University of Nairobi

BIOGAS USE IN POWER GENERATION

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By

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Department of Electrical and Information Engineering
DEDICATION
This report is dedicated to my mother, a woman whose strength, guidance and faith has made me the best I can be.
ACKNOWLEDGEMENTS

I would like to sincerely thank Dr. Cyrus Wekesa, my supervisor and a lecturer at the Department of Electrical & Electronic Engineering for his encouragement and guidance during the course of my project.

I would also like to extend my gratitude to Engineer Wanja, Mr. Kimenye and Mr. James Kangari of Nairobi Water and Sewerage Company for enabling me get the right data during my visits to the Dandora Sewage Plant. Not be forgotten is my classmate and friend, Henry Nduati for his help in working with the RET Screen Clean Energy Analysis Software.
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ABSTRACT
The situation of our country’s energy sector brings to light the need to increase the installed
capacity of electrical power. In the considerations high on the agenda are the cost of generation
and the environmental impact the option will have. It is on these factors that this project has been
based. The recent developments in the use of renewable energy especially wind power is very
encouraging in that it paves the way for the developments in other renewable energy sources
especially biomass.

The potential of biogas in power generation is immense and is definitely an area that deserves a
lot of attention. The project report has fully described the properties and uses of biogas. It has
also gone a step further to look into methane which is the most important component gas of
biogas with special emphasis on its heating properties and its role in the Green House Effect.

The preparation of biogas through anaerobic digestion is governed by factors that are included in
the report detailing the ranges of optimum biogas production. The effective use of Biogas is
hampered due to impurities that it contains. The various impurities and the techniques used to
remove them have been handled in detail.

The various technologies that can be employed in the generation of electricity using biogas are
covered extensively including the latest technology with great potential. The report has also gone
further to explain the utilization of heat from the generation process through Combined Heat and
Power system and the Combined cycle system.

Using data collected from the Dandora Sewage Plant, the potential of power generation from
biogas due to anaerobic digestion of sewage sludge was found to be 1.7 MW. Further analysis of
this data using the RET Screen Clean Energy Project Analysis Software has also been included.
CHAPTER 1: INTRODUCTION

1.1 Background

Energy is not considered as a basic need, but it is a basic ingredient in the successful satisfaction of most basic human needs. The level and intensity of commercial energy use is a key indicator of economic growth in a country. The commercial generation of power in Kenya is dominated by hydro-based supplies most of which comes from what was known as the Seven Forks dams on the Tana river. Of the 1267 MW installed capacity, 707 MW is from hydro (including 30MW imported from Uganda) 121MW geothermal while 398 MW came from fossil fired thermal stations of which 173MW was from Independent Power Producers (IPPs), while the rest belong to the Government owned KenGen, the major power generating company. The maximum demand was 1044 MW. The peak demand has been increasing steadily from 5.6 % in 2003/4 year to 7.8% in 2007/8 year and is expected to reach double digits this fiscal year. These statistics have put the Kenyan Energy sector at a precarious situation.

A considerable energy potential lies in the use of Renewable energy not to mention the environmental benefits it presents. Apart from Geothermal and wind, there are other renewable energy solutions that are available to Kenya: Solar and biomass being the most viable. This report will deal more on biomass and in particular biodegradable material being used to produce biogas that will be used for generation of electric power.

1.2 Problem Statement

The threat of global warming has never before been so clear as it is now. Kenya in the past 10 years has seen a great reduction in the amount of rainfall it receives characterized by long spells of drought. Our dependence on hydropower has compounded the issue as the level of water in our hydroelectric dams has fallen to very low levels thus reducing their electrical power output. This has caused an energy crisis to the extent that rationing measures were introduced.
The emergency measure put in place by the government to increase our installed capacity was the increase in diesel powered thermal stations. The effect has been the increase in the price of electrical energy in proportion to the rising cost of oil that has been passed down to consumers. Domestic consumers are now paying up to 60% more for electricity than they used to 3 years ago. The effect has been greater on the Industrial and Commercial consumers who have seen their operational costs rise considerably due to increasing power costs. The current situation has damaging effects on the businesses because they are now operating below capacity and is a setback to economic recovery. In addition, to balance their budgets companies will be forced to retrench workers and also avoid employing new ones. Therefore unemployment and inevitably poverty will increase; a recipe for social unrest. Aside from the economic side of this, there is also the threat to the environment with an increase in air pollution from the fossil fuel powered thermal plants.

It is therefore important for the country to increase its power output by factoring the cost of producing that power together with the environmental impact it has. It is encouraging to note that the government is promoting the exploitation of renewable energy to increase our power output. The pilot project by KenGen to harness the energy from wind which was started in Ngong hills where a 5MW wind farm has been connected to the national grid is a step in the right direction. However, It is important to put in place long term measures that will prevent the periodic recurrence of energy crises and also have enough energy to achieve the nation’s long term objectives.

1.3 Project objectives

1. To introduce biogas as a viable source of renewable energy

2. Explain the properties, preparation and use in power generation of biogas

3. Using data from the Dandora Sewage Treatment Plant, analyze the viability of a power plant using biogas from sewage sludge.
CHAPTER 2: BIOGAS

Biogas is produced by the fermentation of organic matter including manure, sewage sludge, and municipal solid waste, under anaerobic (having no oxygen) conditions. Biogas is gas combustible mixture consisting mainly of methane and carbon dioxide, together with several impurities.

\[ 2 \text{CH}_2\text{O} \rightarrow \text{CH}_4 + \text{CO}_2 \]

Carbohydrate → methane + carbon dioxide

Biogas with a methane content higher than 45% is flammable. It has specific properties which are listed in Table 1.1

Table 1.1 General features of biogas

<table>
<thead>
<tr>
<th>Composition</th>
<th>55 – 70% methane (CH\textsubscript{4})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30 – 45% carbon dioxide (CO\textsubscript{2})</td>
</tr>
<tr>
<td>Traces of other gases</td>
<td></td>
</tr>
<tr>
<td>Energy content</td>
<td>6.0 ÷ 6.5 kWh m\textsuperscript{3}</td>
</tr>
<tr>
<td>Fuel equivalent</td>
<td>0.60 ÷ 0.65 L oil/m\textsuperscript{3} biogas</td>
</tr>
<tr>
<td>Explosion limits</td>
<td>6 ÷ 12% biogas in air</td>
</tr>
<tr>
<td>Ignition temperature</td>
<td>650 ÷ 750 °C (with the above - mentioned methane content)</td>
</tr>
<tr>
<td>Critical pressure</td>
<td>75 ÷ 89 bar</td>
</tr>
<tr>
<td>Critical temperature</td>
<td>82.5 °C</td>
</tr>
<tr>
<td>Normal density</td>
<td>1.2 kg m\textsuperscript{1.3}</td>
</tr>
</tbody>
</table>
Smell: Bad eggs (the smell of desulfurized biogas is hardly noticeable)

Molar Mass: 16.043 kg kmol$^{-1}$

The amount of each gas in the mixture depends on many factors as the type of digester and the kind of organic matter. The average percentage composition of each gas in the biogas mixture is given in Table 1.2.

