BIOPROCESSING FOR RENEWABLE ENERGY PRODUCTION FROM MUNICIPAL AND INDUSTRIAL WET WASTES IN ZAMBIA

BY

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Declaration

I, LENNOX ZUMBE SIWALE do hereby declare that this thesis represents my own work and it has not previously been submitted before for a degree award at this or another University.

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To my family

Thus far the Lord has brought us

……In whom are hidden all the treasure of wisdom and knowledge
(Col 2:3)
God richly bless you

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B	Specific methane yield in litres per gram of COD
β	Solubilization rate per unit of acidogenic biomass (L/mg day)
Bo	Specific maximum methane yield in litre per gram of COD
$C_{S\,o\,i}$	Volatile solids in the influent (g/l)
C_{S0}, C_{S1}, C_{S2}	Concentration of volatile solids, soluble volatile solids, and volatile Fatty acids (mg/l)
CX_1, CX_2	Concentrations of acidogenic and methanogenic bacteria (mg/l)
D	Dilution rate (/day)
Deg C	Degree Celsius
K	Overall rate constant (T^{-1})
K_e	Overall Decay rate constant (T^{-1})
K_1, K_2	Decay coefficients for acidogenic and methanogenic bacteria (/day)
KS_1, KS_2	Saturation constants for acidogenic and methanogenic bacteria (mg/l)
Ki	Inhibition coefficient for methanogenic bacteria (mg/l)
κ	Substrate utilization rate g COD/gVSS/d
k_h	Kinetic constant of hydrolyzed substrates into the cell
P	Parameter vector
Q	Biogas production rate (l/day)
R	Refractory coefficient
S_e	Effluent COD (M/L^3)
S_o	Influent COD (M/L^3)
S_r	Refractory substrate
S_{To}	Total influent COD
S_T	Total COD in effluent
T	Time, (day)
θ	Hydraulic Retention Time
U_1, U_2	Specific growth rate of acidogenic and methanogenic bacteria (/day)
u_{1max}, u_{2max}	Maximum specific growth rate for acidogenic and methanogenic bacteria (/day)

V	Reactor Volume (L^3)
X	Vector of state variables
X r	VSS (volatile Suspended Solid) in reactor (M/L^3)
Y	Output
Y_1,Y_2	Yield coefficients for acidogenic (mg organism/mg soluble organics) and methanogenic (mg organism/mg volatile acids) bacteria
Y_b	Yield coefficient for the yield of volatile acids from soluble organics (mg Volatile acids/mg organism)
Y_g	Yield coefficient with respect to the gaseous output {L^2mg^{-1})
Y_p	Fraction of volatile solids in the influent that can be solubilized (mg/mg)

LIST OF ABBREVIATIONS AND ACRONYMS

AD	Anaerobic Digestion
APHA	American Public Health Association
BOD_5	Biochemical oxygen demand for 5 days incubation at 20 deg C concentration (mg/l)
BVS	Biodegradable Volatile Solids
$C_{ba}=Ro$	Biogas utilization revenue
C_{biogas}	Cost of biogas handling equipment
C_d	Depreciation cost
C_f	Capital costs
C_{fc}	Capital Charges
$C_{gas\ generator}$	Cost of gas generator
$C_{reactor}$	Cost of reactor
CDM	Clean Development Mechanism
COD	Chemical Oxygen Demand concentration (mg/l)
CSTR	Contact Stirred Tank reactor
GHG	Green House Gases
HRT	Hydraulic Retention Time
IRR	Internal Rate of Return
LWSC	Lusaka Water Sewage Company
NPV	Net Present Value
OLR	Organic loading rate
$Q_{2,n}$	Biogas production rate (litres/day) for growth rate μ_n
RDF	Refuse Derived Fuel
RT	Retention Time
RVS	Refractory Volatile Solids
Roi	Annual rate of investment
SRT	Solid Retention Time
T_{pb}	Payback period
TS	Total Solids concentration (mg/l)
TSS	Total Suspended Solids concentration (mg/l)
UASB	Up flow Anaerobic Sludge Blanket
UNFCCC	United Nation Framework Convention on Climate Change

VS	Volatile solids concentration (mg/l)
WWTP	Waste Water Treatment Plant

ABSTRACT

The poor management of wastewater causes loss of environmental quality. Biomethanation, a biogas-producing technique, as an attractive solution to the problem, was investigated. Biogas, a greenhouse gas, is a mixture of methane and carbon dioxide. While carbon dioxide is returned into the environment in the carbon cycle, methane can be burned as a fuel in existing types of power conversion technology namely, Internal combustion engines or microturbines to produce electric power and heat. This technique has the added incentive of accessing the carbon credit facility of the Kyoto Protocol's Clean Development Mechanism, CDM.

Laplace transformation was used to develop a mathematical model to predict process behavior applicable for municipal and industrial wastewater produced, by way of example, respectively, **Lusaka Water and Sewerage Company** at Manchinchi treatment plant and **Kembe Meat Products Limited**, at their bovine meat processing plant.

Experiments were used to both investigate biodegradability of the wastewater and validate the model developed. Characterizing the waste included determination of Biochemical Oxygen Demand, (BOD), Total Solid (TS), Volatile Solids (VS), biogas yield and determination of μ coefficient in the model calibration. Apparatus used to determine biogas production included a 5-litre mild steel bioreactor where gas was collected by water displacement.

Computing the energy content in the biogas, where 62 percent was methane, the potential of the available power from the wastewater was determined. By using Homer micro-power simulation software, a 350 kW micro turbine was suitable for Manchinchi. This would meet the operating load for in-house energy saving. Where commercialization was considered, a power output of 1 MW with grid sales would be available using gas generator and ancillary equipment. For Kembe, 40 to 60 kW Power can be accessed with a sound waste management system in place.

Due to the smaller footprint, biomethanation is recommended to support financially strapped organizations in their waste management matters. Besides the economic investigations of the application of biogas in energy supply, estimation of the carbon credits of the Kyoto protocol's Clean Development Mechanism, (CDM) represents a key incentive for organizations to adopt Anaerobic Digestion, (AD), where applicable, and therefore address the current global environmental concerns with benefits.

Selecting a gas engine generator and 3x 3,500m^{3}anaerobic digesters, gas handling and storage equipment and exhaust heat recovery facility for process heating, can produce a revenue-generating plant adding benefits to the core business. The operating load at Manchinchi during this investigation was valued at 55kW.

In monetary terms, supposing that the carbon trade facility or the CDM arrangement was accessed, a value of US$ 107,489.5 could be realized annually over seven years. In meeting the demands for emission reduction, it was estimated that 26,872.37 tons of carbon dioxide would fall for mitigation by implementing the energy recovery scheme. The carbon dioxide content measured by a Dansensor gas detector was 37 percent. The remaining 1 percent was other trace gases including hydrogen sulfide. Economic and financial appraisal showed that the NPV was US$ 484,939.89 and IRR 23 percent in the case that the plant was equipped with biogas recovery and energy conversion technology to produce heat and power with the renovation of existing anaerobic digestion tanks.

CHAPTER1 INTRODUCTION

Utility companies that apply ineffective treatment and poor disposal methods for large volumes of degradable organic wastes, is one of the major source of environmental pollution. Exposing domestic or industrial wastewater leaves a negative impact on the environment. Partially decomposing biogenic wastes in wastewater emit a greenhouse gas, methane, into the open-air. Both the developed and developing countries are embattled with the need to find solutions to alleviate this problem. The challenge is to both reap benefits in the way such wastes are managed and to leave a high standard of environmental quality within the surroundings of the treatment plants. Pressure from environmental instruments has mounted and has forced affected companies to seek the best practices to use in their wastewater management. Methane gas, contained in biogas, is an important gas, that when not captured, cause global warming and climatic change. One benefit central to this study is to establish the use of methane as a fuel in prime movers to generate electricity and provide economic value to the business of treating wastewater. Electricity produced this way is an attractive incentive that would otherwise be wasted away by poor wastewater management. Selling power to the national grid creates revenue. The affected utilities can enter into purchase agreements with the power utility companies that distribute electricity national-wide. The extra revenue or income accessed from electricity sales can help to reduce operational costs with the added advantage of mitigating the greenhouse gas.

1.1 STATEMENT OF THE PROBLEM

The problems related to wastes produced at the point source and on transit to disposal sites (non-point source) are as follows:

Wastes at point source:

- Produce offensive odors.
- Restrict infrastructure development by wastes occupying large land space areas.
- Emit gases that cause global warming and climatic change. Methane is the second largest anthropogenic Green House Gas (GHG) [1, 2].

Wastes At non-point (transit) source:

- Cause pollution of the biosphere.
- Cause hazards to public health and hygiene by polluting the air [3,4].
- Cause contamination of surface and underground water resources

For specific sites:

(A) At Manchinchi WWTP in Lusaka

- There are inadequate facilities to handle excessive sludge waste.
- There is break-up of wild fires that burn the dry sludge on the sludge beds.

- There is uneconomical use of land space.

(B) At Kembe, in Lusaka, the problems related to waste management are threefold:

- There is lack of adequate drainage facility to transport the waste to the place of final disposal.
- There is leakage of waste while being transported to the disposal point.
- And there is an occurrence of the emission of obnoxious gases due to the decomposition of the organic wastes.

Therefore there is need to review the approach to the waste management systems used at these sites. The system selected should include the recovery of material and energy resources so that the negative impacts to the environment are reduced. In this study the focus was to reduce the gaseous emission and the cost of excessive sludge treatment by using the improved anaerobic digestion process. This is done through confinement of organic waste in anaerobic digesters to produce methane.

1.2 OBJECTIVES

The general objective of the study was to examine the influence of locally decomposing wet organic wastes in order to recover resources, in this case biogas, and assess possibilities of investing economic resources for the exploitation of biogas. The specific objectives were:

1. To determine the Biochemical Oxygen Demand (BOD5), Volatile Solids (VS), and other related parameters, namely, Total Solids (TS) and Total Suspended Solids (TSS); Hydraulic Retention Time and Solid Retention Time (HRT and SRT) necessary for analyzing the energy production potential.
2. To determine how the above factors respond in the external environment-seasonal effects such as temperature, nature of nutrients and concentrations.
3. To present graphically and critically analyze these parameters in order to have preliminary views for the possible inclusions of waste-to-energy technologies.
4. To model these parameters to determine biogas yield (m^3/ kg VS destroyed) and assess the extent of the viability of producing electricity.
5. To make economic and financial assessments by evaluating Net Present Value, (NPV) Internal Rate of Return, (IRR), and to identify limitations and attractiveness of the selected wastes in the energy recovery scheme.
6. To quantify benefits that can be derived, apart from energy production such as amounts of methane abated.

1.3 SIGNIFICANCE OF THE STUDY

One essential benefit of the application of the Anaerobic Digestion, (AD) technology is the reduced pollution impact of decomposing organic waste on the environment. In Lusaka, there is a general fast growing trend towards urbanization and industrialization. This rapid growth rate is becoming a great concern because of its impact on the quality of life and the environment. There is a causal relationship between population growth and amounts of organic wastes produced. An increase in population leads to increased domestic waste generated, which when coupled with industrial activities, increases the amount of effluent to be treated substantially. Owing to this there is now an urgent need by organizations to focus more on the implementation of best practices in waste management.

Some of these best practices identified include the following:

- Determination of areas where cost can be reduced,
- Replacement and re-arrangement of some of the productions units for energy efficiency,
- Installation of efficient technologies,
- Improvement of processing methodologies for cost savings, and
- Need for compliance with the stringent government regulations and disposal requirements on the impacts of wastes upon the environment [4].

There are other benefits that can be realized through the use of AD. However the energy component has been chosen for this study. Biogas, as an alternative fuel, may be burned either in the boilers coupled with a steam turbine (Rankine cycle) or gas turbines to produce electric power and process heat for industrial application. Therefore from biogas, as an alternative fuel, the following benefits can be realized:

- Fuel to drive stationery internal combustion, I C engines producing shaft power to run process units, generators to produce electric power to run motors and
- Generation of net electric power for lighting or sale to the national grid.
- Biofuel, in the transport sector, used by light and heavy duty vehicles
- Thermal energy for heating and air conditioning
- Substitution of imported and depleting fossil fuels
- Production of a quality environment by combustion of biogas, emitting greener gases (free from GHG)
- Mitigation of green house gases that cause global warming and climatic change

CHAPTER 2 SCIENCE OF BIOMETHANATION

2 INTRODUCTION

Recent concern of global warming and climate change by the anthropogenic emission of greenhouse gases has awakened interest in the AD technology. Environmental pressure has created the need to look after the environment in the course of business. There is indication by and large that in terms of contribution to global warming, anaerobic digestion scores considerably better than other treatment processes such as aerobic systems [5]

The utilization of energy in the form of biogas is one of the environmentally sound alternatives available using renewable energy sources. Alternative energy sources include biomass, which is a general term used to describe photosynthetic products including the organic fractions produced by municipalities, industry and agriculture. These residues have a potential energy value that is today not fully utilized. Biogas, a by-product of anaerobic degradation of wastes, is the main gaseous by-product of decaying organic matter. Biogas is composed of energy-rich methane, carbon dioxide, hydrogen, nitrogen and traces of hydrogen sulfide. Other benefits that are accessible from biogas recovery from wastewater include a reduction of the volume of excess wet waste at treatment plants and production of a biofertilizer. The biofertilizer retains all the nutrients of the original material. If methane is allowed to form under uncontrolled conditions in anaerobic environments, it will be released to the atmosphere where it is believed that 18 percent of the global warming effect is due to methane emission [6].

Anaerobic digestion technology is an old technology that has not widely entered the international market. This has been due to technology failures. However, improved technical support in both developing and developed countries has increased the level of success of its implementation and application in waste management systems. Such support has not only brought economic gains through recovery of resources such as energy and manure but also environmental benefits through the need to use cleaner technologies, a current global concern in process plants [6].

Biomethanation is a process by which complex organic molecules such as polysaccharides, fats, etc are broken down under specific environmental conditions, (such as, pH and temperature), into monomers such as glucose, amino acids, and fatty acids. Fatty acids are in turn converted into acetate, carbon dioxide and hydrogen, the precursors for the formation of methane–rich biogas. This process of biomethanation is carried out by consortia of microorganisms acting in concert and symbiotic manner in the absence of oxygen. The biochemistry of methane fermentation or anaerobic digestion takes place typically in natural environments where organic matter decomposition is mediated resulting in its conversion to methane (CH_4) and carbon dioxide, (CO_2).

The biochemical processes as well as the microbial species involved are classified in three categories: hydrolysis, acidification and methanogenesis. Approximately 70 to 80 percent of the energy content of the initial organic compounds is conserved in the methane product of the methanogenesis stage and the resultant bacterial growth and biomass volume produced is consequently, much lower than during aerobic decomposition [7].

The treatment of organic matter with recovery of material, energy resource and eventual odor management are early vital incentives to consider [8]. Application of biomethanation by completing the decomposition cycle of the waste, creates sanitized residues, and prevents groundwater contamination, nutrient and pathogen loading. Nutrients such as nitrogen, phosphorous, and potassium, are not removed after the digestion process and therefore these elements remain in the effluent- a useful biofertilizer [9]. Although scientists have applied microorganisms in the wastewater treatment processes for decades, capturing the many benefits from AD has not been the goal, but treatment. Despite that not all sites are right for implementing this technology for economic reasons, public health requirements can be the only reason for adopting it [1]. Biofuels as alternative energy sources, derived from biomass, burn environmentally friendly and can substitute fossil fuels such as coal and oil used in transportation, generation of electricity and process heat.

Anaerobic microbes are more sensitive to sudden environmental changes and more difficult to grow in laboratory cultures. In comparison, anaerobic bacteria have proven to be a good alternative to aerobic microbes because of the reduction of the capital outlay in terms of cost of bioreactors with a smaller footprint and their higher tolerances for high concentration of organic compounds.

2.1 MICROBIAL METHANE FERMENTATION

From the three categories or stages of methane fermentation proposed by researchers, that is, hydrolysis, acidification and methanogenesis, methanogenesis also referred to as biomethanation, is the most important phase of the entire methane formation process. It is worthwhile to note that biomethanation can still occur without organic wastes. For instance, methanogenesis can occur in hot Springs, where methane-forming micbroorganisms, hydrogen and carbon dioxide interact. These processes are shown in Fig 2.1.

2.1.1 Hydrolysis

In the first stage of hydrolysis, the organic matter is enzymolyzed externally by extra cellular enzymes (cellulase, amylase, protease, and lipase) of microorganisms. Bacteria decompose the long chains of complex carbohydrates, proteins, and lipids into shorter parts. Proteins are converted through polypeptides into amino acids, carbohydrates are degraded into soluble sugars, and lipids are transformed into long chain fatty acids and glycerin [9]. The primary fermentative bacteria (fig 2.2) carry out this primary task. Hydrolysis is an energy consuming process and the fermentative bacteria responsible for this stage do not form methane [10].

2.1.2 Formation of acids and acetogenesis

The products of hydrolysis (intermediates) are converted into inorganic acids by the fermentative acidogenic bacteria (e.g. *Clostridium spp.*). They convert sugars, amino acids, and fatty acids into inorganic acids like acetic, propionic, formic, lactic, and butyric or succinic acids (carboxylic acids; Fig 2.1 and 2.2)[9]. In this second stage, acid-producing bacteria involved, convert the intermediates of fermenting bacteria (Fig 2.2) into acetic acid (CH_3COOH), hydrogen (H_2) and carbon dioxide (CO_2). These bacteria are facultative anaerobic and can grow under acid conditions. To produce acetic acid they need oxygen and carbon. For this, they use the oxygen dissolved in the solution or bounded–oxygen. In this way, the acid-producing bacteria produce an anaerobic atmosphere that is essential for the methane formation stage [9]. The acetate and hydrogen-producing bacteria called acetogenic bacteria such as *Syntrobacter wolinii* and *Syntrophomonas wolfei* [5,11], transform the products of acidogenesis into acetate, hydrogen, and carbon dioxide, which are the substrates for the methanogenesis. The products from this stage vary with the type of bacteria and environmental conditions such as temperature, pH, alcohols, ketones, acetate, and carbon

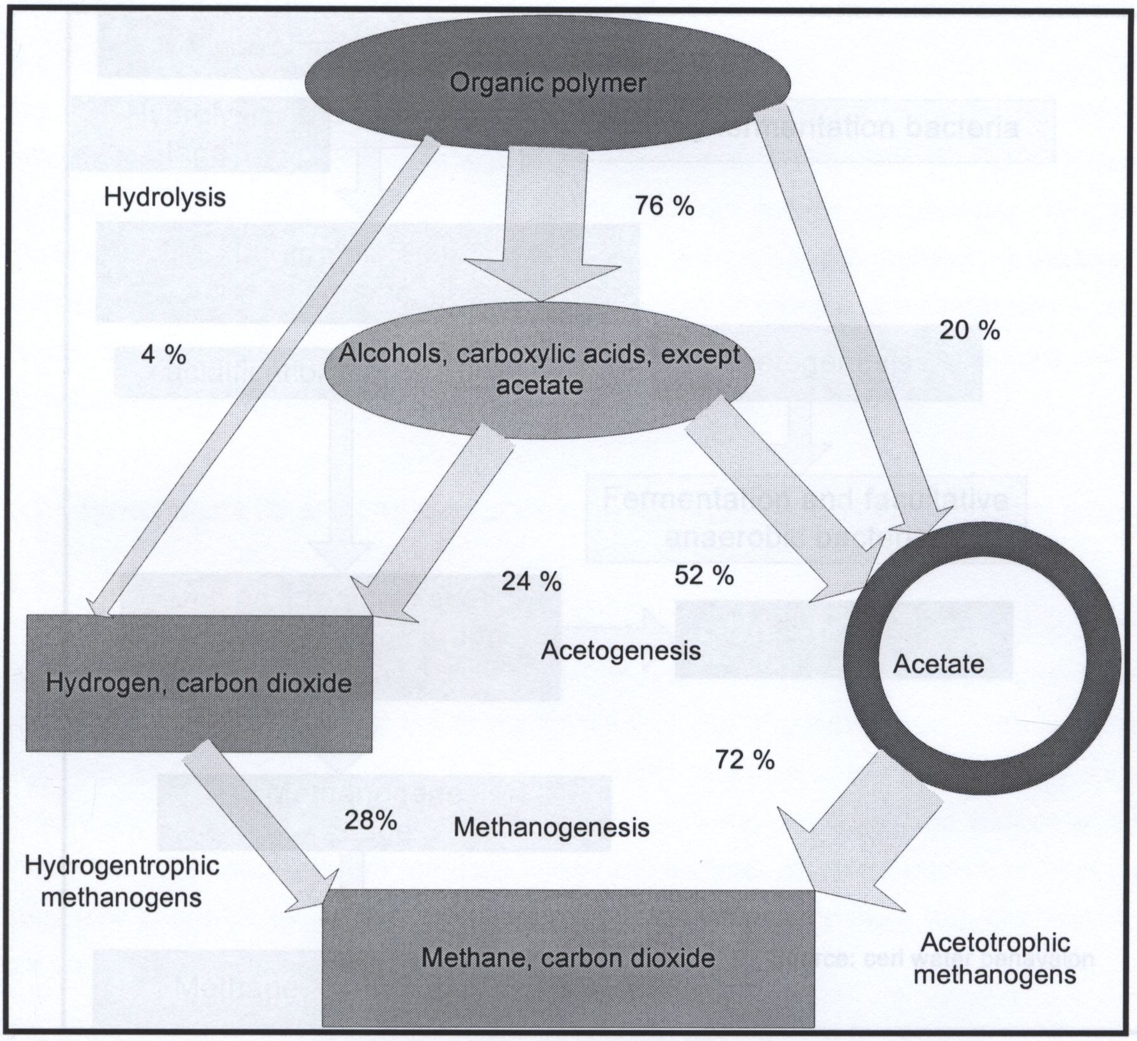

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Figure 2. 1: Anaerobic decomposition of organic matter

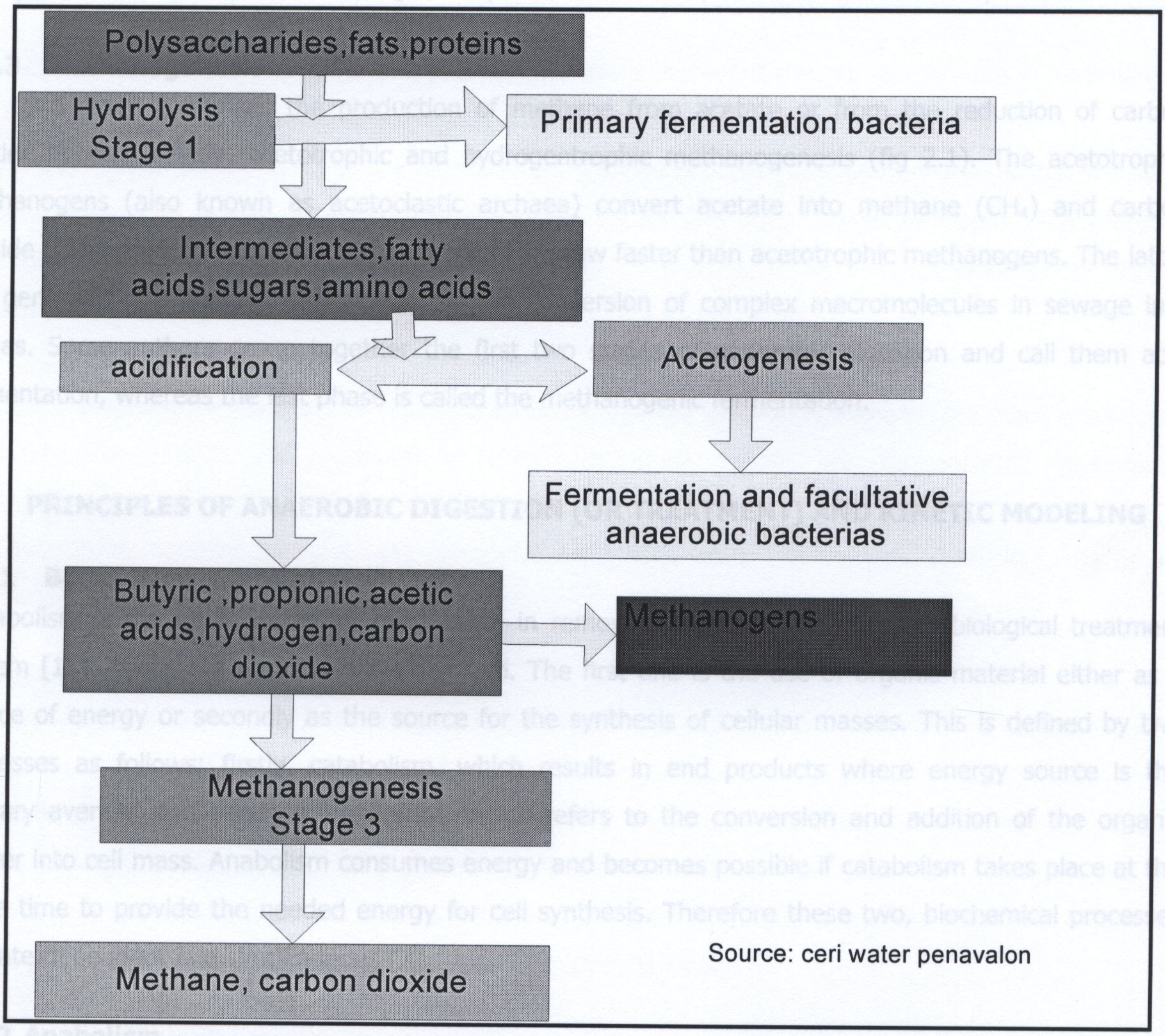

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Figure 2. 2: The three stages of biomethanation

dioxide, hydrogen and redox potential [11]. From figure 2.1 approximately 72 percent of the influent COD is converted to acetate. There may be formation of carbon dioxide or hydrogen along with the acetate depending on the Oxidation State of the original organic matter [12]. In complex substrates such as sewage both the hydrolysis and acidogenesis processes are likely to occur simultaneously.

2.1.3 Methanogenesis

The third stage comprises the production of methane from acetate or from the reduction of carbon dioxide by respectively, acetotrophic and hydrogentrophic methanogenesis (fig 2.1). The acetotrophic methanogens (also known as acetoclastic archaea) convert acetate into methane (CH_4) and carbon dioxide (CO_2). Hydrogentrophic methanogens [13] grow faster than acetotrophic methanogens. The latter are generally rate limiting with respect to the conversion of complex macromolecules in sewage into biogas. Some authors group together the first two stages of anaerobic digestion and call them acid fermentation, whereas the last phase is called the methanogenic fermentation.

2.2 PRINCIPLES OF ANAEROBIC DIGESTION (OR TREATMENT) AND KINETIC MODELING

2.2.1 Bacterial metabolism

Metabolism is the most important mechanism in removing organic matter in any biological treatment system [13]. There are two pathways involved. The first one is the use of organic material either as a source of energy or secondly as the source for the synthesis of cellular masses. This is defined by two processes as follows: firstly, catabolism, which results in end products where energy source is the primary avenue, and secondly anabolism, which refers to the conversion and addition of the organic matter into cell mass. Anabolism consumes energy and becomes possible if catabolism takes place at the same time to provide the needed energy for cell synthesis. Therefore these two, biochemical processes are interdependent and simultaneous [7].

2.2.2 Anabolism

Anabolism causes growth of the bacteria mass and it can be described by the increase in the volatile suspended solids concentration (VSS). Catabolism can be estimated by the methane production. The entire combined effect of these two processes can be determined from the reduction in the substrate concentration (organic matter). The yield coefficient correlates the treatment mass from anabolic activity and the metabolized mass of organic material [11].

2.2.3 Fermentative catabolism

Anaerobic digestion is a fermentative process applicable to wastewater treatment. The process occurs in anoxic conditions (absence of any dissolved oxygen) and takes place without the transfer of electrons (that is net effect) [12]. The following general equation 2.1, describes the process of anaerobic digestion:

$$CxHyOz + \frac{4x-y-2z}{4} H_2 0 \rightarrow \frac{4x-y-2z}{8} CO_2 + \frac{4x+y-2z}{8} CH_4 \qquad (2.1)$$

For each element in the molecular compound, x, y, and z represent the number of atoms. According to the equation 2.1, methane is produced, which is the most reduced compound that exists.

Therefore, AD can be regarded as the ultimate fermentative process [13]. Carbon dioxide that is a more oxidized compound is also produced and the gases escape the liquid phase as biogas. The methane produced by fermentation process keeps the capacity for electron transfer as no oxidation of organic material occurs during the treatment process.

Figure 2.3 presents the fractions of organic fractions converted through anabolism (cell mass production) and catabolism (stable end products) for both conventional aerobic and fermentative metabolisms [10,14]. The constant "p" in figure 2.4 denotes the COD value of a unit mass of

Microorganisms, determined as volatile suspended solid, VSS, while Y is the yield coefficient, that is the cell mass per unit COD.

2.2.4 Bacterial decay

The abundance or lack of nutrients and electron acceptors, as well as the production and accumulation of inhibitory metabolite [15] control microbial growth. The bacterial population is thus subject to decay

And part of this biomass itself is biodegradable and undergoes metabolism, as it constitutes another source of organic matter [5]. This process is known as endogenous respiration (fig 2.4). As the complexity of the system becomes apparent modeling of anaerobic systems become inevitable. Figure 2.4 shows the different pathways found in the anaerobic digestion system.

2.2.5 General kinetic model

In a model of the overall anaerobic process, only a single biomass and lump substrates are considered. In many situations, methane formation controls process performance rate hence validating it by reflecting kinetic coefficients largely associated with methane-formers [16].

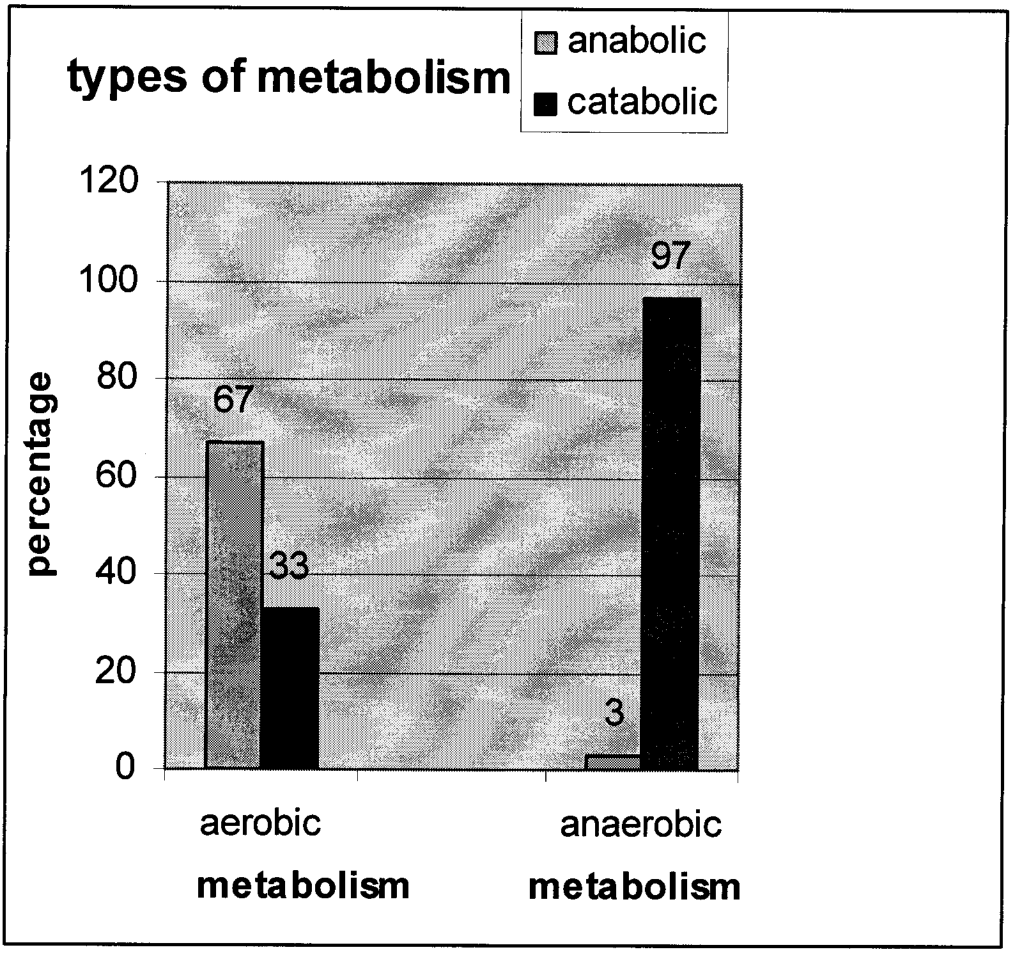

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Figure 2. 3: Fraction of organic matter converted through Anabolism and Catabolism in both conventional aerobic and anaerobic metabolism

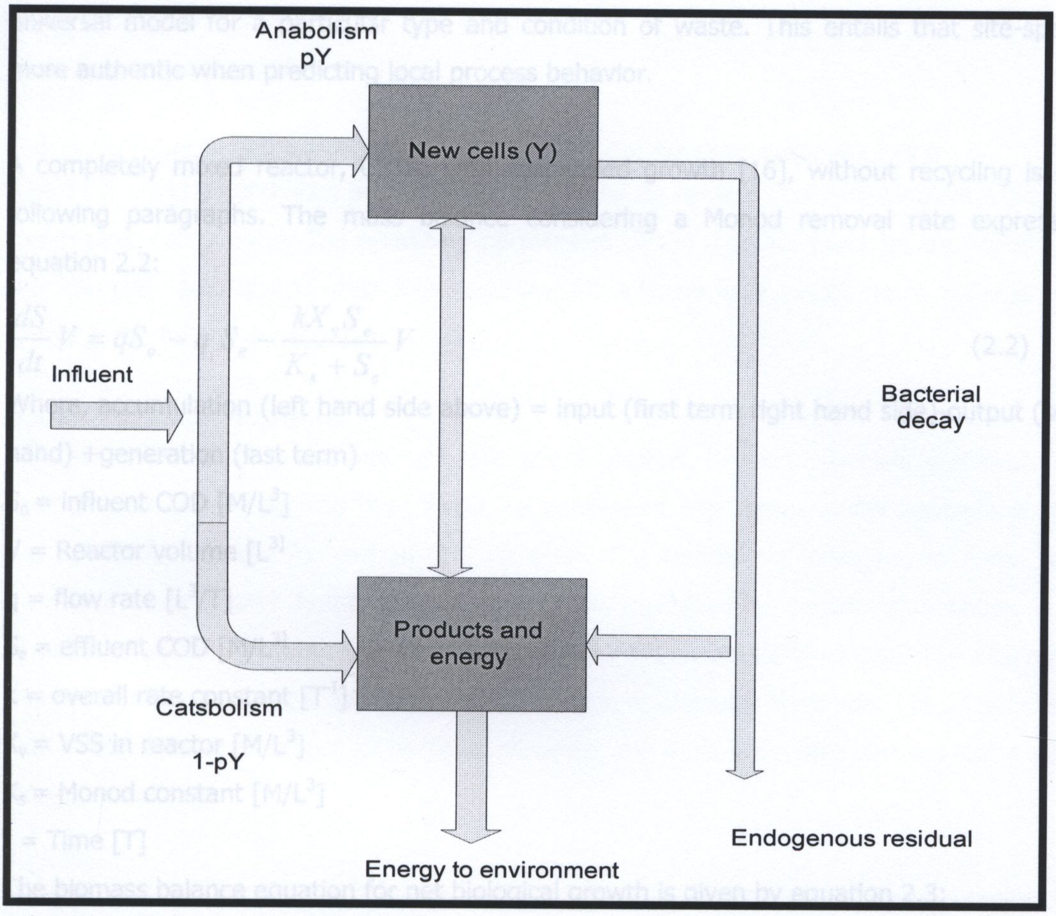

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Figure 2. 4: Bacterial metabolism (anabolism and catabolism) and bacterial decay.

