.2014. Urban Agriculture as a Municipal Waste Reduction Strategy: A study of Commercial Farms in SuanLuang District, Bangkok Metropolis. 931:716-720
- Staffell, I. 2011. The Energy and Fuel Data Sheet. UK: University of Birmingham
- Staszwask, E. Pawlowska, M. 2011. Characteristics of emissions from municipal waste landfills. Environment Protection Engineering, 37:119-129
- Stege, G.A. 2010. Methane Emission Reductions Achieved by landfill Gas Projects in Developing Countries. Journal of Geophysical Research:Atmosphere, 118:5830-5866
- Surroop, D. Mohee, R. 2011. Power Generation from Refuse Derived Fuel. Shanghai, China: ICEEA

- Surroop, D. Mohee, R. 2011. Power Generation from landfill gas. Singapore: IACSIT Press
- Tanapat, S. 2004. A feasibility study of Municipal Waste-to-Energy Management:Measurement of Landfill Gas Quality at Brad Road Landfill in Canada. Manitoba: Natural Resources Institute University of Manitoba
- Tchobanoglous, G. Theisen, H. Vigil, S. 1993. Integrated solid waste management. New York: McGraw-Hill, Inc.
- The World Bank. 2003. Understanding the Landfill Gas Resource and Potential Applications. U.S.A: Conestoga-Rovers & Associates
- Thompson, S. Tanapat,S. 2005. Modeling Waste Management Options for Greenhouse Gas Reduction. Journal of Environmental Informatics, 6(1):16-24
- Thopil, G.A. Pouris, A. 2013. International positioning of South Africa electricity prices and commodity differentiated pricing. Pretoria, South Africa: Institute of Technological Innovation, University of Pretoria
- Udara, S.P.R. Aryal, N. Drag, A. Morten, C. 2013. Viscosities of Pure and Aqueous Solutions of Monoethanolamine (MEA), Diethanolamine (DEA) and N-Methyldiethanolamine (MDEA): Annual Transactions of the Nordic Rheology Society, 21:299-306
- U.S.EPA. 1992. List of Municipal Solid Waste Landfills. Washigton, DC: United States Environmental Protection Agency
- U.S.EPA. 2005. Landfill Gas Emissions Model (LandGEM) Version 3.02 User’s Guide. Washigton, DC: Eastern Research Group, Inc.
- U.S.EPA. 2010. LFG Energy Project Development Handbook. Massachussetes USA: United States Environmental Protection Agency
- U.S.EPA. 2014. Landfill and LFG Energy Project Database. USA: U.S. Environmental Protection Agency
- Vedrenne, F.2005. Estimation of Potential Landfill Gas Yields for theOrdot Dump. Ordot ,Guam:Dueñas& Associates Project Team (Dueñas& Associates, Inc. and URS Corporation)
- Waumans, T. Vleugels, P. Peirs, J. Al-Bender, F. Reynauts, D. 2006. Rotordynamic behavior of a micro-turbine rotor on air bearings: modelling techniques and experimental verification. Belgium: KatholiekeUniveresiteit Leuven

- Weitz, M. 2010. Estimating National Landfill Methane Emissions: An application of the 2006 IPCC Waste Model in Panama, 58(5):636-640
- Wheless, E. Pierce, J. 2009. Siloxanes in Landfill and Digester Gas Update. Carlifornia USA: SCS Energy
- Xebec, I. 2007. Treatment Solutions for Landfill Gas fuel Applications. USA: Xebec Adsorption Inc.
- Xiang Xin, G. Song, Y. 2010. Discuss on the design of MSW landfill gas collection project. Beijing, China: China Academy of Urban Construction
- Yunus, A.C. 2002. Heat Transfer. New York: McGraw-Hill
- Zhao, Q. Leonhardt, E. MacConnell, C. Frear, C. Chen, S. 2010. Purification Technologies for Biogas generated by anaerobic digestion. Washington, D.C.:IEEE Computer Society
- Zioudas, A.P. Dadah, Z. 1985. Absorption rates of carbon dioxide and hydrogen sulphide in sterically hindered amines: Chemical Engineering Science, 41:405-408
- Z.W.S. 2012. Review of options for reducing GHG emissions from landfills in Scotland. Collation of key Information on Small Closed & Operational sites across Scotland ZWS, 1:1-20
- Zygula, M.T. 2007. A design review of steam stripping columns for wastewater service. US, Houston: AIChE Spring National
- Alibaba Manufacturers, Suppliers. 2016. Prices of equipment. http://www.alibaba.com
- Burston, J. 2015. Conference of Parties 21 (2015) on 7-8 December 2015, Paris
- Kanyarusoke, K. 2016. Interview with the researcher on 20 June 2016, Cape Town

