ANALYSIS ON THE PERFORMANCES OF A MICRO GAS TURBINE CO-GENERATION SYSTEM IN SEWAGE TREATMENT PLANTS

MUHAMMAD ZAID BIN NOR AZLAN

A report submitted in partial fulfillment of
The requirements for the award of the degree of
Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI MALAYSIA PAHANG

JUNE 2013

UNIVERSITI MALAYSIA PAHANG

FACULTY OF MECHANICAL ENGINEERING

I certify that the project entitled "*analysis on the performances of a micro gas turbine co-generation system in sewage treatment plants*" is written by *Muhammad Zaid bin Nor Azlan*. I have examined the final copy of this report and in my opinion, it is fully adequate in terms of language standard, and report formatting requirement for the award of the degree of Bachelor of Mechanical Engineering With Automotive. I herewith recommend that it be accepted in partial fulfilments of the requirements for the degree of Bachelor of Mechanical Engineering.

Signature : ....
Name : Dr. ABDUL ADAM ABDULLAH
Position : LECTURER OF FACULTY OF MECHANICAL ENGINEERING
Date : 24th JUNE 2013

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this report is adequate in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :

Name : Dr. MOHAMAD FIRDAUS BASRAWI

Position : LECTURER OF FACULTY OF MECHANICAL ENGINEERING

Date : 24th JUNE 2013

STUDENT'S DECLARATION

I hereby declare that the work in this thesis is my own expect for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of the degree.

Signature : ………………………….

Name : MUHAMMAD ZAID BIN NOR AZLAN

ID Number : MH09062

Date : 24th JUNE 2013

To my beloved

Parent, siblings and friends

ACKNOWLEDGEMENT

I am grateful and would like to express my sincere gratitude to my supervisor Dr Mohamad Firdaus bin Basrawi for his germinal idea, invaluable guidance, continuous encouragement and constant support in making this thesis. This Thesis could not been done without him who not only served as my supervisor but also encourage me throughout the process. I also would like to express very special thanks to the panel member who give valuable comment and suggestion during my final year project presentation 1 and 2.

My sincere thanks go to all laboratory assistant from Faculty of Mechanical University Malaysia Pahang for their teaching and help during the period of my project.

I acknowledge my sincere indebtedness and gratitude to my parents, Encik Nor Azlan bin Zainuddin and Normah binti Abdul Hamid for their love and sacrifice throughout my life. They have always supported my dreams. They did a fine job raising me. Last but not least, for all my friends, who’s supporting and encouraging me to pursue this degree.

ABSTRACT

The main role of this study is to analyse the economics performances of micro gas turbine co-generation systems (MGT-CGSs) in order to define the most interesting solutions from economic point of view. The study consist two type of economic analysis, simple and advanced economic analysis. The simple economic analysis is analysis based on the present and previous data collected that no estimation needed. The advanced economic analysis is the analysis that need to consider the estimation for the future value or parameter. The advanced economic analysis give better over view of the economic analysis of the system. Considering operation of the MGT-CGS under various loads and efficiency of the MGT-CGSs under partial road condition, the optimal combination of MGT-CGS (MGT-combination) with different sizes, 30 kW, 65 kW and 200 kW. Economic performance of MGT-CGSs under three typical ambient temperature conditions and three different scale sewage treatment plant was also investigated. It was found that MGT combination has the highest total capital cost for every scale and every temperature condition. Futhermore MGT combination has the highest total electricity sold. Excluding MGT combination total electricity sold higher when the MGT power output higher.

ABSTRAK

Peranan utama kajian ini adalah untuk menganalisis ekonomi persembahan sistem penjanaan turbin gas mikro (MGT-CGSS) untuk menentukan penyelesaian yang paling menarik dari sudut ekonomi. Kajian ini meliputi dua jenis analisis ekonomi, analisis ekonomi mudah dan maju. Analisis ekonomi yang mudah adalah analisis berdasarkan data semasa dan sebelumnya dipungut bahawa tiada anggaran yang diperlukan. Analisis ekonomi maju adalah analisis yang perlu untuk mempertimbangkan anggaran untuk nilai masa depan atau parameter. Analisis ekonomi maju memberi lebih baik ke atas memandangkan analisis ekonomi sistem. Memandangkan operasi MGT-PS di bawah pelbagai beban dan kecekapan MGT-CGSS di bawah keadaan jalan separa, gabungan optimum MGT-PS (MGT-gabungan) dengan saiz yang berbeza, 30 kW, 65 kW dan 200 kW. Prestasi ekonomi MGT-CGSS di bawah tiga keadaan suhu biasa persekitaran dan tiga skala loji rawatan kumbahan yang berbeza juga disiasat. Ia telah mendapati bahawa gabungan MGT mempunyai kos modal tertinggi jumlah bagi setiap skala dan setiap keadaan suhu. Gabungan MGT Tambahan pula mempunyai jumlah tenaga elektrik tertinggi dijual. Tidak termasuk MGT gabungan jumlah tenaga elektrik yang dijual lebih tinggi apabila kuasa keluaran MGT yang lebih tinggi.

.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF ABBREVIATIONS

MGT	Micro Gas Turbine
MGT-CGSs	Micro Gas Turbine Co-Generation System
O&M	Operation And Maintenance
NPV	Net present value
CHP	Combined heat and power
IGCC	Coal-gasification Combined-cycle
PFBC	Pressurized Fluidizied Bed Combustion
EHE	Exhaust Heat Exchanger
LCC	Life Cycle Costing

LIST OF SYMBOLS

C_{cap}	Capital cost
$C_{,o\&m}$	Operation and maintenance Cost
Pe	Total power generated
$pe_{,max}$	Total electric power capacity
$pe_{,sold}$	Total electricity sold

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

Interest has recently been shown in the utilization of biomass by a co-generation system (CGS) and its applications have been increasing. One of the concept system used of renewable energy if co-generation system that is combination of heat and power to produce useful energy for using. Co-generation, when associated with the gas turbine, is a relatively old technology which dates back to pre-World War II years. The concept of co-generation involves the generation of steam and electricity in one operation. The waste heat from the exhaust of the turbine is then recovered in the form of steam or hot water. In the "bottoming cycle" a gas turbine may be used as a combustor only (Y. H. Kiang, 1981). Co-generation, simply, is the generation of energy for one process from the excess energy supplied to another process (M. Hall, Co-generation. 1981). Co-generation, then, is nothing more than an economically sound method for the conservation of resources. Thus, the benefits from the use of co-generation may be cited as energy conservation, environmental improvement and financial attractiveness to investors. In the near future energy efficiency must no longer be a choice, but a commitment.

Biogas production technology such as anaerobic digestion has been available for many decades, but it has not been widely used because of the availability of cheap fossil fuel. Understanding and application of anaerobic treatment have made significant gains in the past 30 years.

One of the sources of energy is from biogas and from sewage and its only one facility that has been continuously producing biogas by anaerobic digestion is a sewage treatment plant. Anaerobic digestion is an important process for stabilizing and reducing municipal sewage sludge. Although some of the biogas produced by anaerobic digestion has been utilized as fuel to cover the heat demand of the plant, the large amount of remaining biogas has not been fully utilized. For biogas from a sewage treatment, amount of biogas produced in plants, is small especially in middle- and small-scale sewage treatment plants. The application of presently usable prime movers with an output of more than a few hundred kilowatts is difficult because of small scale and medium will produce only small amount of energy base on it efficiency.

Another recently developed of new and renewable sustainability energy is from micro-scale fuel cells, fuel cell micro-grid, reciprocating engines and gas turbines are prime movers that have output power less than this capacity. Fuel cells are one of the most promising technologies for the next generation of green hydrogen applications. They are suitable for many kinds of power plants, ranging from small auxiliary power units to distributed heat and power co-generation systems. Has been tested that fuel cells are one of the most promising technology, but they still have disadvantages and problems in lifetime and cost of production and maintaining (Staffell I, Green R, Kendall K, 2008).

One of largely used of co-generation system is used of micro gas turbine or gas turbine because gas turbine and micro gas turbine produce large amount of wasted heat while it combusted. MGTs are gas turbines that operate on the basis of the Brayton cycle. The biogas-fuelled Micro Gas Turbine Co-generation Gas System (MGTCGS) was mainly composed of the MGT, and an exhaust heat exchanger (EHE), and the MGT was a regenerative single shaft MGT. Atmospheric air enters the MGT passing through a generator, a compressor, a recuperator, a combustion chamber, a turbine and then the recuperator. MGT-CGSs have variant electrical power outputs some have the electrical power outputs of 30 kW (MGT30), 65 kW (MGT-65) and 200 kW (MGT-200). The application of Micro Gas Turbine-Co-generation system (MGT-CGS) is not largely used in on sewage system on middle- and small-scale sewage treatment plants for small office and small building.

1.1 PROJECT BACKGROUND

The main idea of this project is to expose student with many expect of engineering economics that exposure to the costing and estimating of this micro gas turbine-co-generation system project analysis. First and foremost in importance are the cost analysis, estimation, and management of the system of the micro gas turbine-co-generation system. The analysis consist of analysis about simple economic performance and also some advanced economic performances of micro gas turbine-co-generation system. The task follows a common product development activity, where student need to apply all their engineering knowledge and skill to complete this project. In, random student must know some basic knowledge which about the micro gas turbine-co-generation system, engineering economics analysis and estimation of current economic situation.

1.2 PROBLEM STATEMENT

There are different type of MGT with different electricity output capacity that give different power efficiency. The MGT price and cost also different based on it electricity output capacity. From the market , the MGT price is higher when the power output is lower. In this situation how to analyse economic performance of the most suitable MGT used (single or combination) by considering the cost and the efficiency of the MGT that operate under different ambient temperature in different scale of sewage treatment plant with various electricity output capacity of MGT. Based on the information collected the higher the size of electricity output capacity of MGT the higher the power can be generated. The MGT-CGSs will generate power based on the power demand needed and heat demand and power demand of the plant is affected by ambient temperature.When the power demand is high the MGT-CGSs will generated more power or more than one MGT-CGSs will operate to support the demand. The suitable size (electricity output capacity) of micro gas turbine co-generation systems (MGT-CGSs) depending on scale of the sewage treatment plant was. Considering operation of the MGT-CGS under various loads and efficiency of the MGT-CGS under a partial load condition, the optimal combination of MGT-CGSs (MGT-Combination) with different sizes, 30 kW, 65 kW and 200 kW, was also.

What is the result of economics performance of MGT-CGS with different power output when running at different ambient temperature in different scales sewage treatment plants.

1.3 OBJECTIVES

Objectives of this project are:

- To evaluate the economic performances of micro gas turbine-co-generation system (MGT-CGS) in sewage treatment plants
- To compare the economic performances of MGT-CGS base on various electrical power outputs and different ambient temperature condition.