Values from experiments with regard to the most important kinetic constant [17], for acid and methanogenic fermentation, for easy biodegradable wastes, do not represent global identifiable parameters (where there is a unique solution). This makes the models useless in the determination of a universal model for a particular type and condition of waste. This entails that site-specific models are more authentic when predicting local process behavior.

A completely mixed reactor, CSTR, with suspended growth [16], without recycling is examined in the following paragraphs. The mass balance considering a Monod removal rate expression is given by equation 2.2:

$$\frac{dS}{dt}V = qS_o - q\,S_e - \frac{kX_v S_e}{K_s + S_e}V \qquad (2.2)$$

Where, accumulation (left hand side above) = input (first term right hand side)-output (second term right hand) +generation (last term)

S_o = influent COD $[M/L^3]$

V = Reactor volume $[L^3]$

q = flow rate $[L^3/T]$

S_e = effluent COD $[M/L^3]$

k = overall rate constant $[T^{-I}]$

X_v = VSS in reactor $[M/L^3]$

K_s = Monod constant $[M/L^3]$

t = Time [T]

The biomass balance equation for net biological growth is given by equation 2.3:

$$\frac{dX_v}{dt}V = q\,X_o - q\,X_v + Y\frac{kX_v S_e}{K_s + S_e}V - K_e X_v V \qquad (2.3)$$

Y= overall yield coefficient [M/M]

K_e = overall decay rate constant $[T^{-1}]$

X_o = VSS in influent $[M/L^3]$

Other coefficients are as stated in eq (2.2)

Other researchers [18] have given kinetic model equation for methane fermentation as follows:

$$\frac{B}{B_o} = 1 - \frac{(kYK_s/K_h) + K_s/(S_{To} - R\,S_{To})}{\mu_m \vartheta + (kYK_s/K_h) - 1} \qquad (2.4)$$

Where,

B= Specific methane yield in liters per gram of COD

B_o= specific maximum methane yield in liters per gram COD

K_h = hydrolysis rate coefficient [T^{-1}]

μ_m = maximum specific growth rate (1/d)

R= refractory coefficient

S_{To} = Total influent COD

∂ =Hydraulic retention time

2.3 KEY FACTORS AFFECTING DEGRADATION OF ORGANIC MATTER

There are several conditions and variables that must be applied in order to obtain a proper breakdown of the organic compounds. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increases the AD efficiency. Some of these parameters are described briefly in the following sections.

2.3.1 Essential nutrients

Four elements make up the bulk of bacterial cell- carbon, oxygen, nitrogen, and hydrogen. Oxygen and hydrogen are usually derived from water. Of paramount importance in the wastewater treatment field, is the bacteria's demand for carbon and nitrogen. The removal of nitrogen, in some way, reduces the growth of bacteria and therefore negatively affects the biological process that occurs in the stabilization of organic matter. The above elements are present in abundance in sludge. The difference in nutritional requirements of each organism affects its efficacy in wastewater treatment [14]. There are certain critical factors that affect the growth of bacteria. However, the most important physical factor affecting growth is temperature [19].

In order to grow, bacteria require also certain mineral nutrients such as: sulfur, phosphorous, potassium, calcium, magnesium, and trace elements such as iron, manganese, molybdenum, zinc, cobalt, selenium, tungsten, nickel, etc. Biomass, such as agricultural waste or municipal sewage usually contains adequate amounts of the above nutrients. Higher concentration of any individual substance will normally be inhibitory and it is recommended normally to assess each element separately [12].

2.3.2 Total Solids content

Increasing solids content or organic loading rate gradually impairs mobility of the microbes within the substrate [14]. Investigating the slurry in a digester, it was observed [20] that cellulolytic bacteria were the predominant group. Besides it was observed that out of the total cellulolytic population a larger portion was the particulate–bound bacterium. It was also observed that these types of bacteria showed a direct relation to the biogas yield.

There are three different ranges of solid content: Firstly, low solid- (LS), AD systems that contain less than 10 percent Total solids. Secondly, there is medium solids- (MS), from 15-20 percent and thirdly there is high solid systems- (HS), range from 22-40 percent. When increasing the total solids content, the volume of the digester decreases, due to lower water requirements.

2.3.3 Temperature

Certain species of bacteria can only grow in a specific temperature range shown below. In Zambia the temperature range is from 15 to 33 degree Celsius. Significant deviation from this range will destroy the bacteria.

Anaerobic digestion takes place under three main temperature ranges and tolerances per hour,

- The psychrophilic temperature, ranges below 20±2 degrees C /hr
- Mesophilic conditions, between 20-40±1 degrees C /hr
- Thermophilic conditions between 50-60 ± 0.5 degrees C /hr

The optimum temperature of digestion for bacteria growth may vary depending on the feedstock composition and type of digester; but in most AD processes, the optimum temperature should be maintained relatively constant to sustain the gas production rate.

Thermophilic digesters are efficient in terms of retention time, (RT), loading rate and nominal gas production. But they need a higher heat input and have a greater sensitivity to operating and environmental variables, which make the process more problematic than the mesophilic digesters. When the effluent is hot, like in the case of biomethanation of Palm Oil Mill Effluent (POME), in Malaysia the thermophilic process becomes attractive [21].

The sterilization of the waste is also linked to the temperature. The higher the temperature is the more effective the system is in eliminating pathogens, viruses and seeds [22]. As in many, if not all of the biological processes, the rate of activity increases with increasing temperature [23]. Consequently it is not good practice to operate a methane digester under psychrophilic conditions, that is, at ambient temperature and below. However, in Zambia, ambient temperatures are normally above the psychrophilic range.

Methane projects on the farms especially have failed because it is easier to put energy into the process than receive from it. The "heat sink concept" results in a net energy loss when the slurry temperatures for a while go down. When this happens, the system becomes a waste disposal instead of an energy system. By and large, the problems associated with harnessing methane are due to mainly insufficient awareness of the laws of thermodynamics.

When the warmth is allowed to escape and the ambient temperature becomes less than the process requires for maximum output more input than output of energy available is required. For example a digester is capable of producing 0.112 cubic meter of gas for each 0.028 cubic meter of fermenting slurry in a 24-hour period. With any heat loss whatsoever during a cool period, it may require more than 0.112 cubic meter of gas to keep each 0.028 cubic meter of working slurry at optimum temperature for a 24-hour period. Proper design is therefore critical for reaping the benefits of the process [5].

2.3.4 Mixing

There are two other equally important factors that are critical in the processing of organic waste. Namely, mixing and the how the system is kept warm [9]. Mixing within the digester improves the contact between the microorganisms and substrate and improves the bacterial population's ability to obtain nutrients. Mixing also prevent the formation of scum and development of temperature gradients within the digester. However, excessive mixing can disrupt the microorganisms and therefore, slow mixing is preferred. In case of co-digestion, the different feedstocks should be mixed before entering the digestion to ensure a sufficient homogeneity. Use of re-circulated gas for mixing is poor design. This is because air bubbles that are formed rise up and do not go down leaving the digester content not properly mixed [7]. Many ways of mixing mechanisms are reported by [24]. The fact that a mixing system is used does not necessarily justify the selection of the system because of costs. The maintenance of process stability is reported as the reason for substrate agitation. The objectives of agitation are summarized as follows:

- Removal of the metabolites produced by the methanogens (gas)
- Mixing of fresh substrates and bacterial population (inoculation)
- Preclusion of scum formation and sedimentation
- Avoidance of pronounced temperature gradients within the digester
- Provision of uniform bacterial population density
- Prevention of the formation of dead spaces that would reduce the
- Effective digester volume
- Some types of biogas systems function well without any mechanical agitation at all for example Up-flow Anaerobic Sludge Blanket, UASB's

2.3.5 Retention time, (RT)

Retention time is the time needed to achieve the complete degradation of the organic matter. The retention time varies with process parameters such as process temperature and waste composition. The retention time for waste treated in a mesophilic digester ranges from 15 to 30 days and 12 to 14 days for thermophilic digester [25]. In batch type facilities [26], it is possible to accurately determine (RT). In order to determine the mean retention time in a continuous process, the digester volume is divided by the daily feed rate. The retention time in a continuous system depends on vessel geometry, means of mixing, and may vary for individual substrates constituent. Selecting a suitable retention time will depend on process temperature and type of substrate and pre-treatment level. Therefore, the cost efficiency of biological processes is determined by process parameters such as retention time, process temperature, substrate quality, and volumetric load among others. Cost of heating equipment, use of parasitic biogas energy, alternative use of substrates, the cost-benefit ratio, can affect the optimum capture or production and use of methane or biogas. The slow production rate due to biological limitation and difficult control procedure for efficiency and energy yield means that only larger systems are more profitable. However, smaller systems as applied in the rural context have other social-economical and sanitation advantages, especially where public health is a critical factor to consider.

2.4 OPTIMUM PH

The optimum pH values for acidogenesis and methanogenesis stages are different. During acidogenesis, acetic, lactic, and propionic acids are formed and, thus the pH falls. Low pH can inhibit acidogenesis and pH below 6.2-6.4 can be toxic for the methanogens or methane forming bacteria. The optimum range for methanogenesis is between 6.6 and 7. An optimal pH range for all is between 6.4 and 7.2 [27].

2.5 CARBON TO NITROGEN RATIO (C/N)

Microorganisms need both nitrogen and carbon for assimilation into cell structures. Various experiments have shown that the metabolic activity of methanogenic bacteria can be optimized at a C/N ratio of approximately 8-20, whereby the optimum point varies from case to case, depending on the nature of the substrate. Others [29], have reported optimum C/N ratios in anaerobic digesters between 20 and 30. A high C/N ratio is an indication of a rapid consumption of nitrogen by the methanogens and results in a lower gas production. On the other hand a lower C/N ratio cause ammonia accumulation and pH values exceeding 8.5, which are toxic to methanogens. Optimum C/N ratio of the feedstock materials can be achieved by mixing waste of low and high C/N ratio, such as organic solid waste mixed with sewage or animal manure [29].

2.6 ORGANIC LOADING RATE (OLR) OF VOLATILE SOLIDS (VS)

Organic Loading rate is a measure of the biological conversion capacity of the AD system. Feeding the system above its sustainable OLR, results in low biogas yield due to accumulation of inhibiting substances in the digester slurry (that is volatile fatty acids). Under such circumstances, the feeding rate of the system must be reduced. OLR is a particularly important control parameter in continuous systems. Many plants have reported system failure due to overloading. OLR is expressed in kg Chemical Oxygen Demand, (COD), or volatile solids per cubic meter of reactor. It is linked with the RT, for any particular feedstock and anaerobic reactor volume [29]. VS represent the organic matter in a sample, which is measured as solid content minus ash content, as obtained by complete combustion of the feed wastes. Typical values of OLR are a range from 1 to 5.8 kg VS /m^3 working digester volume per day [30]. VS comprise the biodegradable VS (BVS) fraction and the refractory VS (RVS). High VS content with low RVS is more suitable for AD. Because of varying waste characteristics not all sites can be eligible for adopting the anaerobic digestion system.

2.7 BIOLOGICAL TREATMENT, APPLICATION AND CHALLENGES

2.7.1 Wastewater characteristics

Definitions of wastewater, sludge, night soil and sewage are given [31] as follows: Wastewater is a combination of water–carried wastes removed from residences and institutions, waste created by commercial and industrial activity, water from ground and surface water (including storm water). Wastewater sources are generally categorized as municipal, agricultural, or industrial. Municipal wastes are from residential, commercial, and institutional activities, and wastes from street drainage or runoff. Commercial and institutional activities that create waste include hospitals, clinics, department stores, offices, and public recreations, to mention just a few. The contaminants in wastewater are suspended solids, nutrients, biodegradable organics, pathogens, heavy metals, refractory organics, and dissolved inorganic solids. Refractory organics include agricultural pesticides, surfactants, and phenols, which tend to resist conventional wastewater treatment methods. Heavy metals usually come from commercial and industrial activities. Inorganic solids, such as calcium, sodium, and sulfate are found in the domestic water supplies [31].

Sludge contains only feacal matter and urine. Night soil is sewage not mixed with raw sludge but with spent dry sludge. Sewage is human excreta and wastewater flushed along a sewer pipe and includes wastes from kitchen sinks, baths, toilet flushes, laundries, and runoff. Domestic sewage is composed of 99.9 percent water and 0.1 percent impurities, mainly suspended, colloidal, and dissolved solids. There are also gases, microorganisms, and other materials [31].

In wastewater treatment, contaminants are removed by physical, chemical and biological means and the treatment methods are classified as physical, chemical, and biological processes. The physical wastewater treatment process applies physical forces, typically, screening, mixing, flocculation, sedimentation, flotation, and filtration. Chemical precipitation, for example, is accomplished by producing a chemical precipitate, which settles at the end.

A biological treatment is used primarily to remove the biodegradable organic substances (colloidal or dissolved) in wastewater. The substances are converted into gases that can escape to the atmosphere or into biological cell tissues that can be removed by settling. Biological treatment is also used to remove pathogens and nitrogen from wastewater [31].

2.7.2 Advantages of biological systems

Biological treatment has several significant advantages over chemical or physical technologies. Biological systems are more efficient because of the high surface: volume ratio. They have lower construction and operating costs (systems can operate at ambient temperatures), they are robust, and they do not need replacement once loaded. The requirements for treated wastewater, particularly in Europe, are becoming increasingly more stringent. Therefore improved efficiency of biological treatment processes is indispensable [32].

2.7.3 Limitations in anaerobic systems

Problems associated with anaerobic digestion [33] must be understood and kept under control to ensure maximum efficiency and safety. Several factors could severely affect the outcome of digestion. Methanogenic bacteria are very fastidious and can only operate at a particular temperature and pH. In order to avoid extremely long HRT's, it is often necessary to preheat the influent using additional energy. It is also important to maintain alkalinity in the reactor to prevent the pH from dropping to below 6.6.

Foaming occurs in the reactor when there is an excess amount of organics, or when there is an imbalance between the different types of bacteria. An imbalance in the reactor occurs if there is too much grease in the system, extreme temperature fluctuations, and high alkalinity, low total solids, or extensive or inadequate mixing. This imbalance results in foaming of the reactor and production of a scum layer. To control the production of scum and foam, one must remove grease from the sludge influent. Before entering the system, a continuous mixing speed is to be ensured. Explosions occur when there is the proper mixture of air, heat, and gas. Because all these factors are present in the treatment facility, safety precautions are necessary. Since local heat sources cannot be eliminated, mixing the digester gas with the surrounding air is avoided.

Biological treatment is applied not only to different kinds of wastewater such as domestic, municipal, agricultural, but also to the degradation of solid wastes. Biological wastewater treatment processes may be either aerobic or anaerobic. Aerobic systems are ten times faster than anaerobic processes. The sludge produced from aerobic processes is frequently anaerobically treated to reduce the BOD.

There is a great challenge to establish closed decentralized systems where solid organic waste will be efficiently treated together with human excreta. The aims are to decrease costs of pollution due to transportation, use of water, use of agro-chemicals while decreasing retention time, minimizing emissions but increasing hygiene in the working milieu. Reduction of pathogens, protozoa and E. Coli in anaerobic systems, producing quality by-products (biogas and biofertilizers), for energy, improving soil productivity and evolving sustainable ecosystems is a reality [22,34].

2.8 AEROBIC VS ANAEROBIC SYSTEM

The trends of wastewater treatment [8] show that aerobic systems have been developed hitherto than anaerobic systems. However, the former requires higher amounts of capital resources and skilled manpower compared to the latter. This is partly due to the very nature of aerobic wastewater treatment, which requires an external source of oxidant (e.g. oxygen is the natural oxidant of organic matter used in aerobic wastewater treatment). In conventional aerobic metabolism about 67 percent of the organic matter is converted through anabolism to cell mass. This increases the running costs of aerobic treatment systems due to the large daily biological sludge production that requires further treatment. Holding sludge under anaerobic conditions results in a succession of microbial growth and death cycles where decay of cells provides nutrients for the next generation.

2.8.1. Sludge physical characteristics and digesters

Raw sludge from the primary or secondary clarification steps is very wet and becomes putrid on holding [35]. It would be expensive to haul away so much water present. However, AD results in loss of roughly half of the solids, and digested sludge is denser than raw sludge. Nevertheless, very large vessels are required because digestion is slow. Methane evolved during digestion is collected and burned for heating. Several designs for anaerobic treatment have been used, some more efficient, others less efficient. Of these, the anaerobic contact process reactor is most thorough, (a principle of retaining biomass as opposed to biomass growth based systems). Although the contact process is more expensive, it ensures thorough digestion of feed material. The others, for example the plug flow digesters, are only satisfactory. When digesters have to be selected certain other factors have to be considered based on information about the site, nature and volume of sludge intake and the desired quality of the product [36]. The digester must either be a pressure vessel or have a floating lid that holds gas at a pressure sufficient for the weight of the lid.

2.8.2 Biogas physical characteristics and energy content

Methane, the simplest alkane gaseous saturated hydrocarbon, lighter than air, which melts at -184 deg C and boils at -161.4 deg C, is the main constituent of what is popularly known as biogas. It is colorless, odorless, inflammable, and has been referred to as sewerage gas, Kar gas, marsh gas, Refuse Derived Fuel, (RDF), sludge gas, will-o-wisp of marshlands, fool's fire, fuel of the future, or Gobar gas (cow dung gas). The gas mixture produced is composed roughly of 65 percent methane, 30 percent carbon dioxide, 4 percent other gases (ammonia, nitrogen) and 1 percent H_2S. 1,000 cubic feet of processed biogas is equivalent to 600 cubic feet of natural gas, 6.4 gallons of butane, 5.2 gallons of gasoline, or 4.6 gallons of diesel oil [37]. The energy content of pure methane has been estimated to be in the range of 896-1069 Btu /ft^3 or 1000 Btu or 252 kcal [(1055 KJ) / 0.028 cubic meter] per cubic feet or 37.7 MJ per cubic meter. The percentage content of methane will determine the total energy available from the biogas. For example biogas with 65 percent methane will produce 24.49 MJ per cubic meter [30].

CHAPTER 3 METHODOLOGY

In Zambia the biogas technology has not received popular attention as far as its application is concerned. In this study, the Anaerobic Digestion (AD), being considered is an attractive and effective means to use when dealing with excessive, unwanted and mal-odorous wastes that are a nuisance [38,39]. The study focus was limited to two types of wastes: firstly, municipal or domestic sewage and, secondly, bovine meat processing wastes. Two companies in Lusaka were chosen for the purpose of this study.

1. Lusaka Water and Sewerage Company Ltd (LWSC), which generates municipal or domestic sewage waste at Manchinchi Wastewater Treatment Plant (WWTP) and
2. Kembe limited, which generates wet manure and other slaughterhouse, wastes. Preliminary investigation so far conducted at both plants had shown that the problems related to waste disposal of the biological wastes were real and acute.

3.1 RESEARCH QUESTIONS

The operational definition of "bio-processing" terminology emphasizes "small factories" of microorganisms working together to produce a product of some economic value in a controlled environment. A certain quantity of biogas from organic waste produced by a proprietor has or may not have economic value that meets his business need. If there is a benefit, what is the value? And what hidden incentives are present to lure organizations to invest in waste management that pays off?

3.2 BIOGAS PRODUCTION EXPERIMENTS

In the overall assessment of biogas production and utilization potential the following materials were used:

(1) APHA, handbook, a standard method for measurement of water and wastewater to measure BOD, TS and VS [40],

(2) A fabricated 5-liter bioreactor, (see figure 4.1 a, b)

(3) A 1kW immersion heater with thermostatic control,

(4) Gas collection, by means of water displacement with a 500 ml measuring cylinder inverted in a one liter beaker;

(5) Accessories such as a plastic gas collection (bag),

(6) An automatic calibration gas detector, PB1 Dansensor A/S,

(7) Support rig.

Samples were collected by the grab sampling procedure in ten-liter buckets. A portion of the wet organic waste was added in a 5-liter laboratory scale bioreactor after taking the TS and VS measurement. Typical retention time used were 20 to 60 days within the mesophilic range. Measurements included biogas production, methane percent and variation of temperature and its effect on the gas production rate.

There was need to develop a useful model to predict the performance characteristics of the wastewater so that the results could be applied at other similar sites. A generic model was developed using the Laplace transformation technique and a' priori knowledge. In order to calibrate the model, experiments were conducted based on the actual gas produced. Experimentation was considered because the theoretical model developed was limited as far as the actual production patterns were concerned. Moreover the kinetic coefficient,μ, or growth rate was adopted as essential in the building of the model. The coefficient was computed by the use of techniques such as Thomas slope and the Least square estimator. Both these methods depended on the evaluation of BOD for different incubation periods: 2, 4, 6, 8 and 10 days. The theoretical growth rate parameter was firstly assumed to be identical with the one applicable in the actual model. In the theoretical assessment, the Monod equation was used additionally with a priori knowledge to estimate the growth rates using experimental substrate concentrations. After calibration, this procedure yielded the model that can be applied for the domestic or municipal wastewater in Zambia.

3.3 OPTIMAL MATHEMATICAL MODELING OF ANAEROBIC DIGESTION SYSTEMS

Being a complex phenomenon that it is, anaerobic digestion involves numerous changing parameters and coefficients. Mathematical modeling becomes inevitable. It is necessary to develop a model to avoid laborious and time-consuming experiments with only a few results obtainable. The problems of identification (having a unique value) of parameters in model development is solved by optimizing the information carried by those parameters by either lumping them together or by using already existing values from previous similar research work or by conducting own experiments. In this section the approach of using existing variables from previous research work is examined.

The problems in wastewater treatment plant modeling are highlighted in the following section. The difficulties encountered in the need to evaluate each and every coefficient are solved by using what is termed as optimal model complexity or reduced order models [41]. Using this method, a model is developed and variables from other research work are used to predict the model that can be applied in Zambia for the kind of waste selected. The process of developing such models is based on mass balance equations from previous work. The Laplace transformation has been applied in this work to determine the optimal model.

3.3.1 Identifiability

The identification of parameters in modeling of wastewater is difficult to solve [41] because of the high number of unknown (as high as 12) parameters to be estimated and the complexity of the model, and the scarcity of experimental data. Therefore the identification of the 12 parameters was not expected to be possible. The lack of indentifiability of the complex systems was due to the fact that only a portion of information of the systems' behavior was available. The other portion that was not accessible due to its nature showed itself in the variability of the system. Therefore it was not likely to calibrate a model without incorporating data, a priori knowledge from previous experiments. The issue of "complex models versus reduced–order models" [42] was resolved by introducing a new concept of optimal model complexity. The concepts of observability was first introduced by Kalman in the early 1960s but was never implemented in wastewater treatment (WWT) processes mathematical modeling. For example Chen Hashimoto proposed a simple model for continuous flow digesters, which predicted the gas production rate at different temperatures for different loading rates [43].

For computational purposes, the Laplace transformation approach has been chosen in this work due to the simplicity it affords in computation of parameters by algebraic solution of differential mass balance equations.

3.3.2 Model Derivation

In order to have an Indication of the fraction of the organic waste biodegradable it is necessary to determine the substrate utilization rate. The following mass balance Ordinary Differential Equation, (ODE) for substrate utilization in wastewater modeling was used [41].

$$\frac{dCS_0}{dt} = -D\,CS_0 - \beta.CX_1\,CS_0 + D\,Yp\,CS_{0i} \qquad (3.1)$$

Where,

CS_o = Concentration of volatile solids (mg/l)

D = Dilution rate (1/d)

CX_1= Concentration of acidogenic bacteria (mg/l)

Y_p = Fraction of volatile solids in the influent that can be solubilized (mg/mg)

CSO_I =concentration of Volatile solids in the influent (g/l)

β = Solubilization rate per unit of acidogenic biomass (l/mg day)

t = time or Hydraulic Retention Time, HRT

Equation 3.1 shows the breakdown of organic matter / solids to produce diluted substrate, the first term, biomass–substrate composite, the second term. Volatile solids that can be solubilized, is shown by the third term.

The solution to equation 3.1, using the Laplace transformation, is shown in Appendix A2 .The result is shown below:

$$CS\,0(t) = \left(CS\,0(0) + \frac{D\,Yp\,CS\,0_i}{D + \beta\,CX_1} \right) \exp^{-(D+\beta\,CX_1)t} - \frac{D\,Yp\,CS\,0_i}{D + \beta\,CX_1} \qquad (3.2)$$

The equation has SIX parameters that need to be evaluated. Using the optimal complexity approach, it is assumed that D=0. The equation is reduced to the following for a semi- batch process with only THREE unknown variables:

$$CS0(t) = CS0(0)\exp^{(-\beta\,CX_1\,t)} \qquad (3.3)$$

The ODE for the population dynamics [41] is given below:

$$\frac{dCX_1}{dt} = (\mu_1 - K_1 - D)\,CX_1 \qquad (3.4)$$

Where,

CX_1, D, t, are defined above

μ_1=Kinetic growth rate for acidogenic bacteria

K_1=decay coefficient for acidogenic bacteria (/day)

K_2=decay coefficient for methanogenic bacteria (/day)

The solution to equation 3.4 is shown in Appendix A2. The differential equation reduces to the following:

$$CX_1(t) = CX_1(0)\exp^{(\mu_1 - K_1 - D)t} \qquad (3.5)$$

$$CX_2(t) = CX_2(0)\exp^{(\mu_2 - K_2 - D)t} \text{ (for methanogenic bacteria)} \qquad (3.6)$$

Knowing the values of $CX_{1,2}(0)$,$K_{1,2}$,$\mu_{1,2}$, CS0, β, the state space variables for both the population dynamics and substrate utilization rate can be evaluated.

For biogas production [41] the equation is as follows:

$$Q = Y_g \mu_2 CX_2 \qquad (3.7)$$

Q = biogas production rate (liters/day)

Y_g = yield coefficient with respect to gaseous output (l^2/mg)

μ_2, and CX_2 are specified elsewhere.

Since CX_2 is known the equation 3.7 becomes,

$$Q = Yg\,\mu_2\,CX_2 = Yg\,\mu_2\,CX_2(0)\exp^{(\mu_2 - k_2 - D)t} \qquad (3.8)$$

This exponential equation 3.8 indicates that the asymptote is on the abscissa or the hydraulic retention time. However, there is a fixed maximum biogas yield that biodegradable organics manifest. This means that the asymptote is actually on the ordinate. With this in mind equation 3.8 is adjusted as follows:

$$Q = Yg\ \mu_2\ CX_2(0)(1 - \exp^{(\mu_2 - k_2 - D)t}) \tag{3.9}$$

The above is the final equation for biogas production.

Since $CX_{1,2}$ is based on experiments conducted by [41] the GENERAL equation for biogas production from local sewage is given by equation 3.10, :

$$Q = Y_g\ \mu_2\ CX_2(0)(1 - \exp^{(\mu_2 - K_2 - D)}\ t)\frac{V}{3.5} \tag{3.10}$$

Where,

V is the effective volume of the feedstock in Liters, (l.)

3.3.3 Model verification

To assess the performance of the model the values for the coefficients from [41] are used in the model. These values are given below:

$Y_g=74.54$

$CX_2(0)=0.01$

$K_2=0.004$

$\beta=0.092$

In the preliminary assessment of the model performance, it is assumed that the substrate concentration used in the Monod equation [41] is large. Therefore the growth rate

μ_2 computed is equal to respectively μ_{2max}, (0.4, 0.5, 0.6, and 1.0).

$Q_{2,1}$=biogas produced for $\mu_{2max}=0.4$

$Q_{2,2}$=biogas produced for $\mu_{2max=}=0.5$

V=3.5 (liters, l)

For example: Using equation 3.6

For RT =1, $CX_2=0.01*\exp(0.4-0.004-0)*1=0.01$

And equation 3.9 for biogas production

$Q_{2,1}=74.54*0.26*CX_2$

$Q_{2,1}=74.54*0.26*0.01*\exp(0.4-0.004-0)*1*(1-\exp(-(0.4-0.004-0)*1))=0.09$

Where $\mu_2=0.26$ is taken as the average growth rate of the methanoganic population in biogas production -from the science of biomethanation. The values are computed using the spreadsheet (see Table 3.1).

3.3.4 Results and Analysis

The values from Table 3.1 are plotted to obtain the graph (fig 3.1).The graph shows a continued rise in the production rate with increase of retention time. However after an indicative retention time, which depends on the type of substrate, the production rate needs to decrease with increased retention time due to the depletion of the volatile solids. The volatile solids therefore become the limiting factor. The curve must show constancy at some point and start falling according to the law of conservation of mass or energy. For all the values of growth rate there is a limitation in the biogas production rate. It is also assumed that retention time, t, is 10 to 15 days less than what is expected as indicated in fig3.1. Retention 1 day should read, for instance, 10 days. This value represents the incubation time for the substrate. The graph representing the theoretical model requires validation in this case by experiments. The actual performance data on biogas production was obtained by experimentation. This information is used in the calibration process and is shown in tables 4.2 and 4.3 of chapter 4.

Table 3. 1: Theoretical methane production –preliminary model simulation.