Appendix A

Operating Year	Annual input (tonnes)
1970	13 500
1971	14 310
1972	15 169
1973	16 079
1974	17 043
1975	18 066
1976	19 150
1977	20 299
1978	21 517
1979	22 808
1980	24 176
1981	25 627
1982	27 165
1983	28 795
1984	30 522
1985	32 354
1986	34 295
1987	37 220
1988	40 846
1989	43 296

1990	45 894
1991	48 648
1992	51 567
1993	54 661
1994	57 940
1995	59 200
1996	130 000
1997	310 000
1998	329 951
1999	363 620
2000	293 502
2001	245 518
2002	150 804
2003	236 656
2004	306 839
2005	404 512
2006	473 247
2007	580 342
2008	442 434
2009	397 428
2010	409 016
2011	417 196
2012	425 540
2013	434 051
2014	442 732

Calculation of landfill gas using Microsoft excel

Years	DDOCm	LFG (m^3)	Fugitive Gas (m^3)	CH4 Gas (m^3)
1970	0.00176	2198.2	691.4	1506.8
1971	0.00187	2330.1	732.9	1597.2
1972	0.00198	2470.0	776.9	1693.1
1973	0.00210	2618.1	823.5	1794.7
1974	0.00223	2775.1	872.8	1902.3
1975	0.00236	2941.7	925.2	2016.5
1976	0.00250	3118.2	980.7	2137.5
1977	0.00265	3305.3	1039.6	2265.7
1978	0.00281	3503.6	1102.0	2401.7
1979	0.00298	3713.8	1168.1	2545.8
1980	0.00316	3936.6	1238.1	2698.4
1981	0.00335	4172.8	1312.4	2860.4
1982	0.00355	4423.3	1391.2	3032.1
1983	0.00376	4688.7	1474.7	3214.0
1984	0.00399	4969.9	1563.1	3406.8
1985	0.00423	5268.2	1657.0	3611.3
1986	0.00448	5584.3	1756.4	3827.9
1987	0.00486	6060.5	1906.2	4154.4
1988	0.00533	6651.0	2091.9	4559.1
1989	0.00565	7049.9	2217.3	4832.6
1990	0.00599	7472.9	2350.4	5122.5
1991	0.00635	7921.4	2491.4	5429.9
1992	0.00673	8396.7	2640.9	5755.7
1993	0.00714	8900.5	2799.4	6101.1
1994	0.00757	9434.4	2967.3	6467.1
1995	0.00777	9639.5	3031.8	6607.7
1996	0.0170	21167.9	6657.7	14510.2
1997	0.0405	50477.3	15876.1	34601.2
1998	0.0431	53725.9	16897.8	36828.1
1999	0.0475	59208.3	18622.1	40586.1
2000	0.0383	47790.9	15031.2	32759.8
2001	0.0321	39977.7	12573.7	27404.0
2002	0.0197	24555.4	7723.1	16832.3
2003	0.0309	38534.7	12119.9	26414.8
2004	0.0401	49962.6	15714.2	34248.4
2005	0.0528	65866.7	20716.3	45150.4
2006	0.0618	77058.8	24236.5	52822.4
2007	0.0758	94497.1	29721.1	64776.0

2008	0.0578	72041.5	22658.4	49383.1
2009	0.0519	64713.2	20353.5	44359.7
2010	0.0534	66600.1	20947.0	45653.1
2011	0.0545	67932.0	21365.9	46566.1
2012	0.0556	69290.7	21793.2	47497.5
2013	0.0567	70676.5	22229.1	48447.4
2014	0.0578	72090.1	22673.7	49416.4

Appendix B

The properties of landfill gases

Methane

- Gas density (1.013 bar at boiling point) : 1.816 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 0.6797 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.99802
- Specific gravity : 0.555
- Specific volume (1.013 bar and 25 °C (77 °F)) : 1.5227 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0358 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0274 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.3062
- Viscosity (1.013 bar and 0 °C (32 °F)) : 1.0245E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 30.57 mW/(m.K)

http://encyclopedia.airliquide.com/

Oxygen

- Gas density (1.013 bar at boiling point) : 4.4681 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 1.354 kg/m^3

- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.99924
- Specific gravity : 1.105
- Specific volume (1.013 bar and 25 °C (77 °F)) : 0.7643 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0294 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0211 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.3967
- Viscosity (1.013 bar and 0 °C (32 °F)) : 1.9143E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 24.35 mW/(m.K)