1.4 SCOPES OF STUDY

The Scopes for this particular research are bounded by these four matters and therefore will be followed throughout the research which are:

- Analysis the operational system of micro gas turbine-co-generation system in sewage treatment plants.
- Analysis of the calculation about simple economic analysis (initial cost, operation & maintenance cost)
- Analysis of the calculation about advance economic analysis (life-cycle method, by using net present value)
- Analyze and compare the economics performance of micro gas turbine-co-generation system in sewage treatment base on different ambient temperature and micro gas turbine output power.

CHAPTER 2

LITERATURE REVIEW

2.0 INTRODUCTION

This chapter is discussed on some literature studies related to the co-generation system principle, micro gas turbine, micro gas turbine-co-generation system and related system that related to this topic. Apart from that, this chapter is organized in a systematic order so that the reader can understand this chapter easily. Other relevant studies that are related to the performance of this system also been discussed.

2.1 WASTEWATER TREATMENT BIOGAS

Wastewater treatment biogas is produced from the anaerobic digestion of domestic/industrial wastewater sludge. During the wastewater treatment process, solids from primary and secondary treatment are collected and further processed, via digestion, to stabilize and reduce the volume of the sludge. The digestion is performed either aerobically (in the presence of oxygen) or anaerobically (without oxygen) to produce biogas. Anaerobic digestion and wastewater treatment take place in a closed or covered tank to exclude air or oxygen from the waste. Anaerobic treatment has been historically used to biologically stabilize high-strength wastes at a low cost.

In many cases, the biogas has not been used as an energy resource but has been burned in a flare and discharged to the atmosphere. Biogas is also generated from other anaerobic wastewater treatment processes, including anaerobic lagoons and facultative lagoons. (Dr. N. Lymberopoulos, 2004).

Wastewater treatment biogas consists of approximately 55 to 65 percent methane, 30 percent CO2, and other inert gases such as nitrogen. This composition results in a heating value of approximately 550 to 650 Btu/scf.[40] Today, most wastewater treatment plants that employ anaerobic digestion collect and use their biogas on site.

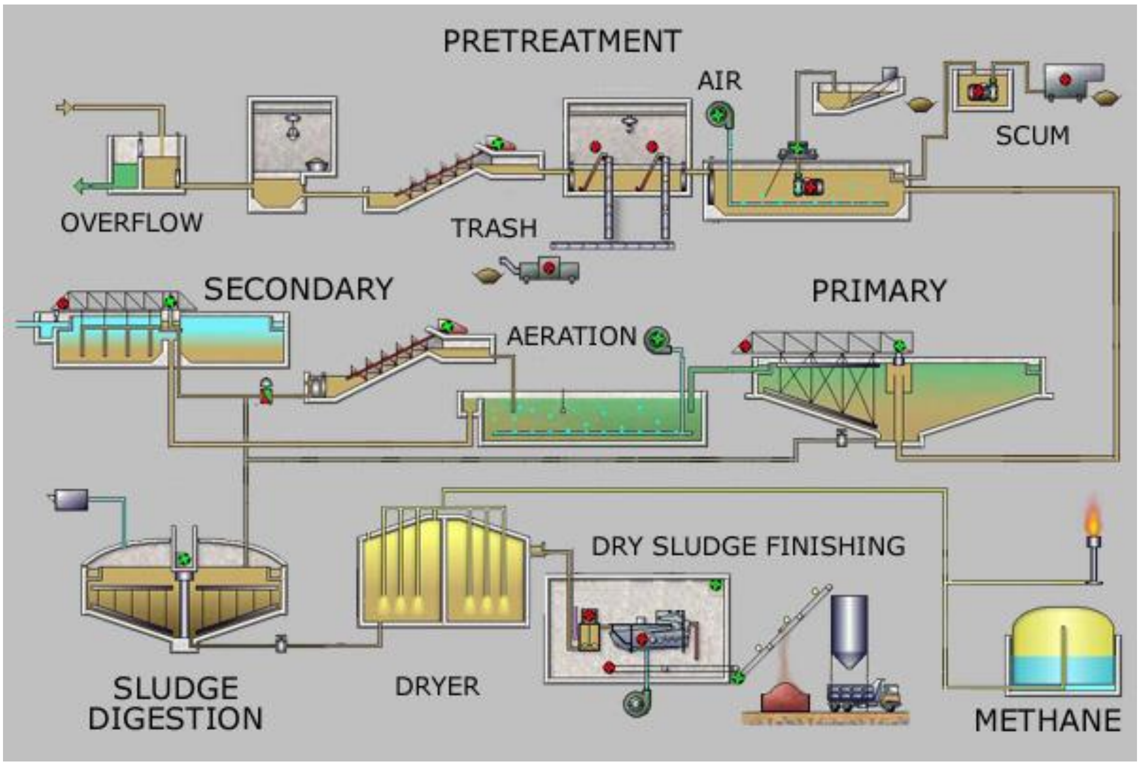

Figure 2.1: Biogas production from sewage treatment plants

There are four main types of biogas applications, production of heat and steam,electricity Generation co-generation, use as vehicle fuel, and possibly production of chemicals. These applications are governed by national frameworks like the tax system, subsidies, green energy certificates and increased feed-in tariffs for electricity, availability of heat or gas grids. Worldwide, biogas is mainly used in combined heat and power (CHP) applications, whereas various EU countries have embarked on programmes to achieve a growing share of biogas in the transport sector, especially attractive in view of the steady increase of the cost of fossil fuels. (I. BODÍK et al, 2010).

2.2 CO-GENERATION SYSYTEM

Co-generation is not a new concept, Co-generation when associated with the gas turbine, is a relatively old technology which dates back to pre-World War II years. The concept of co-generation involves the generation of steam and electricity in one operation. The "topping cycle" generates electricity when the turbine is directly coupled to a generator. The waste heat from the exhaust of the turbine is then recovered in the form of steam or hot water. In the "bottoming cycle" a gas turbine may be used as a combustor only. Industrial plants led to the concept of co-generation back in the1880s when steam was the primary source of energy in industry, and electricity was just surfacing as a product for both power and lighting (Orlando JA,1996).The use of co-generation became common practice as engineers replaced steam driven belt and pulley mechanisms with electric power and motors, moving from mechanical powered systems to electrically powered systems. During the early parts of the 20th century, most electricity generation was from coal fired boilers and steam turbine generators, with the exhaust steam used for industrial heating applications.

In the early 1900s, as much as 58% of the total power produced in the USA by on-site industrial power plants was estimated to be cogenerated (Frangopoulos CA, 2001) .with the exhaust t heat also he exhaust from the turbine may be fed to a steam generator (HRSG), and the resulting steam may be used as process steam or in a steam Rankine cycle. A secondary cycle with an organic fluid may be used at the condenser end to drive a turbine for generating byproduct electricity. During the decade of the 1960s, industrial users recognized the gas turbine as a reliable prime mover for base load process applications. Accordingly, gas turbine co-generation systems were installed in various industries. More recently, worldwide concern about the cost and efficient use of energy is providing continuing opportunities for gas turbine co-generation systems (Y. S. H. Najjar, 1987). In principle, the simplest modification to be introduced to the simple gas turbine engine cycle was to recover part of the exhaust energy in the heat exchanger of a recuperative cycle (Y. S. H. Najjar, 1987). Exhaust energy can be recovered more efficiently, however, in a hot water or heat recovery steam generator (HRSG).

Such a co-generation system may have a power-to-heat ratio of 4 to 5 times that of steam turbines, in addition to the greater potential for generating power in excess of on-site needs (R. H. Williams,1978). The steam may be used in heating, cooling and many other industrial processes.

There is a growing potential in the use of micro-co-generation systems in the residential sector because they have the ability to produce both useful thermal energy and electricity from a single source of fuel such as oil or natural gas with a high efficiency. In co-generation systems, the efficiency of energy conversion increases to over 80% as compared to an average of 30–35% in conventional fossil fuel fired electricity generation systems. Fig. 1 illustrates how the internal energy from the fuel is converted into useful thermal energy and electrical energy for a conventional fossil fuel fired electricity generation and a co-generation system (European Commission, Directorate General for Energy ,1999) .

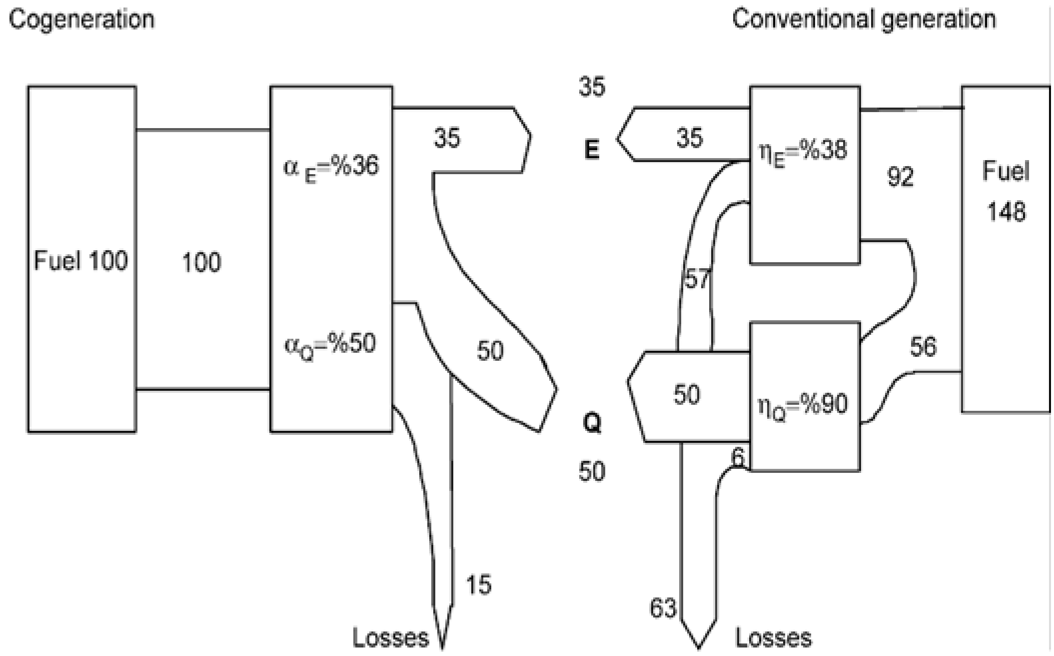

Figure 2.2: Co-generation versus conventional generation

(Source: journal of combined and heat (CHP))

Figure 2.1 Co-generation versus conventional generation, where α_E, part of the energy transformed into electricity in a co-generation unit, α_Q, part of the energy transformed into usable in a co-generation unit, η_E, electrical yield of an electrical power plant (production of electricity only), η_E, yield of a boiler (production of heat only), E, electricity demand, Q, heat demand.