RT	CX2,1	CX2,2	CX2,3	CX2,4	Q2,1	Q2,2	Q2,3	Q2,4	Yg	U2
t(day)	mg/l	mg/l	mg/l	mg/l	l/d	l/d	l/d	l/d	l^2/mg	1/d
1	0.01	0.02	0.02	0.03	0.09	0.12	0.16	0.33	74.54	0.26
2	0.03	0.03	0.04	0.05	0.32	0.40	0.70	0.91	74.54	0.26
3	0.04	0.05	0.05	0.08	0.60	0.74	1.06	1.49	74.54	0.26
4	0.06	0.07	0.07	0.11	0.92	1.10	1.41	2.06	74.54	0.26
5	0.07	0.08	0.09	0.14	1.24	1.46	1.76	2.61	74.54	0.26
6	0.09	0.10	0.11	0.16	1.57	1.81	2.11	3.14	74.54	0.26
7	0.10	0.11	0.13	0.19	1.89	2.16	2.46	3.67	74.54	0.26
8	0.12	0.13	0.15	0.22	2.21	2.50	2.81	4.20	74.54	0.26
9	0.13	0.15	0.16	0.24	2.52	2.83	3.17	4.72	74.54	0.26
10	0.15	0.16	0.18	0.27	2.82	3.16	3.52	5.25	74.54	0.26
11	0.16	0.18	0.20	0.30	3.13	3.49	3.87	5.77	74.54	0.26
12	0.18	0.20	0.22	0.32	3.43	3.81	4.22	6.30	74.54	0.26
13	0.19	0.21	0.24	0.35	3.72	4.13	4.57	6.82	74.54	0.26
14	0.21	0.23	0.25	0.38	4.02	4.45	4.92	7.35	74.54	0.26
15	0.22	0.25	0.27	0.41	4.31	4.77	5.28	7.87	74.54	0.26
16	0.24	0.26	0.29	0.43	4.60	5.09	5.63	8.40	74.54	0.26
17	0.25	0.28	0.31	0.46	4.89	5.41	5.98	8.92	74.54	0.26
18	0.27	0.30	0.33	0.49	5.18	5.73	6.33	9.44	74.54	0.26
19	0.28	0.31	0.34	0.51	5.47	6.05	6.68	9.97	74.54	0.26
20	0.30	0.33	0.36	0.54	5.76	6.36	7.03	10.49	74.54	0.26
21	0.31	0.34	0.38	0.57	6.05	6.68	7.39	11.02	74.54	0.26
22	0.33	0.36	0.40	0.60	6.33	7.00	7.74	11.54	74.54	0.26

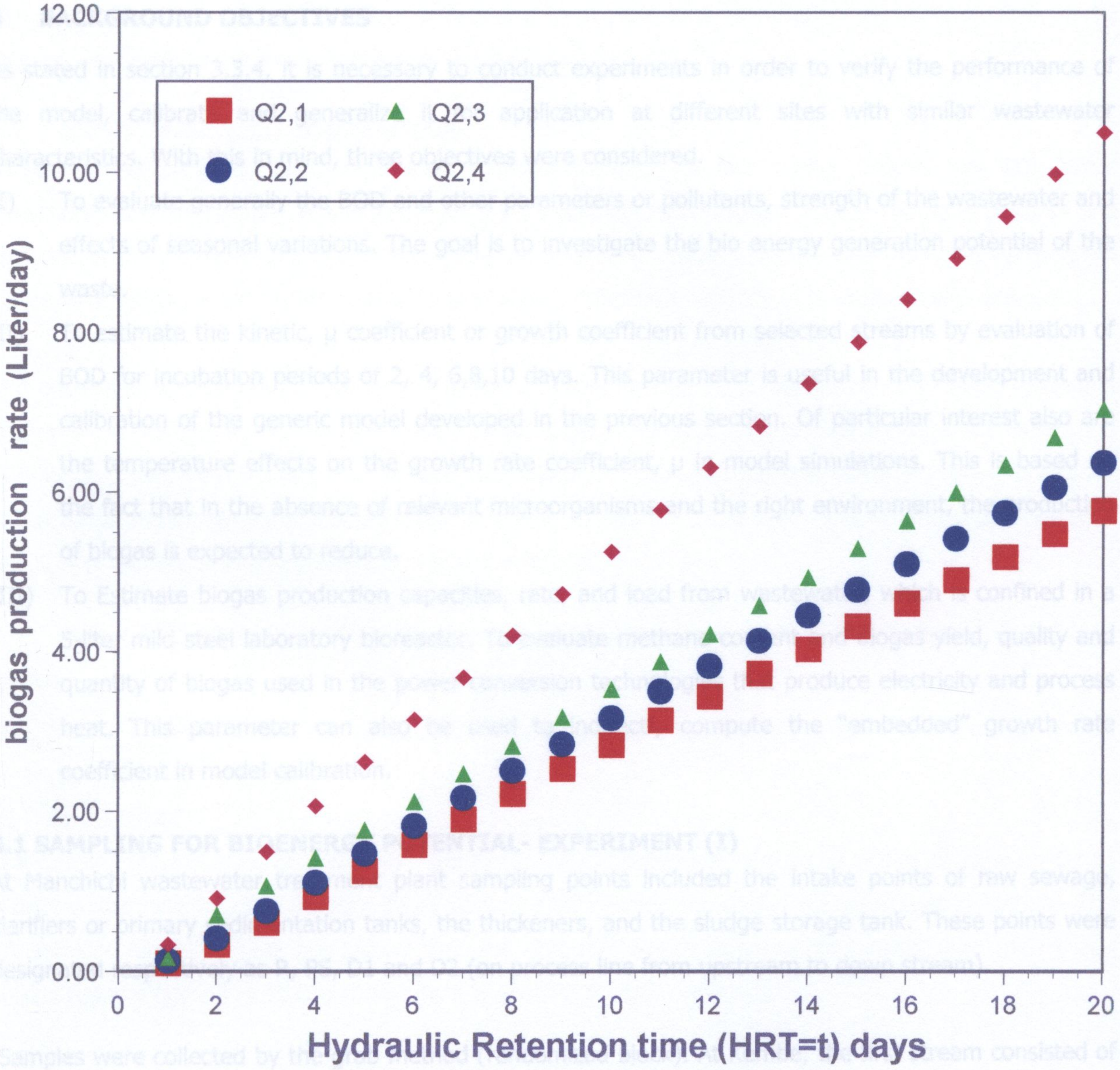


Figure 3.1: Theoretical methane production-preliminary model performance

CHAPTER 4 EXPERIMENTATION

4 BACKGROUND OBJECTIVES

As stated in section 3.3.4, it is necessary to conduct experiments in order to verify the performance of the model, calibrate and generalize it for application at different sites with similar wastewater characteristics. With this in mind, three objectives were considered.

(I) To evaluate generally the BOD and other parameters or pollutants, strength of the wastewater and effects of seasonal variations. The goal is to investigate the bio energy generation potential of the waste.

(II) To estimate the kinetic, μ coefficient or growth coefficient from selected streams by evaluation of BOD for incubation periods of 2, 4, 6,8,10 days. This parameter is useful in the development and calibration of the generic model developed in the previous section. Of particular interest also are the temperature effects on the growth rate coefficient, μ in model simulations. This is based on the fact that in the absence of relevant microorganisms and the right environment, the production of biogas is expected to reduce.

(III) To Estimate biogas production capacities, rate, and load from wastewater, which is confined in a 5-liter mild steel laboratory bioreactor. To evaluate methane content and biogas yield, quality and quantity of biogas used in the power conversion technologies that produce electricity and process heat. This parameter can also be used to indirectly compute the "embedded" growth rate coefficient in model calibration.

4.1 SAMPLING FOR BIOENERGY POTENTIAL- EXPERIMENT (I)

At Manchichi wastewater treatment plant sampling points included the intake points of raw sewage, clarifiers or primary sedimentation tanks, the thickeners, and the sludge storage tank. These points were designated respectively as R, PS, D1 and D2 (on process line from upstream to down stream).

Samples were collected by the grab method (randomized block). At Kembe, the first stream consisted of mainly stomach contents and fats (k_p). The other streams included mainly a mixture of cow dung and process waste, which is finally disposed into the main sewer line (k). Samples were collected once a week or fortnightly in the selected months.

4.1.1 Materials and methods for experimentation (I), line parameters

The materials used for the experiments to assess the bioenergy potential at various points along the treatment process lines included APHA standard methods [8] for measuring BOD, TS and VS. The results are shown in Appendix D2. One-liter serum bottles were used for the collection of BOD samples, which were analyzed in the laboratory situated at the treatment plant. The other parameters evaluated also included: TSS, VS, pH, T and TDS whose results are also shown in Appendix D2.

4.2 EXPERIMENT (II)-μ COEFFICIENTS

The evaluation of the kinetic growth coefficient μ from BOD data (incubation period of 2, 4, 6, 8, 10 days) is according to the least square and Thomas slope [44, 45].

4.3 EXPERIMENT (III)-BIOREACTOR

Samples collected in 10-liter buckets were proportionally (3.5 liter each), poured into the 5-liter laboratory scale bioreactors after measuring the TS and VS initial values. Typical retention times of the wastewater lay between 20 and 60 days within the mesophilic range. Also evaluated was the VS removal. Variation of temperature and its impact on the biogas production capacity of the wastes was examined.

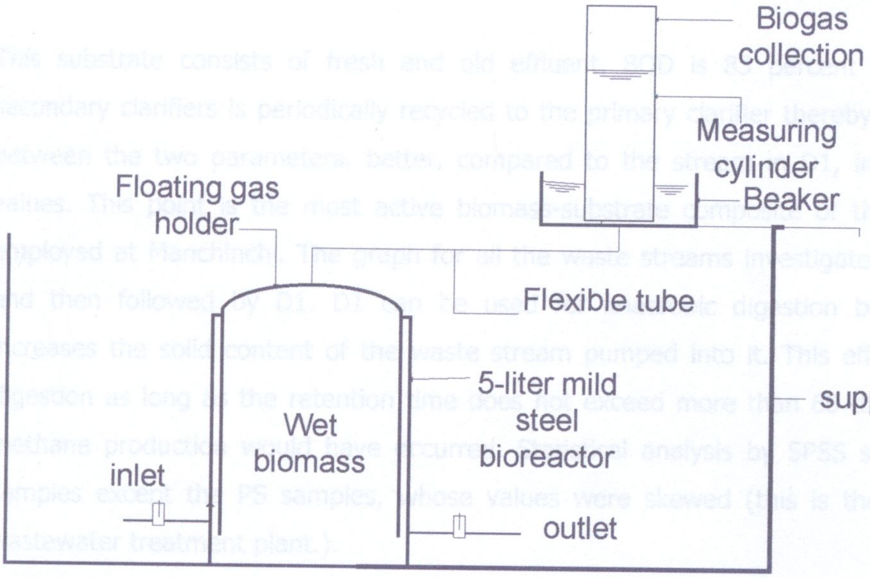
The apparatus to measure biogas production is indicated in figure 4.1 consisting of a 5-liter mild steel tank with a floating holder for gas (sized accordingly, Appendix D1), a 500 ml inverted measuring cylinder, a 1-liter beaker (like in a mercury barometer). A flexible tube was used to move the gas for collection by means of water displacement as shown in figure 4.1a & 4.1b; and for heating, a hot bath and a 1kW immersion-heating element with a thermostat.

4.4 RESULTS AND ANALYSIS from experiment (I) Biochemical Oxygen Demand, BOD5 and others

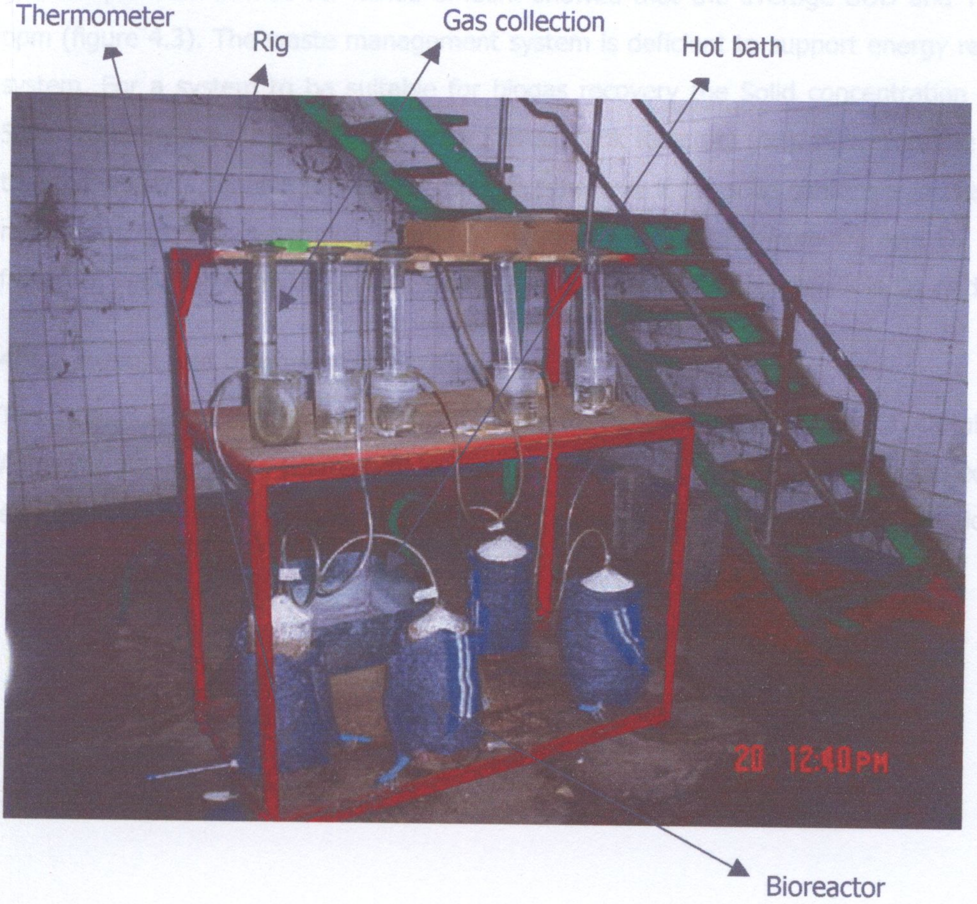
The graphs in figures 4.2, 4.3, B1.1, B1.2 and B3.1 (in Appendix B1 and B3), show the typical characteristics of the wastewater.

a) PS SAMPLE

The average BOD in PS is 25,000 ppm (figure 4.2). This is seen to be the same as the average for D1 as shown in Appendix B1. The average TS, is 40,000 ppm ignoring the outlier measurement in January. The TS and TSS correlate well suggesting that the effluent have high-suspended solids than mineralized solids. The average VS is 30,000 ppm, which is close to the BOD value



(a) Schematic layout of biogas collection by water displacement



(b) **Figure 4. 1:** Pictorial view for sludge fermentation and gas collection

This substrate consists of fresh and old effluent. BOD is 83 percent of the VS. The effluent from secondary clarifiers is periodically recycled to the primary clarifier thereby showing a positive correlation between the two parameters, better, compared to the stream in D1, in this case taking the average values. This point is the most active biomass-substrate composite of the waste management system employed at Manchinchi. The graph for all the waste streams investigated indicated a high BOD for PS and then followed by D1. D1 can be used for anaerobic digestion because this unit (dewatering) increases the solid content of the waste stream pumped into it. This effluent is suitable for anaerobic digestion as long as the retention time does not exceed more than 60 days, a time by which the most methane production would have occurred. Statistical analysis by SPSS showed normal distribution for samples except the PS samples, whose values were skewed (this is the most turbulent point at the wastewater treatment plant.).

b) K SAMPLE

The sample from Kembe for mixed effluent showed that the average BOD and TS was less than 5,000 ppm (figure 4.3). The waste management system is deficient to support energy recovery from anaerobic system. For a system to be suitable for biogas recovery the Solid concentration should be higher than 5,000-10,000 ppm for a CSTR (Contact Stirred Tank Reactor) [46]. However, the μ coefficient indicates that the waste is suitable for energy recovery; but only if the solid content is increased. While biogas was recovered from the k sample, sparingly, nothing was realized from D1 and D2 samples. The dilution factor, D, was limiting in the Kembe sample and methanogenic deficiency in D1 and D2.

4.4.1 Result and analysis for Experiment (II)

The μ coefficients determined by BOD measurements are shown in Table 4.1. Detailed analysis is given in Appendix C1 and modeling procedure in section 4.4.3. The values obtained also represent the endogenous decay of biomass. This is step 3 of the calibration procedure (see section 4.4.2).

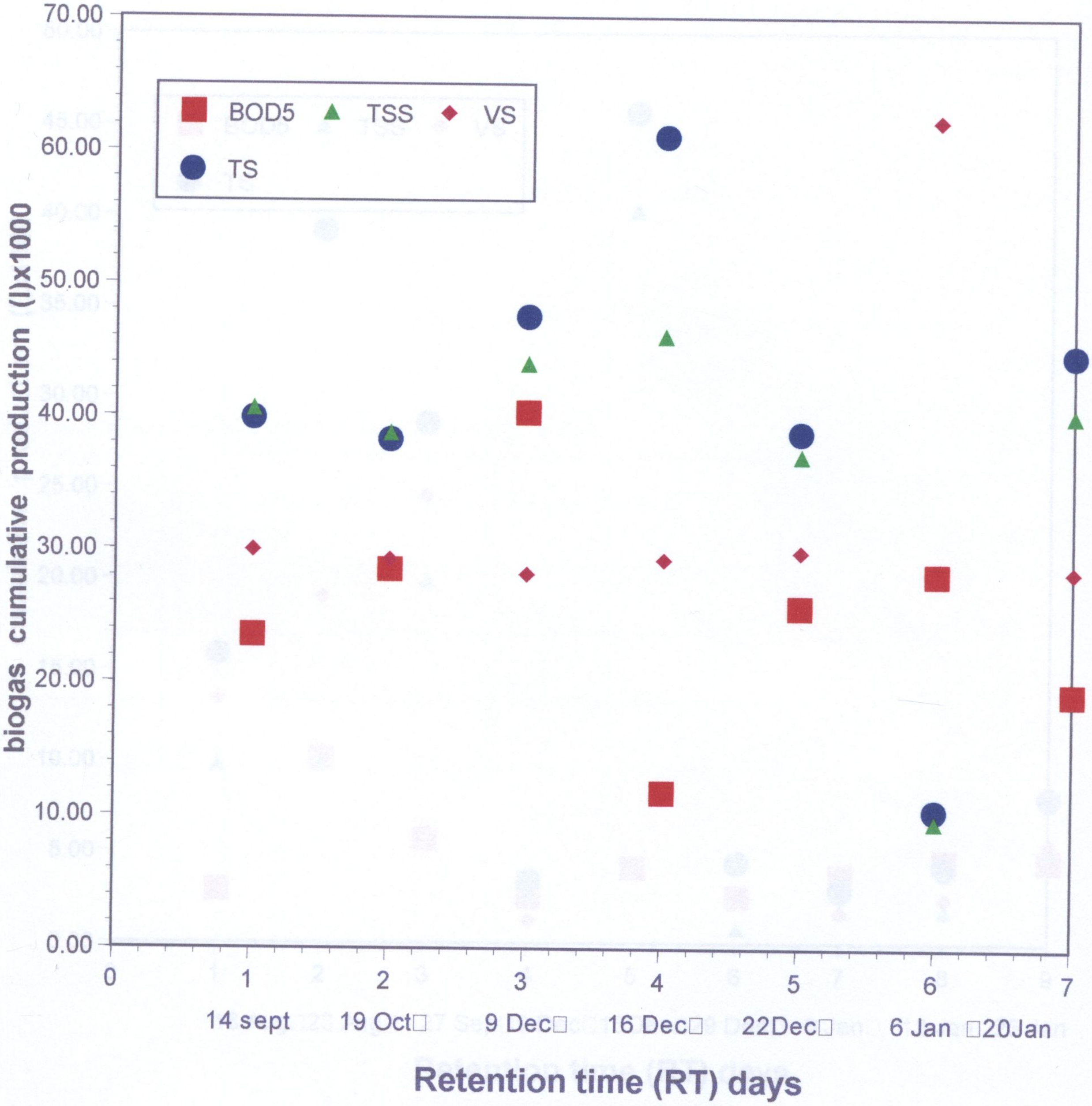


Figure 4. 2: Seasonal effect and variation of pollution parameters at sampling point PS. (Data collected in 2004 and 2005)

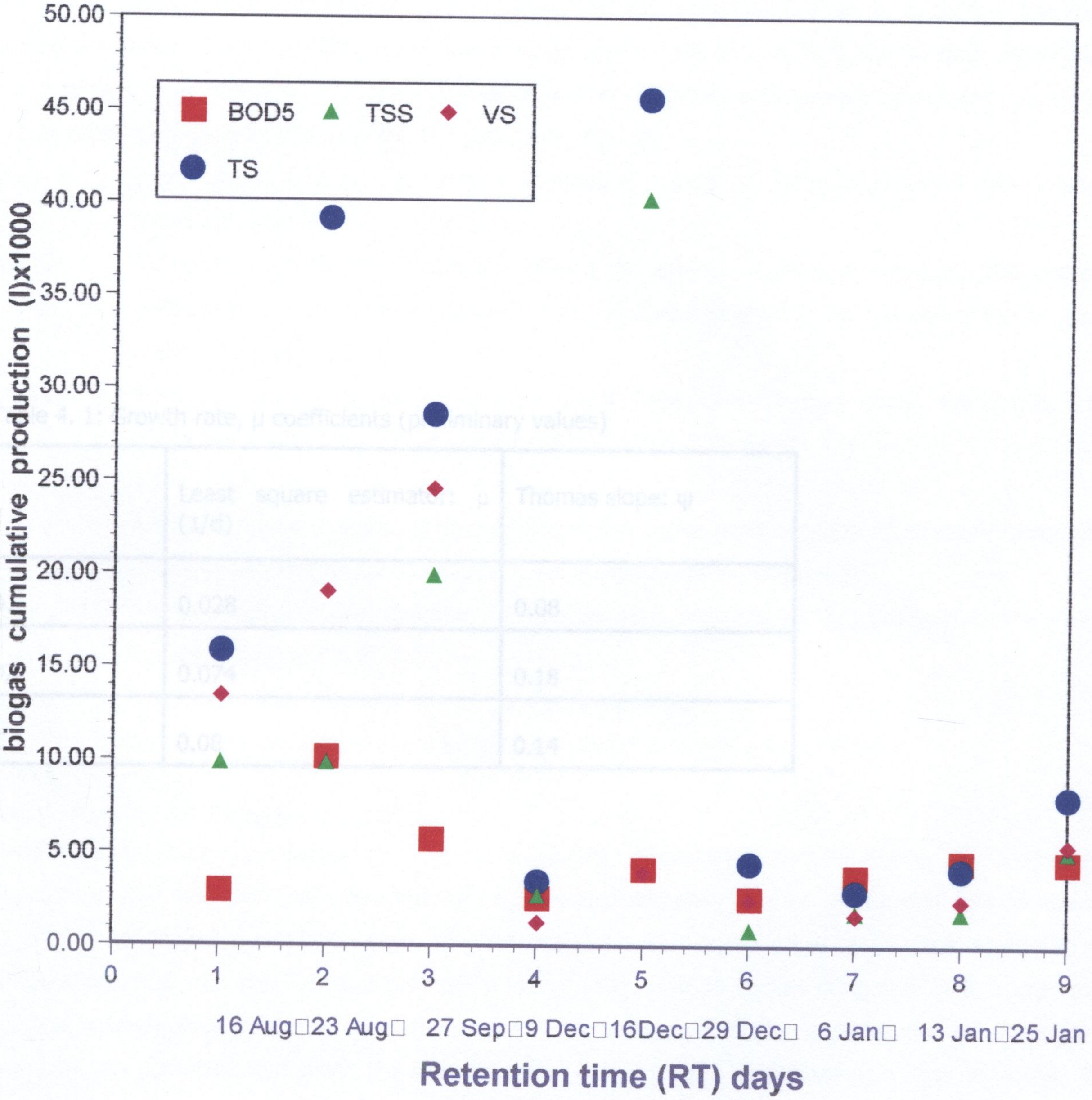


Figure 4. 3: Seasonal effect and variation of pollution parameters at sampling point K.

(Data collected in 2004 to 2005)

4.4.2 Model calibration flow chart

Since several iterations are necessary before arriving at the model that corresponds to the actual production for the type of waste, it is necessary to construct a flow chart in order to follow the steps until the final model is derived. The flow chart that summarizes the procedure is given in figure 4.4. The least square or Thomas slope from BOD for different incubation periods of 2, 4, 6, 8 and 10 days determines the start up values of the growth rate. This value is then compared with the actual values obtained by biogas production experiments step 4 in the procedure (fig4.4).

Steps 1: From mass balance equations a theoretical model is formulated using the Laplace transformation.

Step 2: Substrate concentration from experiment is applied in Monod equation, the growth coefficients,μ, from a priori knowledge are selected and used in the theoretical model. (See section 3.3 and 3.3.1)

Step 3: From parameter estimation procedure (Least Square and Thomas slope), the growth rate coefficient preliminary values are determined using BOD results. (See section 4.2 and Table 4.1)

Step 4: A limitation was observed at step 2. Biogas production from experiments is used to estimate the "embedded" growth coefficient. (See Table 4.5 and equation 4.1)

Step 5: The theoretical model (equation 3.9) is calibrated using specific gas production rates. (See figures 4.5,4.6 and 4.7)

Step 6: The generic model is established. (See equation 3.10)

Step 7: The specific model is verified by plotting. (See figures 4.5,4.6 and 4.7)

Table 4. 1: Growth rate, μ coefficients (preliminary values)

	Least square estimator: μ (1/d)	Thomas slope: ψ
D1	0.028	0.08
D2	0.074	0.18
K	0.08	0.14

4.4.3 Results for Experiment (III)

Table 4.2 shows biogas production from sludge at 38 deg Celsius while table 4.3 shows the same at 20 deg Celsius. It is observed that when the temperature approximately doubles, the growth rate increases by 30 percent in the mesophilic range. VS destroyed was 24 percent for RT= 56 days at 20-deg C temperature. Table 4.4 shows biogas production from a mixture of 70 % cow dung and 30 % sludge and figure 4.7 shows the same at ambient temperature. The biogas production experimental set introduces errors to the data collected since the floating cover allows a part of the methane gas to escape in between the floating cover and the bioreactor vessel. Another source of error is trapped methane in the substrate not collected due to the absence of a mixing device. The lower temperature of the substrate limits the actual methane gas that can be collected due to the solubility factor of gas and liquid mixtures. From table D3.1 of Appendix D3 the upper part of the table column 7 gives the average ratio of VS/TS to be 0.66. From the lower part of the same table D3.1 column 1 the biogas yield is 0.19 m3/kg VS. The biogas yield based on total solid, TS, is therefore the product of the two values, that is 0.12 m3/kg TS,

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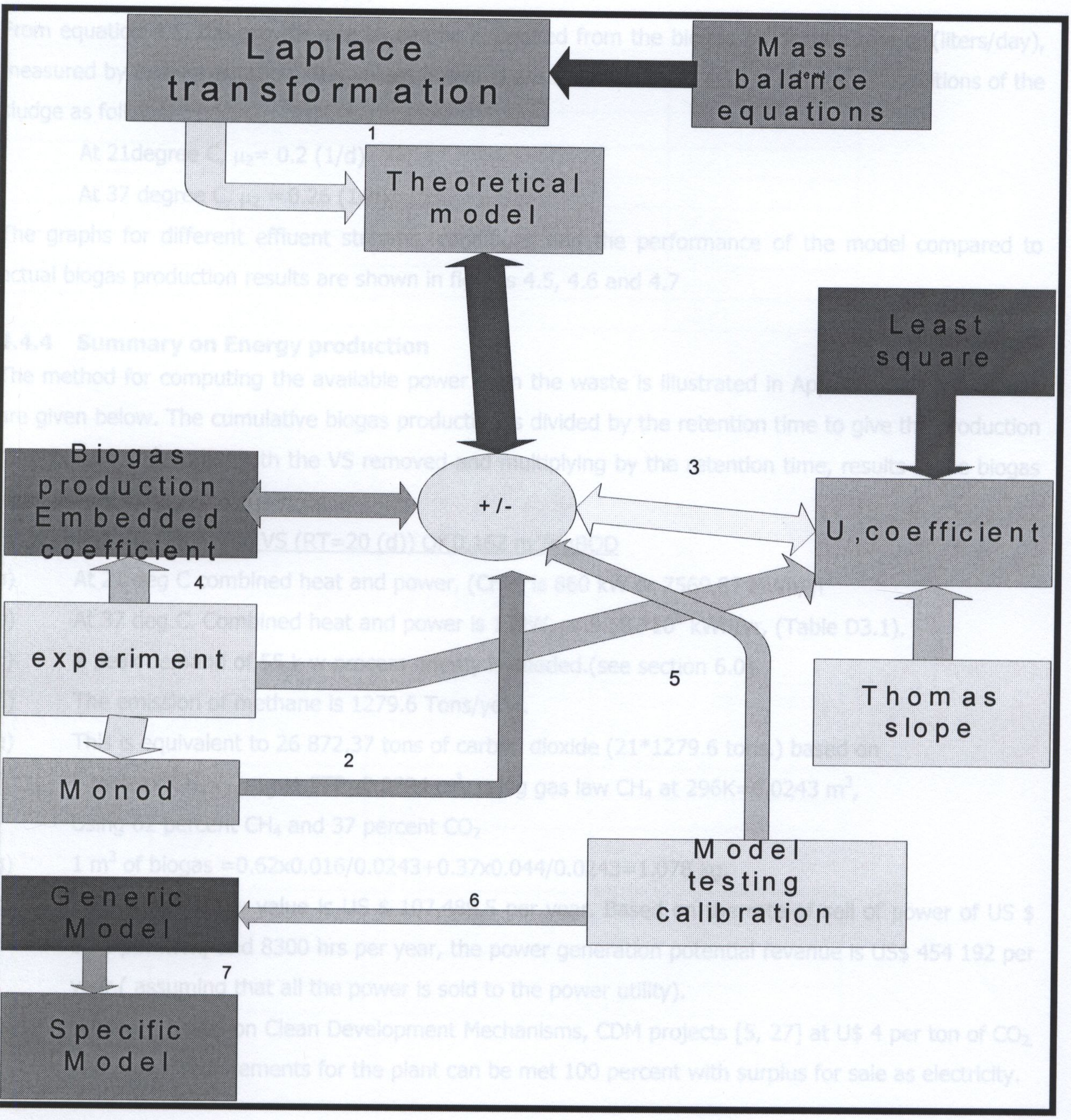


Figure 4. 4: Flow chart for model calibration

Re-arranging the specific biogas equation 3.9 and inserting typical actual biogas volumes produced as follows can do the calibration of the model:

$$(\mu_2 - k2)t = \ln(\frac{q}{(Yg\,\mu\,2CX\ \ 2(0)} - 1) \qquad (4.1)$$

From equation 4.1, the growth rate U_2 can be estimated from the biogas production rate q, (liters/day), measured by experimentation. The values obtained are shown in table 4.5 for the stated conditions of the sludge as follows:

At 21degree C, μ_2= 0.2 (1/d)

At 37 degree C, μ_2 = 0.26 (1/d)

The graphs for different effluent streams, conditions and the performance of the model compared to actual biogas production results are shown in figures 4.5, 4.6 and 4.7

4.4.4 Summary on Energy production

The method for computing the available power from the waste is illustrated in Appendix D3. The results are given below. The cumulative biogas production is divided by the retention time to give the production rate. Dividing this value with the VS removed and multiplying by the retention time, results in the biogas yield.

Biogas yield =0.125 m^3/kg VS (RT=20 (d)) Or 0.162 m^3/KgBOD

a) At 21 deg C combined heat and power, (CHP) is 860 kW or 7569.87 MWh/yr

b) At 37 deg C. Combined heat and power is 1 MW, or 9.58 $*10^6$ kWh/yr, (Table D3.1).

c) A peak demand of 55 k w process energy is needed.(see section 6.0)

d) The emission of methane is 1279.6 Tons/year.

e) This is equivalent to 26 872.37 tons of carbon dioxide (21*1279.6 tons.) based on

f) 1 mole of CH_4=$_{0.016kg}$ at STP=0.0224 m^3, using gas law CH_4 at 296K=0.0243 m^3,
Using 62 percent CH_4 and 37 percent CO_2

g) 1 m^3 of biogas =0.62x0.016/0.0243+0.37x0.044/0.0243=1.078 kg,

h) The Carbon trade value is US $ 107,489.5 per year. Based on the rate of sell of power of US $ 0.06 per kWh, and 8300 hrs per year, the power generation potential revenue is US$ 454 192 per year.(assuming that all the power is sold to the power utility).

i) Above is based on Clean Development Mechanisms, CDM projects [5, 27] at U$ 4 per ton of CO_2.
The power requirements for the plant can be met 100 percent with surplus for sale as electricity.