In any way this mixture is basically made of methane (CH$_4$) and carbon dioxide (CO$_2$), and its heating value is straightly linked to the methane content with the average lower heat value (LHV) of 5,300 kcal/Nm$^3$ (22.2 MJ/Nm$^3$), energy value of methane is 37.78 MJ/Nm$^3$

**Table 1.2 Biogas mixture composition**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH$_4$)</td>
<td>66.5%</td>
</tr>
<tr>
<td>Carbon Dioxide (CO$_2$)</td>
<td>30.5%</td>
</tr>
<tr>
<td>Oxygen (O$_2$) + Nitrogen (N$_2$)</td>
<td>0.5%</td>
</tr>
<tr>
<td>Humidity (H$_2$O)</td>
<td>2.5%</td>
</tr>
<tr>
<td>Sulfuric Acid (H$_2$S)</td>
<td>134 ppm or 0.01%</td>
</tr>
</tbody>
</table>
2.1 Methane

Methane is important for electrical generation by burning it as a fuel in a gas turbine or steam boiler. Compared to other hydrocarbon fuels, burning methane produces less carbon dioxide for each unit of heat released. At about 891 kJ/mol, methane's heat of combustion is lower than any other hydrocarbon but the ratio of the heat of combustion (891 kJ/mol) to the molecular mass (16.0 g/mol) shows that methane, being the simplest hydrocarbon, produces more heat per mass unit (55.7 kJ/g) than other complex hydrocarbons. In many cities, methane is piped into homes for domestic heating and cooking purposes. In this context it is usually known as natural gas, and is considered to have an energy content of 39 mega joules per cubic meter, or 1,000 BTU per standard cubic foot.

Methane in the form of compressed natural gas is used as a vehicle fuel, and is claimed more environmentally friendly than other fossil fuels such as gasoline/petrol and diesel.

Table 1.3 Properties of Methane

<table>
<thead>
<tr>
<th></th>
<th>Temperature]</th>
<th>Pressure [bar]</th>
<th>Density [kg L ( \text{\textdegree} ) L (^{-1} )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical point</td>
<td>82.59 °C (190.56 K)</td>
<td>45.98</td>
<td>0.162</td>
</tr>
<tr>
<td>Boiling point at</td>
<td>161.52 °C (111.63 K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.013 bar</td>
<td></td>
<td>( \ddagger )</td>
<td></td>
</tr>
<tr>
<td>Triple point</td>
<td>182.47 °C (90.68 K)</td>
<td>0.117</td>
<td></td>
</tr>
</tbody>
</table>
temperature increase since the middle of the 20th century has been caused by increasing concentrations of greenhouse gases, which result from human activities such as the burning of fossil fuel and deforestation.

### 2.1.1 Greenhouse effect

The greenhouse effect is the process by which absorption and emission of infrared radiation by gases in the atmosphere warm a planet's lower atmosphere and surface. Methane in the Earth's atmosphere is an important greenhouse gas with a global warming potential of 25 compared to CO$_2$ over a 100-year period (although accepted figures probably represents an underestimate. This means that a methane emission will have 25 times the impact on temperature of a carbon dioxide emission of the same mass over the following 100 years. Methane has a large effect for a brief period (a net lifetime of 8.4 years in the atmosphere), whereas carbon dioxide has a small effect for a long period (over 100 years). Because of this difference in effect and time period, the global warming potential of methane over a 20 year time period is 72. The Earth's atmospheric methane concentration has increased by about 150% since 1750, and it accounts for 20% of the total radiative forcing from all of the long-lived and globally mixed greenhouse gases. Usually, excess methane from landfills and other natural producers of methane is burned so CO$_2$ is released into the atmosphere instead of methane, because methane is a more effective greenhouse gas.

### 2.2 Biogas to energy

Biogas is a promising renewable source of energy. It can be directly converted into electrical power, e.g., in a fuel cell. It can be burnt, releasing heat at high temperature. It can be burnt in a CHP for the simultaneous production of heat and power. Finally, it can be fed into the natural gas network for energy saving purposes or it can serve as fuel for vehicles, being distributed by gas stations.
2.3 Benefits of using biogas

1) Local, available fuel source

2) Easy to capture and use

3) Source of renewable energy

4) Constant supply - 24 hours a day, 7 days a week

5) Reliable technologies exist for using landfill gas ñ more than 90% up time

6) Uses a source of energy that otherwise would have been wasted

7) Helps the global environment by reducing uncontrolled emissions.
2.4 Biogas preparation

2.4.1 Anaerobic digestion

This is the process by which bacteria break down biodegradable substrates in anaerobic conditions (no oxygen) to produce biogas. There are a wide range of substrates that can be used for generation of biogas:

- Animal manure
- Bio waste from collections of residual waste and trade waste similar to domestic waste
- Sewage sludge and co-substrate
- Industrial waste water
- Waste grease or fat
- Wood, straw

Methane fermentation is a complex process, which can be divided up into four phases of degradation: hydrolysis, acidogenesis, acetogenesis, and methanation. The individual phases are carried out by different groups of microorganisms, with different requirements on the environment.

It is crucial that the conditions are conducive enough for the bacteria to thrive. The most important parameters for effective anaerobic respiration are:

1) Light

Light is not lethal for methanogenics, but severely inhibits the methanation. The methane formation should therefore take place in absolute darkness.
2) Temperature

The temperature shows two optima for acidifying bacteria; a smooth one at about 32 °C to 42 °C for mesophilic microorganisms and a sharp one at 48 °C to 55 °C for thermophilic microorganisms. Most of the methanogenic microorganisms belong to the mesophiles. Only a few are thermophilic. A few others are able to produce methane even at low temperatures (0.6 °C to 1.2 °C), e.g., on the surface of permafrost soils. In laboratory tests, methane formation could be proven also with temperatures below freezing, i.e. down to 3 °C. In general, the lowest temperature at which microorganisms grow, is 11 °C. Below 25 °C, even the enzyme activity succumbs. Methanogenics are sensitive to rapid changes of temperature. Thermophilic methanogens are more temperature-sensitive than mesophiles. Even small variations in temperature cause a substantial decrease in activity. Therefore, the temperature should be kept exactly within a range of +/− 2 °C. Otherwise, gas losses of up to 30% have to be taken in consideration. Particularly critical for mesophilic cultures are temperatures in the range of 40 °C to 45 °C, because in that range they lose their activity irreversibly.

Under mesophilic operating conditions, the inhibition of ammonium is reduced because of the lower content of inhibiting free ammonia. In general, it has to be mentioned that the energy balance is better in the mesophilic range than in the thermophilic range.

The thermophilic mode of operation results in ca. 50% higher rate of degradation, and, particularly with fat-containing materials, a better microbial availability of the substrates and thus a higher biogas yield.

Epidemics and phytopathogenic germs are inactivated by higher process temperatures, so that special hygienic procedures are not necessary when using temperatures above 55 °C and a material retention time of more than 23 hours.

Oxygen is less soluble in the thermophilic temperature range, so that the optimal anaerobic operating conditions are reached more quickly.

In many two-stage plants, therefore, different temperatures are applied at the two stages. There are good reasons to drive the methanation thermophilically and the hydrolysis mesophilically.
But, depending on the substrate, it can also be favorable to operate the hydrolysis at higher temperatures than the methanation.

3) pH
The pH optimum of the methane-forming microorganism is at pH of 6.7 ÷ 7.5. Therefore, it is important to adjust the pH-value in the second stage higher than that in the first stage of a two-stage biogas plant. Only *Methanosarcina* is able to withstand lower pH values (pH = 6.5 and below). With the other bacteria, the metabolism is considerably suppressed at pH less than 6.7.

### 2.4.2 Biogas Plants

A biogas plant is made up of the following parts:

1) **Reactor**: This is where the anaerobic digestion of the biodegradable substrate occurs. It can be made either of bricks, concrete or steel. The material used should be able to withstand many deoxygenating substances that substrates contain, which cause fish die-off or groundwater contamination.