The increase in energy efficiency with co-generation can result in lower costs and reduction in greenhouse gas emissions when compared to the conventional methods of generating heat and electricity separately. The concept of co-generation can be related to power plants of various sizes ranging from small scale for residential buildings to large scale co-generation systems for industrial purposes to fully grid connected utility generating stations. Organizations that would benefit from co-generation are those that could use the electricity and heat energy produced by the system. Consequently, co-generation is suitable for building applications provided that there is a demand for the heat energy produced. Building applications suitable for co-generation include hospitals, institutional buildings, hotels, office buildings and single- and multi-family residential buildings.

In the case of single-family applications, the design of systems poses a significant technical challenge due to the non-coincidence of thermal and electrical loads, necessitating the need for electrical/thermal storage or connection in parallel to the electrical grid. However co-generation systems for multi-family, commercial or institutional applications benefit from the thermal/electrical load diversity in the multiple loads served, reducing the need for storage.

2.3 TYPES OF CO-GENERATION WITH APPLICATIONS

The gas turbine is the center of many exciting new power generating technologies such as the integrated coal-gasification combined-cycle (IGCC), pressurized fluidized bed combustion (PFBC) and compressed air energy storage (CAES) .

Moreover, gas turbine CHP plants are highly competitive with steam turbines and internal combustion engines as prime movers, yielding a higher rate of return, better flexibility, higher efficiency, especially when using aero-derived gas turbines that have good part-load efficiencies and low downtime, with the aero-derivative type having a removable gas generator that relates to most of the critical maintenance. Co-generation with gas turbines encompasses heating air for fired heaters (G. Laquaniello and S. Guerrini, 1984) ,production of steam for cooling gas turbine blades (K. Takeya and H. Yasui,1987) using heat rejected from closed-cycle gas turbines (K. Bammert, 1986) , producing chilled water or cold air from an absorption system (Y. S. H. Najjar and A. M. Radhwan,1991) converting heat for space heating by the use of heat pumps (Y. S. H. Najjar and M. Nahas,1989), using liquefied hydrogen as fuel and coolant producing air for compressed air storage plants and producing power from an absorption cycle to drive reverse osmosis desalination .Other co-generation systems include steam power plants ,diesel power plants ,fuel cells and nuclear power plants .There are many gas turbine co-generation projects around the world, some producing hot water and steam for district heating , plus combined-cycle for power, heating and air conditioning and other applications.

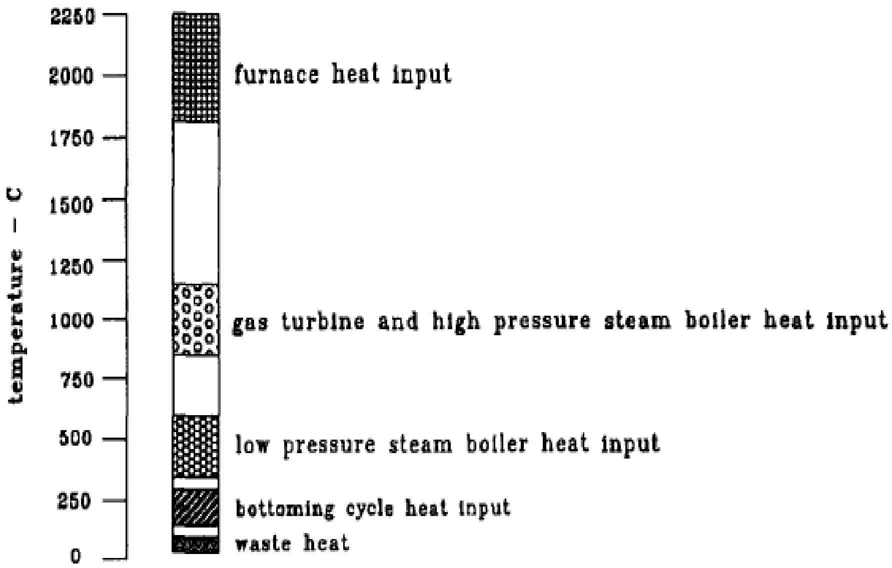

Figure 2.3: Industrial Co-generation

(Source: journal of combined and heat (CHP))

Within the last few years, gas turbines have been integrated into several industries. The paper industry, a long-standing supporter of combined heat and power, has emerged in the last decade as a leading industrial market for gas turbines. In each case, a two-or three-stage steam boiler is used for heat recovery from the exhaust of the gas turbine. Instead of using gas-fired driers, the tail end may be used directly for pulp-drying. It is reported that the gas turbine CHP is replacing ageing diesel co-generation systems in some leather work. Combined-cycle CHP plants are further reported to be supplying chemical complexes with all of their steam and electricity requirements. The said complexes may include salt refineries, electrolytic plants for chlorine production, caustic soda plants, natural gas-based methanol plants and a range of derivative products. It has been suggested that gas turbines fired by blast furnace gas can be installed in combined-cycle in steel works, where a multi-cannular type of combustor may be used to burn the low BTU fuel.

The gas turbine, generator, steam turbine and the fuel gas compressor can be coupled to make a single-shaft combination. One step in producing kaolin requires large spray driers, the heat for which can be supplied directly from the exhaust gas of the gas turbine engine.

2.4 MICRO GAS TURBINE

Micro gas turbines are gas turbines with power ranging approximately from 30 to 250 kW but in certain cases the micro gas turbine power output can be up to 400 kW at different country. These devices can be used in stationary, transport or auxiliary power applications. On this report just stationary application has been used. Usually micro gas turbines come as combined heat and power (CHP) systems. Such micro gas turbine based CHP systems would thus be characterized by;

- a single rotating part consisting of a shaft incorporating the compressor and turbine wheels
- (commonly radial), the alternator and the bearing system
- a combustor
- a recuperator and potentially a heat recovery unit (boiler / heat exchanger)

- a power conditioning system
- enclosure and balance of plant

The term microturbine. has recently been applied to devices that produce a few Watts with volumes of the order of a few cm3, which are some times better termed nano-turbines. Such devices incorporate micro-fabricated components and are being developed to provide power and even propulsion for micro vehicles [Spadaccini 2003, Epstein 1997]. They commonly utilise catalytic combustors and can reach temperatures as high as 1800K with hydrogen as fuel. Lastly, the term .mini-turbine is sometimes used to describe gas turbines from 200 kW to 1 MW.

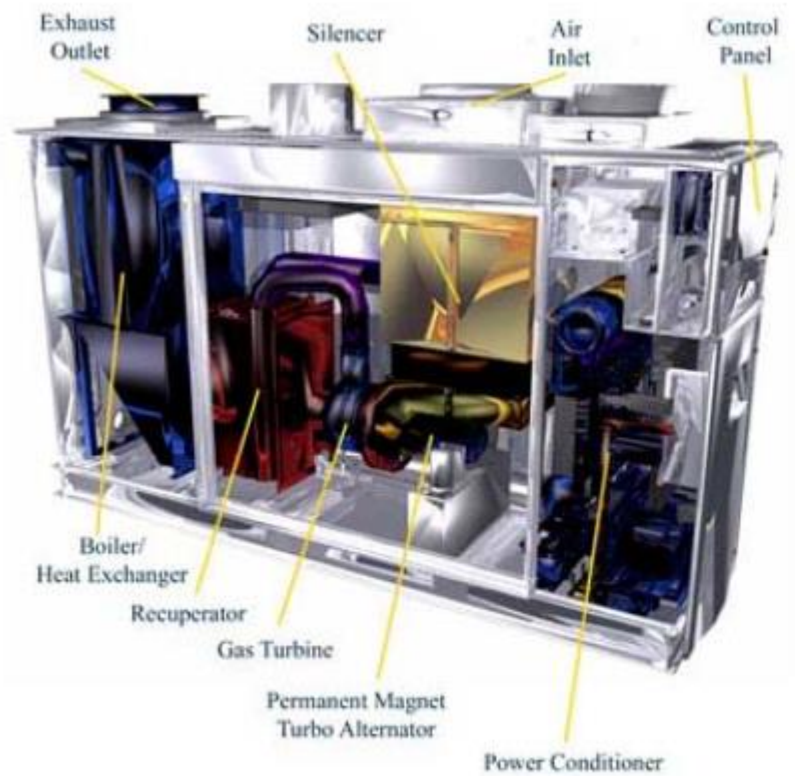

Figure 2.4: Layout of micro gas turbine based CHP unit

(Source: Bowman Power web site)

Micro gas turbine are intended to be simple, flexible and low cost devices for distributed power and heat generation. Micro gas turbine for generation are for stationary applications, not to be confused with gas turbines of the same used for propulsion or for auxiliary power.

2.5 MICRO GAS TURBINE OPERATION SYSTEM.

A schematic of the operation of a recuperated micro gas turbine is shown in figure below

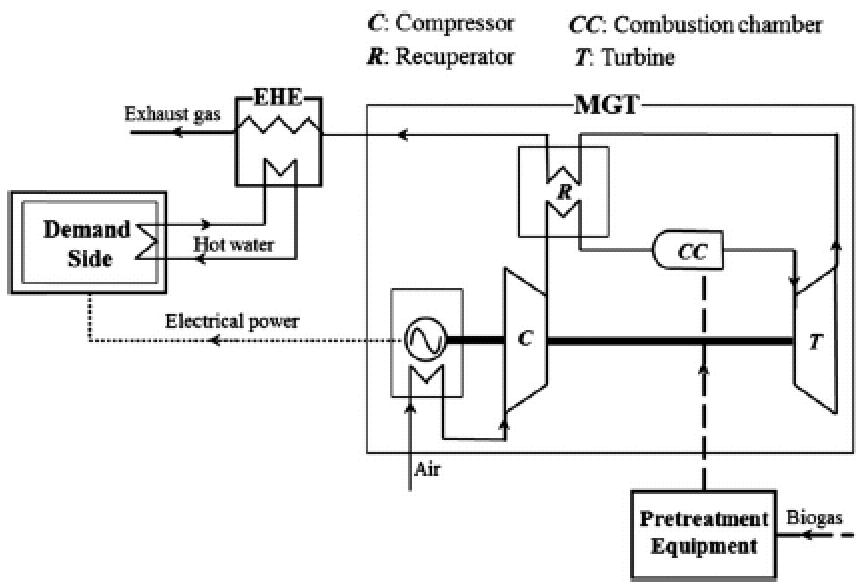

Figure 2.5: Schematic diagram of micro gas turbine

(*source: Basrawi.F 2011*)

MGTs are gas turbines that operate on the basis of the Brayton cycle, and recently developed MGTs are equipped with a recuperator and therefore they have higher efficiency. A MGTs operates on the same principal as a conventional gas turbine that consist of:

- incoming air is compressed to 3 - 5 bar by a single stage centrifugal compressor
- compressed air passes through a recuperator, recovering some of the energy of the exhaust gases
- air enters the combustor where the fuel (usually natural gas or LPG) is combusted, with temperatures reaching 900 to 1000 ^{0}C
- hot exhaust gases expand through the turbine, dropping their temperature to approx. 650 ^{0}C. The turbine is usually single stage and radial and is the device producing mechanical work that is fed to the single microturbine shaft
- exhaust gases then pass through the recuperator where the temperature drops to 250-350 ^{0}C
- Depending on the application there could be another heat exchanger installed that could produce steam, hot water or air for heating or chilling (through an absorption chiller)

2.6 MICRO GAS TURBINE PART AND IT'S FUNCTION

In micro gas turbine system there is consist of many component that make it to be a micro gas turbine. Based on report from Energy Nexus Group[Energy Nexus, 2002] These component are briefly described below:

1. compressor and turbine
2. combustor
3. bearings
4. recuperator
5. high speed generator
6. power conditioning and control unit
7. power Electronics Package

2.6.1 Compressor and Turbine Wheels.

Both compressor and turbine wheel are radial turbimachinery, a technology that is simple, cost effective and also efficient at this power range. The compressor and turbine blased is the core of the micro gas turbine concept. Originaly the design of the compressor and turbine blade originate come from the automotive turbocharger field. In auxiliary power units it is common that the turbine or even the compressor is/are of an axial type, but these units are more complex and for higher power machines, while radial turbomachinery have better efficiencies for powers up to 100 kW.