Table 4. 2: Biogas production from sludge at 38 deg C

Retention time RT	Measured biogas volume, m l	Cumulative Volume m l	Digester temperature ,td Deg C
6	440	440	19
10	700	1,140	20
11	685	1,825	38±1
13	420	2,245	38±1
16	520	2,765	38±1
20	650	3,415	38±1
22	550	3,965	38±1
24	500	4,465	38±1
28	400	4,905	38±1

Table 4. 3: Biogas production from sludge at 20 deg C, TS=6.7percent,

VS=46,067 mg/l

Retention time RT	Measured biogas volume, m L	Cumulative Volume m L	Digester temperature ,td Deg C
14	930	930	21
17	1000	1930	23
22	1030	2960	22
27	1412	4372	20
33	1019	5391	20
45	1388	6779	18
56	1438	8217	20
66	1255	9472	19

Table 4. 4: Biogas production from a mixture of 70 percent cow manure and 30 percent sludge at 22 deg C, TS=4.9 percent; VS=35,950 mg/l

Retention time RT	Measured biogas volume, m L	Cumulative Volume m L	Digester temperature , td Deg C
15	1410	1410	22
16	410	1820	22
20	290	2110	21
22	1300	3410	23
23	1205	4615	23
24	425	5040	20
45	310	5350	21
56	855	6205	23

Table 4. 5: Determination of the (μ) value from biogas production

t	q(t)	YgU2CX2(0)=Φ	ln(1-q(t)/Φ)/t+0.019*
day	l/day	-	-
10		0.149	
11		0.149	
12		0.149	
13		0.149	
14	0.93	0.149	0.14
15		0.149	
16		0.149	
17	1.9	0.149	0.16
18		0.149	
19		0.149	
20		0.149	
21		0.149	
22	2.96	0.149	0.15
23		0.149	
24		0.149	
25		0.149	
26		0.149	
27	4.37	0.149	0.14
28		0.149	
29		0.149	
30		0.149	
31		0.149	
32		0.149	

* Decay coefficient [41]

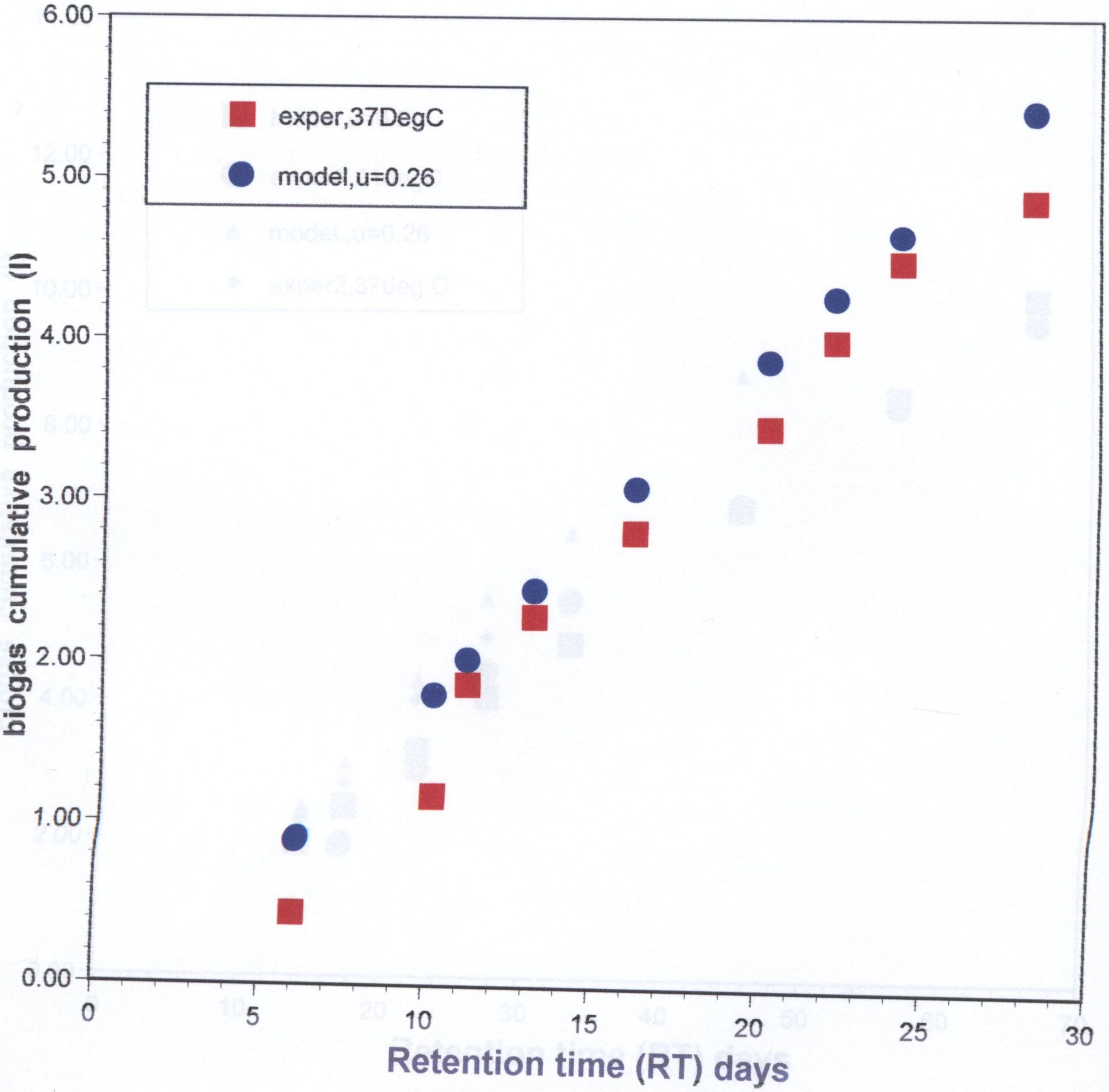


Figure 4. 5: Production of biogas from sludge at 37 deg C (model and experiment)

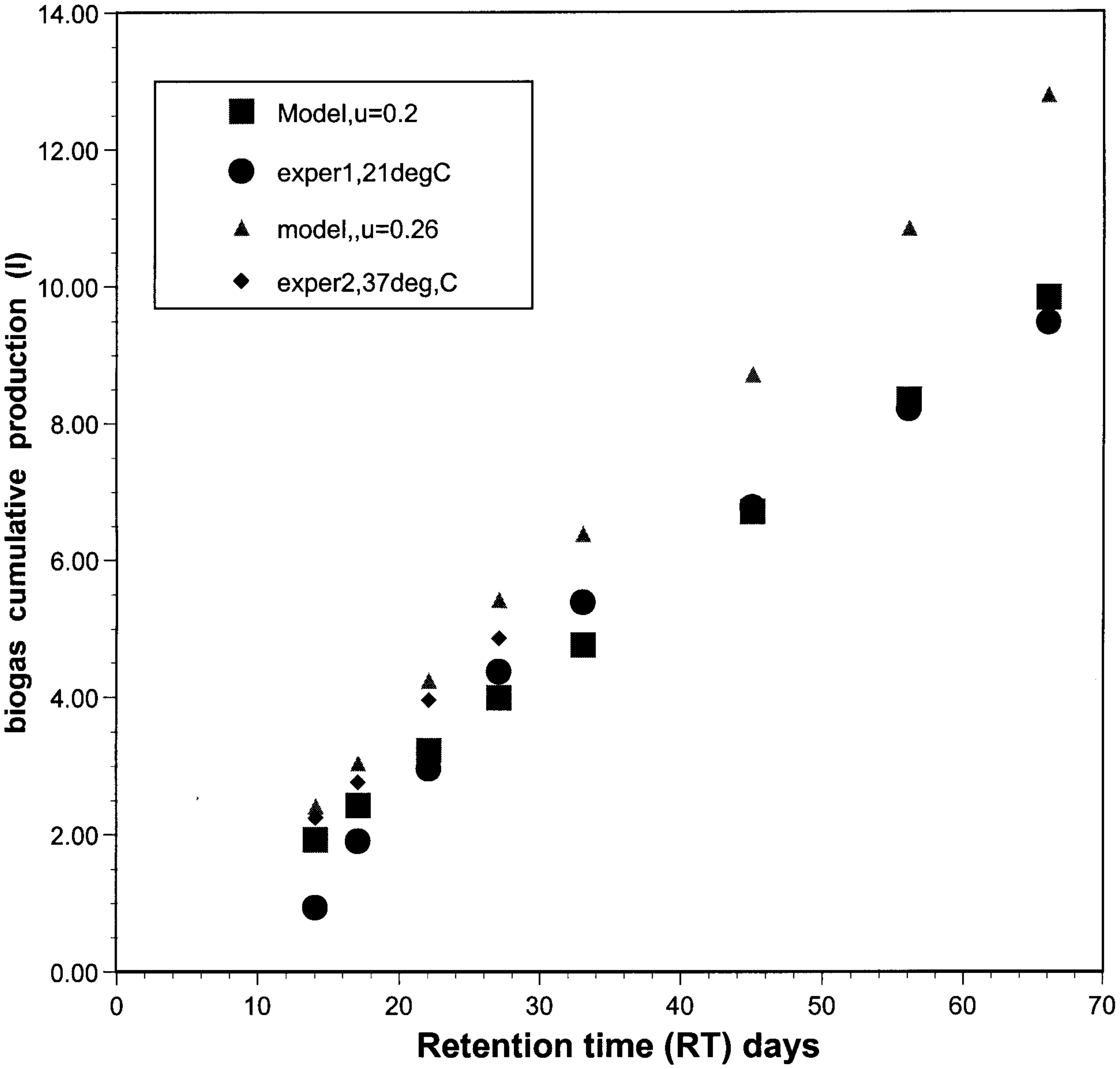


Figure 4. 6: Production of biogas at 21 and 37 deg C for sludge

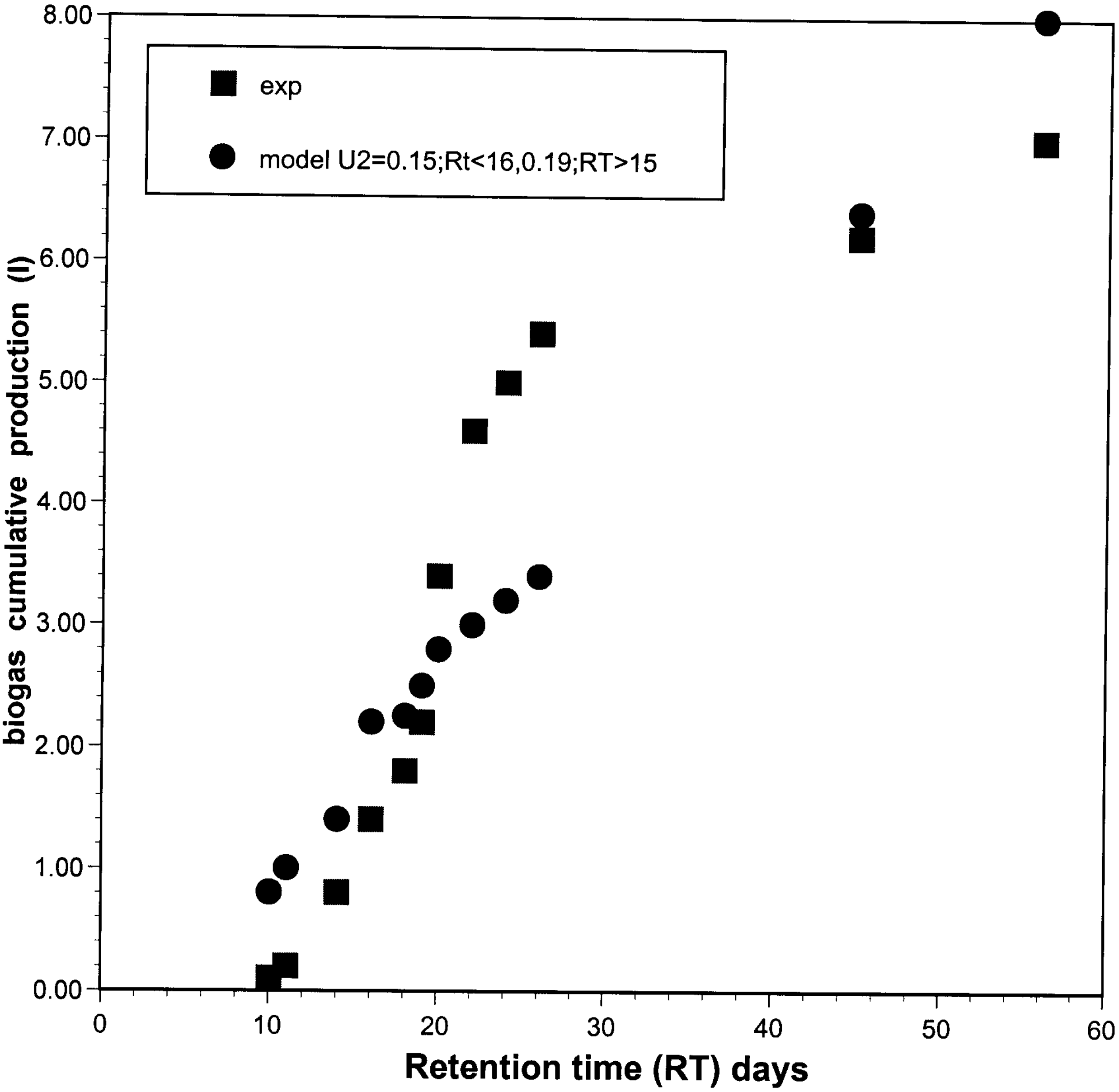


Figure 4. 7: Production of biogas from 70 percent cow manure and 30 percent sludge ambient temperature (23 deg C)

CHAPTER 5 BIOGAS AND POWER TECHNOLOGIES

5 BACKGROUND

Use of biogas as a biofuel in existing types of power generation technology is at commercial status. The purpose of this section is to assess these technologies in order to design the appropriate site-specific systems that can be used. One important criterion for choosing technologies is cost that meets the investment requirement. Table 5.1 shows the level of maturity of anaerobic digestion and other types of technology [47].

5.1 INVESTMENT COSTS

Costs represent an important consideration [47] since users will opt for the least cost alternative that serves their power needs. In this respect, there will be no single answer to the question of which power supply option is most cost-effective since the determining factors are site-specific. Some may see cost first as the most important consideration, in many cases opting to continue with power-by-wire. Others will consider the whole lifecycle cost incorporating installed capital cost, fuel cost, operation and maintenance, utilization, site and environmental costs etc.-cost from "cradle to grave." It may be likely that some renewable technologies and fuel cells will remain rather more expensive than turbine technology [48]-competing on overall lifecycle cost and non-quantifiable benefits. Costs include transportation of feedstock, the anaerobic digestion technology and the DG technologies as indicated in fig 5.1 in the Biogas–fuelled Distributed generation, (BDG), which brings together biogas and power generation technology.

The issues that are important in the mix of biogas and power conversion technologies include the following:

- The cost of generated electricity is an important factor that determines the competitiveness of embedded generation. Users will opt for the lowest cost option that is a solution to their power generation needs.
- Technologies offering the most attractive environmental benefits currently have capital costs too high to stimulate volume sales.
- Capital costs must be reduced to enter the market. This means that
- The Distributed Generation, DG, expansion of the markets is in the hands of the decision-makers or policy makers.

Table 5. 1: Commercial status of biomass -based renewable technology

Conversion technology	Resource type	Examples of fuels	Product	End-use	Technology status
Combustion	Mainly solid biomass	Wood logs chips and ,agricultural residuals, chicken litter pellets	Heat	Heat ,electricity,(steam turbine, stirling ,reciprocating steam engines)	Commercial (boilers and steam turbines)
Gasification	Mainly solid biomass	Wood-logs chips agricultural residuals, & pellets	Product gas	Heat(boiler),Electricity (engine, gas turbine ,fuel cell ,combined cycles),transport fuels(methanol, Hydrogen)	Demonstration Early commercial
Pyrolysis	Mainly solid biomass	Wood-logs chips and pellets,agricultural residuals	Pyrolysis oil+by-poduct (product gas ,char)	Heat(boiler),Electricity (engine, gas turbine)	Demonstration
Anaerobic digestion	Wet biomass	Manure ,sewage sludge	Biogas +by-product	Heat (boiler) electricity, gas turbine ,fuel cell ,transport fuels	Commercial

Source: Econnect Report

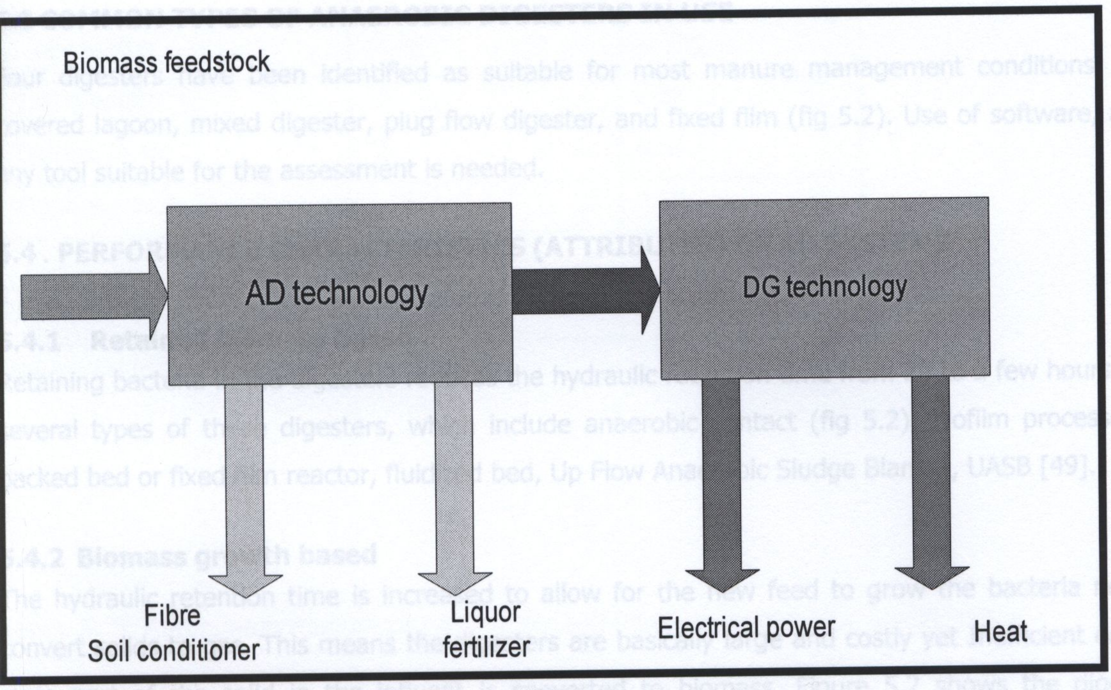


Figure 5. 1: Principle of the Biogas-Fuelled Distributed Generation

- Technically distribution systems, together with the engineering standards that relate to them, were never designed to cope with embedded power.
- Deregulation and liberalization of electricity markets strongly favors smaller scale projects.
- CHP is the most natural application for biogas from purpose built digesters.

5.2 BIOGAS TECHNOLOGIES AND EVALUATION PROFILE

The biomethanation process is discussed in chapter 2. Matching the end-user needs with the power capacity will determine the type of waste management system to be used at premises. The choice of the digester to use is also driven primarily by the climate and characteristics of the existing manure management system that is, how the system affects the total solids content of manure or waste and the type of animal manure and diet [49]. Table 5.2 shows feedstock characteristics and Table 5.3 the manure handling systems.

5.3 COMMON TYPES OF ANAEROBIC DIGESTERS IN USE

Four digesters have been identified as suitable for most manure management conditions. These are covered lagoon, mixed digester, plug flow digester, and fixed film (fig 5.2). Use of software, a model or any tool suitable for the assessment is needed.

5.4 . PERFORMANCE CHARACTERISTICS (ATTRIBUTES) OF AD SYSTEMS

5.4.1 Retained biomass based

Retaining bacteria in the digesters reduces the hydraulic retention time from 20 to a few hours. There are several types of these digesters, which include anaerobic contact (fig 5.2), biofilm processes such as packed bed or fixed film reactor, fluidized bed, Up Flow Anaerobic Sludge Blanket, UASB [49].

5.4.2 Biomass growth based

The hydraulic retention time is increased to allow for the new feed to grow the bacteria necessary to convert solids to gas. This means the digesters are basically large and costly yet Inefficient economically since part of the solid in the influent is converted to biomass. Figure 5.2 shows the digester types commonly used in the anaerobic digestion processes.

5.4.3 Solid content criteria

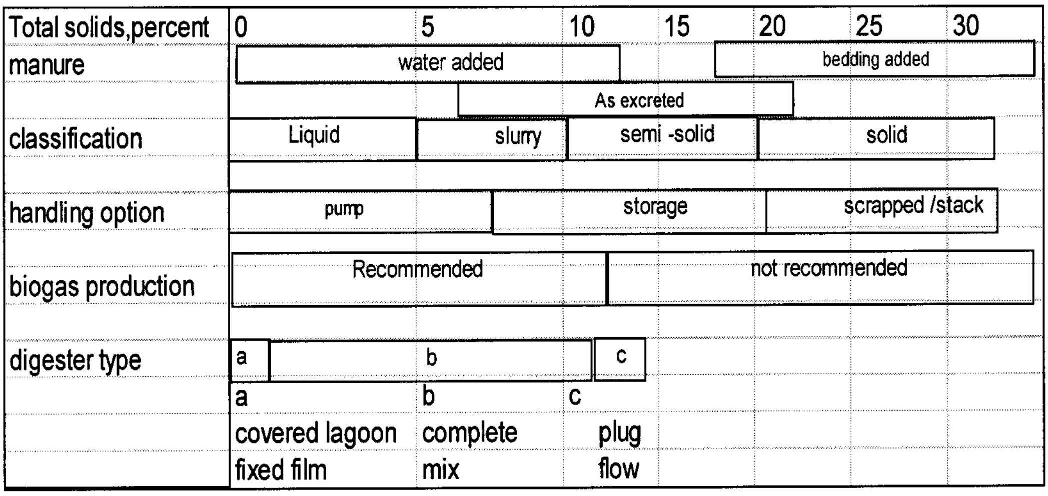
Total solids depend on the animal or waste type, the animal physiology, while the feed regimen determines the "as excreted" TS content. The solid content can be increased by various ways, such as air-drying or the addition of materials or bedding, (figure 5.3). Adding fresh water, wastewater, or recycling flush water lowers the TS content collected in manure. Figure 5.3 also shows ways of reducing TS of waste and anaerobic systems that may be used depending on the solid content percent (Table 5.3) [49].

Table 5. 2: Biogas yields for different feedstock

Feedstock	**Availability**	**Gas yield**
Dry matter	Kg/d	m^3/kg
Cattle waste	10	0.36
Buffalo waste	15	0.54
Piggery waste	2.25	0.18
Chicken waste	0.18	0.11
Human excreta	0.4	0.028

Source: An Indian perspective, India

Table 5. 3: Appropriate manure characteristics and handling systems for specific types of digesters.



Total solids,percent	0	5	10	15	20	25	30
manure	water added				bedding added		
		As excreted					
classification	Liquid	slurry	semi -solid		solid		
handling option	pump		storage		scrapped /stack		
biogas production	Recommended			not recommended			
digester type	a	b	c				
	a	b	c				
	covered lagoon	complete	plug				
	fixed film	mix	flow				

Source: Agstar handbook, EPA

Legend; T =Thermophilic, M= Mesophilic, BG= biogas, in=influent, out= effluent (a) Fixed film, (b) Anaerobic baffled, (c) Completely mixed egg shaped, (d) Lagoon, (e) Phased, (f), Contact), (g) plug flow, (h) Up flow Anaerobic Sludge Blanket, (UASB)

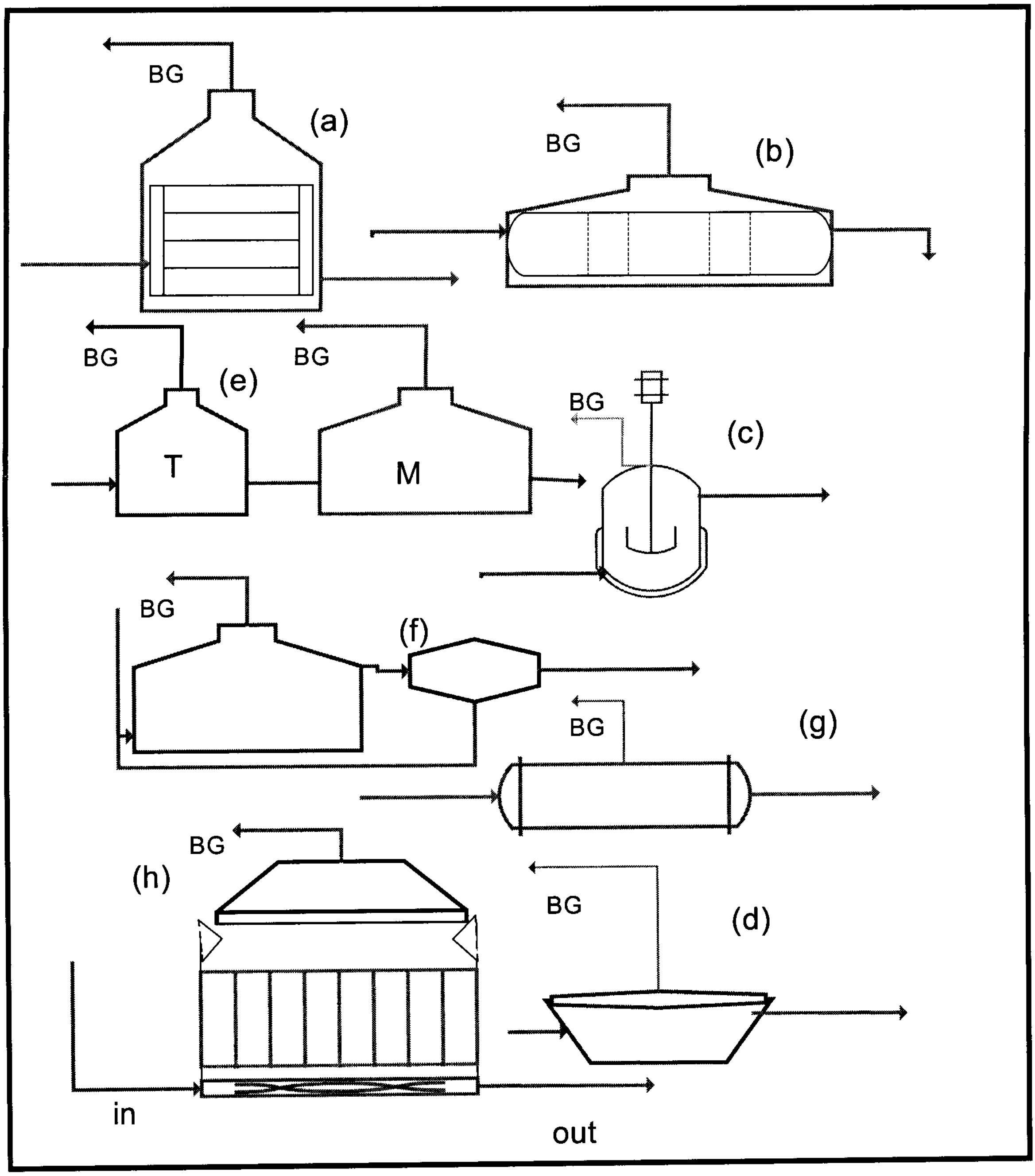


Figure 5. 2: Different types of anaerobic digesters

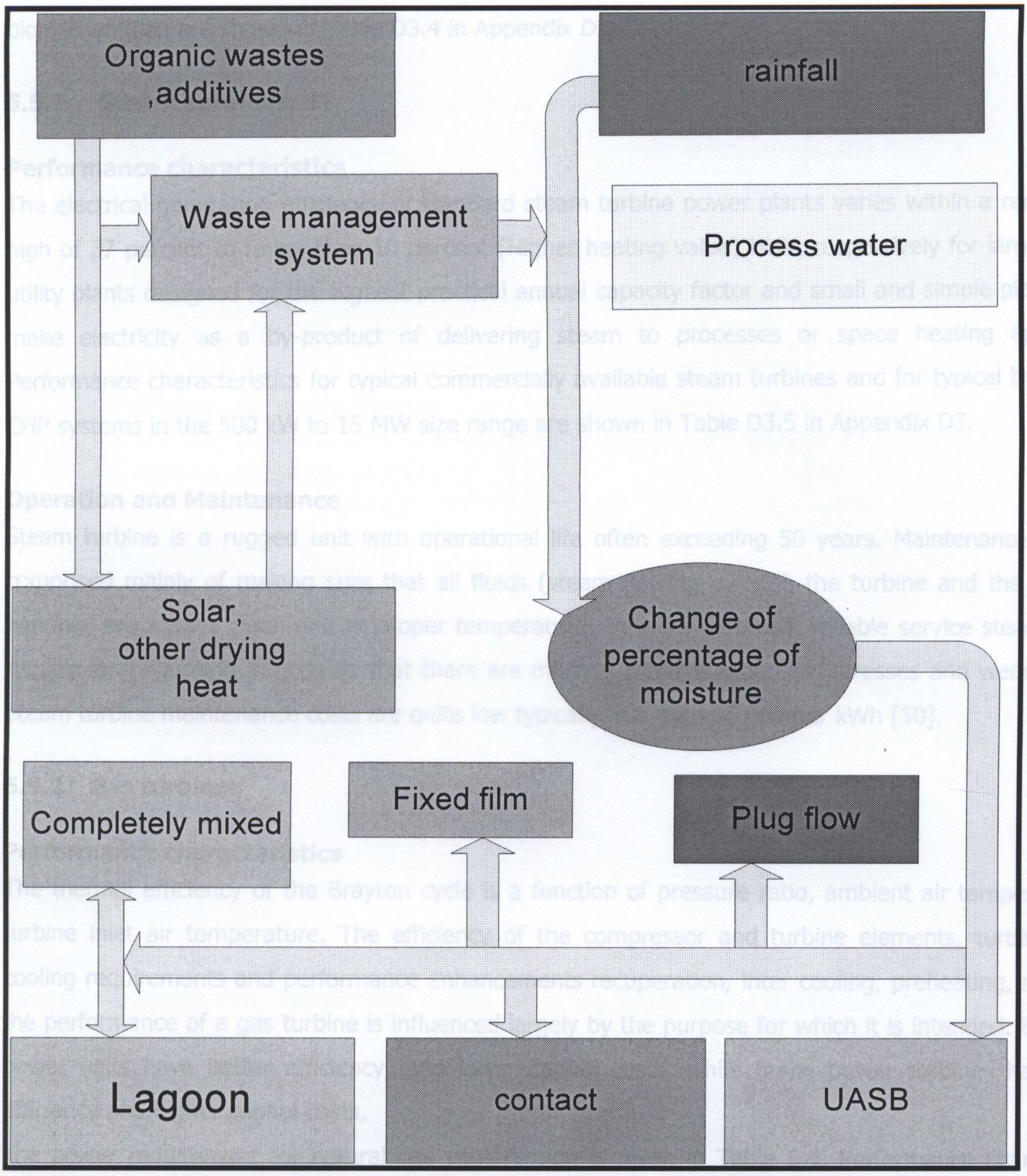


Figure 5. 3: Types of anaerobic systems and different moisture contents of organic wastes

5.5 PERFORMANCE CHARACTERISTICS OF POWER TECHNOLOGIES

The advantages and disadvantages of the different types of power technologies that may be applied with biomethanation are shown in Table D3.4 in Appendix D3.

5.5.1 Steam Turbines, ST

Performance characteristics

The electrical generating efficiency of standard steam turbine power plants varies within a range from a high of 37 percent to fewer than 10 percent (Higher heating value) HHV, respectively for large electrical utility plants designed for the highest practical annual capacity factor and small and simple plants. These make electricity as a by-product of delivering steam to processes or space heating applications. Performance characteristics for typical commercially available steam turbines and for typical boiler/steam CHP systems in the 500 kW to 15 MW size range are shown in Table D3.5 in Appendix D3.

Operation and Maintenance

Steam turbine is a rugged unit with operational life often exceeding 50 years. Maintenance is simple, comprised mainly of making sure that all fluids (steam flowing through the turbine and the oil for the bearing) are always clean and at proper temperature. In order to obtain reliable service steam turbines require long warming periods so that there are minimal thermal expansion stresses and wear concerns. Steam turbine maintenance costs are quite low typically less than $0.004 per kWh [50].

5.5.2 Gas turbines

Performance characteristics

The thermal efficiency of the Brayton cycle is a function of pressure ratio, ambient air temperature and turbine inlet air temperature. The efficiency of the compressor and turbine elements, turbine blades, cooling requirements and performance enhancements recuperation, inter cooling, preheating, re-heating, the performance of a gas turbine is influenced largely by the purpose for which it is intended. Emergency power units have better efficiency, and lower capital costs, while prime power turbines have higher efficiency and higher capital costs.

The power requirement for natural gas compression is given in Table 5.4. Performance characteristics and costs for typical commercially available gas turbines for CHP systems over the 1 to 40MW size ranges are summarized in Table D3.6 in Appendix D3 and Table 5.6. Heat rates shown are from manufactures' specifications and industry publications. Available thermal energy (steam output) was calculated from published turbine data on turbine temperature and flows. Gas turbines need minimum gas pressure of about 100psig for the smallest turbines with substantially higher pressures for large turbines and aero derivative machines.

Table 5. 4: Power requirement for natural gas compression[1]

Turbine (typical gas turbine)	Type 1	Type 2	Type 3
Turbine electric capacity(kW)	1,000	5,000	10,000
Turbine pressure ratio	6.5	10.9	17.1
Required compression power(kW)			
50 psig gas supply pressure	17	125	310
150 psig gas supply pressure	NA	26	120
250 psig gas supply pressure	NA	NA	40

SOURCE: Energy Nexus Group

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[1] fuel gas supply pressure requirements calculated assuming delivery of natural gas at an absolute pressure are 35 percent greater than the compressor discharge in order to meet the requirements of the gas turbine flow control system and combustor mixing nozzles. Mass flow of fuel is based on the fuel flow of reference gas turbines in the size range considered, and assuming an electric motor of 95 percent efficiency driving the booster compressor, gas supply pressure of 50 psig, 150 psig and 250 psig from the basis of the calculation.

Operation and Maintenance

Non-fuel operation and maintenance (O&M) costs are presented in Table 5.5, based on gas turbine manufacturer's estimates for service contracts, which include routine inspections and scheduled overhauls. Routine maintenance practices include on-line running maintenance, predictive maintenance, performance testing, plotting trends, fuel consumption, heat rate, vibration analysis, and preventive maintenance procedures. The O&M costs presented in the table include operating labor. Daily maintenance includes visual inspection every 4,000 hrs for On-site-hot gas path horoscope inspections and non-destructive component testing. a gas turbine overhaul is needed every 25,000 to 30,000 hrs ypical. Table 5.5 shows gas turbine maintenance costs for 1 to 10 MW capacity ranges. As the capacity f gas turbines increases the maintenance costs are reduced because of the reduced number of rotation. The estimated cost for typical CHP gas turbines is shown in Table 5.6.

5.5.3 Micro Turbines

Micro turbines (figure 5.4) are similar to the gas turbines; but smaller, more efficient and robust. Micro turbines are derivatives of the turbocharger. They are small (output range is 30kW-350kW) [1]. There are a number of manufacturers of turbines including Capstone Turbine Corporation, Ingersoll Rand, Elliott/Bowman and Turbec. The electrical out put range is given in Table 5.7. Compared to industrial turbines and gas engines, micro turbines produce extremely low exhaust gas emissions; because they are run with more excess air compared to industrial turbines and, at the same time, lower combustion chamber pressure [51].