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Carbon dioxide

- Gas density (1.013 bar at sublimation point) : 2.813 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 1.8714 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.99435
- Specific gravity : 1.53
- Specific volume (1.013 bar and 25 °C (77 °F)) : 0.5532 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0374 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0289 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.2941
- Viscosity (1.013 bar and 0 °C (32 °F)) : 1.3711E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 14.674 mW/(m.K)

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Carbon monoxide

- Gas density (1.013 bar at boiling point) : 4.362 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 1.1849 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.99953
- Specific gravity : 0.97
- Specific volume (1.013 bar and 25 °C (77 °F)) : 0.8734 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0292 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.0208 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.4013
- Viscosity (1.013 bar and 0 °C (32 °F)) : 1.6515E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 24.74 mW/(m.K)

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Hydrogen Sulphide

- Gas density (1.013 bar at boiling point) : 1.997 kg/m^3
- Gas density (1.013 bar and 15 °C (59 °F)) : 1.4534 kg/m^3
- Compressibility Factor (Z) (1.013 bar and 15 °C (59 °F)) : 0.99148
- Specific gravity : 1.19
- Specific volume (1.013 bar and 25 °C (77 °F)) : 0.7126 m^3/kg
- Heat capacity at constant pressure (Cp) (1.013 bar and 25 °C (77 °F)) : 0.0346 kJ/(mol.K)
- Heat capacity at constant volume (Cv) (1.013 bar and 25 °C (77 °F)) : 0.026 kJ/(mol.K)
- Ratio of specific heats (Gamma:Cp/Cv) (1.013 bar and 25 °C (77 °F)) : 1.331
- Viscosity (1.013 bar and 0 °C (32 °F)) : 1.1298E-04 Poise
- Thermal conductivity (1.013 bar and 0 °C (32 °F)) : 15.609 mW/(m.K)http://encyclopedia.airliquide.com/

Appendix C

Estimation of landfill gases from 2013-2014 using IPCC Model:

Decomposable DOC from waste disposal data

$$DDOC_m = W.DOC.DOC_f.MCF$$

Where:

$DDOC_m$= mass of decomposable DOC deposited, Gg

W = mass of waste deposited, Gg

DOC = degradable organic carbon in the year of deposition, fraction, Gg C/Gg waste

DOC_f = fraction of DOC Dissimilated, was found to be 0.77

MCF= methane correction factor for aerobic decomposition in the year of decomposition fr

W = 434.051Gg

DOC= 0.4(A)+0.17(B)+0.15(C)+0.3(D)

A=% paper and textile-20% of Bellville landfill wastes

B=% garden waste-13% of Bellville landfill wastes

C=% food waste-25% of Bellville landfill wastes

D=% wood straw-10% of Bellville landfill wastes

=0.4(0.2)+0.17(0.13)+0.15(0.25)+0.3(0.1)

=0.1696 ton Carbon/ ton waste

MCF= 1 for well managed landfill sites (Park et al., 2011)

$$DDOC_m = 434.051Gg \times 0.0001696Gg\ C/Gg \times 0.77 \times 1$$

$$DDOC_m = 0.05668Gg$$

CH_4 generated from decomposable $DDOC_m$

The amount of CH_4 formed from decomposable material is found by multiplying the CH_4 fraction in generated landfill gas and the CH_4/C molecular weight ratio.

CH_4 generated from decayed $DDOC_m$

$CH_4 generated_T = DDOCm\ decomp_T . F . 16/12$(Park et al., 2011)

Where:

$CH_4 generated_T$ =amount of CH_4 generated from decomposable material

DDOC$m\ decomp_T$= $DDOC_m$ decomposed in year T, Gg

F =fraction of CH_4, by volume in generated landfill gas (fraction)

$16/12$ =molecular weight ratio CH_4/C (ratio)

(Park et al., 2011)

With the following data then methane generated from the landfill site can be determined;

Whereby;

DDOC$m\ decomp_T$= $DDOC_m$ decomposed in year 2013 =$0.05668Gg$

F = 63.3% volume detected from Bellville landfill site Cape Town

$16/12$ =molecular weight ratio CH_4/C (ratio)

$$CH_4 generated_T = 0.05668Gg \times 0.633 \times \frac{16}{12}$$

$$CH_4 generated_T = 0.04784095Gg$$

Amount of methane produced in m^3 in the year 2013: density of methane at atmospheric conditions is 0.6797kg/m^3(Mitri et al., 2006). Therefore, the volume of methane can be determined from the following equation: $density = \frac{mass,kg}{volume,m^3}$