Material used for the compressor wheels can range from aluminium to inconel to titanium. For the turbine wheel the material used is made of alloy like inconel this is because turbine wheel need to operate at much higher temperature up to 1000 ^{0}C. In further research the used of ceramics for increased operating temperatures, aerodynamic design of compressor and rotor blades and reduction of tip clearances, aiming to maximise efficiency. This can be as high as 30% or even 35% for larger units (of the order of a few hundreds of kW)

2.6.2 Combuster

Combustors were originally designed for obtaining a stable flame, meaning having a primary combustion zone of high temperature, producing high NOx emissions (diffusion flame combustion). There exist three types of combustion technologies for gas turbines, namely:

1. **Diffusion flame** combustion; where fuel and air mix at the same time and the same space as they react, characterised by a very hot combustion zone (around 2000 oC) and high thermal NOx emissions, but with stable, robust flames.
2. **Premixed flame** combustion or lean combustion; where fuel is homogeneously distributed, generating lower combustion temperatures (600 K below diffusion flames) and low themal NOx emissions, that require high turbulence and other provisions to achieve flame stability

3. **Catalytic** combustion; aims to prevent NOx formation by burning the fuel inside a porous ceramic medium.

At this time micro gas turbine combustor has achieve a various improvement that it very minimam and low NO_x emission level. Such system involve lean combustion that is combustion of fuel in the presence of excess air, resulting in lower peak temperature and reduced Nox.

Usually a single can combustor is used but some microturbine systems utilise an annular combustor that allows for reduced size. The different of micro gas turbine to other heat engines for distrbuted generation is their capability to burn a variety type of fuels, ranging from natural gas, dieasel and LPG, to waste and biomass derived fuel like landfill gas or gasification product from biomass

2.6.3 Recuperator

Recuperators are air-to-air heat exchangers of variuos shapes (box or annual), where weight and size and cost are importance. Micro gas turbine at the size of a few tens of kWs would have efficiency that would be as low as 10%. This is because the small size of rotating turbomachinery component make the clearances analogically higher. The recuperator make the efficiency of the micro gas turbines increase by exploiting the heat of the exhaust gases in preheating the air exiting the compressor.

2.6.4 Bearings

Most of the available microturbines are units with a single rotating shaft, where the compressor wheel, turbine rotor and generator are incorporated. This shaft is supported on bearings that originally were oil lubricated but, in accordance again with automotive turbochargers, are now air bearings that are self-aligned.

2.6.5 High-Speed Generator

The generator additionally acts as the starting motor of the gas turbine. The generators are based on either permanent magnet alternators that have an efficiency that can be as high as 95% or on permanent magnet discs that remove iron losses and eddy current losses and whose efficiency can be as high as 98%.

2.6.6 Power Electronics Package

The power electronics package of a microturbine converts the output of the high-speed generator into AC of the desired frequency and voltage, through a rectifier and an inverter. Thus, the generator output has a frequency of 1,000 to 2,000 Hz and a voltage of 500V that is converted to 50 or 60 Hz and 120 or 220 V depending on location. In the case of grid-connected operation, the power electronics ensure that the voltage and frequency are matched and synchronised with the grid.

2.6.7 Balance of Plant

Balance of plant (BoP) usually include filter, sensors, tinstrumentation and control, writing and pluming. It is common that the co-generation heat exchanger sits in a separate enclosure next to the micro gas turbine.

2.7 Component Cost

The cost of the various component or subsystems ranges estimation from the total cost of the micro gas turbine;

- compressor and turbine 14-17%
- combustor 9-12%
- bearings 3-4%
- recuperator 21-24%
- high speed generator 7-9%
- power conditioning and control unit 15-18%
- power Electronics Package 23-26%

2.8 COMMERCIAL MICRO GAS TURBINE

Commercial micro gas turbines are offered in atrractive enclosures that meet various electrical noise attenuation and safety standards. Some of the enclosre are weather resistant. This is the example of commercial micro gas turbine and it specification;

Table 2.1: Micro gas turbine specification based on capstone and Ingersoll rand power.

Table 1. Microturbine CHP - Typical Performance Parameters* Cost & Performance Characteristics3	System 1	System 2	System 3
Nominal Electricity Capacity (kW)	30	65	250
Compressor Parasitic power (kW)	2	2	8
Package Cost (2007 $/kW)4	$1,290	$1,280	$1,410
Total Installed Cost (2007 $/kW)5	$2,970	$2,490	$2,440
Electric Heat Rate (Btu/kWh), HHV6	15,075	13,891	13,080
Electrical Efficiency (percent), HHV7	22.6%	24.6%	26.09%
Fuel Input (MMBtu/hr)	0.422	0.875	3.165
Required Fuel Gas Pressure (psig)	75	75	75
CHP Characteristics			
Exhaust Flow (lbs/sec)	0.69	1.12	4.7
GT Exhaust Temp (degrees F)	530	592	468
Heat Output (MMBtu/hr)	0.17	0.41	1.2
Heat Output (kW equivalent)	50.9	119.5	351.6
Total CHP Efficiency (percent), HHV8	63.8%	71.2%	64.0%
Power/Heat Ratio9	0.55	0.53	0.69
Net Heat Rate (Btu/kWh)10	7,313	5,796	6,882
Effective Electrical Efficiency (percent), HHV11	46.7%	58.9%	49.6%

(Source: Journal of microturbines and their applicationin bio-energy)

Each micro gas turbine manufacturer represented in table 2.1 uses a different recuperator, and each has made individual tradeoffs between cost and performance. Performance involves the extent to which the recuperator effectiveness increases cycle efficiency, the extent to which the recuperator pressure drop decreases cycle power, and the choice of what cycle pressure ratio.

Characteristics presented are representative of “typical” commercially available or soon to be available micro gas turbine systems. Table data are based on: Capstone Model 330 – 30 kW; Capstone C65 – 65kW, Ingersoll Rand Power MT250 – 250 kW.

Figure 2.6 : Capstone Micro Gas Turbine

(Source: Journal of   microturbines and their applicationin bio-energy)

. A 400 kW microturbine genset was also marketed with a Walter microturbine, capable to burn kerosene, diesel and NG. The combustor is not a low emissions one. The company is a spin off from Imperial College, UK. Turbo Genset was a partner of the TETLEI project where a microturbine was installed in a Rover vehicle to be used a as taxi. Turbogenset has been collaborating with GE of the US for the development of a 200 kW microturbine for CHP applications [Etemad 2003].

CHAPTER 3

METHODOLOGY

3.0 INTRODUCTION

Chapter 3 discusses methodology of the project in general, with specific on the analysis of economics performances of the micro gas turbine-co-generation system running on different ambient temperature at small and medium scale sewage treatment plant. The based on methodology flow chart. Chapter 3 present current progresses on research by calculating the economics performances of the micro gas turbine-co-generation system on selected parameters. Understanding prior and current research in this project provides method for the research contributions outlined in subsequent chapters.

3.1 METHODOLOGY FLOW CHART

Methodology flow chart is used as guidelines and the sequences to make this project go smoothly. Thus, the process begin with title selection and conformation of the title selected. Then, the process continue with finding the articles relate and identify the objectives, project background and the problem statement related to this project. The process proceeds by starts with study and understands the concept of micro gas turbine-co-generation system. After that we find data and parameter that we want to analyze on this project. When the data and parameters finding was done, analysis on economics performances of micro gas turbine will be conduct. In this analysis of MGT-CGS in sewage treatment, analysis of economic performance is main objective.

The economic performance can be calculated and separated into simple economic performance and advance economic performances.

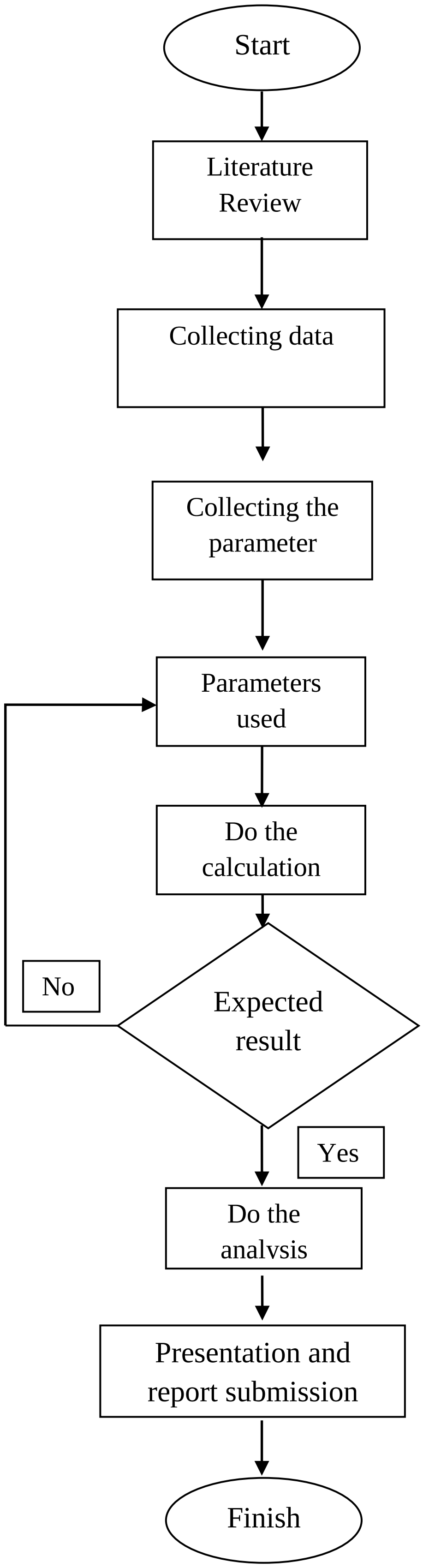

Figure 3.1: Methodology flow chart

3.2 COLLECT INFORMATION

This project is required to do preliminary study and research about project. The various resources have been searching from previous research (book, articles, and journals) and internet webpage to develop a personal plan for information processing. From literature review we can conclude that the performances of micro gas turbine- co-generation system will be different when running in different ambient temperature condition with different power output of micro gas turbine in small and medium sewage treatment plant. Based on the data collected, analysis on economics performances of the system can be calculated and based on the result comparison can be made.