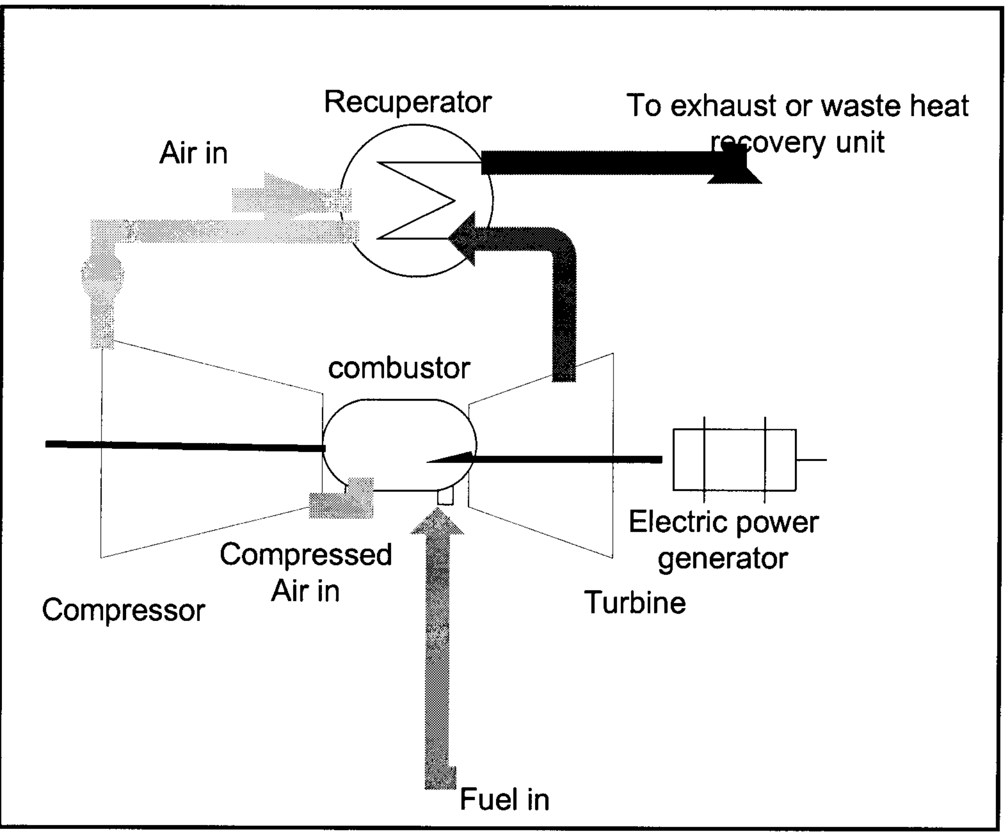

Figure 5. 4: Micro turbine with recuparator

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[1] Units with outputs of above 100kW were not available according to this citation; but are now available in sizes: 30,70, 100 and 350 kW [30].

Table 5. 5: Gas turbine non-fuel (O&M) costs year (2000)

Gas turbines	Type 1	Type 2	Type 3
O & M Costs			
Electricity capacity, Kw	1,000	5,000	10,000
Variable (service contract) $/ kWh	0.0045	0.0045	0.0045
Variable (consumables) $/kWh	0.0001	0.0001	0.0001
Fixed $/kW-yr	40	10	7.5.
Fixed $/kWh @ 8000 hrs /yr	0.0050	0.0013	0.0009
Total O & M Costs,$/kWh	0.0096	0.0059	0.0055

Source: Energy Nexus Group

Table 5. 6: Estimated costs for typical gas turbines-based CHP systems ($000s) [2]

Cost component for gas turbine Nominal turbine capacity (MW)	Type 1 1	Type 2 5	Type 3 10
Equipment	(000 $)	(000 $)	(000 $)
Turbine Generator set	675	1,800	4,000
Heat Recovery Steam Generators, (HRSG)	250	450	590
Water treatment services	30	100	150
Electric equipment	150	375	625
other equipment	145	315	575
Total equipment	1,250	3,040	5,940
Materials	144	346	589
Labor	348	879	1,752
Total process capital	1,742	4,265	8,381
Project construction management	125	304	594
Engineering	63	153	260
Project contingency	87	215	419
Project financing	129	316	518
Total plant cost	2,146	5,253	10,272
Actual Turbine Capacity(kW)	1,210	5,200	10,600
Total plant cost per net kW($)	1,781	1,010	969

Source: Energy Nexus Group

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[2] combustion turbine costs are based on published specifications and package prices. The total installed cost estimation is based in part on the use of a proprietary cost and performance model-SOAPP-CT25 (for the state of the art power plant combustion turbine). The model output was adjusted based on Energy Nexus Group engineering judgment and experience and input from vendors and packagers. And cost can vary widely and are affected by site requirements and conditions, regional price variations and environmental and other local permitting requirements.

Table 5. 7: Electrical output range of gas turbines regimes

	Gas micro turbine	Industrial gas turbine
Electrical output range	30 to 500 kW^3	0.5 to 10 MW
Combustor chamber pressure	3.5 to 4 bar	9 to 16 bar
Combustor chamber temperature	Approx. 950 ° C	Approx. 1,100 deg C
Exhaust temperature	200 to 300 ° C	450 to 550 deg C
Pressure ratio	Approx.3.5 to 8.5	Approx 3.2 to 4.5
Gears	Electronic. Operation	Mechanical

Source: Pro2 GmbH

Performance characteristics

Micro turbines are more complex than conventional simple cycle gas turbines, as the addition of the recuperator both reduce fuel consumption (thereby substantially increasing the efficiency) and introduce additional internal pressure losses that moderately lower efficiency and power. Further detailed features of the design of micro turbines, performance curves and efficiency, related pressure losses, heat recovery, fuel gas booster compressors and recuperators are described by Energy Nexus Group EPA report [52].

Cost estimates for combined heat and power and power-only applications respectively are presented in Tables 5.8 & 5.9, assuming that the CHP system produces energy as recovered heat. Performance characteristics for typical micro turbine CHP systems are shown in Table D3.7 in Appendix D3. The typical estimates for the installed cost of micro turbines are presented in Table D3.7. Installed costs can vary significantly depending on the scope of the plant equipment, geographical area, competitive market conditions, special site requirements, emissions control requirements, prevailing labor rates, and whether the system is new or a retrofit application.

Operation and Maintenance

Micro turbines are still on a learning curve in terms of maintenance as initial commercial units have been n operation for only a few years from 2000. Most manufacturers offer service contracts for maintenance priced at $0.01/kWh. This includes periodic inspections of the combustor (and associated hot section parts) and the oil bearing in addition to regular air and oil filter replacement [52].

5.5.4 Internal combustion, IC engine

The IC sizes range from 20kW up to 6MW industrial type, and 200 to 600 kW truck engines, above 1 MW for locomotive.

Performance characteristics

Performance characteristics are summarized in TableD3.8 in Appendix D3. Typical commercially available natural gas spark ignition, (SI) engine CHP systems are over 100kW to 50 MW size range. The size range covers the majority of the market applications for engine driven CHP. Heat rates and efficiencies shown were extracted from manufacturers' specification and industry publications. Available thermal energy was calculated from published engine data on engine exhaust temperatures and engine jacket, lube system and coolant flows [53]. CHP thermal recovery estimates are based on producing hot water. As shown in Table D3.8, 50.to 60 percent of the waste heat from the engine system is recovered from jacket cooling water and lube oil cooling system at a temperature too low to produce steam.

Table 5. 8: Estimated capital cost for micro turbine in grid-interconnected CHP

Cost component for microturbine Nominal capacity (Kw)	System 1 30	System 2 70	System 3 100	System 4 350
Cost ($ /kW) Equipment				
Micro turbine	1,000	1,030	800	750
Gas booster compressor	Incl.	Incl.	Incl.	Incl.
Heat recovery	225	Incl.	Incl.	Incl.
Controls /monitoring	179	143	120	57
Total equipment	1,403	1,173	920	807
Labor/Materials	429	286	200	160
Total process control	1,832	1,459	1,120	967
Engineering and fees	154	146	112	86
Project contingencies	72	58	45	38
Project financing (interest during construction)	40	32	25	21
Total plant cost ($ / kW)	2,516	2,031	1,561	1,339

Source: Energy Nexus Group

Table 5. 9: Estimated capital cost for microturbine in grid–interconnected power-only applications

Cost component for micro turbine	System 1	System 2	System 3	System 4
Nominal capacity (kW)	30	70	100	350
Cost ($ /Kw)				
Equipment				
Micro turbine	1,000	980	750	700
Gas booster compressor	0	0	0	0
Heat recovery	0	0	0	0
Controls /monitoring	179	143	120	57
Total equipment	1,179	1,123	870	757
Labor/Materials	300	200	140	112
Total process control	1,479	1,323	1,010	869
Project and construction management	266	245	188	206
Engineering and fees	130	85	64	44
Project contingencies	56	50	38	34
Project financing (interest during construction)	31	27	21	18
Total plant cost ($ / kW)	1,962	1,729	1,320	1,171

Source: Energy Nexus Group

The CHP system is assumed to produce hot water, although the multi-megawatt size engines are capable of producing low-pressure steam. Typical gas-engine cost function is shown in Table 5.10. Maintenance costs shown in Table 5.11 are based on engine manufacturer estimates for service contracts consisting of outine inspections and scheduled. Overhauls of the engine generator set are shown in Table 5.12. Costs are based on 8,000 annual operating hours expressed in terms of annual electricity generation.

5.6 POWER GENERATION

5.6.1 Induction and synchronous motors

Two types of generators are used for electricity generation: the induction and synchronous generators. Induction generators operate in parallel with the utility and cannot operate as a stand alone power source. Induction generators derive their phase, frequency and voltage from the utility. Synchronous generators operate as isolated system or parallel to the utility, and require more sophisticated intertie systems to match output to utility phase, frequency, and voltage. Control systems are required to protect the engine and utility. Control packages are available that can shut the engine off due to mechanical problems, utility power outage or utility voltage and frequency fluctuations, or in the event that excess power is generated that the utility will not accept. The primary advantage of a synchronous generator is its ability to act as a stand-alone power source. However, if operated as an isolated system, a synchronous generator must be oversized to meet the highest electrical demand, while operating less efficiently at average or partial loads. Due to the system size and more complicated control requirements, a synchronous generator operating as an isolated system is typically more expensive than an induction generator [54].

5.6.2 Waste heat recovery

Biogas engines reject approximately 75 to 82 percent of energy input as waste heat [54]. This waste heat can be used to heat the digester and /or provide hot water or space (air conditioning) heat to the facility. Commercial heat exchangers can recover waste heat from the engine water-cooling system and engine exhaust of up to 2.05 kW (7000 Btu /hour) for each kW of generator load. Waste heat recovery increases the energy efficiency of the system to 40 to 50 percent.

Table 5. 10: Estimated capital cost for typical gas engine generators in grid inter-connected Combined heat and power applications. $/ kW

Cost component for gas engine generator Nominal capacity (kW)	System 1 100	System 2 300	System 3 800
Cost ($ /kW) Equipment GenSet Package	260	230	269
Heat recovery	205	179	89
Interconnect Electrical	260	90	40
Total equipment	725	499	398
Labor/Materials	359	400	579
Total process control	1,084	899	777
Engineering and fees	129	81	45
Project contingencies	43	34	28
Project financing (interest during construction)	24	25	31
Total plant cost ($ / kW)	1,515	1,197	1,002

Souce : Nexus Energy Group,USA

Table 5. 11: Maintenance of typical Natural Gas,(NG), engine

O & M Costs* for NG engine	System 1	System 2	System 3
Electricity capacity ,kW	100	300	800
Variable (service contract)$/ kWh	0.017	0.012	0.009
Variable (consumables) $/kWh	0.00015	0.00015	0.00015
Fixed $/kW-yr	10	5	4
Fixed $/kWh @ 8000 hrs /yr	0.00125	0.00063	0.0005
Total O & M Costs, $/kWh	0.0184	0.0128	0.0097

Source: Energy Nexus Group

*Typical maintenance costs for gas engine generator sets 2001

Table 5. 12: Representative overhaul intervals for NG engines in base load

Service

	Time between overhauls-(thousand operating hours)				
Engine speed	720 rpm	900rpm	1,200rpm	1,500rpm	1,800rpm
Minor overhaul	>30	15-36	24-36	10-20	8-15
Major overhaul	>60	40-72	48-60	30-50	30-36

Source: SFA Pacific Inc.

5.7 QUANTITATIVE ASPECTS OF POWER AND HEAT ENERGY RECOVERY

5.7.1 Calculation of the total available energy

European generators [55], obtain 0.15kW of electric power per cow on a continuous basis, while American counterparts manage 0.2 k w (4.8kWh/day). The power potential calculations are based on the yield of the sludge that is site specific. Electric Power Potential (EPP) is defined as the maximum of electrical power that can be generated on a continuous basis for a given amount/ number of cows or sludge quantity (0.04kW/t for local sludge) [55]. The amount of energy available for resale depends on two factors. The first is the EPP. The second is the amount of timing of electricity use for the organization–the load curve.

5.7.2 Pricing and flexibility

Interesting categories of regimes governing the use of the electricity are described [55]. The price regimes considered fall under three categories. Either the price at which a farm may sell its electricity (P_s) exceeds, is equal to, or is exceeded by, the price at which it buys electricity (P_b). As an example of a price regime in the first category, there are prices P_s=$0.09/kWh, and P_b=$0.035/kWh. The second category is $P_s = P_b$ = US$ 0.0725/kWh or =0.067/kWh

5.7.3 Choice of turbines

The market dictates the available sizes from manufacturers. Manufacturers of turbines do not cater for small capacities. The least powerful micro-turbine suitable for use with biogas on the market is a 30kW model from Capstone Turbine Corporation. [55]. Other sizes are illustrated below. For instance a 400 (minimum) dairy cow has an EPP of 80 kW (701,280 kWh/yr) and therefore digester electricity requirement of one third, that is, 26.67 kW (233,760 kWh/yr). It also requires an average 12 kW (104,827kWh/yr) of electricity for its dairy operations. Given that the total average power requirement is 38.87 kW, the capacities of micro-turbines can be chosen from the range (depending on future expansion considerations) 40, 50, 60 70 and 80 kW [55].the concept of electric power potential,

CHAPTER 6 SYSTEM DESIGN FINANCIAL AND ECONOMIC ANALYSIS FOR THE APPLICATION OF BIOMETHANATION TECHNOLOGY AT SPECIFIC SITES

6 BACKGROUND

The recovery of energy from sewage sludge in the form of methane–rich biogas was not envisaged at the initial design stage of the Manchinchi treatment plant and meat processing plant at Kembe. For municipal wastewater, anaerobic digestion plants were primarily constructed for sewage stabilization to satisfy statutory effluent discharge requirements. The gas was generally vented into the atmosphere when the anaerobic plants were still in use. The purpose for the following sections is to prepare grounds for designing systems at the sites that are cost effective and meet requirements and specifications for disposal statutory demand.

6.1 STUDY SITES

6.1.1. Manchinchi sewage treatment plant

The Manchinchi sewage treatment plant consists of the old and new plants. The new plant was an extension of the old plant to cater for the increased treatment load due to the population increase in the city and the number of sewer connections. The treatment plant receives organic discharge from households, institutional and commercial buildings, such as hospitals, shops and restaurants, in addition to surface run off. It serves catchments with sewer connection coverage of 400,000 people. It is the largest wastewater treatment facility in Lusaka with 2 million people. The effluent entering the treatment plant is 95 percent domestic wastewater [1]. The plant layout is shown in fig 6.1.

The old treatment plant was commissioned in 1956 and has a capacity of 2300 m^3/d. It is a system comprising of conventional sewage treatment units including trickling filters and clarifiers. This plant has not been operational for a long time. Most of the plant units are dilapidated and need replacement. The new plant as seen in figure 6.1 was commissioned in four stages [56]. The first stage in 1959, second, third, and fourth stages between 1969 and 1980.

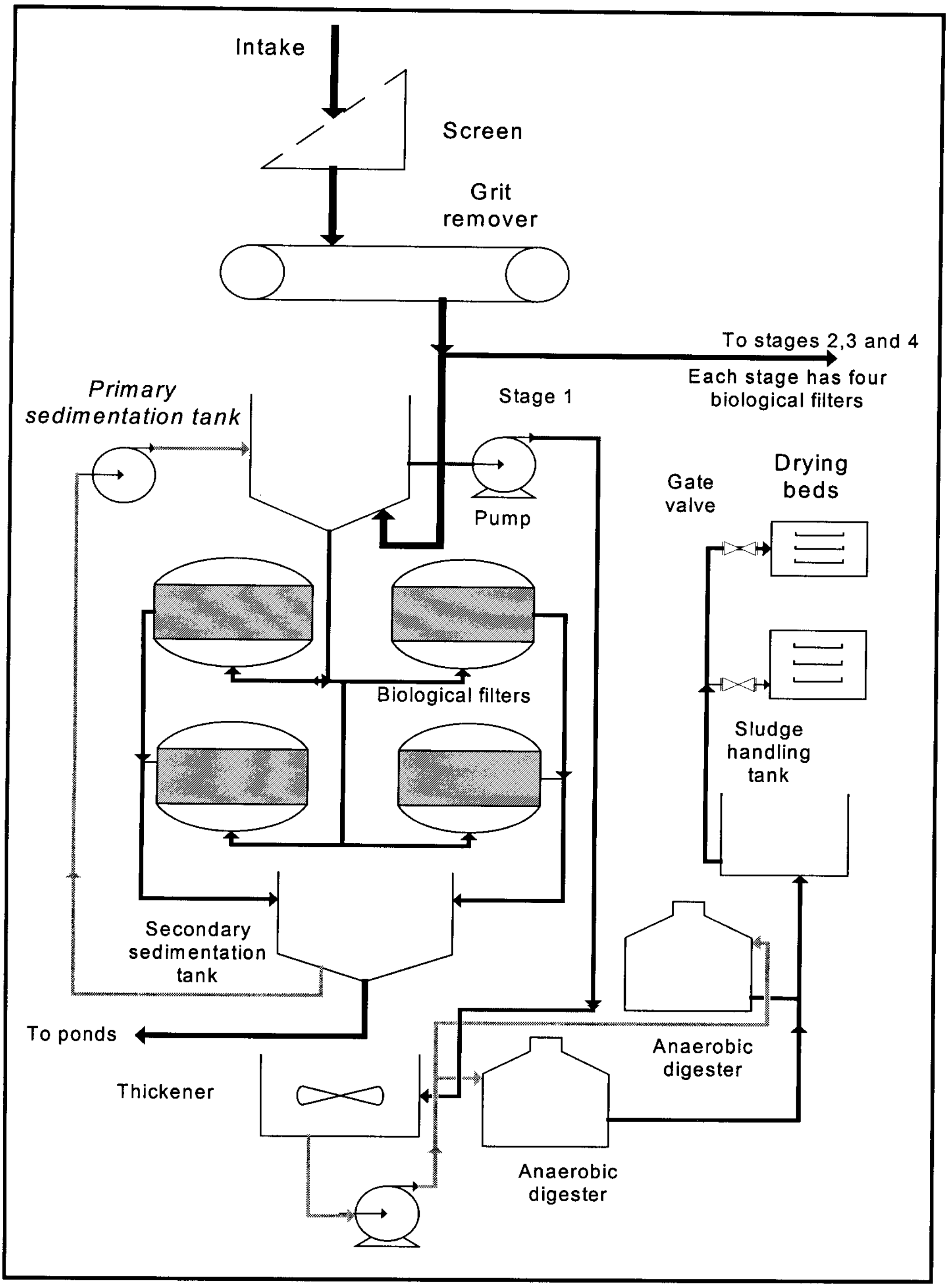

Figure 6. 1: Layout of Manchinchi treatment plant

The plant consists of pretreatment, sedimentation, bio filtration, dewatering and drying that is, mechanical screens, clarifiers, trickling filters, and thickeners, through anaerobic digesters to drying beds. The anaerobic digesters are used for pretreatment of the sewage. The plant performance is around 30 percent efficient (Only about 5 out of the 16 trickling filters were working at the time of this study). About 69,000 m^3/d of influent enters the plant. The plant is equipped with a number of pumps and motors that respectively lift the effluent between units and drive mechanical devices such as scrapers. The pumps are used for effluent re-circulation and mixing before finally leaving the plant. Figure 6.2 shows the thickener and part of the treatment plant. The thickener is in the forefront and the biological filters, clarifiers and intake in the background. The two anaerobic digesters treat sludge from the primary clarifiers. The sludge is then taken into a sludge storage tank/digester before emptying into the drying beds (fig 6.3). The rest of the effluent is taken to the stabilization ponds for post-treatment.

6.1.2. Bovine meat processing plant at Kembe

Samples collected from three different points within the premises were designated; k_p, (kp is sampling point from a floor gully) k_{eff1}, and k_{eff2} (also k). The effluent at the manure pit consists of a mixture of different flows from the slaughter floor namely wastes from offal room, gut room, intestines and stomach contents (paunch) and reticulum (second stomach). Other source of wastes includes dung from the open lot. The system employed in transporting carcasses is shown in fig 6.4, a continuous conveyorized method in which heavy beef trolleys or runners from the overhead rail suspend the carcass. The mixed effluent is transferred from the building to a collecting pit, where a drainage pump transfers the effluent to the manure pit (fig 6.5). The type of disposal system used and the nature and condition of wastes at the different stages of the processing plant as shown in figure 6.6, characterizes the kind or type of effluent. The drainage system used inside the building is the flush method, where waste collecting on the floors is flushed into Gully traps, (GT) and manholes. The system of effluent disposal is the pit-recharge method, where the pit is periodically filled and drawn. A scum forms in these pits on the surface notably in the first tank, which acts as the solid separator for the incoming slurry. The scum is periodically and manually removed from the surface of the tank. The effluent from the first tank finally enters the second tank where, over a weir, it is discharged from the premises into the main sewerage system.

Figure 6. 2: Thickener

Figure 6. 3: Drying beds

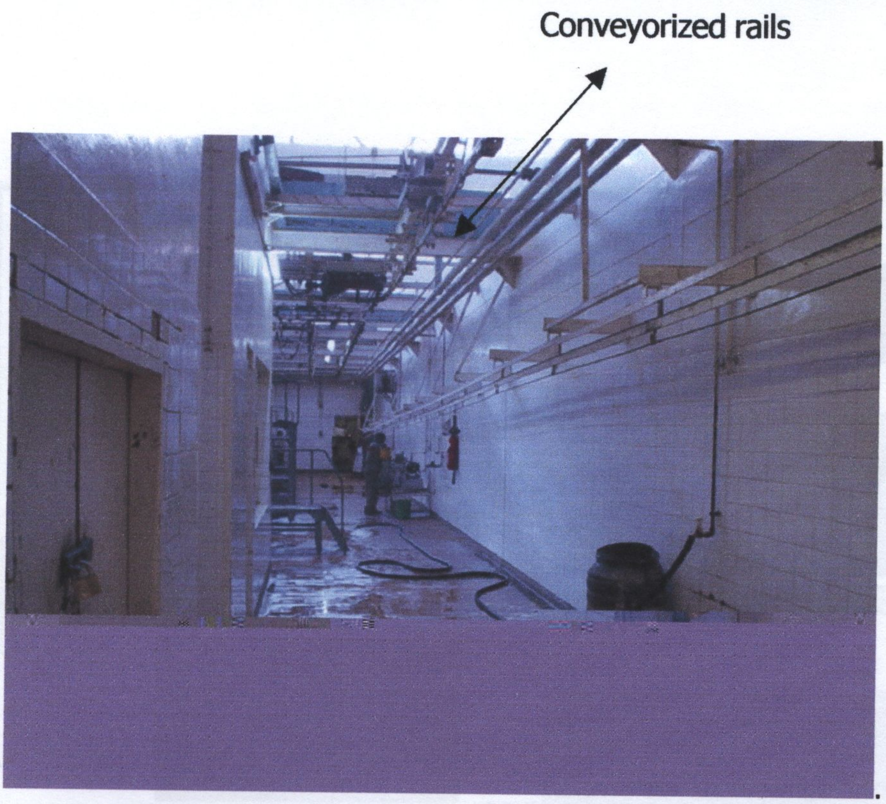

Figure 6. 4: Overhead conveyor rails

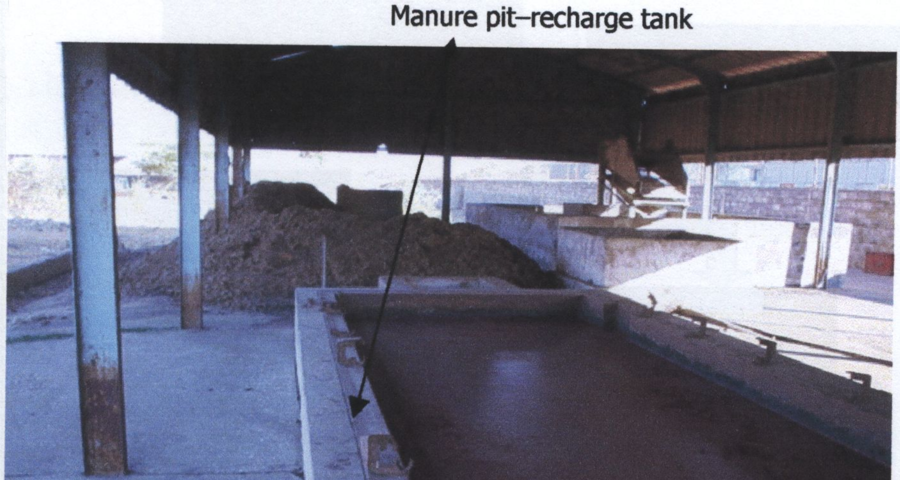

Figure 6.5: animal manure pit-recharge tank

The main sewer line leads to Manchinchi treatment plant situated 4-km north of the city. An average of 300 animals is slaughtered daily when the plant is operating at full capacity.

6.1.3. Load curve.

The operating load curve is shown in fig 6.7. Anaerobic digest [illegible] reactors (fig 6.8) that are not equipped with biogas recovery mechanism [illegible] pital cost to ignore and there are in place at the site, use for them cannot be waived. There is need to adapt the systems' operation, maintain them to include rigo [illegible] nd of the three-tier principle of cleaner production. This adaptation w [illegible] n up new routes of enterprise [illegible] gases, reduce cost of treatment and provide grid energy [illegible] technology there is need to recognize that the first-stage treatment of wastewater should be anaerobic digestion. Design consideration [illegible] that the maximum organic fraction of the wastewater is fed into anaerobic tre [illegible] ctice of [illegible] works wells when considering tr [illegible] with bio energy recovery. Application of anaerobic digestion [illegible] away the original purpose of the application, that is, protecting the environment from nutrient loading, pollution, eutrophication and reduction of the threat on biodiversity in water resources due to insufficient wastewater tr [illegible]

6.2 ENVIRONMENTAL CONSIDERATION

The urgent need to reduce the emission of greenhouse gases worldwide in order to control global warming [illegible] cern about methane generation from anaerobic digestion and anaerobic lagoons [illegible] ponds systems [21]. On sustainable development, the Zambian government [illegible] the creation of other energy routes such as the promotion of [illegible] energy sources [illegible] Sources [illegible] the con [illegible] supplies of hydro [illegible] petroleum [illegible] need to [illegible] lations Framew [illegible] Climate Cha [illegible] ocol.

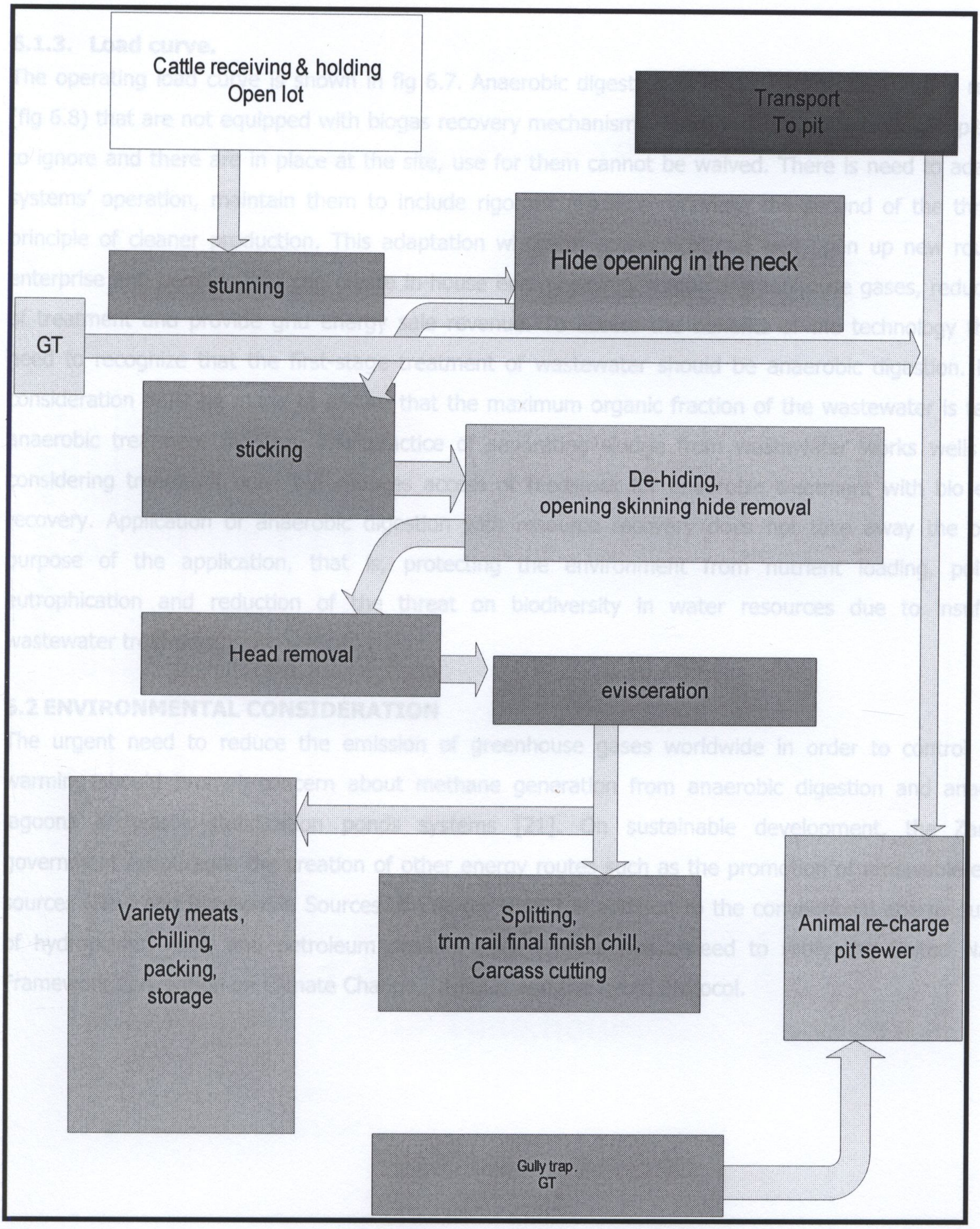

Figure 6.6: Layout for beef slaughtering, cutting and packaging.

The main sewer line leads to Manchinchi treatment plant situated 4-km north of the city. An average of 300 animals is slaughtered daily when the plant is operating at full capacity.

6.1.3. Load curve.

The operating load curve is shown in fig 6.7. Anaerobic digesters at Manchichi are closed-tank reactors (fig 6.8) that are not equipped with biogas recovery mechanisms. Since these tanks are a big capital cost to ignore and there are in place at the site, use for them cannot be waived. There is need to adapt the systems' operation, maintain them to include rigorous resource recovery, the second of the three-tier principle of cleaner production. This adaptation wherever economical can well open up new routes of enterprise and benefits that can create in-house energy saving, mitigate greenhouse gases, reduce cost of treatment and provide grid energy sale revenue. To access the benefits of the technology there is need to recognize that the first-stage treatment of wastewater should be anaerobic digestion. Design consideration must be made to ensure that the maximum organic fraction of the wastewater is fed into anaerobic treatment facilities. The practice of separating sludge from wastewater works wells when considering treatment only; but reduces access of feedstock for anaerobic treatment with bio energy recovery. Application of anaerobic digestion with resource recovery does not take away the original purpose of the application, that is, protecting the environment from nutrient loading, pollution, eutrophication and reduction of the threat on biodiversity in water resources due to insufficient wastewater treatment.

6.2 ENVIRONMENTAL CONSIDERATION

The urgent need to reduce the emission of greenhouse gases worldwide in order to control global warming should prompt concern about methane generation from anaerobic digestion and anaerobic lagoons or waste stabilization ponds systems [21]. On sustainable development, the Zambian government encourages the creation of other energy routes such as the promotion of renewable energy sources (New and Renewable Sources of Energy, NRSE) in addition to the conventional energy supplies of hydropower, coal, and petroleum product [57]. Zambia has agreed to ratify the United Nations Framework Convention on Climate Change, UNFCCC and the Kyoto Protocol.