As such, must be reliably tight, so that no substrates can penetrate into the groundwater. The tightness of the components, above all the connections, valves, and in particular the mechanisms for leakage recognition, must be easily and reliably controllable.

Corrosion is induced by sulfuric acid, ammonia, and nitric acid, particularly in the area where the water surface meets the wall of the bioreactor is prone to leakage if pH values are low.
Figure 1: Biogas reactor

2) **Thermal insulation:** Depending on whether the tank is underground, above ground, or in a building, it must be more or less thermally insulated in order to avoid heat losses and/or to offer contact protection when the reactor is run in a thermophilic process.

As insulating material, expanded plastic slabs of polyurethane are used within the lower zone of the wall. They are equipped with moisture barriers in order to prevent the penetration of water. In the upper zone of the tank wall, expanded polystyrene slabs or mineral wool mats are often installed, or alternatively plastic foam is attached. As blinds and as protection from humidity, the thermal insulation is covered with riveted metal sheets.

3) **Piping system:** The piping system of biogas plants should be installed above ground to allow the easy detection of corrosion and leakages caused by any acidifying agents in the plant.

Such an above-ground system requires good insulation of frost-exposed pipes and armatures with additional trace heating.

Any subterranean pipes should be installed deep enough so that no damage can occur because of above-ground weight. All the pipes should be frost-protected, and special precautions must be taken to avoid any potential leakage.

The inlet and delivery pipes of all tanks should have at least one slide valve. Two gate valves and an additional compensator are mandatorily required only for such pipes that pass through the bioreactor wall below the sludge surface. The valves should be installed directly one after the other.

Regular checks of the whole system are required to guarantee that the pipes are all intact. Therefore, sight glasses need to be installed which should be rinsable and illuminatable.
In case of emergency, all the pipes should be of adequate dimensions and should be installed with a slight inclination to allow the complete system to be emptied and deaerated. The gate valves should always be on top. For the gas pipes, steam or foam traps need to be installed, sufficiently dimensioned to accommodate the maximum gas volume and a velocity of \( v_F = 10 \text{ m s}^{-1} \) in the discharge pipe and \( v_F = 5 \text{ m s}^{-1} \) in the intake pipe.

The material of partly filled delivery pipes or pipes that carry biogas and exhaust air should ideally be HDPE, PP, or PE. The connections must be welded. It is common practice that the company in charge of the installation proves and signs off the tightness of the whole piping system for normal daily conditions and for emergency cases where the pressure is at its maximum.

All the external plastic pipes need to be resistant to UV light. Pipes that carry the substrate are wrapped with aluminum foil for special protection against UV radiation.

4) **Pump system:** Pumps are in general needed in order to transport substrate to and from the equipment in the plant. Centrifugal pumps are to be found in 50% of all biogas plants. In 25% of all plants, positive-displacement pumps are installed to handle high solid concentrations. 16% of all biogas plants are operated without pumps, depending on geographical conditions. Other pumps like mono pumps or gear pumps, etc., are seldom used. Cutting pumps are used preferably in the pretreatment tank in particular for long-fiber materials in liquid manure such as straw, fodder remainders, grass cuttings, etc. They have hardened cutting edges at the impeller and a stationary cutting blade at the housing.

Pumps must be easily accessible, because they have to be controlled and maintained regularly. The moving parts of the pumps are wearing parts, which are subject to special stress and have to be replaced from time to time, especially in biogas plants.

Blockages of the pump occur despite various precautionary measures and prudent planning, and these have to be eliminated promptly.
5) Measurement, control, and automation technology: The process control equipment is used for the supervision and regulation of the operation of the plant and for the limitation of damage. In cases of emergency, e.g., breakdown of the electrical power supply, the biogas plant must be automatically transferred to safe operating conditions by the process instrumentation. Necessary electrically driven devices must be supplied with emergency power.

6) Mechanisms for monitoring and regulation

The operation of many simple agricultural biogas plants is dependent on the substrate accumulation and/or the gas consumption of the gas engine. They do not have regulation and the bioreactor is fed once or twice a day. The gas production is estimated from the running time of the CHP. If it runs inefficiently, substrate is fed in order to increase gas production. The only measuring instruments are a thermometer and a manometer at the CHP.

2.5 Biogas cleaning

The most important component of biogas is methane gas for its heating properties. In fact the only difference between natural gas and biogas is the percentage of methane where it is 80-90% for the former and usually 55-70% for the latter. The other components of Biogas need to be removed to increase the methane percentage but also to get rid of the negative effects they have on the power generation equipment and methane’s heating value.

The most common impurities in biogas are:

- Humidity: it can compromise the operation of microturbine’s internal parts (injector, combustion chamber, turbine rotor), besides reducing the biogas heating value.
- H₂S: it can damage drier’s internal parts, as well as the compressor and the microturbine, because H₂S is corrodible;}
- Air presence into the pipeline: reduces the biogas heating value;
- CO\textsubscript{2}: inert gas that also reduces the biogas heating value

Biogas is not absolutely pure, but contains droplets, dust, mud, or trace gases. All this contamination has to be removed, depending on the further utilization of the biogas.

Solid particles in the biogas and sometimes oil-like components are filtered out of the biogas with the usual dust collectors.

1) The removal of trace gases is carried out stepwise:
2) Rough separation of hydrogen sulphide in the bioreactor or a separate scrubber
3) Removal of traces of hydrogen sulphide
4) Separation of carbon dioxide and other biogas components
5) Dehumidification (if the carbon dioxide removal is a dry gas process, drying must be carried out before step 3).

2.5.1 Removal of hydrogen sulphide

Hydrogen sulfide in the fermentation gas impairs the lifetime of pipework and all installations for the utilization of biogas. It is toxic and strongly corrosive to many kinds of steel.

When the hydrogen sulfide-containing biogas burns it is converted into sulfur oxides, which on the one hand corrode metallic components and on the other hand acidify the engine oil, e.g., of the engine in the CHP.

The removal of hydrogen sulphide is done by use of Iron (III) oxide (Fe\textsubscript{2}O\textsubscript{3}) and Zinc oxide.
2.5.2 Removal of carbon dioxide

Methane-enriched biogas is biogas with a methane concentration of more than 95%. To reach this concentration, CO₂ has to be removed, i.e., the gas volume has to be reduced by approximately 40%.

Methane and carbon dioxide are differently bound to liquids. In water as a scrubbing agent the acidic components in the biogas such as CO₂ are more easily dissolved than hydrophobic, nonpolar components such as hydrocarbons. The physical absorption can be explained by different van der Waals forces of the gases, and the chemical absorption by different covalent binding forces. Besides CO₂, the warm water takes up traces of H₂S and other impurities in the biogas. Only oxygen and nitrogen cannot be removed from the biogas by the water scrubbing process.

Chemical absorption into alkaline solvents occurs under medium or low partial pressure. Absorbents are mainly amines such as monoethanolamine (MEA), diglycolamine, diethanolamine (DEA), triethanolamine and methyldiethanolamine (MDEA) or a hot potassium carbonate solution. At present, the best approved and most established procedure is the separation of CO₂ with MEA.

2.5.3 Removal of oxygen

Too high oxygen content in the biogas can only occur exceptionally. This oxygen can be removed using desulfurization procedures. Adsorption processes, e.g., with activated charcoal, molecular sieves, or diaphragm technology are also applicable.