3.2.1 Micro gas turbines co-generation system and its cost

MGTs are gas turbines that operate on the basis of the Brayton cycle, and recently developed MGTs are equipped with recuperator and therefore they have higher efficiency. The model of a single biogas-fuelled MGT-CGS is shown in Fig. 3. The biogas-fuelled MGT-CGs was mainly composed of the MGT, and an exhaust heat exchanger (EHE), and the MGT was a regenerative single shaft MGT.

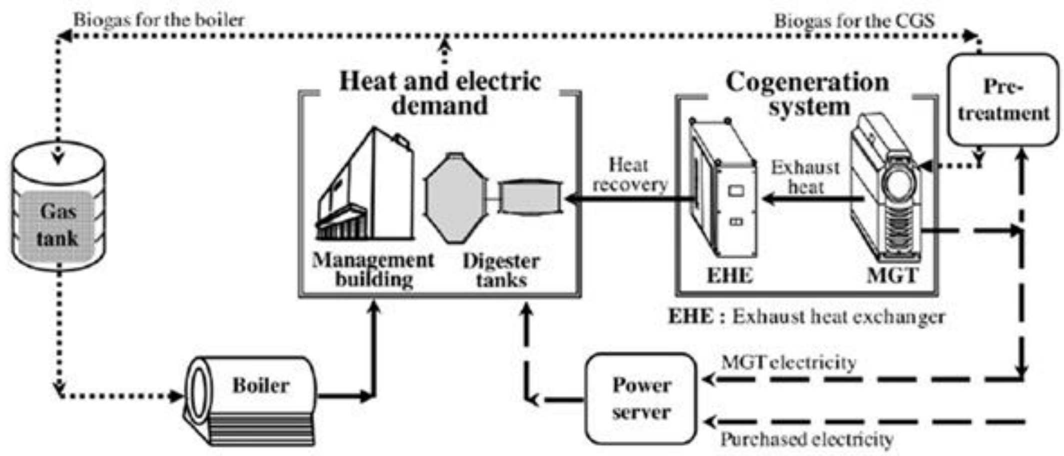

Figure 3.2: Micro Gas Turbine-Co-generation System

(source: Journal of Analysis of the performances of biogas-fuelled micro gas turbine co-generation system)

Atmospheric air enters the MGT passing through a generator, a compressor, a recuperator, a combustion chamber, a turbine and then the recuperator. For this analysis MGT-CGSs with electrical power outputs of 30 kW (MGT30), 65 kW (MGT-65) and 200 kW (MGT-200) were investigated in this study.

Micro Turbine capital costs range from $1000 - 2500$/kW. These costs include all hardware,associated manuals, software, and initial training. Adding heat recovery increases the cost by$75 - 350kW. Installation costs vary significantly by location but generally add 30-50% to the total installed cost. The cost for MGT 30, MGT 65 and MGT 200 shown in table 3.1 below.

Table 3.1: MGT cost for the analysis process

Sources	Electricity Capacity	Installed cost for CHP	O&M Cost for power only
	kW	$/kW	$/kWh
Energy Solutions Center	30	2636	0.01
Technology Characteristics	65	2490	0.01
Distributed generation technology	200	1200	0.005

3.2.2 Temperature condition

Since the MGT-CGS is practically used for an outdoor application, the inlet air temperature was assumed to be equal to the ambient temperature. In different season the temperature is different and sometimes high and sometimes low. The table below show the temperature range for low, medium and high.

Table 3.2: Temperature range conditions for the analysis process

Temperature Condition	Average Ambient Temperature (°C)
Low	-9.5 to 25.0
Medium	5.1-29.0
High	15.7-29.9

(source : Basrawi. F 2011)

3.2.3 Sewage Treatment Plant

In order to investigate the economics performances of MGT-CGS under different scale conditions, this plant was scaled down to 0.25, 0.5 and 1. Comparison of parameters of sewage treatment plant in different scales;

Table 3.3: Sewage Treatment plant parameters for analysis process

Scale		0.25	0.50	1.0
Population Covered	[People]	25000	50000	100000
Average Electricity Demand	$[kW]$	160	319	638
Digester Tank Total Volume (2 Units)	$[m^3]$	2524	5044	10088
Average Influent Sludge Amount	$[m^3/month]$	1883	3766	7533
Average Biogas Production	$[m^3/month]$	32415	64827	129654

(Source:Basrawi. F 2011)

3.2.4 Operation conditions

3.2.4.1 Full load

From this table, total number of MGT-CGS used every condition and scales in full load can be calculated.

Table 3.4: Total number of MGT used in full load

				Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Low	0.25	MGT-30		0	0	0	0	1	1–2	2	2	1–2	1	0	0
		MGT-65		0	0	0	0	0	1	1	1	1	0	0	0
		MGT-200		0	0	0	0	0	0	0	0	0	0	0	0
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-65	0	0	0	0	0	1	1	1	1	0	0	0
			MGT-200	0	0	0	0	0	0	0	0	0	0	0	0
	0.50	MGT-30		0	1	1	1	2–4	4–5	4–5	4	4	2–4	2	1
		MGT-65		0	0	0	0	1–2	2	2	2	2	1–2	1	0
		MGT-200		0	0	0	0	0	1	0	0	0	0	0	0
		MGT-Combination	MGT-30	0	1	0	0	0	0	0	0	0	0	0	1
			MGT-65	0	0	0	0	1	0	0	0	0	1	1	0
			MGT-200	0	0	0	0	0	1	0	0	0	0	0	0
	1.00	MGT-30		1–2	2	2	2	5–8	9	9–10	8–9	8–9	5–9	5–6	2
		MGT-65		1	1	1	1	2–4	4–5	4–5	4	4	2–4	2–3	1
		MGT-200		0	0	0	0	1	1–2	1	1	1	1	1	0
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	1	0	0
			MGT-65	1	0	1	1	1	1	0	0	0	0	0	1
			MGT-200	0	0	0	0	1	1–2	1	1	1	1	1	0
Medium	0.25	MGT-30		1	1	1	1	2	2	2	2	2	1–2	1–2	1
		MGT-65		0	0	0	0	1	1	1	1	1	1	1	0
		MGT-200		0	0	0	0	0	0	0	0	0	0	0	0
		MGT-Combination	MGT-30	0	0	1	0	0	0	0	0	0	0	0	1
			MGT-65	0	0	0	0	1	0	0	0	0	1	1	0
			MGT-200	0	0	0	0	0	0	0	0	0	0	0	0
	0.50	MGT-30		2–4	2–4	2–4	2–4	4–5	4–5	4–5	4–5	4–5	3–4	4–5	3–4
		MGT-65		1	1–2	1–2	1–2	2	2	2	2	2	2	2	1–2
		MGT-200		0	0	0	0	0	1	1	0	0	0	0	0
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-65	1	1	1	1	0	0	0	0	0	0	0	0
			MGT-200	0	0	0	0	0	1	1	0	0	0	0	0
	1.00	MGT-30		6–9	8	7–9	7–8	8–10	9–11	10	9	9	7–9	9	8–9
		MGT-65		3–4	3–5	4	3–4	4–5	4–5	4–5	4–5	4	4–5	4–5	4–5
		MGT-200		1	1	1	1	1	1–2	1–2	1	1	1	1	1
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-65	1	0	1	1	0	0	0	0	0	0	0	1
			MGT-200	1	1	1	1	1	1–2	1–2	1	1	1	1	1
High	0.25	MGT-30		2	2	1–2	1–2	2	2	2	2	2	2	2	2
		MGT-65		1	1	1	1	1	1	1	1	1	1	1	1
		MGT-200		0	0	0	0	0	0	0	0	0	0	0	0
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-65	1	1	1	1	0	0	0	0	0	1	0	1
			MGT-200	0	0	0	0	0	0	0	0	0	0	0	0
	0.50	MGT-30		4	4–5	3–4	3–4	4–5	4–5	5	4–5	4–5	4–5	4–5	4
		MGT-65		2	2	1–2	1–2	2	2	2	2	2	2	2	2
		MGT-200		0	0	0	0	0	1	1	0	0	0	0	0
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-65	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-200	0	0	0	0	0	1	1	0	0	0	0	0
	1.00	MGT-30		8–9	8–10	7–9	7–9	9	10	10–11	9–10	8–10	9	9–10	8–9
		MGT-65		4–5	4–5	4	3–4	4–5	4–5	5	4–5	4–5	4–5	4–5	4
		MGT-200		1	1	1	1	1	1–2	1–2	1	1	1	1	1
		MGT-Combination	MGT-30	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-65	0	0	0	0	0	0	0	0	0	0	0	0
			MGT-200	1	1	1	1	1	1–2	1–2	1	1	1	1	1

(source: Basrawi. F 2011)

3.2.4.2 Partial Load

The figures below show the electrical efficiency and operation condition of MGT-CGSs for partial load at different temperature and different scales. From this data the MGT that operate in partial load can be calculate.

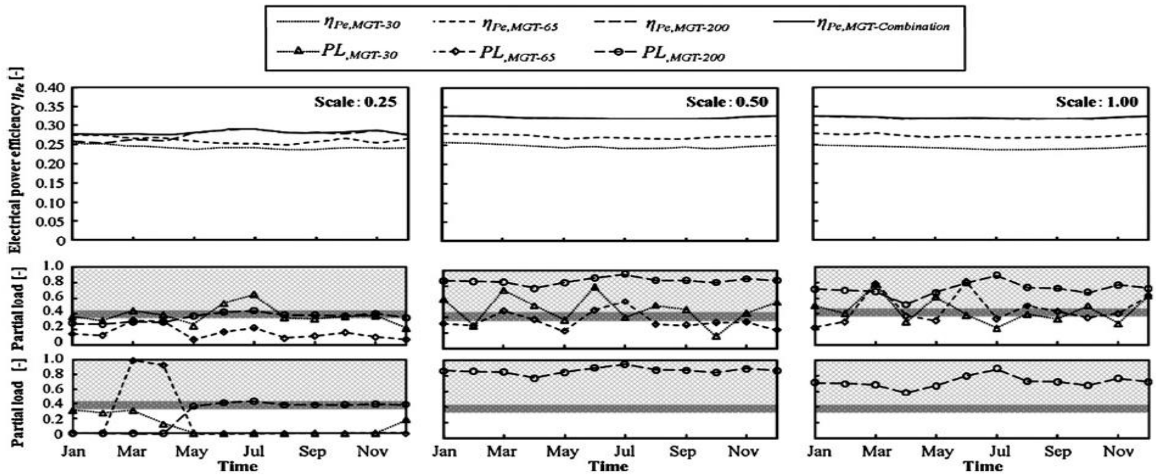

Figure 3.3: Electrical power efficiency and MGTs operation at partial load under low temperature condition.