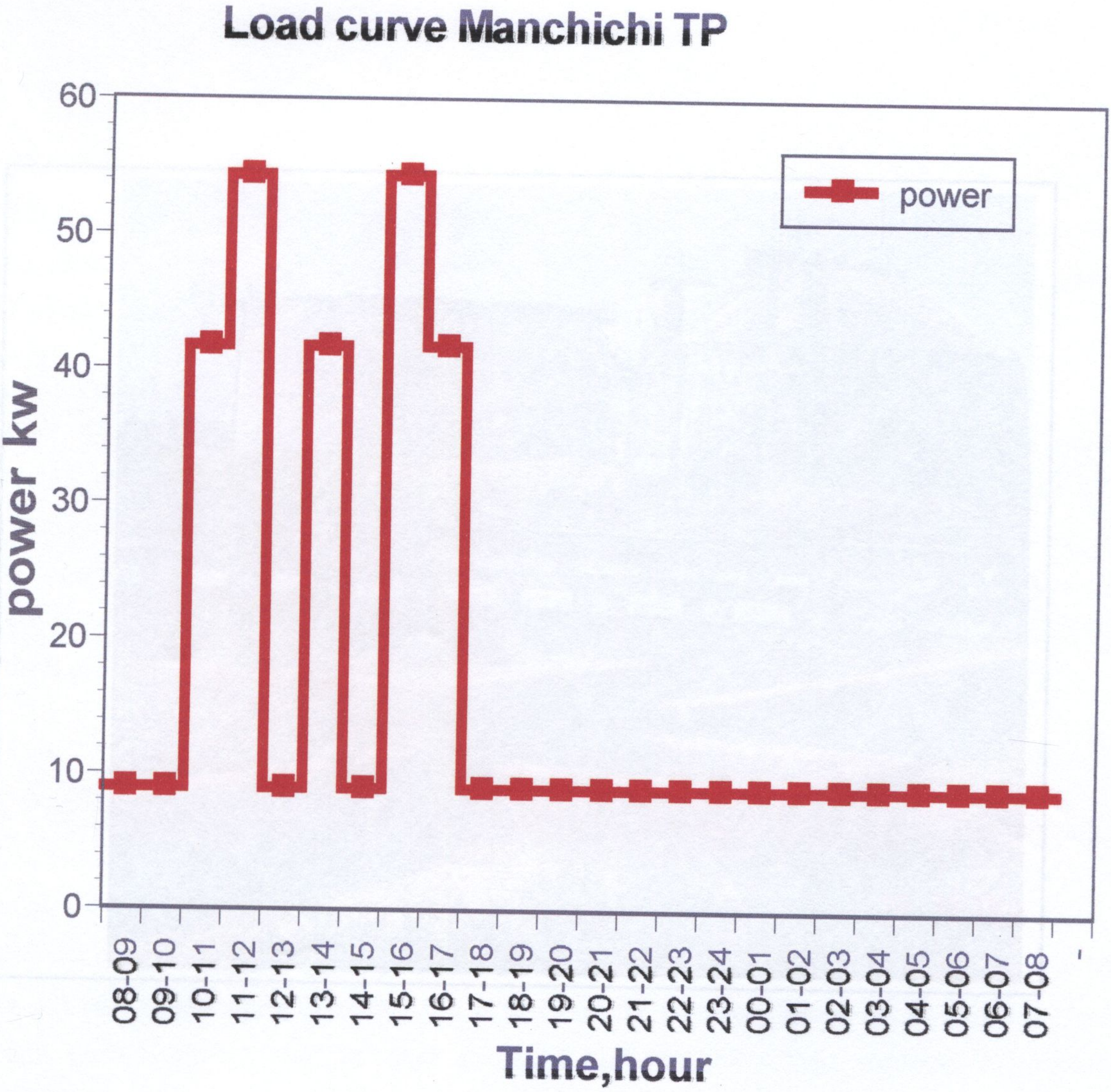

Figure 6.7: operating Load curve for Manchinchi treatment plant

Figure 6. 8: closed tank anaerobic digester

6.3 COST OF PLANT EQUIPMENT

The basic design information and the characteristics of the sewage sludge and regulatory discharge limits are shown in Table 6.1, 6.2, and 6.3. The following equations are used to evaluate costs of components of the system that can be used at Manchinchi treatment plant [21].

The equation for cost of an anaerobic vessel or reactor is computed as follows:

$$C_{reactor} = 2.9x10^{5}\left(\frac{V_{reactor}}{3800}\right)^{0.7} \qquad (6.1)$$

, Where US \$ 2.9x10^6 is the cost of a 3800 m^3 digester based on 1999 prices [21]

Selecting 2,500 m^3 capacity for each reactor $C_{reactor}$= US\$ 216 325.4.The output design parameters at mesophilic digestion and condition are shown in Table 6.2. Table6.3 shows the design parameters at Mesophilic temperatures- 21 deg C and 37 deg C.

6.3.1 Cost of biogas handling and gas generator system

Biogas storage and handling system comprise pressurized storage vessels, scrubbers, compressors, pumping and housing. Where, 2.12 x10^6 is the biogas volume per year m^3/year;0. 22 x10^6 in Malaysia currency, RM, is cost of biogas storage system comprised of pressurized storage vessels, scrubbers, compressors, piping and housing;3.8 is the exchange rate 1 US\$=3.8 RM, 5% is the inflation rate, V_{biogas} is the biogas volume capacity in m^3 per year, which is 1.5x 10^6 m^3 (see Table D3.1 appendix D3)

This is given by

$$C_{biogas} = 0.05407V_{biogas} \qquad (6.2)$$

$$C_{biogas} = \frac{V_{biogas}}{2.12x10^{6}}\frac{0.22x10^{6}}{3.8}(1+0.05)^{15}$$

C_{biogas}= US= 81,105, where V_{biogas}=1.5x10^6 m^3/year

The cost of generator can be computed using a power value of 1kW is equivalent to 1000 US \$ [21]. The net cost of generator considers the adjustment for digester heating at 12 percent. The available energy units in kilowatt-hour per year are 9.588 x10^6 (see Table D3.1 appendix D3). Assuming that electricity generation demand is equal to 8300 running hours per year, and fifty percent of the maximum estimated biogas volume is used,the cost of the gas generator is estimated as follows:

$$C_{gasgen} = \frac{0.5x0.88x9.588x10^{6}}{8300}(1000) = \text{US \$ 508,279.52} \qquad (6.3)$$

It is assumed that no land application of the digester effluent is considered. Therefore the land cost is not included in the computation.

Table 6. 1: Characteristic and design data of wastewater at Manchinchhi Treatment plant

Parameter	Value (1)	Regulatory discharge limit
Temperature	24.7 deg C	45
PH	6.68	5.0-9.0
BOD_5	21591	100(50)
Total Solid, TS	32164	-
Total Suspended solid, TSS	42857	400
Total Volatile Solids, TVS	33814	
Ammonia $-NH_3$-N		150
Ammonia nitrogen(TKN)	35100	200
Phosphorous, P	154.7(2)	
Potassium K	1.22(3)	

(1) All values, except pH and temperature, are expressed in mgL^{-1}

(2) Value expressed in mg/kg

(3) Value expressed in me/100g

Table 6. 2: Mesophilic digestion output design parameters for wastewater at Manchinchi treatment plant

Reactor temperature	Biogas yield $m^3\,kg^{-1}$BOD added	Mean CH_4 content Percent	CH_4yield $m^3\,kg^{-1}$BOD added
21 deg C	0.195	62	0.121
37 deg C*	0.254	62	0.157
39 deg C*	0.254	62	0.157

* The temperature range used is 38±1

Table 6. 3: Other design parameters at Mesophilic conditions for Manchinchi

Design basis Digestion temperature (deg C)	Main stream 21	bioreactor 37-39
Manchinchi wastewater hydraulic load	69,500 m^3/d	69,500
Digester Influent BOD (mg/l)	21, 591	21, 592
Maximum digester effluent, BOD (m g/l)	5000(1)	5000
Operating parameters		
Minimum retention time (d)	20	15
Minimum effective reactor volume (m^3)	4,400	4,400
Hydraulic retention time,(d)	45-30	28-15
Expected digestion effluent, BOD (mg/l)	5,000	-
BOD loading rate ($kg/m^3/d$)	0.48-0.72	1.44-0.771
Biogas production rate ($m^3/m^3/d$)	0.046	0.054
Annual biogas production (m^3)	72,864* (90kW)(2)	85,536 (104kW)

(1)Arbitrary

(2)(72,864x35MJ/3.6kWh/8000kW) where, 3.6MJ=1kwh, 8000 hours per annum, 35 MJ/m^3 is calorific value for 95 % methane- rich biogas.

* Based on 360 days per annum and batch fermentation, RT=30

(=4,400*0.046*30 *12 ; where 4,400 is the digester effective volume in m3, 0,046 biogas production rate and 12 batch number, 30 retention time)

6.3.2 Capital charges

Capital charges, (C_{fc}) consists of two components: the financial cost of fixed capital and depreciation as follows [21]:

(a) Financial cost of fixed capital
Assuming i=0.08, interest rate

$$C_{fc} = \left(C_{reactor} + C_{biogas} + C_{gasgen}\right)x(0.08)x\frac{1.08^{15}}{1.08^{14}} = 69{,}613.3 \text{ US \$} \qquad (6.4)$$

(b) Depreciation, C_d
Based on straight line depreciation:

$$C_d = \frac{C_f = (C_{reactor} + C_{biogas} + C_{gasgen})}{n} = 805{,}709.52/15 = 53{,}713.96 \text{ US \$} \qquad (6.5)$$

6.3.3 Annual maintenance cost and operating revenue

The operations and maintenance costs [21] are shown in Table 6.4.The values are based on the prevailing labor rates found in Zambia for the skilled staff as listed. Biogas of 1 m^3 is equivalent to 0.65 liter, (l) of diesel, and 1 kWh is generated by 0.34 l of diesel. Therefore 1.9 kWh is produced by 1 m^3 of biogas. Biogas utilization is 0.5 m^3 per kWh. Taking the cost of diesel per liter, ZMK 4750 (US$1.02) the cost equivalent for biogas is US $ 0.66 per m^3 assuming diesel is substituted for biogas. In the case of grid power substitution the tariff must be agreed upon with the power utility. There should be an incentive for green energy independent production. Currently power-by wire is at US $ 0.03 per kWh. The off grid tariff is the agreed selling price with the power utility (assuming 0.075 US $/kWh). The computation of the annual return on investment and the payback period based on the costs of components given above is shown in Table 6.5 and 6.6. The analysis includes with and without carbon credits in Clean Development Mechanisms, and without land application of the digester effluent. There are two preliminary options that can be considered in the design of biogas recovery systems.

Option 1

The optimum biogas production for the sewage is 0.054l/l /d from the experiment at RT=30 days. A 1x10, 000m^3 capacity is required for the biogas capacity of 1.5*10^6 m^3 /a

Option 2

For the second option it is recognized that it may not be economical to construct gigantic or multiple digesters as an initial investment. Therefore to increase production from low-yield sewage gas it is recommended that either the plant runs at thermophilic or enhanced or two stage temperatures phased, that is

Table 6. 4: Operation and maintenance Cost Estimates in US $

Operation	Labor	Annual expense	Energy requirement
Wastewater treatment (i)	1 operator	3950	Pumps and motors
Biogas storage (ii)	1 operator	3950	(see section 6.4.5)
Electricity generation (iii)	1 operator	3950	50kW for 4560 hr p. a
	1 engineer	11000	
	2 technicians	2x3950	
Power purchase from Utility		13200	for 4000 hr pa (=4000hrx55kwx0.06 $/kwh)
Maintenance 3 percent of (i)		6,684	(i)= $C_{reactor}$
Maintenance 3 percent of (ii)		2433	(ii)= C_{biogas}
Maintenance 5 percent of (iii)		25,414	(iii)= $C_{gas\ gen}$ (see section 6.4)

thermophilic first stage and second stage mesophilic, thereby reducing on the RT, the size and cost of digesters. Or feedstock must be identified, readily available containing a high C/N ratio for blending with sewage. For example waste such as the organic fraction of Municipal solid waste, OFMSW or animal manure and market waste. For the feedstock chosen, consideration ought to be made for the nature, volume and the transportation costs to the site. In Table 6.5 " i" is the inflation rate.

The rate is based on the source country [21]. The Total power selected for gas generation is 485 kW based on 8300 hours p.a operation (.4.58+E6kWh/8300h). It is assumed that the firm can buy utility energy for 4,500hrs pa at US$ 0.06 and sale at the same price. Savings are a function of the mode of power consumption for operational mode such as deferred, standby, emergency or prime load that is adopted. If utility power can be cut off, this would cancel 100 percent the utility expense on power purchased. The surplus energy can then be sold off to the grid. It should be noted that the capital investment is based on 4400m^3 new capacities and the existing 2 x 2200 m^3 anaerobic digesters. The project for biogas recovery and electricity generation is viable, as NPV is positive and a high IRR as shown in Table 6.6.

6.4 SYSTEM DESIGN FOR THE PLANT AT MANCHINCHI

Since there is a high potential for investment at the treatment plant, a system design layout is proposed (fig 6.9). The three tanks are each 3,500m^3 as proposed capacities. The gas is distributed from the tanks by a system of pipes and valves into the gas storage and handling pieces of equipment, where it is purified or scrubbed. The gas generator consists of a reciprocating engine with a design capacity of 1000 kW. Table 6.7 shows different investment scenarios where column 2 shows the investment in a new anaerobic digester of capacity 4400 m^3 and column 3 is the budget and cash flows for renovation of the existing 2x2200 m^3 only. N is the period in years,

6.5 SYSTEMS DESIGN AT KEMBE LTD

When a wastewater management system is put in place, the design for the meat processing plant at Kembe would be as shown in figure 6.10. If the plant operates normally, the power rating is computed using the American rate [55] of 0.2 kW per cow; the range of cattle population is 200 to 300. The power ratings would be 40 to 60 kW.

Table 6. 5: Cost benefit analysis of the anaerobic digestion at Manchinchi treatment

Plant with electricity generation without CDM and land application of digester effluent

Description	cost US$	item	value	units
CAPITAL COST		Vreactor	4950	m3
Capital Cf=Creact+Cbiogas+C gas gen	520135	Vbiogas	550000	m3/a
anaerobic reactor,Creactor	348958	inflation,i	0.05	
biogas handling equip.Cbiogas	31225	energy	1320000.00	kwh/y
gas generator,C gas gen	139952	n,period	15.00	
annual capital charges	34676	load	50	kw
ANNUAL OPERATION AND MAINTENANCE		tarrif	0.06	$/kwh
COST Co&m	51724	operating	4500	hrs
OPERATION Co= (i) + (ii) + (iii) + (iv)	40300			
anaerobic treatment(i)	3950	no	1	staff
biogas handling (ii)	3950	no	1	staff
utility (iii)	13500			
gas generator,C gas gen (iv)	18900		1	group
MAINTENANCE (v) + (vi) + (vii)	11423.93	off grid /tarrif	0.075	$/kwh
(v) 3 % of Creactor	3490	NB		
(vi) 3 % of Cbiogas	937	INCL 4 NO.SED TANKS		3491m3
(vii) 5 % of C gas gen	6998	8.NO BIOFILTERS		6111m3
AN NUAL OPERATING REVENUE				
Biogas utilization Cba=Ro	99000			
Annual cost-benefit (Ro-Co&m)	47276			
Annual Return on investment	**INDECIES**			
Roi= Cba/Cf *100	9.1			
payback period				
Tpb=Cf/(Ro-Co&m)	11.0			
NPV	485000			
IRR	23			

Table 6. 6: Cost-benefit analysis of the anaerobic digestion at Manchinchi treatment plant with electricity generation, with CDM and without land application of digester effluent

Description	Cost US $	item	value	unit
CAPITAL Cf		Vreactor	4950	m3
Capital Cf=Creact+Cbiogas+C gas gen	520135	Vbiogas	550000	m3/a
anaerobic reactor,Creactor	348958	inflation,I	0.05	
biogas handling equip.Cbiogas	31225	energy	1320000.00	kwh/y
gas generator,C gas gen	139952	n,period	15	
annual capital charges	34676	load	50	kw
ANNUAL OPERATION AND MAINTENANC	58703	tarrif	0.06	$/kwh
Co&m		oper	4500	hrs
OPERATION Co= (i) + (ii) + (iii) + (iv)	40300			
anaerobic treatment(i)	3950	no	1	staff
biogas handling (ii)	3950	no	1	staff
utility (iii)	13500			
gas generator,C gas gen (iv)	18900		1	group
MAINTENANCE (v) + (vi) + (vii)	18403.09	off grid tar	0.075	$/kwh
(v) 3 % of Creactor	10469			
(vi) 3 % of Cbiogas	937	taking	50000	CDM US$
(vii) 5 % of Cgas gen	6998			
AN NUAL OPERATING REVENUE				
Biogas utilization Cba	99000			
Annual cost-benefit	40297			
Annual Return on investment	**INDECIES**			
Roi= Cba/Cf *100	7.7			
payback period				
Tpb=Cf/(Ro-Co&m)	12.9			
NPV	$897,201.00			
IRR	36			

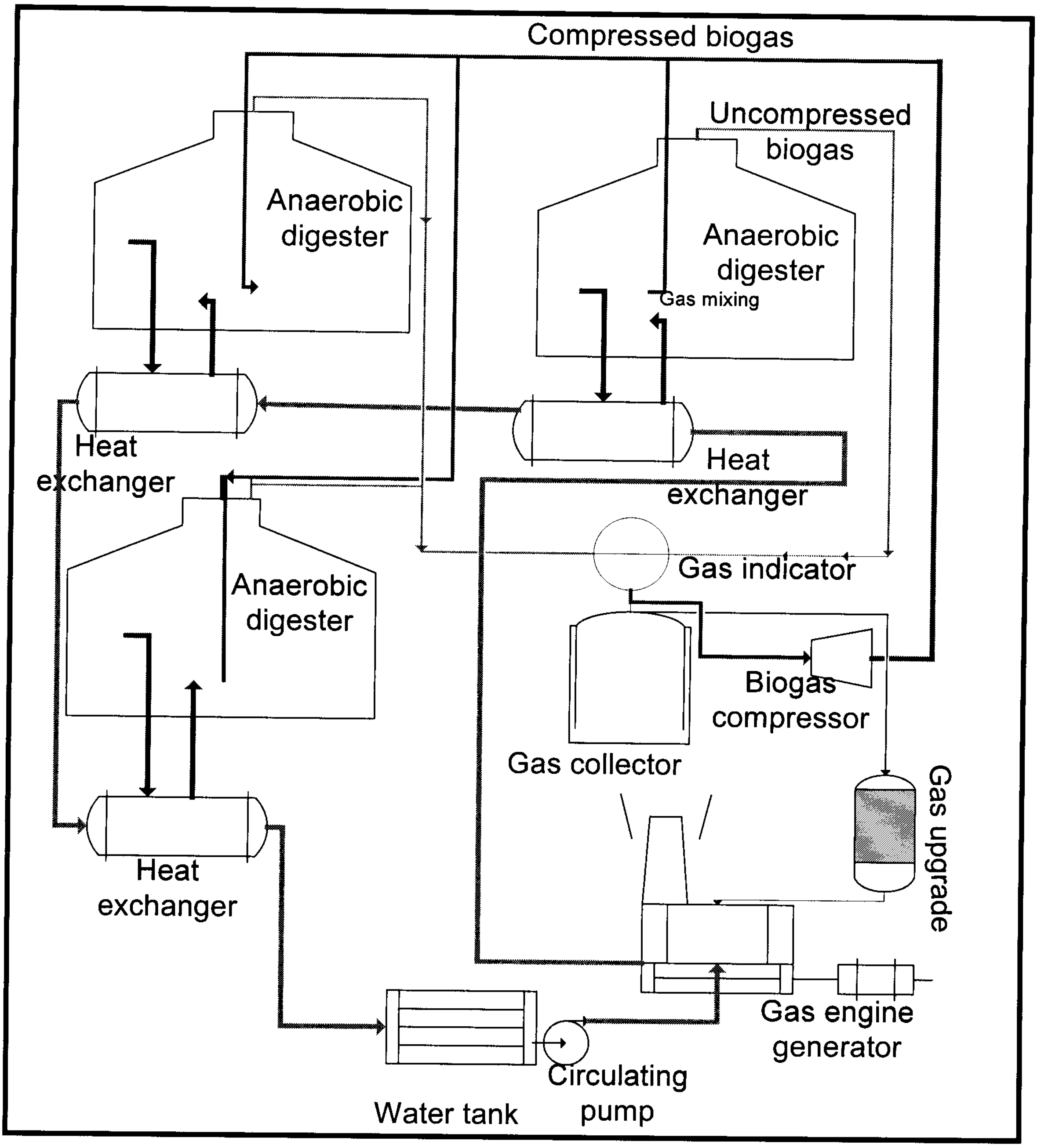

Figure 6.9: Proposed layout for power generation at Manchinchi

Table 6. 7: Cost-benefit analysis of the anaerobic digestion at Manchinchi treatment plant.

	COSTBEN	COSTBEN	COSTBEN	COSTBEN	COSTBEN
N	140kW	140kW	250kW	500kW	1000kW
0	-520135	-410000	-625099	-870015	-1,360,000
1	99000	99000	116278	277282	599291
2	99000	99000	116278	277282	599291
3	99000	99000	116278	277282	599291
4	99000	99000	116278	277282	599291
5	99000	99000	116278	277282	599291
6	99000	99000	116278	277282	599291
7	99000	99000	116278	277282	599291
8	99000	99000	116278	277282	599291
9	99000	99000	116278	277282	599291
10	99000	99000	116278	277282	599291
11	99000	99000	116278	277282	599291
12	99000	99000	116278	277282	599291
13	99000	99000	116278	277282	599291
14	99000	99000	116278	277282	599291
15	250000	250000	300000	400000	599291
NPV	-$173,047.14	$484,989.89	$428,096.90	$1,542,060.20	$3,769,618.54
IRR	18%	23%	17%	31%	44%

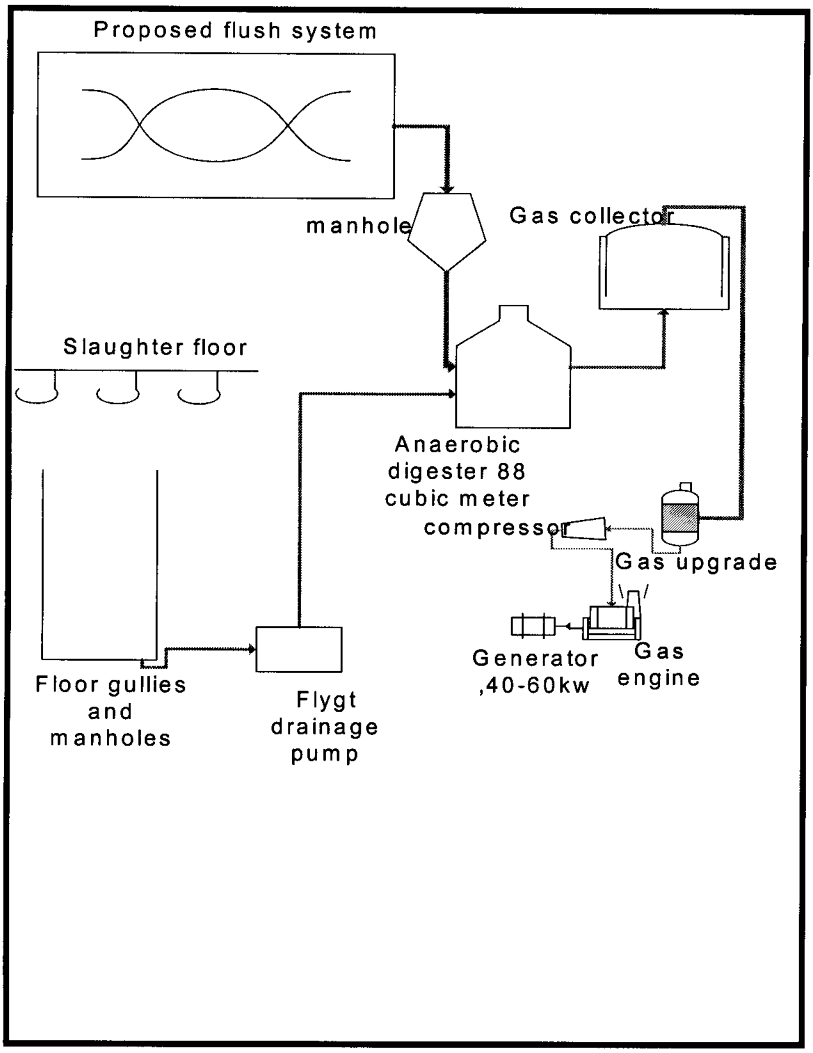

Figure 6.10: Proposed layout for power generation at Kembe Limited:

CHAPTER 7 DISCUSSIONS AND CONCLUSIONS

7.0 DISCUSSIONS

Wastewater treatment processes are not productive. Motivation for this study has been economics; oriented towards investigating avenues that can yield benefits for the wastewater plant apart from the continuous treatment that does not produce any profit. The route was bio energy recovery in the form of biogas by the anaerobic digestion technique.

The anaerobic degradation of organic matter is a complicated biological process. The conversion of organic matter consists of several independent; consecutive, and parallel reactions in which close-knit community of bacteria co-operate to form a stable, self-regulating fermentation that transforms organic matter into a mixture of methane and carbon dioxide gases [41]. The science of biomethanation has been elaborated through this study although research has shown that this is still a black box. Wastewater treatment of sewage sludge is rarely complete and so there is insufficient security provided in the disposal of the effluent and pathogens that can affect humans are still a risk in the handling of the effluent at both point and non-point sources.

Researchers have generally agreed that the biological systems applied in the treatment of wastewater are complex. Research groups have been instituted to investigate modeling of wastewater such as the ADM1 (Anaerobic Digestion Model 1) proposed as the starting point for development of mathematical modeling of the processes in the anaerobic digestion of organic waste [17]. The researchers' aim has been to elucidate the bioprocesses involved in all their physical, chemical, and biological interactions between the feedstocks and the relevant microorganisms.

The question of identification of parameters for numerous models that exist has not been easy to answer because of the lack of appropriate techniques, instrumentation and methods to directly evaluate model parameters as a requirement in model validation. However having a model that equates the variables that are known or can be measured or easily inferred with the level of complexity of the model derived is good enough. Many researchers have used this principle of optimum complexity whereby the method is not stringent on evaluating each and every parameter in the model.

Along these lines, in this study, a model has been developed that considers the concepts of optimum model complexity. These researchers followed the argument that it is not necessary to verify every single variable in the model in order to have a good model. In this study such a model has been derived from the mass balance equations developed by others and evaluated by using the Laplace transformation. A set of coefficients in literature [41] had been selected and the variables that can be measured included in the consolidation of the model. This model can be used for other applications with modification making other considerations discussed later. The model developed in chapter 3 can be used for much similar locally produced effluent for site-specific conditions.

7.1 BIOENERGY POTENTIAL OF ORGANIC MATTER.

Not every wastewater meets the specification for bioenergy recovery.

Important observations made suggest that wastewater must have capacity for physical separation. Besides, organic matter separated must be able to form flocs and proceed to fermentation in anaerobic environments without difficulties-biodegradability. An imbalance of the AD process is caused by many factors that do not form the scope of this investigation but are implied. Cow dung or manure was added to the sludge to develop the methanogenic group. The results are shown in chapter 4. The biogas production yield for the sewage is $0.05m^3/m^3/d$.

7.1.1 Experimentation and results

The following results show the BOD and other parameters for the wet sludge at Manchinchi and kembe bovine meat processing plants.

a) D1 Sample

From figure B1.1 (Appendix B1), for D1 stream, the average BOD is about 25,000 ppm (mg/l), the volatile solids, VS, peaks around 34,000 ppm around September, TS is 40,000 ppm. The TS and TSS values are correlating well. This means that the stream has a higher percentage of suspended solids than other solids namely, Total Dissolved Solids,(TDS). From the graph of BOD and VS there are two cases. The first case is where the VS data form a 'ridge' and the BOD form a 'valley'. This means that the biomass is not active and is therefore old aged. The second case is when the curves both form 'valleys' and are almost the same. At this point there is a positive correlation between them and signifies an active biomass composite. From this it can be deduced that the waste management is such that the decayed biomass is mixed with the active biomass or remains inactive in an inconsistent manner. This should be expected since the unit is a thickener and is designed for a different function from the interest of this investigation. From results obtained there is a relationship between the TS and the BOD by a factor of 1.6 (TS/BOD) or 62.5 percent of the TS is the BOD, meaning that the waste consists of 62.5 percent active biomass. It should be noted that this is the effluent pumped from the primary clarifiers that also has a component from the secondary clarifiers coming through by periodic recirculation done for enhancing efficient treatment of the sludge at the biological filter stage.

b) D2 sample

The average BOD for D2 sample is 10,000 ppm with two outliers at the two ends of the investigation periods as shown in the figure B1.2. There is a gradual increase of the TS from 40,000 ppm to 60,000 ppm from September towards Nov (fig B1.2). This could be explained from the compaction of the sludge due to the incoming fed effluent before disposal to the drying beds. As the BOD is small; more substrate is either decaying or has high solid content without anaerobic treatment. The TSS and TS correlates well indicating a higher suspended solid in the effluent than other mineralized wastes. The VS is about 30,000 ppm and BOD is 33 percent of the TS. This signifies that the effluent is not very active and is old compared to D1.

7.2 KINETICS AND BIOGAS PRODUCTION

It was observed that the age of the wastewater matters. The age factor must be considered in the selection of organic matter suitable for fermentation. Although the BOD levels for the sampling points D1, D2, and K showed signs of a good digestion material, it was observed that it was difficult to ferment this type of effluent in a laboratory scale digester. These materials could not support methanogenesis due to the low rate kinetics present in the fermentation of the substances. Possible reasons included age and toxicity caused by endogenous decay. Also important is volatilization of organic substances over time and conditions occasioning the diversion to different biological pathways other than the anaerobic or anaerobic pathway with or without methane capture. In the modeling, the μ coefficient from BOD determinations for different RT does not correspond to the μ in the actual model of the same waste. This value must be modified to accommodate factors that affect process behavior.

The measured VS from D1 indicated VS of 39 percent of the TS. This meant that the substrate was weak to support economic production of biogas. The value of μ also indicates the activity position of methanogenesis process. The Thomas slope method closely approximates (values by this method are closer to the actual μ and compares well with the model) the μ factor in methanogenesis. The μ factor values for different conditions of temperature are shown in the relevant graphical biogas production in chapter 4.

The model does not closely predict the actual case when the conditions in the wastewater change. This is seen in the 70 percent cow manure and 30 percent sludge fermentation. When the temperature increased by 2 degrees above the mean, there was a large deviation noticed in the graphs (fig 4.7).

The kinetics that truly predicts actual process behavior is sensitive to the second decimal point, for instance, an increase of 30 percent (affecting only the second decimal digit) of the μ value, the temperature increased by 72 percent in the fermentation of sewage sludge. The deductions are that the μ coefficients are not linearly proportional to biogas production kinetics. This observation is shown in the preliminary theoretical investigation of the rate of production that reaches equilibrium when RT increases.

Enhancement of wastewater is required to make biomethanation of sludge economically attractive. The temperature raise from 22 degrees ambient to 38-degree C, does not show any significant increase in the production rate. This can be explained in the nature of the wastewater.

The C/N ratio can be a limiting factor in the process of methanogenesis. A mixture of two wastes one with a higher C/N ratio than the other can enhance the production of biogas as long as the stockpile for the identified material to mix with the sewage sludge is not competing for other uses. One such candidate for the sewage sludge is the OFMSW.

7.3. BIOGAS PRODUCTION AND ELECTRICITY GENERATION

The BOD present in a waste can limit the output (biogas). There are several reasons that can cause this to happen, for instance age of the waste, toxicity, and dilution factor, poor separation of the wastewater and the insoluble refractory organic solids, formation of scum and foaming especially in meat processing wastewater. When this happens, the biomethanation process is affected because there is no formation of the flocs. Use of excessive process water dilutes the waste solids in the wastewater thereby reducing the density and contact of organic material necessary for methanogenesis to occur as seen in appendix B2. Although there can be an active diluted wastewater, the production rate will not be sufficient to make any impact as far as energy production is concerned with biological means. In Appendix B2 the curve plotted shows a good start followed by a rapid departure from the actual gas collected. The model is not adjusted to accommodate the changed condition of dilution factor, which was considered zero in the model. The critical parameters such as type of wastewater, growth coefficients and concentration of organic wastes, retention time, biochemical oxygen demand, and other environmental conditions namely pH and temperature, were identified in this research. These enabled the simulation of the output (biogas production) variable with the aid of a model.

Biomethanation is recommended to support financially strapped organizations in their waste management matters. Besides the economic investigations of the application of biogas in energy supply, estimation of the carbon credits of the Kyoto protocol's Clean Development Mechanism, (CDM) represents a key incentive for organizations to adopt AD where applicable and therefore address the current global environmental concerns with benefits. Selecting a gas engine generator and 3x 3,500m^{3}anaerobic digesters, gas handling and storage equipment and exhaust heat recovery facility for process heating, can produce a revenue-generating plant adding benefits to the core business. The operating load during this investigation was valued at 55kW. In monetary terms, supposing that the carbon trade facility or the, CDM arrangement [58,21] was accessed, a value of US$ 107,489.5 could be realized annually for seven years. In meeting the demands for emission reduction, it was estimated that 26,872.37 tons of carbon dioxide would fall for mitigation by implementing the energy recovery scheme. The biogas quality measured was 62 percent methane and 37 percent carbon dioxide, 1 percent was for trace gases including hydrogen sulfide.

Economic and financial appraisal showed that the NPV was US$ 484,939.89 and IRR 23 percent in the case that the plant was equipped with biogas recovery and energy conversion technology to produce heat and power with the renovation of existing anaerobic digestion vessels.
Careful consideration is required when choosing the AD. Retrofitting engines and adaptation of some old buildings and tanks can reduce the capital outlay.