2.5.4 Removal of water

Biogas can be dried by compression and/or cooling of the gas, by adsorption at activated charcoal or silica-gel, or by absorption, mostly in glycol solutions.
After compression to pressures up to 12 bars, which is necessary for many biogas decontamination procedures, the biogas leaves predried, when the condensate is removed from the compressor.

Landfill gases are sometimes cooled down to 2 °C or even to −18 °C by a refrigerating machine in order to lower the dewpoint to 0.5–1 °C. After separation of the condensate, the landfill gas is heated to ambient temperature.
CHAPTER 3: BIOGAS FOR POWER GENERATION

3.1 Technologies employed for biogas power generation

3.1.1 Steam turbine

A steam turbine uses high pressure and saturated or superheated steam produced in a boiler, and converts the thermal energy by expanding it in the turbine to generate shaft power that drives a generator to produce electricity.

Turbines can be of two types, radial or axial flow. Axial flow is the most common for power generation. The steam is directed by nozzles to rotating blades or buckets mounted radially on a rotating wheel. The length of the blades is short in proportion to the radius of the turbine. Several stages of expansion are used in high efficiency turbines. Vacuum exhaust can be achieved by mounting the different stages on a single shaft, and supporting the nozzles of all the stages from a continuous housing. Large turbines must not be operated in conditions where the exhaust steam contains more than 10 to 13% water. Water droplets can seriously erode nozzles and blades. Some turbines may have special stages designed for the removal of moisture. This type of design is used when the superheated steam temperature is limited. The moisture content of the exhaust is dependent on the inlet steam pressure combination.

Superheating the steam increases the cycle efficiency. Reheat is sometime used to further increase the efficiency. The steam is then re-superheated after partial expansion.

*Back pressure operation* refers to non-condensing steam turbines designed to utilize the exhaust steam for heating or a process. In a condensing turbine the steam exhausts to a condenser and the latent heat of the steam is transferred to the cooling water. The condensed steam is returned to the boiler as feed water.
Extraction, controlled automatic operation, refers to a steam turbine designed to permit a controlled extraction steam flow to be matched to the steam demand; steam can be used for heating or process purposes. Steam that is not extracted is condensed. Large steam turbines might have more than one extraction port.

### 3.1.2 Gas turbine

A gas turbine is a machine that compresses a gas (typically air), and then adds heat energy into the compressed gas. The heat can be added either firing (combusting) a fuel in the compressed air or transferring the heat via a heat exchanger. This is followed by the expansion of the hot pressurized gas to produce work. Part of the work produced is used to compress the gas, and the remaining part can either drive a generator for electricity production or some other machinery. An aircraft jet engine is a gas turbine where the useful work is produced as thrust from the exhaust.

Conventional combustion turbines are a mature technology with several suppliers worldwide. Turbines can be fueled with natural gas or oil. Units range in size from 500 kW to 250 MW.

There are two types of land based gas turbines namely, heavy frame engines and aero derivative engines. Heavy frame engines are larger and typically operate at lower compression rates than the smaller and more compact aero derivative engines.

Biogas can be converted to current via gas turbines of medium and large capacity (20 MW and more) at a maximum temperature of ca. 1200 °C. The tendency is to go to even higher temperatures and pressures, whereby the electrical capacity and thus the efficiency can be increased.

The main parts of a gas turbine are:

- the compressor
• the combustion chamber

• the turbine

Ambient air is compressed in the compressor and transmitted to the combustion chamber, where biogas is introduced and combustion takes place. The flue gas that is so formed is passed to a turbine, where it expands and transfers its energy to the turbine. The turbine propels on the one hand the compressor and on the other hand the power generator. The exhaust gas leaves the turbine at a temperature of approximately 400 – 600 °C. The heat can be used for driving a steam turbine downstream, for heating purposes, or for preheating the air that is sucked in.

The gas turbine is regulated by changing the biogas supply into the combustion chamber.

Gas turbines are characterized by very low emission values. When feeding decontaminated biogas, the NOx value in the exhaust gas is ca. 25 p.p.m. The CO content can be considerably reduced by a catalyst downstream.

Higher efficiencies can be obtained by higher turbine inlet temperatures, which presupposes particularly temperature-resistant materials and complicated technologies for blade cooling. Therefore gas turbines of the highest efficiency are relatively maintenance-intensive.

Single cycle turbines have efficiencies from 20 to 45% at full load, with efficiency increasing with size. Combining a gas turbine with a steam turbine cycle can improve efficiencies further to over 50% for large units. Gas turbines generally have a higher capital cost than reciprocating engines but this is balanced by lower operating costs. For plants above 10 MW, gas turbines are generally less expensive than reciprocating engines.

Gas turbines require a supply of high pressure feed gas and would require a gas compressor to operate on sewage biogas. This will increase the capital cost and reduce the efficiency of conversion to electricity.
3.1.3 Micro gas turbine

Micro gas turbines are small high-speed gas turbines with low combustion chamber pressures and temperatures. They are designed to deliver up to 200 kW of electrical power. Nearly all micro gas turbine manufacturers offer turbines of radial design with combustion air compressor, combustion chamber, generator, and heat exchanger. Micro gas turbines are characterized by a single shaft on which the compressor, the turbine, and the generator are fixed. The turbine propels the compressor, which compresses the combustion air, and at the same time the generator.

Thus radial forces to the bearings and to the shaft are avoided, which allows a simple design; e.g., the bearings can be gas-lubricated because of the low load. The gas lubrication can be accomplished by passing compressed air through the bearings. Oil changes as required for normal turbines are not necessary because of the oil-free running of the micro gas turbine.

For normal operation, the turbine sucks in the combustion air. The fuel is normally supplied to the combustion air in the combustion chamber. When biogas with a low calorific value is used it can also be mixed with the combustion air before the turbine. In the latter case, a little biogas has only to be supplied directly to the combustion chamber for fine adjustment.

The up to 100 000 revolutions per minute rotating generator produces high-frequency alternating current, which is converted in an electronic device, so that it can be fed synchronously into the power network.

The electrical efficiency of 15–25% of today's micro gas turbines is still unsatisfactorily low. An attempt to increase the efficiency has been made by preheating the combustion air in heat exchange with the hot turbine exhaust gases. But great improvements are still necessary before micro gas turbines will penetrate the market of industrial biogas plants. However, already today the coupling of a micro gas turbine with a micro steam turbine to form a micro gas and steam turbine seems interesting and economical because of its high electrical efficiency.

Micro gas-turbines are regulated only by varying the fuel supply.
3.1.4 Reciprocating engines

Reciprocating engine based systems are the most developed and most common cogeneration systems. Reciprocating engines fueled by natural gas or hydrocarbon liquid fuels are available in sizes from several kW to 10 MW. The amount of fuel energy converted to electricity generally increases with size, ranging from 30% for small units to 40% for large engines. The amount of fuel converted to thermal energy is from 40 to 50% resulting in overall efficiencies of 80 to 85%. Of the small cogeneration systems available, reciprocating engines offer the highest conversion of fuel energy to electricity. Figure 3 shows a combined heat and power system that uses a diesel engine for combustion of the gas with recovery of heat from the engine coolant, engine oil circulating system and exhaust manifold.

Operating and maintenance costs can be a significant portion of total electricity cost with reciprocating engine cogeneration plants as discussed above. The engine requires frequent oil changes and minor overhauls. Most engines require a major overhaul about every 5 years. These costs must be factored in during the selection and costing process. Based on 200 m$^3$/hr of biogas production with a conservative heat content equivalent to 40% methane the engine generator set would produce 300 kW of electric power. The capital cost shown does not include the
synchronizing switch gear that may be required if the generator was to be tied into the electric grid to enable electricity sales to the transmission system.