(source: Basrawi. F 2011)

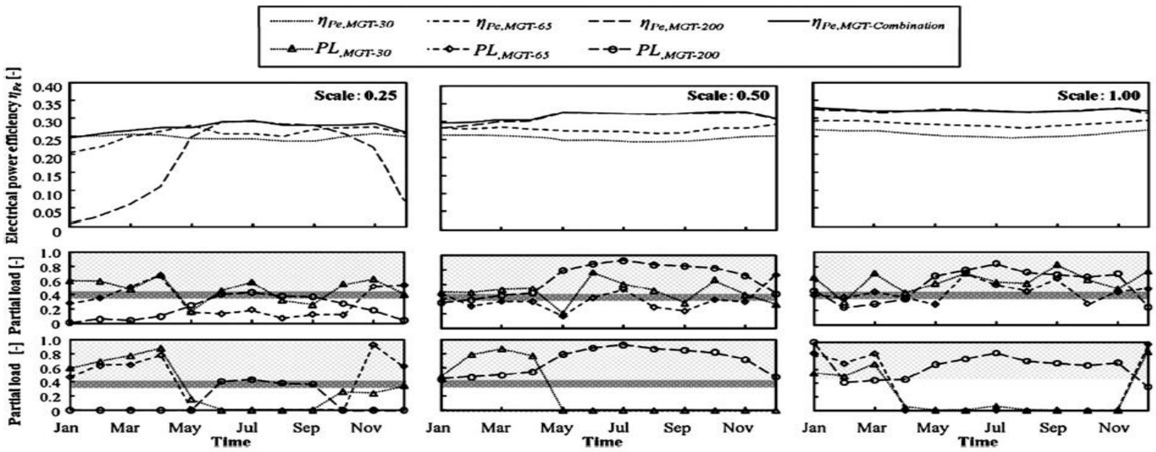

Figure 3.4: Electrical power efficiency and MGTs operation at partial load under medium temperature condition.

(source: Basrawi. F 2011)

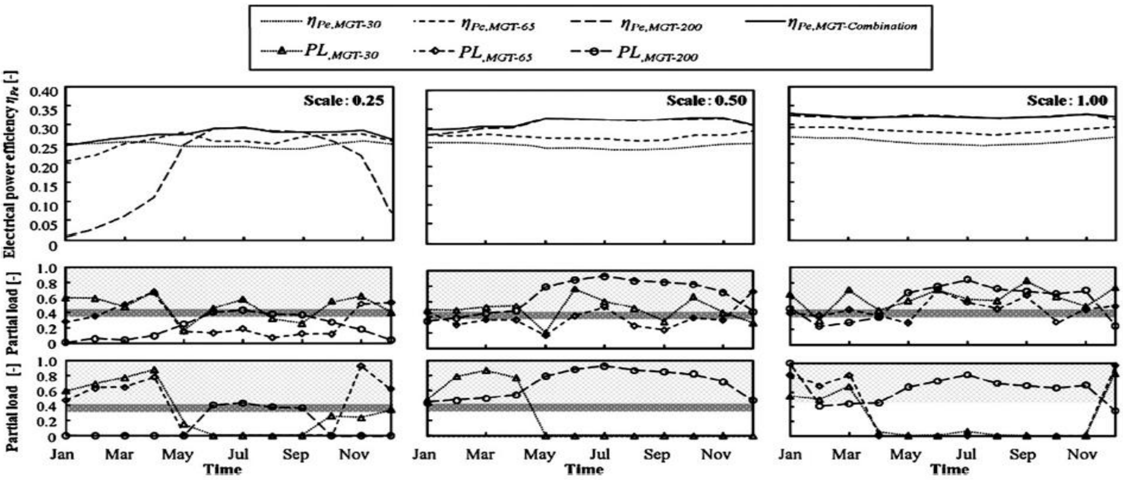

Figure 3.5: Electrical power efficiency and MGTs operation at partial load under high temperature condition.

(source: Basrawi. F 2011)

3.2.5 Power generated

The tables below show the total power generated for every MGT in every scale of sewage treatment plants and under all ambient temperature condition.

Table 3.5: Total power generated of MGT-CGSs in all scales under low ambient temperature condition

Temperature	Scale	MGT power	Total power generated (kWh)
Low	0.25	MGT 30	215496
		MGT 65	227760
		MGT 200	210240
		MGT Combination	236172.3086
	0.5	MGT 30	617138.7588
		MGT 65	650781.4512
		MGT 200	596298.3684
		MGT Combination	678621.7824
	1	MGT 30	1397987.376
		MGT 65	1521879.18
		MGT 200	1478698.512
		MGT Combination	1556016.9

Table 3.6: Total power generated of MGT-CGSs in all scales under medium ambient temperature condition

Temperature	Scale	MGT power	Total power generated (kWh)
Medium	0.25	MGT 30	437649.6
		MGT 65	474236.616
		MGT 200	462974.76
		MGT Combination	484272.1596
	0.5	MGT 30	1055747.69
		MGT 65	1143905.77
		MGT 200	1137883.717
		MGT Combination	1168114.306
	1	MGT 30	2312443.005
		MGT 65	2546218.602
		MGT 200	2590865.913
		MGT Combination	2657102.26

Table 3.7: Total power generated of MGT-CGSs in all scales under high ambient temperature condition

Temperature	Scale	MGT power	Total power generated (kWh)
High	0.25	MGT 30	561841.1
		MGT 65	598777.6
		MGT 200	602898.7
		MGT Combination	647918.1
	0.5	MGT 30	1148097
		MGT 65	1262421
		MGT 200	1502432
		MGT Combination	1502432
	1	MGT 30	2310754
		MGT 65	2586916
		MGT 200	2983716
		MGT Combination	2984060

3.3 ECONOMICS PERFORMANCES ANALYSIS

3.3.1 Simple economic performances analysis of MGT-CGS

After all data has been compiling and analyze, calculate the simple economics performance of the MGT-CGSs. The simple economics performances of MGT-CGS conclude;

1. Capitol cost of the MGT-CGSs
2. Running cost, O&M cost
3. Electricity sold
4. Payback period

3.3.1.1 Capital cost calculation

The capital cost of MGT-CGSs are the cost that include all hardware, associated manuals, software, and initial training and also heat recovery system. The cost of MGT usually state at price per kW. The capitol cost:

$$C_{cap} = pe_{,max} \times price_{,MGT} \times n \qquad 1.0$$

Where $pe_{,max}$ is the total electric power capacity from table 3.1, $price_{,MGT}$ is the price of MGT ($/kW) from table 3.1 and n is total number of MGT from table 3.4 and from figure 3.3, figure 3.4 and figure 3.5. The C_{cap} is state in dollar $.

3.3.1.2 Operation and maintenance calculation

Non-fuel operation and maintenance (O&M) costs, are based on gas turbine manufacturer estimates for service contracts, which include routine inspections and scheduled overhauls of the turbine generator set. Routine maintenance practices include online running maintenance and preventive maintenance procedures. These procedures include predictive techniques, such as plotting trends in performance, fuel consumption, heat rate, and vibration.

The cost for operation and maintenance cost can be expressed as the following equation:

$$C_{,o\&m} = Pe \times price_{,o\&m} \times n \quad 1.1$$

Where Pe is the total power generated from table 3.5, table 3.6 and table 3.7, $price_{,o\&m}$ is the cost for the operation and maintenance from table 3.1 and n is the total number of MGT used from table 3.4 and from figure 3.3, figure 3.4 and figure 3.5

3.3.1.3 Electricity sold calculation

Electricity sold can be expressed as the following equation:

$$pe_{,sold} = Pe \times tar \quad 1.2$$

Where Pe is the total electric power generated from table 3.5, table 3.6 and table 3.7 and tar is the electric tariff. For this calculation electric tariff used is 0.138 $/kWh

3.3.1.4 Payback period calculation

Pay back period refer to the period of time required for the return on an investment to repay in year.

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Periodic Cash Flow}} \quad 1.3$$

3.3.2 Advanced economics performances analysis of MGT-CGS

After calculated the simple economics performance of the MGT-CGS, do the advanced economics performances of MGT-CGS based on the simple economics analysis result. For this advanced economics analysis, net present value in life cycle method was used. The net present value is the current worth of cash flows over the life cycle .Every net present value needs discount rate. This is because we used time value of money to represent the amount of money in the future and bring it to present.

To get the NPV of the cash in flow and cash out flow, it need to consider the time value of factor (PVIF). From this method, NPV of cash-out and cash in-flow can be estimated.

1. NPV of electricity sold
2. NPV of operation and maintenance cost
3. NPV of profit
4. Payback period(based on NPV method)

For this method some additional parameter need to consider. The parameter can be decided based on what expectation and estimation. For this analysis, assume that;

- Period of life cycle is 20 years
- The system operate 365 day per year
- operate 24 hour a day
- Electric tariff = 0.13$/kWh
- Discount rate/interest rate = 6%
- All price in dollar.

3.3.2.1 NPV of electricity sold calculation

NPV of electricity sold is total estimated amount of electricity sold by the system for 20 years with discount rate of 6%. The NPV of electricity sold can be expressed as the following equation:

$$NPV_{,electricity\ sold} = pe_{,sold} \times \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \quad 1.4$$

Where $pe_{,sold}$ is the amount of electricity sold, n is the total number of period (year) and i is the discount rate.

3.3.2.2 NPV of operation and maintenance cost calculation

NPV of operation and maintenance cost is total estimated amount O&M cost by the system for 20 years with discount rate of 6%. The NPV of O&M cost can be expressed as the following equation:

$$NPV_{,O\ \&\ M\ cost} = C_{,O\&M} \times \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] \qquad 1.5$$

Where $C_{,O\&M}$ is the amount O&M cost that take from the equation 1.1, n is the total number of period (year) and i is the discount rate.

3.3.2.3 NPV of profit calculation

NPV of profit is the estimation of profit that will get in 20 years of operation with the discount rate of 6%.

$$NPV_{profit} = NPV_{,electricity\ sold} - NPV_{,O\ \&\ M\ cost} - C_{cap} \qquad 1.6$$

Where $NPV_{,electricity\ sold}$ is net present value electricity sold that take from the equation 1.4, while $NPV_{,O\ \&\ M\ cost}$ is net present value for O&M take from the equation 1.5 and lastly is C_{cap} which is capital cost of the MGT-CGSs from the equation 1.0.

3.4 CHAPTER SUMMARY

In this chapter 3 was discussing about the flow to calculate the economics performances of MGT-CGSs running at the different ambient temperature condition with different output power of MGT at small and medium scale sewage treatment plan. Then, the result of every condition and scales of every power output of micro gas turbine will be compared.