And the density of methane produced in 2013: $0.6769kg/m^3 = \frac{0.04784095Gg \times 10^6}{m^3}$

Then the volume of methane produced in 2013: $volume, m^3 = \frac{0.04784095Gg \times 10^6}{0.6769kg/m^3}$

$$volume = 70\ 676.5m^3/year$$

$Fugitive\ \ Methane\ emissions = methane\ production \times (1 - fraction\ collected\ ) \times (1 - fraction\ oxidized)$ (Reinhart et al., 2010)

$$Fugitive\ Methane\ emissions = 70\ 676.5m^3/year \times (1 - 0.633) \times (1 - 0.143)$$

$$Fugitive\ methane\ emissions = 22\ 229m^3/year$$

And the actual methane produced for landfill to gas energy process plant;

=70 676.5m^3/year -22 229m^3/year

=**<u>48 447m^3/year for 2013</u>**

<u>Estimation of landfill gases for 2014 using IPCC Model</u>:

$$DDOC_m = W.DOC.DOC_f.MCF$$

$$DDOC_m = 442.732Gg \times 0.0001696Gg\ C/Gg \times 0.77 \times 1$$

$$= 0.05782Gg$$

CH_4 generated from decayed $DDOC_m$

$$CH_4 generated_T = 0.05782Gg \times 0.633 \times \frac{16}{12}$$

$$= 0.04879776Gg$$

Then the volume of methane produced in 2014: 0.6769kg/m^3

$$\frac{0.04879776Gg \times 10^6}{0.6769kg/m^3} = 72\ 090m^3/year$$

$$Fugitive\ Methane\ emissions = 72\ 090m^3/year \times (1 - 0.633) \times (1 - 0.143)$$

$$Fugitive\ methane\ emissions = 22\ 674m^3/year$$

And the actual methane produced for landfill to gas energy process plant;

= 72 090m^3/year -22 674m^3/year

=**49 416m^3/year for 2014**

Appendix D

Landfill gas (methane) produced and energy that could be generated from Bellville landfill site in Cape Town if the gas was not to be treated

Years	CH4 Gas (kg)	Energy Wh/year
1970	1020.0	7286.5
1971	1081.2	7723.7
1972	1146.1	8187.3
1973	1214.8	8678.5
1974	1287.7	9198.8
1975	1364.9	9751.0
1976	1446.8	10336.0
1977	1533.7	10956.2
1978	1625.7	11613.6
1979	1723.2	12310.4
1980	1826.6	13048.8
1981	1936.2	13831.9
1982	2052.4	14662.1
1983	2175.6	15541.8
1984	2306.0	16474.0
1985	2444.5	17462.8
1986	2591.1	18510.4
1987	2812.1	1903.5
1988	3086.1	22046.3

1989	3271.2	23368.6
1990	3467.5	24770.9
1991	3675.5	26257.3
1992	3896.1	27832.8
1993	4129.8	29502.8
1994	4377.6	31272.6
1995	4472.8	31952.7
1996	9822.0	70166.4
1997	23421.6	167319.8
1998	24928.9	178088.1
1999	27472.8	196260.7
2000	22175.1	158415.1
2001	18549.7	132516.2
2002	11393.8	81395.1
2003	17880.2	127733.0
2004	23182.8	165613.6
2005	30562.3	218331.8
2006	35755.5	255430.9
2007	43846.9	313234.5
2008	33427.4	238799.8
2009	30027.1	214508.3
2010	30902.6	220762.8
2011	31520.6	225177.9
2012	32151.0	229681.5
2013	32794.1	234275.2
2014	33449.9	238960.7

Appendix E

Determination of the Net Present Value of the project

The following are the calculations for the cost:

Gross profit: $R - C_{op} = R\ 4\ 787\ 144 - R\ 2\ 548\ 455 = R\ 2\ 238\ 689$

Tax: $(R - C_{op} - d)t = (R\ 4\ 787\ 144 - R2\ 538\ 421)0.41 = R\ 917\ 862$

Net Profit: $P_{gross} - T = R\ 2\ 238\ 689 - R\ 917\ 862 = R\ 1\ 320827$

Cash flow: $P_{net} - C_k = R\ 1\ 320827 - R\ 36\ \ 026 = R\ 1\ 284\ 801$

Payback time: $\frac{Total\ Capital\ Investment}{Net\ Profit} = \frac{R\ 2\ 548\ 455}{R\ 1\ 320\ 827} = 1.91 \approx 2$ years

Discount Cash Flow: $\frac{C_k}{(1+r)^k} = \frac{R\ \ 1\ 284\ 801}{(1+0.0625)^1} = R\ 1\ 209\ 224$