Maintenance costs are a significant portion of the total cost of ownership of a reciprocating engine generator set. Table 5 shows an example breakdown of lifecycle costs for a reciprocating engine generator set and the impact of 200 ppm H$_2$S in the feed gas on the relative proportion of maintenance and fuel cost. Some of the cogeneration options under development promise lower maintenance costs. Industrial turbines and microturbines potentially have low maintenance costs but their conversion efficiency to electricity is not as high as reciprocating engines. Stirling cycle engines have totally enclosed moving parts that do not come into contact with combustion gases and also no need for oil changes. Although not yet commercially available, Stirling engines should have minimal maintenance costs.

### 3.1.5 Fuel cell

Compared to combustion engines, the fuel cell converts the chemical energy of hydrogen and oxygen directly to current and heat. Water is formed as the reaction product. In principle, a fuel cell works with a liquid or solid electrolyte held between two porous electrodes—anode and cathode (Figure 5.9). The electrolyte lets pass only ions and no free electrons from the anode to the cathode side. The electrolyte is thus electrically non-conductive. It separates the reaction partners and thereby prevents direct chemical reaction. With some fuel cells, the electrolyte is also permeable to oxygen molecules. In this case the reaction occurs on the anode side.

The electrodes are connected by an electrical wire. Both reaction partners are continuously fed to the two electrodes. The molecules of the reactants are converted into ions by the catalytic effect of the electrodes. The ions pass through the electrolyte, while the electrons flow through the electric circuit from the anode to the cathode. Taking into account all losses, the voltage per single cell is 0.6 – 0.9 V. The desired voltage can be reached by single cells arranged in series, so-called stack. In a stack, the voltages of the single cells are added.
Depending on the type of fuel cell, the biogas has to be purified, especially by removing CO and H\textsubscript{2}S, before feeding the fuel cell. Only a small number of fuel cell plants, mostly pilot plants, are in operation for the generation of electricity from biogas.

Fuel cells are devices that directly convert chemical energy to electricity at high efficiency. There are several types of fuel cells with different operating conditions, fuel requirements and efficiencies. Fuel cell technology is developing rapidly due to their potential for simplicity and high efficiency of conversion to electricity. The leading fuel cell technologies are proton exchange membranes (PEM) and solid oxide electrolytes.

Fuel cells are likely 5 to 10 years to commercial production. For use in a fuel cell, sewage gas will require extensive cleaning to remove corrosive compounds such as hydrogen sulfide.

### 3.1.6 Stirling engines

A Stirling engine is a closed system that converts thermal energy into mechanical energy by cyclic compression and expansion of the working fluid. The work energy can subsequently be converted into electricity using a generator. A Stirling engine can use several sources of heat, which makes it theoretically ideal for electricity generation from waste heat sources. Test engines have been run on solar heat, heat from gas, oil or biomass flames and waste heat from existing operations. As the Stirling engine uses an external combustor and all moving parts are sealed from the combustion products, unlike internal combustion engines and turbines there is no need for high quality fuel. By design, Stirling engines are quiet and should require little maintenance, which makes them attractive for remote sites or for domestic use.

Stirling engines are a technology within 1 to 5 years of commercial production, assuming they can be demonstrated to have acceptable reliability and energy conversion efficiency for their target markets. Stirling engines have several potential applications in cogeneration, conversion of waste heat to electricity and remote power generation. Beta test units are available at sizes up to 25 kW. To be effective, Stirling engines should be used in a cogeneration mode as efficiencies of
conversion from heat energy to electricity are only 15 to 25%. When used in a cogeneration system, overall energy use will be 80 to 85%.

Stirling engines would be suitable for biogas applications as they do not have a requirement for pressurized fuel gas supply and should also be tolerant to moisture and corrosive gases such as hydrogen sulfide in the fuel gas. Figure 6 is a cutaway drawing of a Stirling engine showing the burner and high temperature side of the Stirling engine.

![Figure 3: Stirling engine](image)

### 3.2 Power systems for the generation of heat and power

Biogas can be used either for the production of heat only or for the generation of electric power.

When current is obtained, normally heat is produced in parallel. Two power systems exist in making sure that both power and heat are utilized:

- Combined Heat and Power system
- Combined Cycle (Gas and Steam)
In both systems, therefore, it is important to have a mechanism for heat recovery. This is achieved through a heat recovery steam generator (HRSG)

3.2.1 Heat Recovery Steam Generator (HRSG)

In the design of an HRSG, the first step normally is to perform a theoretical heat balance which will give us the relationship between the tube side and shell side process. We must decide the tube side components which will make up our HRSG unit, but only it considers the three primary coil types that may be present, Evaporator, Superheater and Economizer.

**Evaporator Section:** The most important component would, of course, be the Evaporator Section. So an evaporator section may consist of one or more coils. In these coils, the effluent (water), passing through the tubes is heated to the saturation point for the pressure it is flowing.

**Super heater Section:** The Super heater Section of the HRSG is used to dry the saturated vapour being separated in the steam drum. In some units it may only be heated to little above the saturation point where in other units it may be superheated to a significant temperature for additional energy storage. The Super heater Section is normally located in the hotter gas stream, in front of the evaporator.

**Economizer Section:** The Economizer Section, sometimes called a preheater or preheat coil, is used to preheat the feedwater being introduced to the system to replace the steam (vapour) being removed from the system via the super heater or steam outlet and the water loss through blowdown. It is normally located in the colder gas downstream of the evaporator. Since the evaporator inlet and outlet temperatures are both close to the saturation temperature for the system pressure, the amount of heat that may be removed from the flue gas is limited due to the approach to the evaporator, whereas the economizer inlet temperature is low, allowing the flue gas temperature to be taken lower.
3.3 Combined Heat and Power system (CHP)

The principle behind combined heat and power (CHP) is to recover the waste heat generated by the combustion of a fuel in an electricity generation system. This heat is often rejected to the environment, thereby wasting a significant portion of the energy available in the fuel that can otherwise be used for space heating and cooling, water heating, and industrial process heat and cooling loads in the vicinity of the plant. This cogeneration of electricity and heat greatly increases the overall efficiency of the system, anywhere from 25 - 55% to 60 - 90%, depending on the equipment used and the application.

Combined heat and power generation plants (CHP) and are normally furnished with a four-stroke engine or a Diesel engine. A Stirling engine or gas turbine, a micro gas turbine, high- and low- temperature fuel cells, or a combination of a high- temperature fuel cell with a gas turbine are alternatives. Biogas can also be used by burning it and producing steam by which an engine is driven, e.g., in the Organic Rankine Cycle (ORC), the Cheng Cycle, the steam turbine, the steam piston engine, or the steam screw engine.

CHPs are very common in biogas plants. In parallel to the generation of current, a more or less high percentage of heat is developed in CHPs, depending on the power generator technology.

Approximately 50% of the CHPs installed in biogas plants in Europe run with four-stroke engines and about 50% with ignition oil Diesel engines. More modern technologies like fuel cells or micro gas turbines are very seldom to be found. A CHP plant based on a gas turbine is shown in Figure

The total efficiency, i.e. the sum of the electrical and thermal efficiencies, is within the range 85 ÷ 90% with modern CHPs. Only 10 ÷ 15% of the energy of the biogas is wasted. But the electrical efficiency (maximum 40%) is still very low: from 1 m 3 biogas only 2.4 KWh electric current can be produced.
The equipment of a complete CHP includes

- a generator set consisting of drive unit and generator
- a waste gas system
- a ventilator for the supply of the combustion air on the one hand and on the other hand for the removal of the radiant heat of the engines, generators, and pipework
- a sound-damping hood
- an automatic lubricant supply.