CHAPTER 4

RESULT AND DISCUSSION

4.1 INTRODUCTION

The purpose of this chapter was explained about the analysis of the project. This analysis shows the result of simple and advanced economics analysis of the MGT-CGS in different temperature condition at sewage treatment plant. This chapter represents the result and calculation from the data. The full results were shown in this chapter.

4.2 ECONOMIC PERFORMANCE

The analysis of economics performances was conducted on the MGT-CGSs in different ambient temperature condition at sewage treatment plant. Two type of economics analysis was conducted simple and advanced economics analysis. From the result, we can make a comparison on the economics performances of the system and make a conclusion what system is give more benefit.

4.3 CAPITAL COST OF MGT-CGSs IN ALL SCALES AND UNDER ALL AMBIENT TEMPERATURE CONDITIONS

4.3.1 Low temperature condition

Figure 4.1 shows that total capital cost of MGT under low temperature condition in all scales. From the left the graph show total capital cost for every MGT-CGSs in every scale.

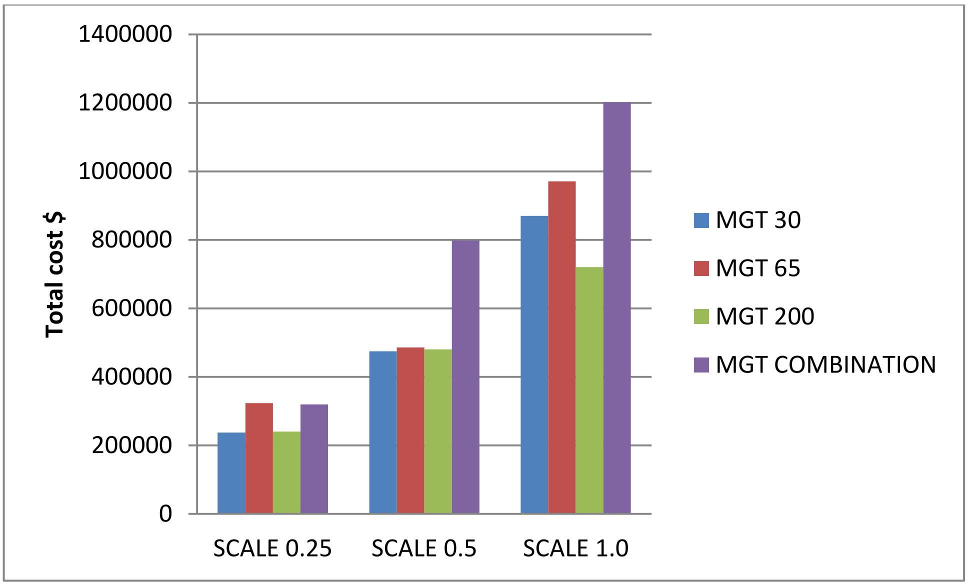

Figure 4.1: Result of total cost of MGT-CGSs under low temperature condition.

The highest total cost in scale 0.25 is 323700 USD which is at MGT 65, for the scale 0.5 the highest value is 798180 USD which is at MGT Combination and for scale 1 the highest value is 971100 $ at MGT 65. For the overall, the highest total price at the low temperature is 1201860 USD in scale 1.0 which is MGT combination. On the other, the lowest value for total cost is 237240 $ in scale 0.25, MGT 30. The cost of MGT is different for every scale and every type of MGT is because the total number of MGT operates is different for every scale and every type of MGT.

4.3.2 Medium temperature condition

Figure 4.2 shows that total capital cost of MGT under medium temperature in all scales. From the left the graph show total capital cost for every MGT-CGSs in every scale.

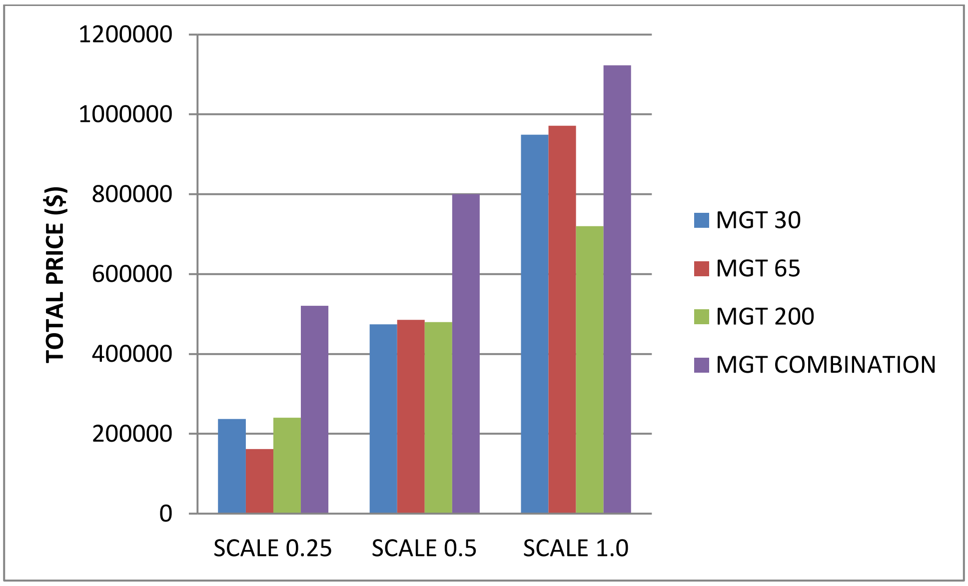

Figure 4.2: Result of total cost of MGT-CGSs under medium temperature condition.

It has the same graph pattern with the graph of total capital cost of MGT-CGSs under low temperature condition The highest total cost is in scale 0.25 with the value of 520470 USD which is at MGT combination, for the scale 0.5 the highest value is 800010 USD which is at MGT Combination and for scale 1 the highest value is 971100 USD at MGT 65. For the overall, the highest total price at the low temperature is 1122780 at scale 1 which is MGT combination. On the other, the lowest value for total cost is 237240 USD at scale 0.25, MGT 65. It has the same graph pattern with the graph of total capital cost of MGT-CGSs under low temperature condition.

4.3.3 High temperature condition

Figure 4.3 shows that total cost of MGT under high temperature condition with three types of scale which is 0.25, 0.5 and 1. From the left the graph show total capital cost for every MGT-CGSs in every scale.

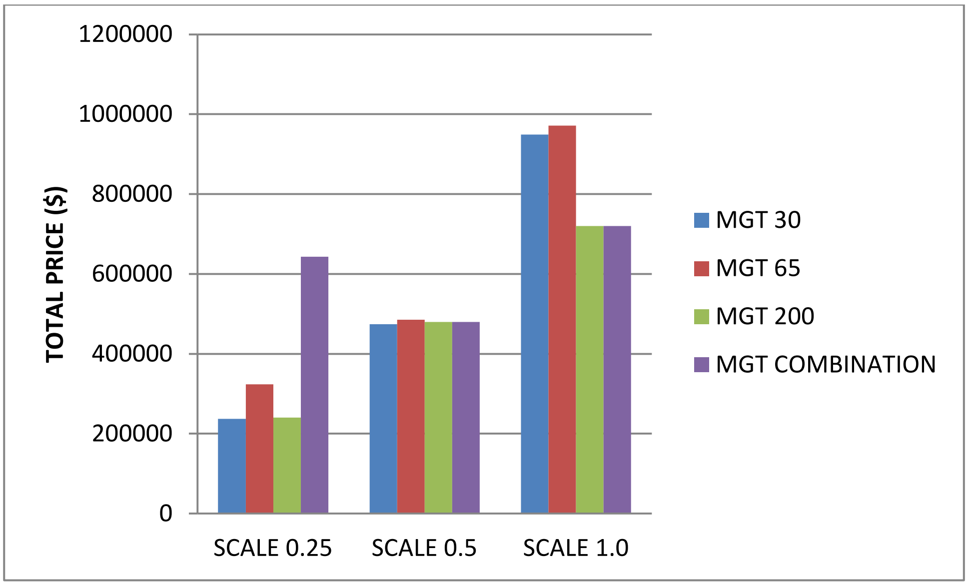

Figure 4.3: Result of total cost of MGT-CGSs under high temperature condition.

The highest total cost in scale 0.25 is 642780 USD which is at MGT combination, for the scale 0.5 the highest value is 485550 USD which is at MGT 65 and for scale 1 the highest value is 948960 USD at MGT 30. For the overall, the highest total price at the high temperature is 948960 USD at scale 1 which is MGT 30. On the other, the lowest value for total cost is 237240 USD at scale 0.25, MGT 30. The result of total capital cost under high temperature condition is vary for every scale because the total MGT-CGSs use in every scales are different and also based on the MGT power output capacity.

4.4 TOTAL ELECTRICITY SOLD OF MGT-CGSs IN ALL SCALE AND UNDER ALL AMBIENT TEMPERATURE CONDITION.

4.4.1 Low temperature condition

Figure 4.4 shows the result of electric sold for all MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under low temperature condition. The graph show the total amount of electricity sold for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total value of electricity sold by simple economics calculation and followed by the total value of electricity sold from advanced economics calculation. The graph pattern is the same. From the graph, show that the result for advanced economics analysis has more greater value than the simple economic analysis, this is because the advanced economic analysis used of life cycle estimation calculation. Every value must be calculated with sum of estimation for 20 years with the time value of factor for every year. The advanced economic analysis show the estimation of total electricity sold by every MGT-CGSs for 20 years and the simple economics analysis graph show the total electricity sold cost for present year based on data collected.

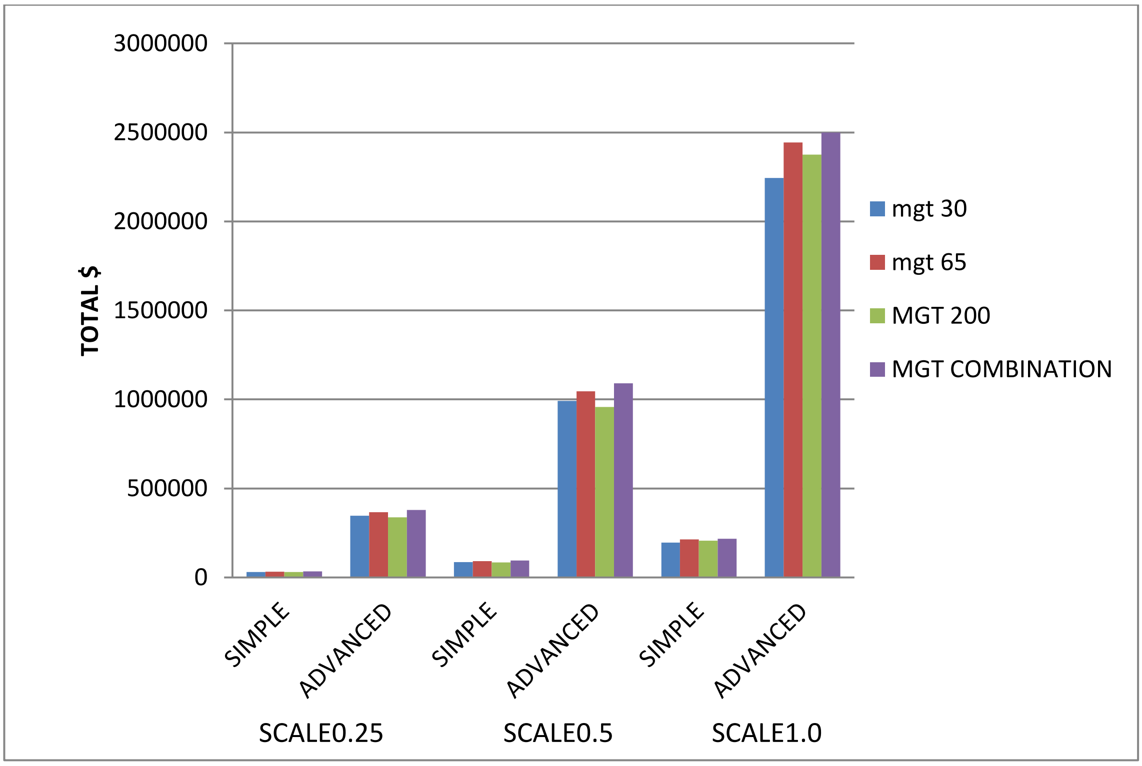

Figure 4.4: Result of total electricity sold of MGT-CGSs under low temperature condition.