Power from biogas can be introduced in smaller packages. Options include use of the complete mixed egg shaped and the contact type digesters. Electricity generation from the sewage sludge is a reality. The study has shown that there is potential to convert sludge to useful by-products including electricity.

When coefficients used do not "fit well" in process models, the models become useless. In this case not all the critical factors were considered during the implementation of the validation procedure for the model. The procedure needs to be repeated.

7.4 CONCLUSIONS

There is energy potential for the application of anaerobic digestion at both sites according to the investigation. The wastewater treatment plant at Manchinchi had the highest potential due to the magnitude of the sludge that reached there. A sound wastewater management system needed to be put in place at Kembe before considering energy recovery from the organic wastewater.

A model, which could be applied at different sites producing similar waste, was developed for the sludge. Financial analysis showed a positive NPV making the project viable including a high IRR. A gas generator engine of 1 MW was suitable to provide maximum energy from the wastewater including electricity sales to the grid. For staged implementation, a 350 micro turbine was the most economical piece of equipment to meet the in-house power demand at Manchinchi including gas handling and ancillary equipment. Micro power simulation software, Homer, [59] was used to choose from different CHP options (see Appendix A1)

Through carbon trading facility of Kyoto Protocol, (CDM), there was found an attractive incentive for investors in greenhouse gas mitigation. For waste management purposes at the Kembe site there was need to overhaul the wastewater disposal practice. These recommendations are pointed out in section 7.5. There is need to consider staged implementation of bioenergy recovery at Manchinchi treatment plant and to ascertain the market for the independent power supply.

In the experiments, there was need to investigate further how other factors such as dilution and mixing of the solids affected the output. This eventually would affect the overall capital costs such as digesters, and mixing devices that may, or may not be required.

7.5 RECOMMENDATIONS

For future expansion, there is need to introduce a flush system at Kembe at the receiving bay as opposed to the open lot. The open lot makes it difficult or costly to properly manage the waste disposed from the animals. The development of a sound wastewater disposal method will follow certain steps these are as follows: To investigate the reduction and control of process water in waste management, develop a flush system for the removal of dung into a central tank. Assess design of a preliminary recovery unit for bioenergy, if viable decide on the feasibility of the construction of a wastewater disposal unit that takes into account the recovery of energy and material in the most effective and environmentally sound way.

For Manchinchi treatment plant the steps for expansion are as follows: There is need to investigate the biogas market and practical considerations for power sale to the grid. There is need to identify a consultant experienced in the design and build of anaerobic digestion and biogas recovery. The Implementation and upgrading and overhaul of the plant must include resource recovery. The performance of the improved treatment plant should be monitored and evaluated. Lessons learnt and investment should be replicated elsewhere. The CDM incentive should be included in the overall design to meet the challenges and opportunities of the Kyoto protocol.

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APPENDICES

Appendix A1

FINANCIAL ASSESSMENT AND EVALUATION WITH HOMER SOFTWARE

Homer (software) application And Renewable Energy Technology, (RET) optimization

Homer is software [59] that creates models and performs simulation analysis of distributed power, DP. The software assesses the sub units and system configurations or components for on and off-grid applications. HOMER simulates configurations, creates a list of feasible systems designs, and sorts the list by cost-effectiveness. In addition HOMER performs a sensitivity analysis.

HOMER is an optimization model for DP, which describes technology options, component costs, and resource availability. HOMER uses inputs to simulate system configurations, or combinations of components, and generates results that can be viewed as a list of feasible configurations sorted by net present cost.

The software also displays simulation results in a wide variety of tables and graphs that can help compare configurations and evaluate them on their economic and thermal merits.
The model can be used to perform sensitivity analysis by exploring the effect that changes in factors such as resource availability, and economic conditions or constraints that might affect the cost-effectiveness of different systems configurations.

Homer is designed to simulate operations of a system by making energy balance calculations for each of the 8,760 hours in a year. For each hour, HOMER compares the electric and thermal demand in the hour to the energy that the system can supply in the hour, and calculates the flows of energy to and from each component of the system. Where batteries or fuel-powered generators are included in the system, HOMER decides for each hour how to operate the generators and whether to charge or discharge the batteries.

Homer performs these energy balance calculations for each system configuration that is considered by the designer. The software determines whether a configuration is feasible, i.e., whether it can meet the electric demand under the conditions that are specified, and estimates the cost of installing and operating the system over the lifetime of the project. The system costs include calculation for costs such as capital, replacement, operation and maintenance, fuel and interest. After simulating all of the possible system configurations, HOMER displays a list of configurations sorted by **net present cost** (sometimes called **life cycle cost**), that can be used to compare system design options.

Sensitivity analysis

When the sensitivity variables are defined at the input stage, HOMER repeats the optimization process for each sensitivity variable that is specified by the designer.

Examples

HOMER answers a wide variety of questions about the design of small power systems. It is useful to have a clear idea of a question that HOMER can help answer before working with the application software. Examples of such questions include the following:

- Is it cost effective to add a wind turbine to the diesel or biogas generator in a system considered for simulation?
- How much will the cost of Diesel fuel need to increase to make PV cost effective
- Will my design meet a growing electric demand?
- Is it cost-effectiveness to install a micro turbine to produce electricity and heat for my grid connected facility?

Typical example of how HOMER can be used to simulate system configurations and sensitivity analysis is shown in the GETTING STARTED GUIDE [59].

Methodology -Homer question

Which CHP technology from the five excluding one (fuel cell too expensive) is suitable for electricity generation as a stand-alone or grid-interconnected facility incorporating the design data collected from the wastewater treatment plant?

The energy potential for both thermal and electrical capacity at Manchichi treatment plant is 1 MW. Input data for this simulation is obtained from section 5 for the described technology characterization of each individual CHP technologies. This data includes capital costs and Operation and maintenance. Several sizes are also simulated such as 100, 150, 200, 350, 450, 500, 600 kW. Gas turbines have not been considered in this analysis because their range starts at 1MW, which is a minimum for the maximum possible energy potential of the wastewater.

Generator 1 is the IC and Generator 2 the Micro turbine in the first simulation. Generator1. micro turbine and generator (2) steam turbine in the second level of the simulation. The simulations involve the choice between the micro turbines, and the internal combustion engine. The most cost effective CHP technology from the two CHP's is then simulated against the steam turbine with power rating of 500 kW and 1000kW.

The following section is a summary of this approach for each design component.

a) Boiler resource

The boiler resource is an idealized component that can serve an unlimited thermal load at only the fuel cost. Waste heat recovered from the generator reduces the fuel consumption of the boiler [105].

b) Thermal load

The values are preliminary design data selected for heating application at the treatment plant. About 30 percent of the energy production is designed for heating applications.

c) The primary load

The load serves the AC demand of the plant and machinery. The values correspond to the range of the minimum and maximum installed energy.

d) Grid rate

The purchase price rate is $ 0.01 /kWh and the sellback $0.05.These are default values in Homer. These values do not affect the simulation as the comparison is between the CHP technologies inter-connected to the same grid.

e) Efficiencies of the CHP technologies

The steam turbine, micro turbine, gas turbine and internal combustion engine overall efficiencies are as follows respectively: 80,73,68,81 percent from chapter 5.0

f) Biomass resource

Biomass resource is the source of biogas (gasified biomass) for generator fuel. The value is determined by the rate 30 l/head/d, after [60]

g) Cost design parameters for CHP technologies

The following table 6.6 gives the cost used in the simulation.

TableA1.1: Simulation cost parameters for the CHP technologies

CHP	Internal C engine	Micro turbine	Steam turbine
Sizes kW	350,100,etc	70,100,350	500,1000
Capital cost/kW	$1200	$910	$918
O&M/kWh	0.0128	0.01	0.004
Hours/year	4000	4000	4000

Homer simulation results

The highest cost-effective CHP technology for the first simulation of the IC and micro turbine is the micro turbine with the size of 300 kW. However 350 kW is selected which is commercially available. Other simulation results are contained in the homer simulation results [59]. In the second simulation the micro turbine size 300 (commercially available 350) kW is the highest cost–effective when compared with the steam turbine. Other simulation results are contained in the homer results.

Sensitivity analysis

The preliminary simulation shows that the sensitivity is critical with the thermal loads and Load percentage. The following sensitivity components were therefore used:

Table A1.2: Thermal load and load percentage sensitivity components

Thermal load kWh/d	Micro turbine Load percent
1524.0	30
2000	40
2500	
3000	

SYSTEMS SELECTION CRITERIA BY LEAST COST OR LIFE CYCLE COSTING

Homer simulation results indicate that the micro turbine of capacity of 350 kW is suitable for the application of biogas at Manchinchi wastewater treatment plant to cater for process energy demand. It is assumed that part of the power is used to serve the load at the plant while the rest is sold to the grid and heat generated is used as process heat to improve biogas production.

RESULTS: INPUT DATA AND RESULTS OF SIMULATION BY HOMER

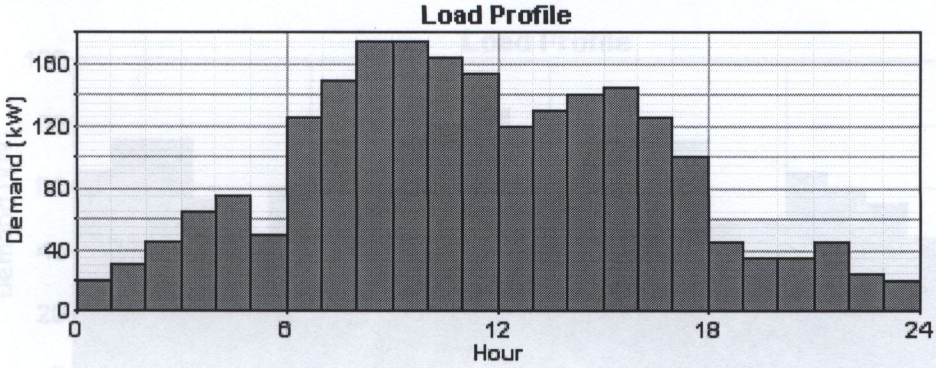


Fig A1.1: Load profile

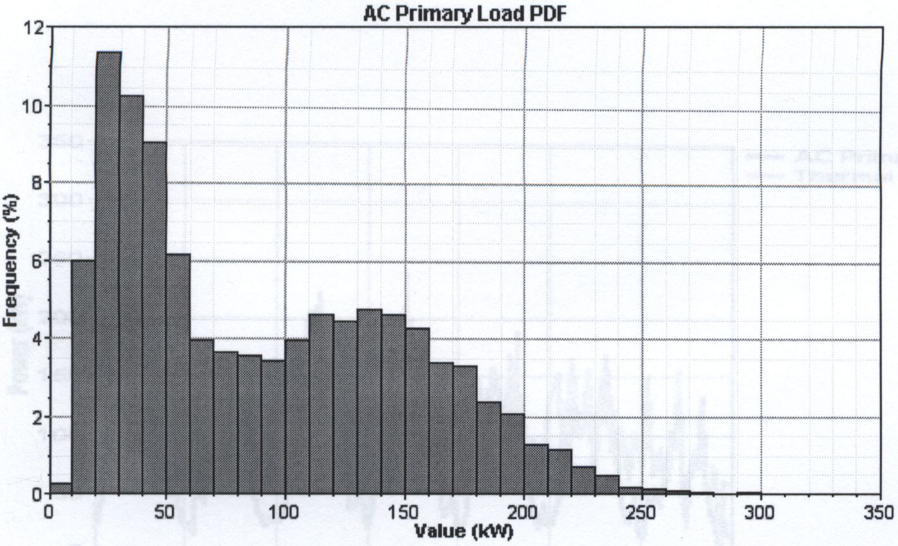


Fig A1.2: AC primary Load PDF

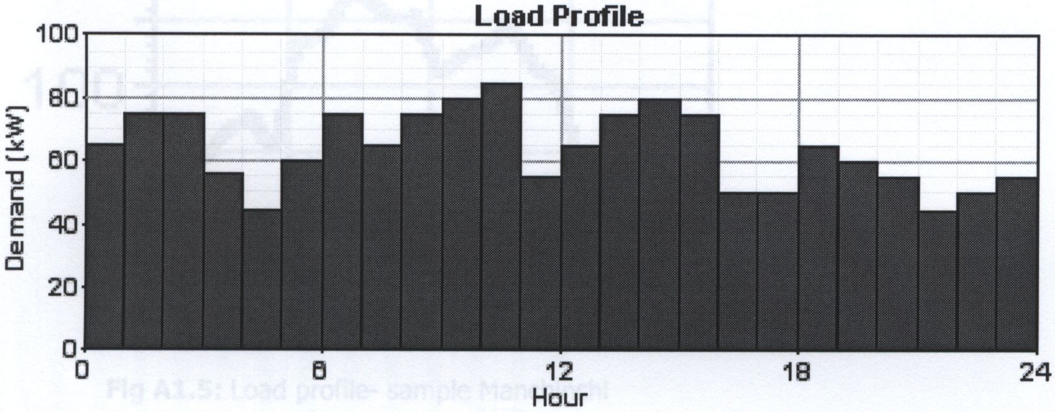


Fig A1.3: Thermal load profile.

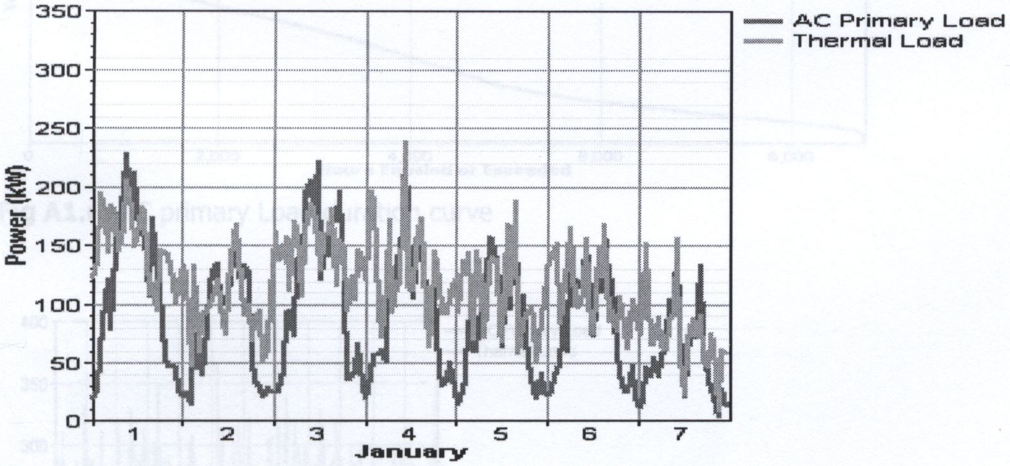


Fig A1.4: AC primary load and thermal load

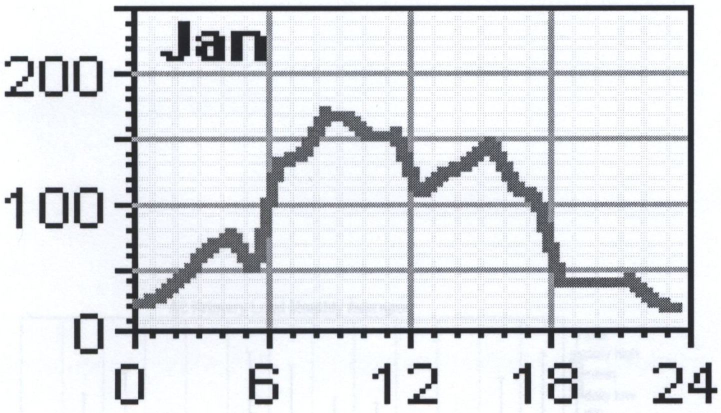


Fig A1.5: Load profile- sample Manchinchi

(Prime load assumed constant for the entire year)

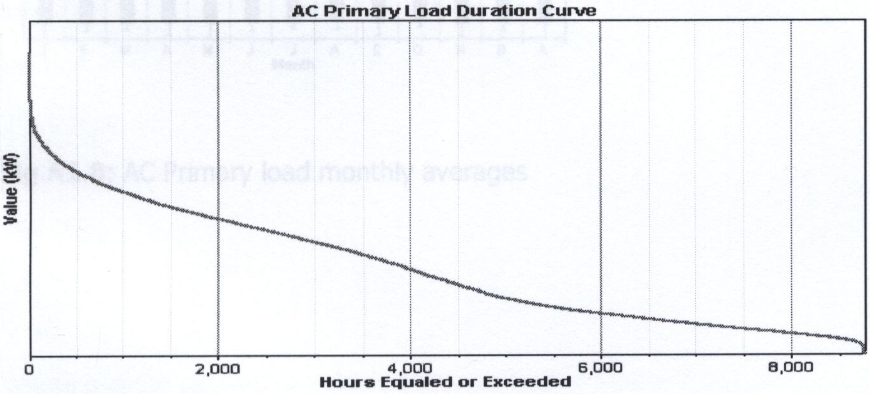


Fig A1.6: AC primary Load duration curve

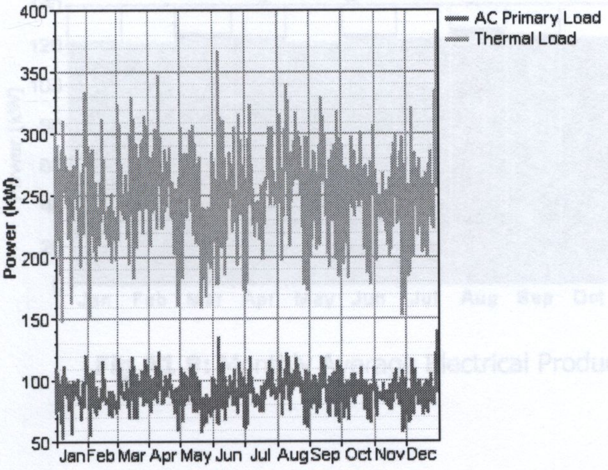


Fig A1.7: AC Primary and thermal Load

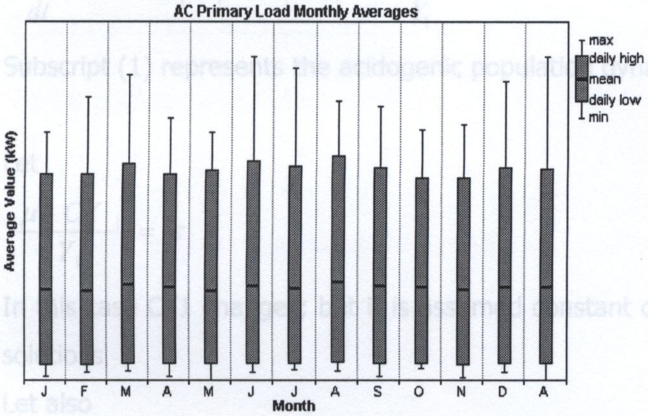


Fig A1.8: AC Primary load monthly averages

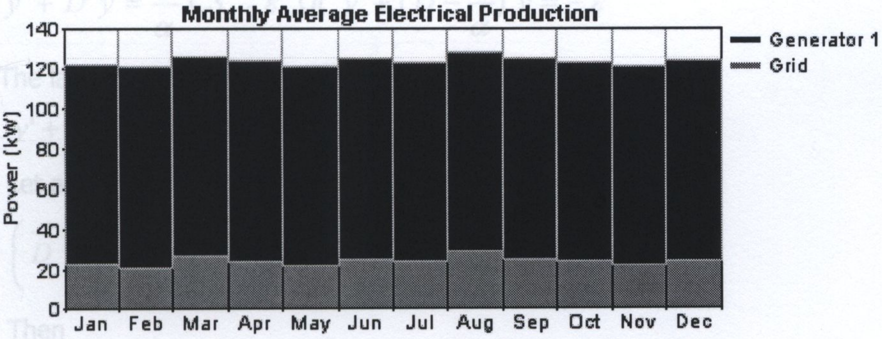


Fig A1.9: Monthly Average Electrical Production

Appendix A2 Modeling

The differential equation for soluble volatile solids mass balance is given according to [41] as follows

$$\frac{dCS_1}{dt} = -D\,CS_1 + \beta\,CX_1\,CS_0 - \frac{\mu_{1}\,CX_1}{Y_1} \qquad \text{(A2.1)}$$

Subscript (1) represents the acidogenic population dynamics.

Let

$$\frac{\mu_1\,CX_1}{Y_1} = \varepsilon$$

In this case CX1 changes; but it is assumed constant otherwise it would be extremely difficult to find the solutions

Let also

$$\beta.CX_1 = \eta$$

Where both ε, η are constants

Denoting

$$\frac{dCS_1}{dt} = y' = \frac{dy}{dt}; \qquad CS_0 = \frac{CS_1}{\alpha_1}$$

Where α is the percent of volatile solids in the Dry Matter (DM).

Therefore,

$$y' + D\,y = \frac{\eta}{\alpha}\,CS_1 - \varepsilon \text{ Or } y' + (D - \frac{\eta}{\alpha})\,y = -\varepsilon$$

The last equation is in the form

$$y' + P(x)\,y = Q(x)$$

Let also

$$\left(D - \frac{\eta}{\alpha}\right) = \Omega$$

Then

$$y' + \Omega\,y = -\varepsilon$$

Applying the Laplace transform on both sides

Where the definition of Laplace F(s)=L [f(t)] = $\int_0^\infty f(t)\,\exp(-s\,t)\,dt$

The equation in the frequency domain is

$$sY(s) - y(0) + \Omega\ Y(s) = L(-\varepsilon) = -\frac{\varepsilon}{S}$$

Re -arranging the equation results in

$$Y(s)\ (\ S + \Omega) = y(0) - \frac{\varepsilon}{s}$$

Re -arranging the equation results in

$$Y(s) = \frac{y(0)}{s + \Omega} - \frac{\varepsilon}{s\ (s + \Omega)}$$

From Laplace tables and taking the inverse: the solution in the time domain is given as follows:

$$y(t) = y(0)\exp(-\Omega\, t) - \frac{\varepsilon}{-\Omega}(1 - \exp(-\Omega\, t))$$

Rearranging

$$y(t) = \left(y(0) - \frac{\varepsilon}{\Omega} \right) \exp(-\Omega t) + \frac{\varepsilon}{\Omega}$$

Substituting

$$CS_1(t) = \left(CS_1 - \frac{\mu_1\ CX_1}{Y_1\left(D - \frac{\beta\ CX_1}{\alpha} \right)} \right) \exp - (D - \frac{\beta\ CX_1}{\alpha})t + \frac{\mu_1\ CX_1}{Y_1\left(D - \frac{\beta\ CX_1}{\alpha} \right)} \qquad \text{(A2.2)}$$

For cases where D=0 to

$$CS_1 = \left(CS_1\ (0) + \frac{\mu_1\ \alpha}{Y_1\ \beta} \right) \exp\left(\frac{\beta\ CX_1\ t}{\alpha} \right) - \frac{\alpha\ \mu_1}{Y_1 \beta} \qquad \text{(A2.3)}$$

Similarly,

$$CS0\ (t) = \left(CS\ (0) + \frac{D\ Yp\ CS0_i}{D + \beta\ CX_1} \right) \exp^{-(D + \beta\ CX_1)t} - \frac{D\ Yp\ CS0_i}{D + \beta\ CX_1} \qquad \text{(A2.4)}$$

For D=0

$$CS0\,(t) = CS\;(0)\exp(-\beta\;CX_1\;t) \qquad \text{(A2.5)}$$

First order kinetics have been considered for population dynamics as follows:

$$\frac{dCX_1}{dt} = (\mu_{.1} - K_1 - D)\,CX_1$$

Solution of the form

$$y' + \beta\;y = Q(x)$$

Where Q (x) = 0

$$y = c\exp\;(-b\,x)$$

Or from the Laplace transformation

$$s\;CX_1(s) - (b)\;CX_1\;(s) = CX_1(0)$$

Re-arranging

$$CX_1(s)(s-b) = CX_1(0) \quad or \quad CX_1(s) = \frac{CX_1}{s-b}$$

Taking the inverse Laplace transform on both sides:

$$CX_1(t) = CX_1(0)\exp\;(b)t$$

Or

$$CX_1(t) = CX_1(0)\exp\;(\mu_1 - k_1 - D)\,t \qquad \text{(A2.6)}$$

Similarly for methanogenesis, Subscript (2) represent the methanogenic population dynamics.

$$CX\;2(t) \;=\; CX\;_2(0)\exp(\;\mu_2\;-\;k_2\;-\;D\,)t \qquad \text{(A2.7)}$$

Biogas production is given by the following equation:

$$Q = Yg\;\mu_2\;CX_2$$

$$Q = Yg\;\mu_2\;CX_2 = Yg\;\mu_2 CX_2(0)\exp\;(\mu_2 - k_2 - D)\;t \qquad \text{(A2.8)}$$

If it is assumed that the growth rate, u $_2$ is constant and D=O and the maintenance energy is increased during the methane forming stage. The production rate for methane becomes

$$Q = Yg\,\mu_2\;Cx_2(0)\exp(\mu_2 - k_2)\,t \qquad \text{(A2.9)}$$

As shown by the last model, equation (2.12) proposed by [61] and [62]. The ultimate or maximum specific methane yield obtainable, B_o, from a particular waste is not asymptotic on a unique HRT but on a unique volume of methane which depends on or is limited by the nature of the waste. Therefore the equation is mathematically corrected as follows. This is the final model.

$$Q = Yg\,\mu_2\,CX_2(0)\,(1-\exp(\mu_2-k_2)\,HRT) \qquad \text{(A2.10)}$$

The above equation compares well with equation (2.4) by expressing the last term on the right, in exponential form:

$$\frac{B}{B_o} = 1 - \frac{(kYK_s/K_h) + K_s/(S_{To} - R\,S_{To})}{\mu_m \vartheta + (kYK_s/K_h) - 1} \qquad \text{(2.4)}$$

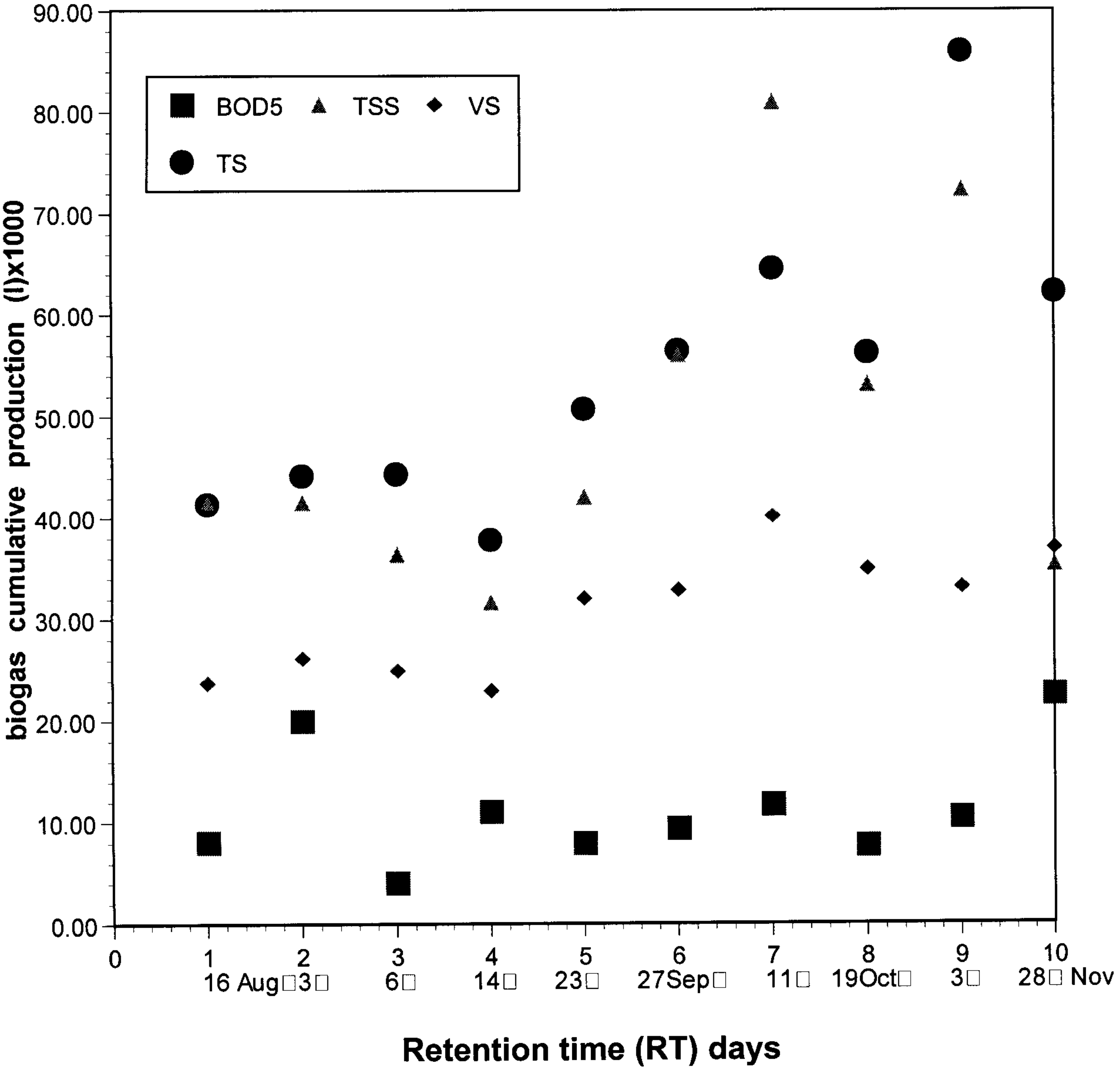


Figure B1.2: Seasonal effect and variation of pollution parameters at sampling point D2. (2004)

APPENDIX B2 GRAPH- MODEL LIMITATION

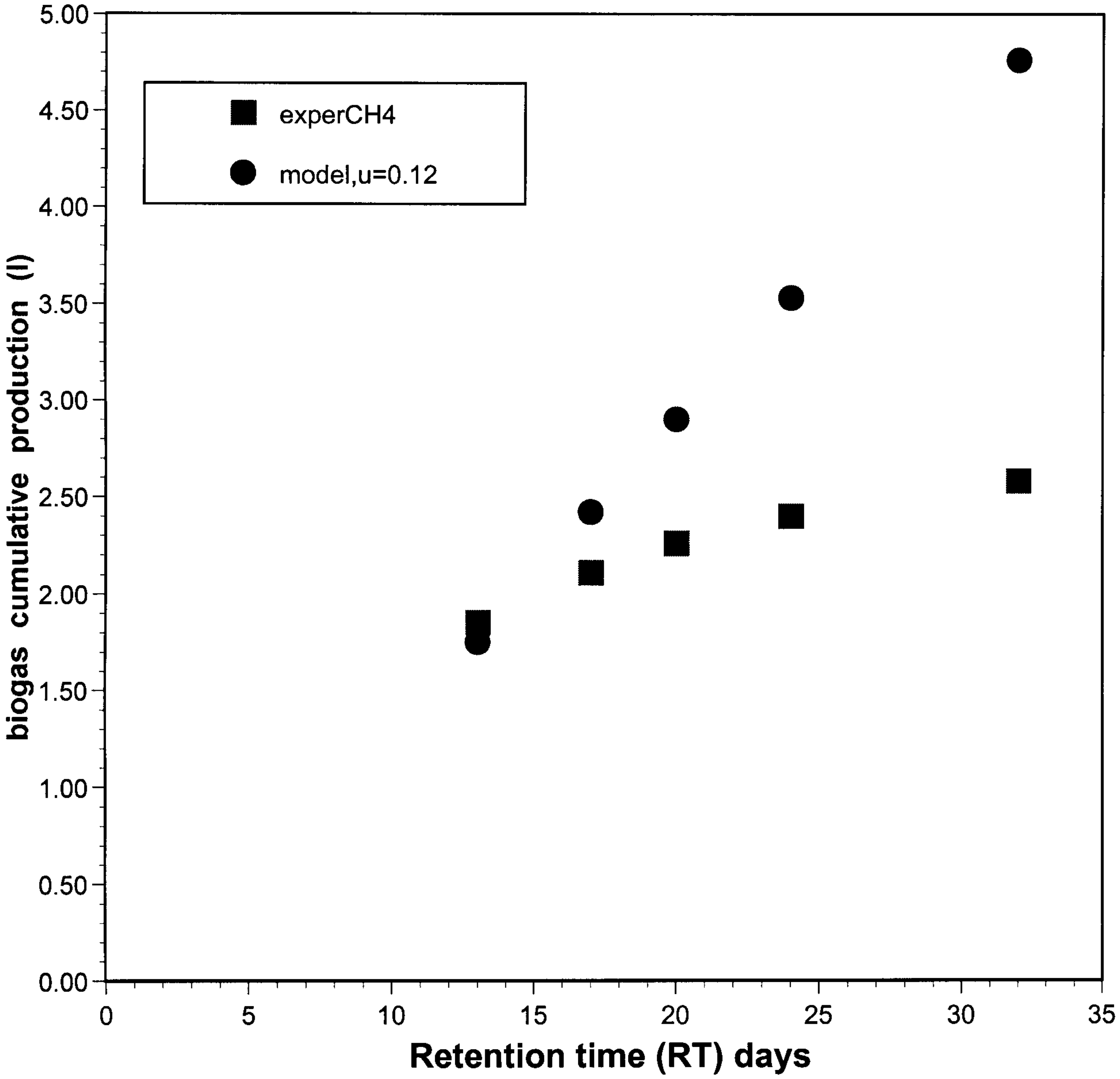


Figure B2.1: Actual biogas production versus model simulation with effluent from slaughterhouse wastewater at 21 Deg C