Combined heat and power systems can be implemented at nearly any scale, as long as a suitable thermal load is present. For example, large scale CHP for community energy systems and large industrial complexes can use gas turbines, steam turbines, and reciprocating engines with electrical generating capacities of up to 500 MW. Independent energy supplies, such as for
hospitals, universities, or small communities, may have capacities in the range of 10 MW. Small-scale CHP systems typically use reciprocating engines to provide heat for single buildings with smaller loads. CHP energy systems with electrical capacities of less than 1 kW are also commercially available for remote off-grid operation, such as on sailboats. When there is a substantial cooling load in the vicinity of the power plant, it can also make sense to integrate a cooling system into the CHP project. Cooling loads may include industrial process cooling, such as in food processing, or space cooling and dehumidification for buildings.

A CHP installation comprises four subsystems: the power plant, the heat recovery and distribution system, an optional system for satisfying heating and/or cooling loads and a control system. A wide range of equipment can be used in the power plant, with the sole restriction being that the power equipment rejects heat at a temperature high enough to be useful for the thermal loads at hand. In a CHP system, heat may be recovered and distributed as steam (often required in thermal loads that need high temperature heat, such as industrial processes) or as hot water (conveyed from the plant to low temperature thermal loads in pipes for domestic hot water, or for space heating).

3.4 Combined Cycle system

The exhaust from a stationary gas turbine can be recovered to generate heat or steam for power generation in a steam turbine. In the combined cycle arrangement the heat is converted to steam in a heat recovery steam generator. This steam is then typically used to produce power. A schematic diagram of a typical combined cycle power system is shown in Figure The basic principle of the Combined Cycle is simple: burning gas in a gas turbine (GT) produces not only power - which can be converted to electric power by a coupled generator but also fairly hot exhaust gases. Routing these gases through a water-cooled heat exchanger produces steam, which can be turned into electric power with a coupled steam turbine and generator.

This set-up of Gas Turbine, waste-heat boiler, steam turbine and generators is called a combined cycle. This type of power plant is being installed in increasing numbers round the world where there is access to substantial quantities of natural gas. This type of power plant produces high
power outputs at high efficiencies and with low emissions. It is also possible to use the steam from the boiler for heating purposes so such power plants can operate to deliver electricity alone.

Figure 5: Combined cycle system

Efficiencies are very wide ranging depending on the lay-out and size of the installation and vary from about 40-56% for large new natural gas- fired stations. Developments needed for this type of energy conversion is only for the gas turbine. Both waste heat boilers and steam turbines are in common use and well-developed, without specific needs for further improvement.
3.5 Biogas from sewage wastewater for power generation

Wastewater Treatment plants (WWTPs) provide a ready source of biodegradable substrates in form of human excrement and industrial wastes. The use of sludge from wastewater treatment operations to generate energy is common throughout the Europe, the United States of America and The Asia but is unheard of in Africa. Subjecting sludge to anaerobic bacteria in a closed vessel (digester) produces biogas consisting of approximately 60% methane and 40% carbon dioxide. Biogas from wastewater treatment plants (WWTPs) has been successfully used to provide both heat and electricity.

3.5.1 Technical Challenges of Producing and Using Biogas

Successfully capturing and using biogas as a fuel source from wastewater sludge has been described as an art as much as a science. Maintaining the bacteria population in the digesters that is needed to breakdown wastewater solids is challenging due to the sensitivity of the bacteria to a number of factors, especially temperature and alkalinity. Variability in the type of sludge, amount of sludge, moisture content, temperature, and other factors can cause a massive die-off of the bacteria and subsequent cessation of methane production. In such cases, the resulting gas emissions will frequently consist of carbon dioxide and odorous hydrogen sulphide. Operator skill and detailed knowledge of the plant are critical factors in successful operations.

3.5.2 Biogas yield and power output

Electricity generation using biogas from anaerobic digestion varies depending on the generation technology employed. Research shows that anaerobic digestion with biogas utilization can produce about 350 kWh of electricity for each million gallons of wastewater treated at the plant. It is also estimated that approximately 491 kWh of electricity can be produced with a microturbine and 525 kWh of electricity can be produced with an internal combustion engine for each million gallons of wastewater treated at a plant with anaerobic digestion. Findings also show that wastewater treatment plants with treatment capacities less than 5 million gallons per day (MGD) or 18,900 m³ per day do not produce enough biogas to make electricity generation feasible or cost-effective.
The following Engineering Rules of Thumb are to be used for Considering CHP at a WWTP:

- A typical WWTP processes 100 gallons per day of wastewater for every person served.

- Approximately 1.0 cubic foot (ft$^3$) of digester gas can be produced by an anaerobic digester per person per day. This volume of gas can provide approximately 6-7 Watts of power generation.

- For each 4.5 MGD processed by a WWTP with anaerobic digestion, the generated biogas can produce approximately 100 kilowatts (kW) of electricity.

### 3.6 Sewage sludge fermentation

Sewage sludge fermentation is also known as digestion. It occurs in the so-called digestion towers. Their volume (size) depends on the number of residents of the cities where the sewage comes from. For settlements from 10,000 to 15,000 residents, there are sewage water treatment plants with single-stage digestion where the substrate is mixed a few times per day. The plants run at mesophilic temperature.

For cities with a larger number of residents (between 100,000 to 1,000,000), two-stage plants are preferred. For instance, at a level of 100,000 residents, often two sewage sludge digestion towers, each of volume 2250 m$^3$ (diameter 15 m), are built. The plant is run with different temperatures in the two towers.

#### 3.6.1 Equipment

In sewage sludge digestion towers, attachments for phase separation and for avoiding post-gassing are necessary in addition to the digestion tower itself with its devices for mixing and heating of the sludge. The most important ones are described below.
**Digestion tower:** The digestion tower should be built in such a way that the following aims are achieved:

- Thin walls for cost reasons
- Small surface to save on insulation
- Easy outgassing of biogas from the substrate
- Intensive mixing for a regular distribution of nutrients and metabolism products
- Avoiding the development of layers, especially of a scum
- Avoiding uncontrolled accumulations.

A degradation dump—a so-called sludge-bed reactor—is found in the smallest plants. For plants with a volume up to 2500 m$^3$, digestion towers of classical continental form have achieved acceptance. That means that the vessels have a cone-shaped bottom, a cylindrical mid part and a frustum as ceiling. The digestion towers are mostly made of steel sheets and do not require corrosion protection where they are in contact with liquids because of the anaerobic degradation process. Only the gas space is painted with a corrosion protection layer. The outside is heat insulated and covered with a weather protection layer.

Larger plants with a digestion tower volume of 2000 to 15000 m$^3$ show a parabolic or similar shape, also called a digestion egg. These often consist of reinforced concrete, which is air- and gas-tight and has good heat insulation and corrosion resistance. Approximately 1/10 to 1/3 of the digestion tower height is located below ground. The heat insulation above the ground, with a $k$-value of 0.25 to 0.35 W/m$^2$.K, is achieved with mineral wool and foamed plates. Below the ground, no insulation is usually applied. The insulation is encased with aluminium sheet strips on the outside. A gap is located between the aluminium sheets and the insulation material in order to avoid it becoming wet and to allow it to dry out.