APPENDIX B3

TEMPERATURE VARIATION IN SEWAGE EFFLUENT

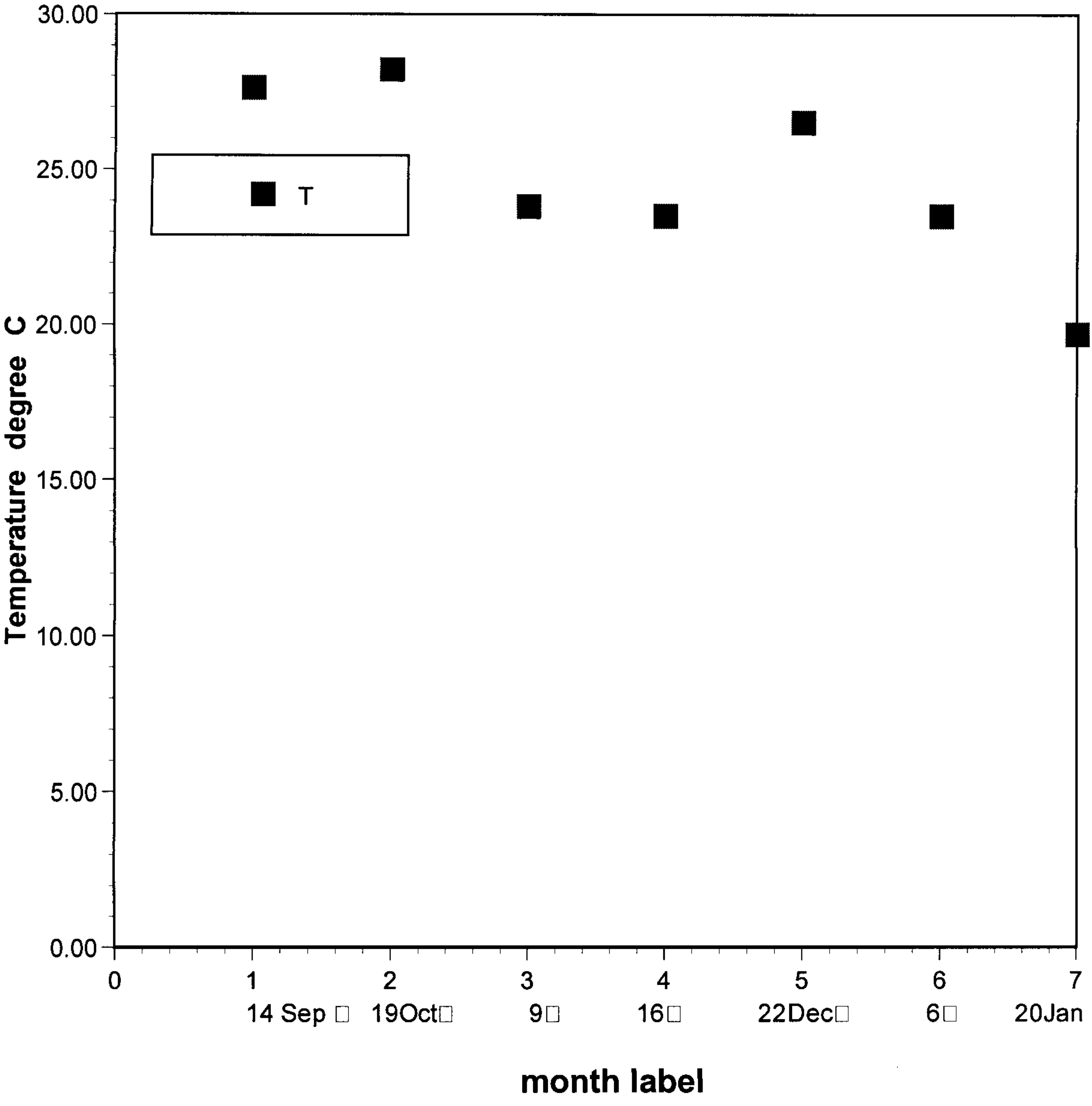


Figure B3.1: Temperature variations at sampling point PS. (2004/5)

APPENDIX C1 LEAST SQUARE ESTIMATION AND THOMAS SLOPE COMPUTATIONS

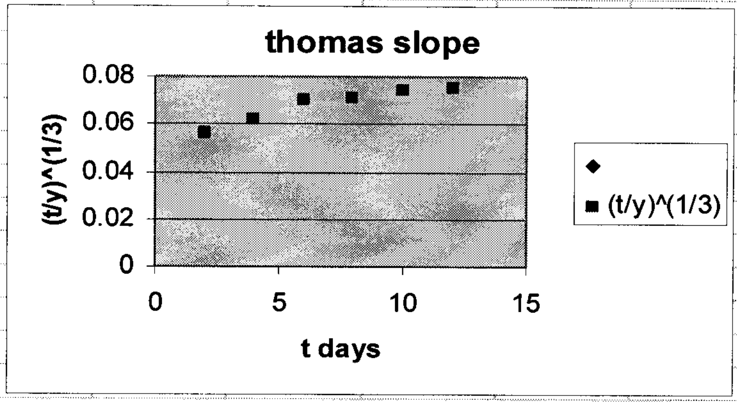
TableC1.1

SAMPLE	thickener							
LEAST SQUARE ESTIMATOR								
n	t/d	y	y^2	y'	yy'	k'=-b	a	L=-(b/a)
		10500						
1	**2**	**11500**	1.32E+08	1600	18400000	0.028894	2022.121	69984.19
2	**4**	**16900**	2.86E+08	1537.5	25983750			
3	**6**	**17650**	3.12E+08	1450	25592500			
4	**8**	**22700**	5.15E+08	1750	39725000			
5	**10**	**24650**	6.08E+08	1325	32661250			
6	**12**	**28000**	7.84E+08	962.5	26950000			
		28500	8.12E+08					
sum		121400	2.64E+09	8625	1.69E+08			

Thomas slope

t,time,d	**2**	**4**	**6**	**8**	**10**	**12**
y	**11500**	**16900**	**17650**	**22700**	**24650**	**28000**
(t/y)^(1/3)	0.055818	0.061857	0.069791	0.070635	0.074028	0.075395

t/day		(t/y)^(1/3)				
2		**0.06**				
4		**0.06**				
6		**0.07**				
8		**0.07**				
10		**0.07**				
12		**0.08**				
	a=	0.05				
	slope	b	0.000684		L	42330.24
		k	0.035679			
		k'	0.08217			

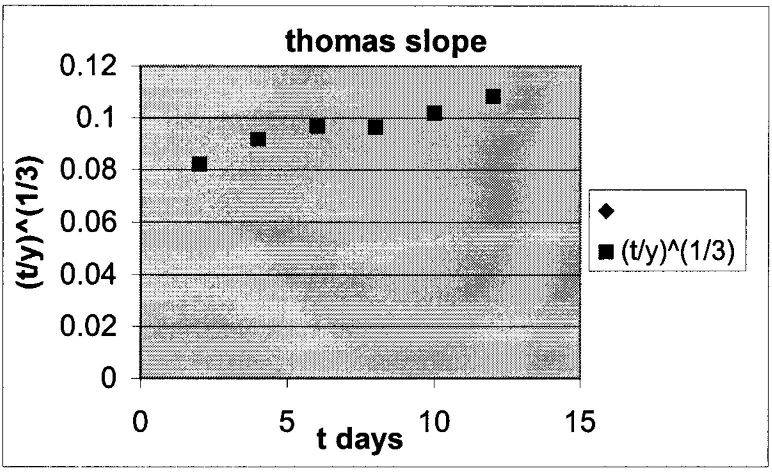


TableC1.2
SAMPLE DIGESTER
LEAST SQUARE ESTIMATOR

n	t/d	y	y^2	y'	yy'	k'=-b	a	L=-(b/a)
		3200						
1	**2**	**3600**	12960000	483.25	1739700	0.074498	1038.481	13939.66
2	**4**	**5133**	26347689	750	3849750			
3	**6**	**6600**	43560000	929.25	6133050			
4	**8**	**8850**	78322500	712.5	6305625			
5	**10**	**9450**	89302500	137.5	1299375			
6	**12**	**9400**	88360000	12.5	117500			
		9500	90250000					
sum		43033	3.39E+08	3025	19445000			

Thomas slope

t,time,d	**2**	**4**	**6**	**8**	**10**	**12**
y	**3600**	**5133**	**6600**	**8850**	**9450**	**9400**
(t/y)^(1/3)	0.082207	0.092023	0.096873	0.09669	0.101904	0.10848
t/day		(t/y)^(1/3)				
2		**0.08**				
4		**0.09**				
6		**0.10**				
8		**0.10**				
10		**0.10**				
12		**0.11**				
	a=	0.085				
	slope	b	0.002627		L	8775.65
		k	0.080674			
		k'	0.185793			



TableC1.3

SAMPLE kembe

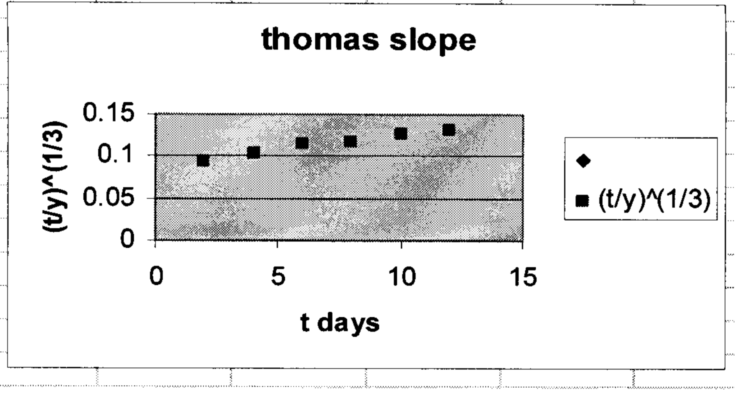
LEAST SQUARE ESTIMATOR

n	t/d	y	y^2	y'	yy'	k'=-b	a	L=-(b/a)
		2000						
1	**2**	**2340**	5475600	392.5	918450	0.085598	640.332	7480.72
2	**4**	**3570**	12744900	385	1374450			
3	**6**	**3880**	15054400	360	1396800			
4	**8**	**5010**	25100100	275	1377750			
5	**10**	**4980**	24800400	95	473100			
6	**12**	**5390**	29052100	180	970200			
		5700	32490000					
sum		25170	1.12E+08	1687.5	6510750			

Thomas slope

t,time,d	**2**	**4**	**6**	**8**	**10**	**12**
y	**2340**	**3570**	**3880**	**5010**	**4980**	**5390**
(t/y)^(1/3)	0.094901	0.103864	0.11564	0.116883	0.126161	0.130576

t/day		(t/y)^(1/3)				
2		**0.09**				
4		**0.10**				
6		**0.12**				
8		**0.12**				
10		**0.13**				
12		**0.13**				
	a=	0.09				
	slope	b	0.002208		L	4044.673
		k	0.064028			
		k'	0.147456			



APPENDIX D1 LAB SCALE REACTOR DESIGN

Apparatus

The reactor capacity design was calculated as follows:
Slurry of 4 percent dry matter, DM, is assumed. Diluting this 100percent that is adding 100 parts gives a solution of 200 parts. Let this part be grams.
Mixing ratio 1: 1

Fermentation slurry amount sd
100 g x 2 = 200 ml
(1g water=1ml)
DM=4/200=2percent
Taking, Retention time = 25 days

Digester volume, Vd
200 ml x 25 = 5000 ml
Specific gas production from graph [27] 22 l/kg/d

Daily production

22 l /kg/d x 0.1 kg = 2.2 l/d = 2200 ml /d
Taking gas holder capacity, C = 60 percent
Gas holder volume
V g = 0.6 x 2200 =1320 ml
Applying safety factor =2
V g = 2 640 ml

Notes
The calculations are based on cow dung.
The specific gas production and the design procedure is based on [27]

APPENDIX D2 RAW DATA
TableD2.1

D1							
	BOD5	**TS**	**TSS**	**VS**	**PH**	**T**	**Deg C**
16/08/04	14725	28520	30500	19580	6.64	26.7	_
03/09/04	16550	35860	32700	24680	6.75	24.4	_
06/09/04	28300	38700	34900	27800	6.53	25.2	_
27/09/04	21700	46200	53000	33100	6.46	26.2	_
14/09/04	21950	43300	43200	32300	6.55	26.6	_
11/10/04	28300	46500	38400	29800	6.49	17.3	_
19/10/04	20400	34000	32500	24300	6.78	26.6	_
28/10/04	26800	68300	53200	24550	6.46	27	_
03/11/04	18500	35300	32700	25000	6.8	27.6	_
09/11/04	18500	38300	32200	23200	6.42	23.7	_
16/12/04	27600	12800	9000	8400	6.42	23.7	_
D2	**BOD5**	**TS**	**TSS**	**VS**	**PH**	**T**	**Deg C**
16/08/04	7983	41300	41500	23720	7.01	24.9	
23/08/04	9900	44120	41500	26100	6.35	25.4	
06/09/04	3950	44300	36300	24900	7.33	23.7	
27/09/04	10950	37750	31600	22900	7.23	24.8	
14/09/04	7833	50700	42000	32000	7.2	26.4	

11/10/04	9283	56400	56000	32800	7.11	26.3
09/10/04	11620	64500	80900	40100	6.96	17
28/10/04	7617	56200	53100	34900	7.46	26.6
03/11/04	10360	85900	72300	33100	7.33	27.6
28/10/04	22450	62200	35300	36900	7.5	27.8
PS	_	_	_	_	_	_
14/09/04	23500	39800	40500	29900	6.29	27.6
19/10/04	20400	38200	38700	29200	6.66	28.2
09/12/04	_	47400	43900	28100	6.5	23.8
16/12/04	11750	6100	4600	29200	7.08	23.5
22/12/04	25600	38700	37000	29800	6.43	26.5
06/01/05	28050	10350	95200	62200	7.13	23.5
20/01/05	19150	44600	40100	28300	6.64	19.7
K	_	_	_	_	_	_
16/08/04	2920	15810	9800	13410	6.94	25.1
23/08/04	10066	39080	9800	18999	6.65	25.7
27/09/04	5680	28550	19900	24550	6.52	19.4
09/12/04	2525	3400	2700	1200	7.08	23.5
16/12/04	4100	45600	40200	3900	6.5	23.8
29/12/04	2525	4400	850	2450	6.38	22.8
06/01/05	3688	2900	1800	1650	7.08	23.2
13/01/05	4500	4150	1800	2400	7.08	23.2
20/01/05	4500	8050	5150	5400	7.02	19.5
R	_	_	_	_	_	_
16/08/04	295	1582	30500	366	6.89	25.8
23/08/04	278	738	356	380	7.17	24.4
03/09/04	583	2040	31600	1480	6.74	24.4
KP	_	_	_	_	_	_
22/12/04	5338	7250	4250	5250	6.79	25.6
KEEF1						
29/12/04	2450	7100	13150	4200	6.77	22.9
06/01/05	7088	13050	9900	10550	6.92	22.8
13/01/05	19150	13150	10050	9850	6.92	22.8

APPENDIX D3 ENERGY CONTENT ASSESSMENT

Computation of biogas yield

Illustration (sludge)

From the experimental data the biogas production for 52 days retention time for sludge only with 10 percent cow manure seed (inoculum) used is 163.46 ml/d , the initial VS concentration is 46067 mg/l in a 5 L mild steel bioreactor.

5L * 46067 mg/l =230.3 g

with a VS removal of 24 percent the VS destroyed=230.3 *0.24=55.3 g

The biogas yield becomes

0.163 (L/d) *52 (d) /55.3(g) = 0.15 m^3/KgVS

Average VS/BOD = 1.3

Biogas yield is 0.195 m^3/ Kg BOD

Calculation of energy based on TS

Estimation using the yield of the waste is shown in the following illustration according to [6].

Taking 6.6 percent of sludge slurry (TS) (it is necessary to add dry matter of other waste say cow dung)

The treated sludge is about 170 000 t p a

(430 l/head/per annum assumed, Average of 360-500 [59]; 400 000 population [4])

Calculated VS , percent of TS varies from 57 to 68; selected 68percent

Assumed yield=0.25 m^3/kgVS; methane content calculated 74 percent

170000 * 6.6 percent==11220 t pa of TS

11220*68percent=7629.6 t pa VS

7629 600*0.25= 1907400 m^3

217.74 m^3 /hr

The electricity and heat production is with a calorific value of biogas of 22 MJ/m^3

217.74*22*10^6 /3600= 1,330,633 w that is approximately

1331 KW, so that the power available assuming that the CHP unit is 55 percent

For electricity and 30 percent for heat

Power =1331 * 60percent=798.6 K w or approximately <u>800 K w</u>

800kW*8760=7008MWh/y

(7008000*150(cost Z m k per K w h) =ZMK 1,051,200,000 pa)

ZMK86, 400,000 worth of electricity per month can be produced

The production of electricity will be

7008 M W h/yr

1331 * 30percent=399.3 k w heat

399.3*8760hr= 3497868kWh/yr

Heat =3,498Mw/yr

The heat could be used for the process (digester heating, sterilization)

And for many other applications

It can be expressed as k w h/t as well

Electricity =7008*10^6/170000 = 41.22 k w h/ ton

Heat = 3,498 *10^6/170000= 20.57 k w h/ton

The total energy value based on the above computation is given in table D3.1

Table D3.1: Energy potential for sludge at 38 deg C for Manchinchi treatment plant

TS %	sludge			VS	TS	VS/TS	VS	BOD	VS/BOD
	Head	l/head/a	tpa	ppm	ppm	tpa	tpa	tpa	1.3
2.90	400000	30	12000	19580	28520	0.69	8238	6337	
3.60	400000	30	12000	24680	35860	0.69	8259	6353	
3.80	400000	30	12000	27800	38700	0.72	8620	6631	
4.60	400000	30	12000	33100	46200	0.72	8597	6613	
4.30	400000	30	12000	32300	43300	0.75	8952	6886	
4.60	400000	30	12000	29800	46500	0.64	7690	5916	
3.40	400000	30	12000	24300	34000	0.71	8576	6597	
6.80	400000	30	12000	24550	68300	0.36	4313	3318	
3.50	400000	30	12000	25000	35300	0.71	8499	6537	
3.80	400000	30	12000	23200	38300	0.61	7269	5591	
1.20	400000	30	12000	8400	12800	0.66	7875	6058	
3.86				24791.82	38889.09	0.66	7899	6076	
average									

						assume			
				gas		CHP		electr./y	heat/yr
gas yield	gas vol /a	gas/d	gas/h	power	power	electr.	heat	per ton	
m3/kgVS	m3/a	m3/d	m3/h	{23.MJ/m3}		55%	30%		
				MW	MWh/yr	MWh/yr	MWh/yr	kwh/y/t	kwh/y/t
0.19	1565302	4288.50	178.69	1.14	10000.54	5100.27	3000.16	425.02	250.01
0.19	1569169	4299.09	179.13	1.14	10025.25	5112.88	3007.57	426.07	250.63
0.19	1637829	4487.20	186.97	1.19	10463.91	5336.59	3139.17	444.72	261.60
0.19	1633506	4475.36	186.47	1.19	10436.29	5322.51	3130.89	443.54	260.91
0.19	1700785	4659.69	194.15	1.24	10866.13	5541.73	3259.84	461.81	271.65
0.19	1461161	4003.18	166.80	1.07	9335.20	4760.95	2800.56	396.75	233.38
0.19	1629529	4464.46	186.02	1.19	10410.88	5309.55	3123.26	442.46	260.27
0.19	819531	2245.29	93.55	0.60	5235.90	2670.31	1570.77	222.53	130.90
0.19	1614731	4423.92	184.33	1.18	10316.34	5261.33	3094.90	438.44	257.91
0.19	1381097	3783.83	157.66	1.01	8823.67	4500.07	2647.10	375.01	220.59
0.19	1496250	4099.32	170.80	1.09	9559.38	4875.28	2867.813	406.27	238.98
average	1500808	4111.80	171.33	1.09	9588.50	4890.13	2876.55	407.51	239.71

Table D3.2: Total installed power Status at Manchichi treatment plant as in 2004/5

location/manchichi TP	type	motor rating	working	run hours	distribution
turn table 1		1.1	yes	24	
turn table 2		1.1	yes	under repair	
grit elevator 1		2.2	yes	4 per day	every after
grit elevator 2		2.2	yes	4 per day	every after
detritus chamber		1.1	yes	24	
PST 1		0.75	yes	24	
PST 2		0.75	yes	24	
PST 3		0.75	yes	24	
PST 4		0.75	yes	24	
Raw sludge 1		7.5	yes	after 2 hrs	
Raw sludge 2		7.5	yes	after 2 hrs	
SST 1		0.95	yes	24	
SST 2		0.95	yes	24	
SST 3		0.95	yes	24	
SST4		0.95	yes	24	
Humus Stage 1		3	yes	after 2 hrs	
Humus recirc pump Stage 1&2 p1		11	yes	4 times aft	every after
Humus recirc pump Stage 1&2 p2		3.95	yes	2 hours per day	
Humus recirc pump stage 3&4		7.5	yes	4 times aft	every after
Humus raw sludge pump stage 1&2		no name plate	yes	under repair	
Humus raw sludge pump stage 3&4		7.5	yes	4 hour afte	every after
thickener mixer		no name plate	yes	under repair	
thickener no. 1		7.5	yes	4 hour afte	every after
thickener no 2		7.5	yes	4 hour afte	every after
supernatant no,1		11	not	after 2 hrs	
supernatant no,2		11	yes	after 2 hrs	
NB PST Primary sedimentation Tank					

Table D3.3: Maximum installed power at Manchichi treatment plant

Manchichi treatment plant	**Power consumption**			
location	**no.**	**kw**	**total**	**hp**
thickener	2.00	7.50	15.00	
type DV 132 M4			0.00	
			0.00	
pumphouse stage 3&4	2.00	7.50	15.00	
			0.00	
pumphouse stage 1&2	2.00	7.50	15.00	
			0.00	
humus pump	2.00	3.00	6.00	
			0.00	
PST/thickener	2.00	15.00	30.00	
			0.00	
clarifiers	8.00	2.10	16.80	
			0.00	
drying bed/thickener	2.00	11.00	22.00	
			0.00	
			0.00	
			0.00	
irrigation pumps	1.00	5.60	5.60	7.50
not working	4.00	3.73	14.92	5.00
	1.00	11.19	11.19	15.00
			0.00	
screening devices			0.00	
grit elevator 1	2.00	2.24	4.48	3.00
peddlers	2.00	1.10	2.20	
communitor	1.00	11.00	11.00	
grit elevator 2	4.00	0.75	2.98	1.00
	2.00	2.24	4.48	3.00
recirculation pumps			0.00	
stage 1&2	3.00	5.60	16.79	7.50
stage 3&4	2.00	29.84	59.68	40.00
anaerobic digesters/ not w	2.00	7.09	14.18	9.50
maximum installed power/KW			267.29	

Table D3.4: CHP systems Advantages and Disadvantages

CHP system	Advantages	Disadvantages	Available size
Gas turbine	High reliability ;Low emissions ;High grade heat available;No cooling required	Require high pressure gas or in-House gas compressor Poor efficiency at low loading Output falls as ambient temperature rises	500kW to 40 MW
Micro turbine	Small number of moving parts Compact size and light weight ;Low emissions ;No cooling required	High cost Relatively low mechanical efficiency Limited to lower temperature Cogeneration application	30kW to 350 kW
Spark ignition Reciprocating engine	High power efficiency with part load operational flexibility Fast start-up Relatively low investment cost Can be used in island mode and have good load following capability , Can be overhauled on site with normal operations Operate on low pressure gas	High maintenance costs Limited to lower temperature Cogeneration applications Must be cooled even if recovered heat is not used High levels of low frequency noise	<5MW
Diesel /compression ignition(CI) Reciprocating engine			High speed (1200RPM) ≤ 4 MW
			Low speed (60-275 RPM) ≤65 MW
Steam turbine	High overall efficiency Any type of fuel may be used Ability to meet more than one site heat grade requirement Long working life and high reliability Power to heat ratio can be varied	Slow start-up Low power to heat ratio	50kW to 250 MW

Source:Nexus Energy group,USA

TableD3.5: Cost and performance characteristics steam turbine parameters

Cost and performance characteristics[1] steam turbine parameters	System 1	System 2	System 3
Nominal Electricity capacity(kW)	500	3000	15000
Turbine type	Back pressure	Back pressure	Back pressure
Equipment cost ($/kW)[2]	540	225	205
Total installed cost ($/kW)[3]	918	385	349
Turbine isentropic efficiency(percent)[4]	50percent	70percent	97percent
Generator gearbox efficiency (percent)	94percent	94percent	97percent
Steam flow(Ibs/hr)	21,500	126,000	450,000
Inlet pressure (psig)	500	600	700
Inlet temperature (deg F)	550	575	650
Outlet pressure (psig)	50	150	150
Outlet temperature (deg F)	298	366	366
CHP system parameters			
Boiler efficiency (percent) HHV	80percent	80percent	80percent
CHP electric efficiency (percent)HHV[5]	6.4percent	6.9percent	9.3percent
Fuel input (MMBtu/h)[6]	26.7	147.4	549
Steam to process (MMBtu/h)	19.6	107	386.6
Steam to process (kW)	5.74	31.352	113.291
Total CHP Efficiency(percent),HHV[7]	79.6percent	79.5percent	79.7percent
Power / heat ratio[8]	0.09	0.1	0.13
Net heat rate (Btu/kW)[9]	4,515	4,568	4,388
Effective electrical efficiency(percent)HHV[10]	75.6percent	75.1percent	77.8percent

Source:Nexus Energy group,USA

TableD3.6: Cost and performance characteristics of gas turbine

Cost and performance characteristics [11] gas turbine	System 1	System2	System3
Electricity capacity(kW)	1,000	5,000	10,000
Total installed cost (2000$/kW)[12]	1,780	1,010	970
Electric heat rate(Btu/kWh)HHV[13]	15,580	12,590	11,765
Electric Efficiency (percent) HHV	21.9	27.1	29
Fuel input (MMBtu/h)	15.6	62.9	117.7
Required fuel gas pressure (psig)	95	160	250
CHP characteristics			
Exhaust flow(1000Ib/h)	44	162	316
GT exhaust temperature (deg F)	950	950	915
HRSG Exhaust temperature (deg F)	280	280	280
Steam output (MMBtu/h)	7.1	26.6	49.6
Steam output (1000Ib/h)	6.7	25	46.6
Steam output (kW equivalent)	2,080	7,800	14,540
Total CHP Efficiency(percent),HHV[14]	68	69	71
Power / heat ratio	0.48	0.64	0.69
Net heat rate (Btu/kW)	6,673	5,947	5,562
Effective electrical efficiency (percent)	51	57	61

Source: Nexus Energy Group, USA

Table D3.7: Cost and performance characteristics of Micro turbine

Cost & performance characteristics[15] Micro turbines	System 1	System 2	System 3	System 4
Nominal electricity capacity (2000 $/kW)	30	70	100	350
Package cost (2000 $/kW)[16]	1,000	950	800	750
Total installed cost (2000 $/kW)[17]	2,516	2,031	1,561	1,339
Electric heat rate (Btu/kWh)HHV	14,581	13,540	12,637	11,766
Electrical efficiency (percent) HHV	23.4	25.2	27	29
Fuel input (MMBtu/hr)	0.437	0.948	1.264	4.118
Required fuel Gas pressure (psig)	55	55	75	135
CHP characteristics				
Exhaust flow (Ibs/sec)	0.72	1.4	1.74	5.00
GT Exhaust temperature (deg F)	500	435	500	600
Heat exchanger exhaust temp(deg F)	150	130	131	140
Heat output (MMBtu/hr)	0.218	0.369	0.555	1.987
Heat output (kW equivalent)	64	108	163	582
Total CHP efficiency (percent) HHV	73	64	71	77
Power/heat ratio	0.47	0.65	0.62	0.6
Net Heat Rate (Btu/kWh)	5,509	6,952	5,703	4,668
Effective Electrical Efficiency (percent) HHV	62	49	60	73

Source: Nexus Energy Group,USA

Table D3.8: Cost and performance characteristics for gas engine generator set

Cost &performance characteristics[18]gas engine generator set	System 1	System 2	System 3
Base load Electric capacity (kW)	100	300	800
Total Installed Cost (2001 $/kW)[19]	1,515	1,200	1000
Electric heat rate (Btu/kWh)HHV[20]	11,147	10,967	10,246
Electric efficiency (percent) HHV	30.6	31.1`	33.3
Engine speed (rpm)	1,800	1,800	1,200
Fuel input(MMBtu/hr)	1.11	3.29	8.2
Required fuel Gas pressure (psig)	<3	<3	<3
CHP Characteristics			
Exhaust flow (1000lbs/hr)	1.0	3.3	10.9
Exhaust temperature (Fahrenheit, F)	1,060	1,067	869
Heat recovered from exhaust (MMBtu/hr)	0.2	0.82	2.12
Heat recovered from cooling jacket (MMBtu/hr)	0.37	0.69	1.09
Heat recovered from lube jacket (MMBtu/hr)	0	0	0.29
Total heat recovered (MMBtu/hr)	0.57	1.151	3.5
Total heat recovered (kW)	167	443	1,025
Form of recovered heat	Hot water	Hot water	Hot water
Total efficiency (percent)	81	77	76
Power/heat ratio	0.60	0.68	0.78
Net heat rate (Btus/kWh)	4,063	4,687	4,774
Effective electrical efficiency	0.84	0.73	0.71

Source: Energy Nexus Group, USA

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[1] Characteristics for "typical" commercially available steam turbine generator systems; Steam turbine data is based on information from turbo Steam .Inc for 500kW and 3MW; General electric for 15MW turbine.

[2] equipment cost includes turbine gearbox, generator ,controls, and switchgear :boiler and steam system costs are not included

[3] installed cost vary greatly based on site-specific conditions: Installation costs of a "typical" simple installation were estimated to be 70 percent of the equipment costs

[4] The isentropic efficiency of a turbine is a comparison of the actual power output compared to the ideal .or isentropic output. It is a measure of the effectiveness of extracting work from the expansion process and is used to determine the outlet conditions of the steam from the turbine.

[5] CHP electrical efficiency =Net electricity generated/Total fuel into boiler .A measure of the amount of boiler fuel converted into electricity

[6] Fuel input based on condensate return of steam outlet pressure and saturation temperature.

[7] Total CHP efficiency=(Net electrical power output(Btu)+net steam produced for thermal needs)/total system fuel input (Btu)

[8] Power/heat ratio =CHP electrical power output (Btu) /useful heat output (Btu)

[9] Net heat rate =(total fuel input to boiler-the fuel that would be required to generate the steam to process assuming the same boiler efficiency /steam turbine electric output (kW)

[10] Effective Electrical Efficiency =(steam turbine electric power output/(Total fuel into boiler-(Steam to process boiler /boiler efficiency)).Equivalent to 3.41 Btu/kWh/Net Heat Rate.

[11] Characteristics of "typical" commercially available gas turbine generator system. Data based on Solar turbines Saturn 20-1 MW ;Solar turbines: Taurus 60-5MW;Solar turbines Mars 100-10MW;

[12] installed costs based on CHP system producing 150 psig saturated steam with an unfired Heat Recovery Steam Generator, HRSG

[13] All turbines and engine manufacturers quote heat rates in terms of the lower heating value (LHV)of the fuel .On the hand ,the usable energy content of fuels is typically measured on a higher heating value basis (HHV).In addition electric utilities measure power plant heat in terms of HHV. For natural gas the average heat content of natural gas is 1030 Btu/ scf on an HHV basis and 930 Btu/scf on an LHV basis –or a 10 percent difference.

[14] Total efficiency =(net electric generated-net steam produced for thermal needs)/total system fuel input

[15] characteristics presented are representative of "typical" commercially available micro-turbine systems. tables are based on Capstone Model 330-30KW;IR energy systems 70LM-70kW(two-shaft);TurbecT100;DTE model currently under development (now already available) -350kW

[16] equipment cost only .The cost for all units except for the 30 kW unit include integral heat recovery water heater .All units include a fuel gas booster compressor

[17] Installed cost based on CHP system producing hot water from exhaust heat recovery. The 70 kW and 100 kW systems are offered with integral hot water recovery built into the equipment. The 30 kW units are currently built as electric(only) generators and the heat recovery water heater is a separate unit. Other units entering the market are expected to feature built in heat recovery water heaters.

[18] Characteristics for "typical" commercially available natural gas engine gensets. Data based on: MAN 150 kW-100kW:Cummins GSK19G-300kW;caterpillar G3516LE-3MW;Wartsila 5238 LN-5MW.Energy use and exhaust flows normalized to normal system sizes.

[19] Installed costs based on CHP system producing water from exhaust heat recovery (250 Deg F exhaust from heat recovery heat exchanger),and jacket and lube system cooling

[20] All engine manufacturers quote heat rates in terms of the lower heating value (LHV)of the fuel .However the purchase price for the fuels on an energy basis is typically measured on a higher heating value basis (HHV).For natural gas ,the average heat content of natural gas is 1030 Btu/ scf on an HHV basis and 930 Btu/scf on an LHV basis –or a 10 % difference .

Publications and presentations

1. 5th International Conference on Sustainable Energy Technologies (SET 2006) Vicenza Italy 30th August -1st Sept 2006 pre-prints. Paper presentation p369