For construction, the digestion towers are striked. The conical framework made of steel and pressure rings is mounted on, e.g., movable stairs, from inside the tower. Modern degradation towers are erected with a "climbing" framework. In this case, no framework scaffolding is constructed, but the framework is put on the already completed tower wall and practically climbs up along it.
Nevertheless, there are also many large digestion towers of the classical form, which are made from steel sheets. This construction method possesses the following advantages:

• The base is more stable, which is advantageous especially for unstable ground.
• If the digester with the bottom conical area is put into the ground, it is supported by a vertical frame. Between the concrete base, the vertical frame, and the container bottom, an accessible space is left where fittings and tubing for heating, sludge inlet and outlet, and sludge mixing devices can be accommodated.
• Comparatively low weight of the base.
• The assembly is hardly affected by weather conditions.
• Shorter building time.
• Additional cost savings are possible by pre-assembly and manual welding of the segment sheets.

At least the following devices have to be mounted onto the gas cover of the digestion tower.

- Gas withdrawal dome with manometer and vacuum meter
- Over- and underpressure safeguard with in-line water trap
- Sight glass with inside and outside wipers and protective cover
- Swiveling spraying nozzles with ordinary water connection (hose coupler)
- Scum removal
- Manhole
- Explosion prevention
- Gas filter
- Foam trap
- Condensate trap

The scum removal can be constructed either as a rectangular scum gate or a cylindrical scum slider. The allowed minimal opening amounts to 400 × 400 mm for doors and 400 mm for the slider diameter. The closure must to be opened quickly, e.g., through a lever mechanism. The
Figure 6: Digestion towers. Bioreactors for the degradation of sewage sludge.
drain must be opened to such an extent that the bulky floating part of the sludge can be removed easily. For the internal supervision of the digestion tower, a manhole is required. The minimal diameter of the opening has to be 600 mm. The closing cover must be fitted so that it can be swivelled.

The degradation proceeds asymptotically, and is thus stopped at the technical degradation limit. This limit is reached when 90% of the degradation gas quantity developed at 15 °C is generated. At this point, approximately half of the organic substance fed into the process is degraded.

The digestion tower's volume depends on the sewage sludge quantity, the solids concentration in the sludge, and the residence time. Per resident (IN) and per day, 80 g DM accumulates. The digestion tower volume depends on how much the biomass can be concentrated before digestion and on the residence time.

Depending on process engineering and machines, the following residence times are normally chosen:

- Fermentation time of 120 days if using unheated bioreactors like ground basins.
- Fermentation time of 60 days if using simple digesters like Imhoff tank.
- Fermentation time of 30 days if applying mesophilic fermentation.
- Fermentation time of 10 days if applying thermophilic degradation. Thermophilic fermentation is used rather rarely, even though the sewage gas yield can be increased by 25%, and the sludge's sanitization and stabilization can be improved if the fermentation lasts longer than 10 days.

For rain water, an additional 25% of the calculated digestion tower volume is necessary. Trash and inhibiting substances can partially lead to a massive dysfunction of a digestion tower and require significantly longer residence times.

Because of seasonally changing climatic conditions, the fermentation temperature can, for instance, vary between 33 °C and 38 °C in the mesophilic range, leading to considerable variations in the course of the fermentation process and sewage gas development.

In general, the degree of degradation increases with the residence time, and the volume load decreases accordingly.

In modern plants, the sludge is circulated continuously in order to keep an optimal temperature distribution, to destroy the scum, and to avoid a harmful concentration of decomposition.
products and a sedimentation of the biomass. Then, a residence time of 18 ÷ 22 days can be enough.

3.5.3 Types of Electric Generators
The three main technologies used to produce electricity from biogas are microturbines, fuel cells, and internal combustion engines. The appropriate technology is largely determined by the size of the wastewater treatment plant.

Microturbine technology is usually more appropriate for WWTPs treating small volumes of flow less than 6.8 million gallons per day (MGD). Minimum flow required for fuel cells and internal combustion technologies are 10.7 MGD and 41.4 MGD respectively. In 2007 The United States of America’s Environmental Protection Agency (EPA) estimated the typical costs of installing a CHP system using a 126 kW microturbine was $564,953, with a cost per kW of $4,484. Installing a CHP system using 300 kW fuel cells costs approximately $2,227,890 (approximately $7,426 per kW). A CHP system using a 1060 kW internal combustion engine costs approximately $2,161,425 with a cost per kW of $2,039. These cost estimates do not include the expense of purchasing, installing, and operating the sludge digesters.

3.5.4 Obstacles to increasing production and use of biogas
Equipping WWTPs with anaerobic digesters to produce biogas may not be feasible in some cases, as the feasibility of such is dependent on the availability of space, the waste water flow, chemical composition of the methane gas, methane production rate, and other considerations. Until recently, the flow levels considered conducive for anaerobic digesters and the use of combined heat and power systems was greater than 5 million gallons a day (MGD), although facilities with flows greater than 10 MGD had greater potential.

The equipment and installation cost associated with pretreating raw biogas for use in turbines is expensive, and may be a major obstacle inhibiting the use of biogas at some WWTP facilities. Pretreatment is needed to remove moisture, hydrogen and siloxanes prior to being as a fuel.
3.5.5 Benefits of increasing production and use of biogas

In addition to the cost savings associated with the transport and disposal of wastewater sludge, energy from biogas (as oppose to electricity from the grid), can provide heat and power for use in the general operation of a WWTP.

The environmental benefits of using biogas are also significant. Anaerobically treating wastewater sludge can significantly reduce the amount of methane (a powerful greenhouse gas) and other greenhouse gases that would otherwise be released to the atmosphere.

Anaerobic digestion also decreases the smell - forming components, organic sludge solids and disease causing pathogens in the sludge.

Being a renewable energy source with great gains in reducing GHG emissions, biogas energy projects can obtain carbon credits which can be bought by industrial polluters through carbon trading. This provides innovative financing for the projects.

Reduces reliance on wastewater lagoons and ponds

The protection of the groundwater: the quantity of organic waste materials can be reduced down to 4% sludge when the residue is squeezed off and the waste water from the biogas plant is recycled into the waste water treatment plant.

The sludge produced after anaerobic digestion is free of disease causing pathogens and once dewatered can be used as high quality organic fertilizer
CHAPTER 4: RESULTS AND ANALYSIS

4.1 Results

From the data received from the Dandora Sewage Treatment plant, the average inflow of the waste water was found to be 91565 m$^3$ per day during the year 2010.

The average inflow in million gallons per day is as follows;

1 gallon = 3.78 litres

1 m$^3$ = 1000 litres

We have that:

91,565 m$^3$ = 91,565,000 litres = 24,223,544 gallons

The plant uses about 79.68 KWh per day of electricity for the day to day operations

4.2 Analysis

The plant treats over 24MGD of wastewater per on average day thus will be able to produce enough biogas to generate a considerable amount of electricity. The least amount of inflow for a WWTP to be considered for electricity generation from biogas is 5 MGD.

Using the relation that on average a WWTP treats 100 gallons of wastewater per day per person which produces 0.028 m$^3$ of biogas, we have that:

If 100 gallons = 0.028 m$^3$ of biogas

24,223,544 gallons = 6782.59 m$^3$ of biogas
Therefore we will have an average of 6782.59 m$^3$ of biogas produced everyday. The energy value of biogas is given as 6.0- 6.5 KWh/m$^3$. The energy that can be produced from the biogas produced calculated from this value will be:

$$6782.59 \times 6.25 = 42391.2 \text{ KWh}$$

The power output will thus be:

$$42391.2/24 = 1.76 \text{ MW}$$

### 4.3 Further analysis using RET Screen Clean Energy Project Analysis Software

The RET Screen Analysis software is a product of The Ministry of Natural Resources-Canada used in the analysis of renewable energy projects. It provides an overview of the use of climate and renewable energy resource data, the greenhouse gas emission reduction calculation, the financial analysis.

For generation of power in order to maximize all the energy within the biogas, I proposed the use of a combined cycle system that uses a gas turbine and a steam turbine. This will make sure that energy from the hot exhaust gases of the gas turbine are utilized in the steam turbine. Table 4.1 shows the emission analysis detailing the amounts of GHG emissions reduced. Table 4.2 shows the analysis of the combined cycle power system. The Financial viability of the project is as shown in Table 4.3.
### Table 4.1: GHG emission reduction analysis

<table>
<thead>
<tr>
<th>Base case electricity system (Baseline)</th>
<th>Fuel type</th>
<th>GHG emission factor (excl. T&amp;D) tCO2/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country – region</td>
<td>All types</td>
<td>0.313</td>
</tr>
<tr>
<td>Kenya</td>
<td>All types</td>
<td>0.313</td>
</tr>
<tr>
<td>Electricity exported to grid</td>
<td>MWh</td>
<td>14,389</td>
</tr>
<tr>
<td>Base case</td>
<td>tCO2</td>
<td>4,734.8</td>
</tr>
<tr>
<td>Proposed case</td>
<td>tCO2</td>
<td>424.0</td>
</tr>
<tr>
<td>Gross annual GHG emission reduction</td>
<td>tCO2</td>
<td>4,310.8</td>
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<tr>
<td>Net annual GHG emission reduction</td>
<td>tCO2</td>
<td>4,310.8</td>
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</table>
**Table 4.2: Power system Analysis**

<table>
<thead>
<tr>
<th>Proposed case power system</th>
<th>Gas turbine - combined cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>%</td>
</tr>
<tr>
<td>Fuel selection method</td>
<td></td>
</tr>
<tr>
<td>Fuel type</td>
<td>Sewage gas</td>
</tr>
<tr>
<td>Fuel rate</td>
<td>$/t</td>
</tr>
</tbody>
</table>

**Gas turbine - combined cycle**

| Power capacity (GT)       | kW                          | 1,100                         |

**Manufacturer**

<table>
<thead>
<tr>
<th>Model</th>
<th>Yanmar Diesel Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat rate</td>
<td>kJ/kWh</td>
</tr>
<tr>
<td>Heat recovery efficiency</td>
<td>%</td>
</tr>
<tr>
<td>Fuel required</td>
<td>GJ/h</td>
</tr>
<tr>
<td>Heating capacity</td>
<td>kW</td>
</tr>
</tbody>
</table>

**Duct firing**

| No                        | |

**Steam turbine**

| Operating pressure        | kPa                         | 14,500                        |
| Saturation temperature   | °C                          | 339                           |
| Superheated temperature  | °C                          | 540                           |
| Steam flow               | kg/h                        | 1,987                         |
| Enthalpy                 | kJ/kg                       | 3,429                         |
| Entropy                  | kJ/kg/K                     | 6.51                          |
| Extraction port          | No                          |                               |
| Back pressure            | kPa                         | 6.0                           |
| Temperature              | °C                          | 36                            |
| Mixture quality          |                             | 0.77                          |
| Enthalpy                 | kJ/kg                       | 2,004                         |
| Theoretical steam rate (TSR) | kg/kWh                     | 2.53                          |
| Steam turbine (ST) efficiency | %                         | 80.0%                         |
| Actual steam rate (ASR)  | kg/kWh                      | 3.16                          |

**Summary**

| Power capacity (ST)       | kW                          | 629                           |
| Total power capacity (GTCC) | kW                      | 1,729                         |
### Table 4.3: Power Project Financial Analysis

<table>
<thead>
<tr>
<th>Financial Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Financial parameters</strong></td>
</tr>
<tr>
<td>Inflation rate %</td>
</tr>
<tr>
<td>Project life yr</td>
</tr>
<tr>
<td>Debt ratio %</td>
</tr>
<tr>
<td>Debt interest rate %</td>
</tr>
<tr>
<td>Debt term yr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Initial costs</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power system $</td>
</tr>
<tr>
<td>Other $</td>
</tr>
<tr>
<td>Total initial costs $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Incentives and grants</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Annual costs and debt payments</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>O&amp;M (savings) costs $</td>
</tr>
<tr>
<td>Fuel cost - proposed case $</td>
</tr>
<tr>
<td>Debt payments - 20 yrs $</td>
</tr>
<tr>
<td>Total annual costs $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Annual savings and income</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel cost - base case $</td>
</tr>
<tr>
<td>Electricity export income $</td>
</tr>
<tr>
<td>Total annual savings and income $</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Financial viability</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-tax IRR - equity %</td>
</tr>
<tr>
<td>Pre-tax IRR - assets %</td>
</tr>
<tr>
<td>Simple payback yr</td>
</tr>
<tr>
<td>Equity payback yr</td>
</tr>
</tbody>
</table>

| 2.0% | 20 |
| 70%  | 20 |
| 7.00%| 20 |
| 5,074,852 | 0 |
| 392,877 | 863,346 |
| 35.1% | 10.2% |
| 6.3 | 3.0 |
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The properties of biogas and the mode of preparation were explained in great detail. The various uses of biogas were also explored to some extent giving the reader an idea of the positive effects biogas can have on our energy sector if properly exploited. The nature of methane which is the most important component of biogas was discussed especially its role as a major Green House Gas (GHG).

The various technologies that can be employed in the generation of electricity using biogas were brought out in great detail together with the most recent and least used but show great potential such as fuel cells and Stirling Engines. During the generation of power, the heat generated is usually lost to the environment but the report showed that it can be utilized further. This is discussed greatly under Combined Heat and Power and Combine Cycle systems.

After visits to the Dandora Sewage Treatment Plant, the data collected was used to analyze the possibility of a power plant using biogas from sewage sludge being constructed at the site. The results were very encouraging and the analysis showed that the power plant construction was indeed viable.

The objectives of the project were satisfactorily met and the material can be used for reference in a study of similar biogas power plants.

5.2 Recommendations

I recommend greater government focus on biogas as a viable renewable energy source that can provide the much needed energy but also help the country cut down on GHG emissions. A comprehensive policy detailing incentives, tariffs on electricity form biogas and facilitation of carbon trading will help the country realize huge gains in the energy sector and also provide innovative financing of the power projects.

The Dandora Sewage Plant has a power capacity that will enable them meet the energy demands of the plant and still leave more to be sold to the national grid. This will save them a lot of money in electricity costs and generate income from the sale of the power.
APPENDIX

APPENDIX A: SEWAGE SLUDGE TREATMENT PROCESS

SEWER SOURCE

(DOMESTIC & INDUSTRIAL WASTE)

RAW SEWAGE

PHYSICAL TREATMENT

SCREENING

GRIT REMOVAL

ANAEROBIC PONDS

(5-10 DAYS)

BOD REMOVAL

FACULTATIVE PONDS

(35 DAYS)

MATURATION PONDS

(3 PONDS EACH 5 DAYS)

PATHOGENIC ORGANISMS REMOVAL

NAIROBI RIVER
APPENDIX B: DANDORA SEWAGE TREATMENT WORKS PONDS LAYOUT
REFERENCES

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C Trade Philippines, USAID