From the graph at all scale 0.25, 0.5 and 1.0 the total of electric sold increasing either in simple or advanced economic analysis calculation throught the scale increase. The electric sold by every MGT and MGT combination is almost the same at every scales. The highest total electric sold at every scale is from MGT combination. This because at different scale the heat demand and power demand is different at the power generated by the MGT-CGSs also different.

4.4.2 Medium temperature condition

Figure 4.5 shows the result of electric sold for all MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under medium temperature condition. The graph show the total amount of electricity sold for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total value of electricity sold by simple economics calculation and followed by the total value of electricity sold from advanced economics calculation.

The graph pattern is the same. From the graph, show that the result for advanced economics analysis has more greater value than the simple economic analysis, this is because the advanced economic analysis used of life cycle estimation calculation. Every value must be calculated with sum of estimation for 20 years with the time value of factor for every year. The advanced economic analysis show the estimation of total electricity sold by every MGT-CGSs for 20 years and the simple economics analysis graph show the total electricity sold cost for present year based on data collected.

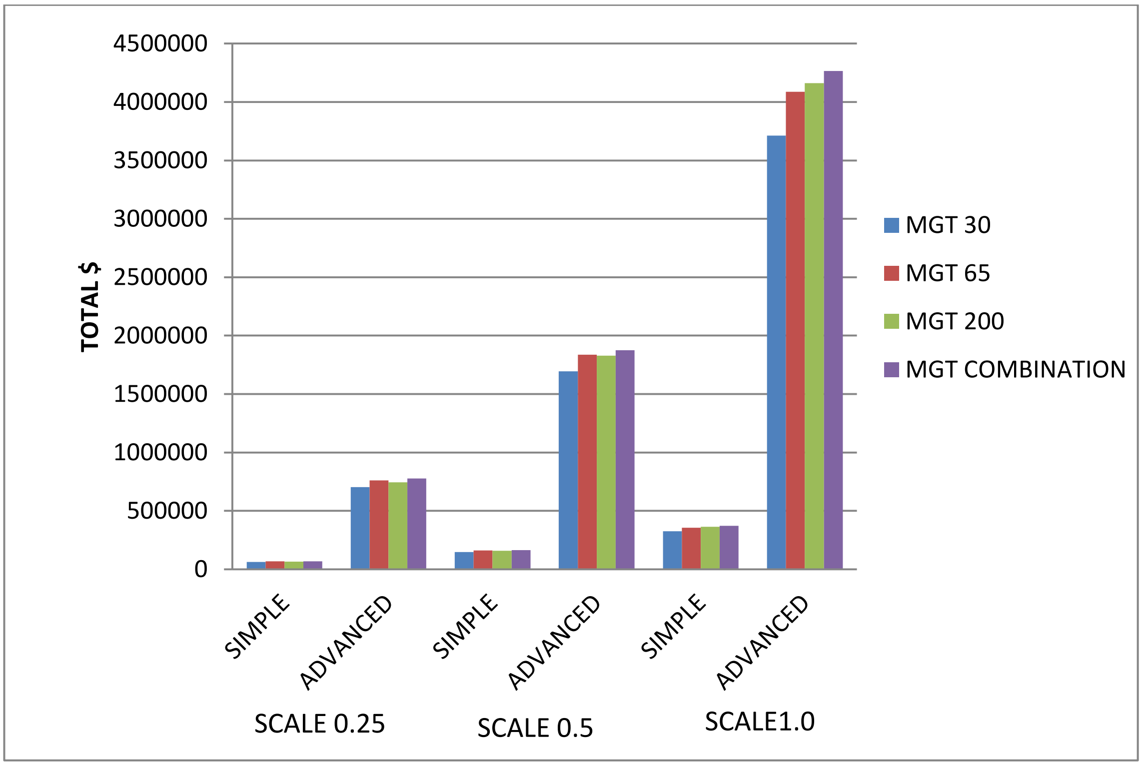

Figure 4.5: Result of total electricity sold of MGT-CGSs under low temperature condition.

From the graph, the pattern of the total electric sold by every MGT was increasing as the scale increase. For the simple economics analysis calculation .The highest total of electric sold for every scale is from the MGT combination. The total electric sold of every MGT was almost the same at scale 0.25 and 0.5, at scale 1.0 the total electric sold increase from MGT 30 to MGT 65 to MGT 200 and the highest at MGT combination in scale 1.0 with total electric sold at 371994.3164 USD.

From the graph the pattern of advanced economics calculation of electric sold for every MGT the highest total NPV of electric sold is from MGT combination and the lowest total NPV of electric sold is from MGT 200 accept for scale 1.0 that the lowest NPV of electric sold is from MGT 30.

4.4.3 High temperature condition

Figure 4.6 shows the result of electric sold for all MGT in scale 0.25, scale 0.5 and scale 1.0 under high temperature condition. The graph show the total amount of electricity sold for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total value of electricity sold by simple economics calculation and followed by the total value of electricity sold from advanced economics calculation. From the graph, show that the result for advanced economics analysis has more greater value than the simple economic analysis, this is because the advanced economic analysis used of life cycle estimation calculation. Every value must be calculated with sum of estimation for 20 years with the time value of factor for every year. The advanced economic analysis show the estimation of total electricity sold by every MGT-CGSs for 20 years and the simple economics analysis graph show the total electricity sold cost for present year based on data collected.

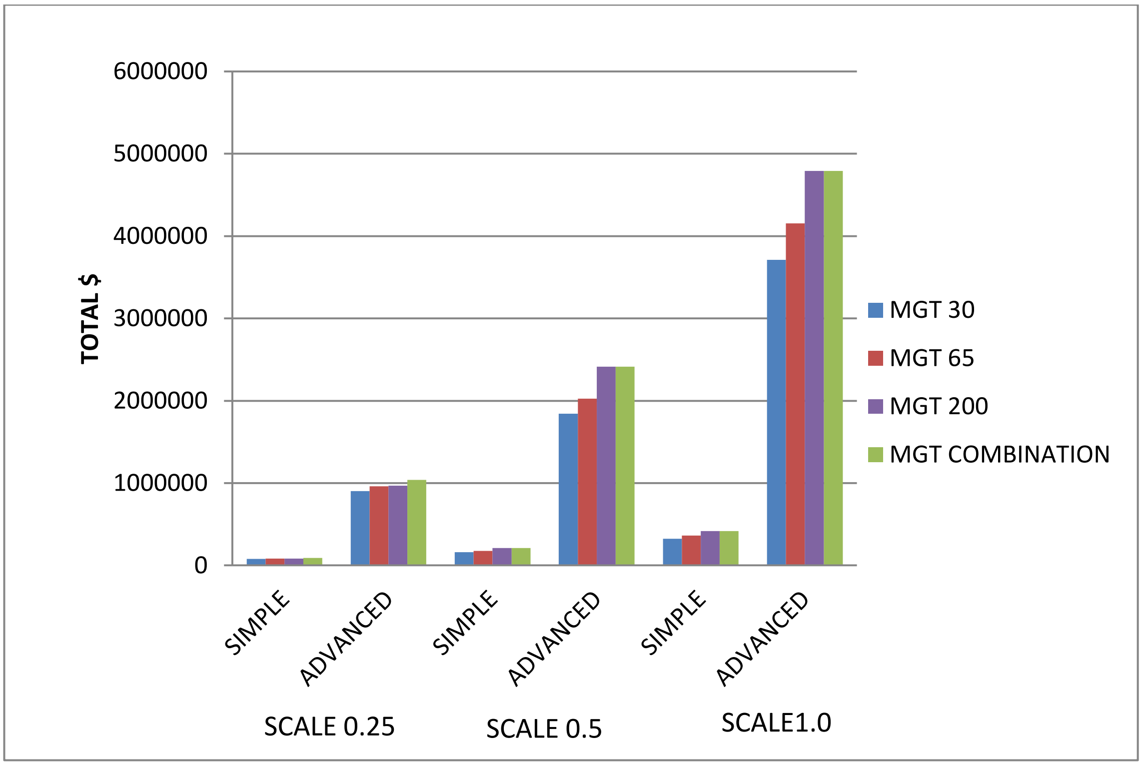

Figure 4.6: Result of total electricity sold of MGT-CGSs under high temperature condition.

Figure 4.6 shows the result of electric sold for all MGT in scale 0.25, scale 0.5 and scale 1.0 at high temperature condition. Figure 4.6 shows that the total electric sold for all MGT increases as the scale increase. The total amount of electric sold for every MGT at scale 0.25 MGT almost the same just slightly different. At scale 0.5 MGT 200 and MGT combination hasthe same amount of total electric sold. For scale 1.0 the electric sold is increasing as the MGT power increase.

4.5 TOTAL OPERATION AND MAINTENANCE COST (O&M) OF MGT-CGSs IN ALL SCALE AND UNDER ALL AMBIENT TEMPERATURE CONDITIONS

4.5.1 low temperature condition

Figure 4.7 shows the result of O&M cost of MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under low temperature condition. The graph show the total amount of O&M for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total value of O&M by simple economics calculation and followed by the total value of electricity sold from advanced economics calculation. From the graph, show that the result for advanced economics analysis has more greater value than the simple economic analysis, this is because the advanced economic analysis used of life cycle estimation calculation. Every value must be calculated with sum of estimation for 20 years with the time value of factor for every year. The advanced economic analysis graph show the estimation of total O&M cost by every MGT-CGSs for 20 years and the simple economics analysis graph show the total O&M cost for present year based on data collected.

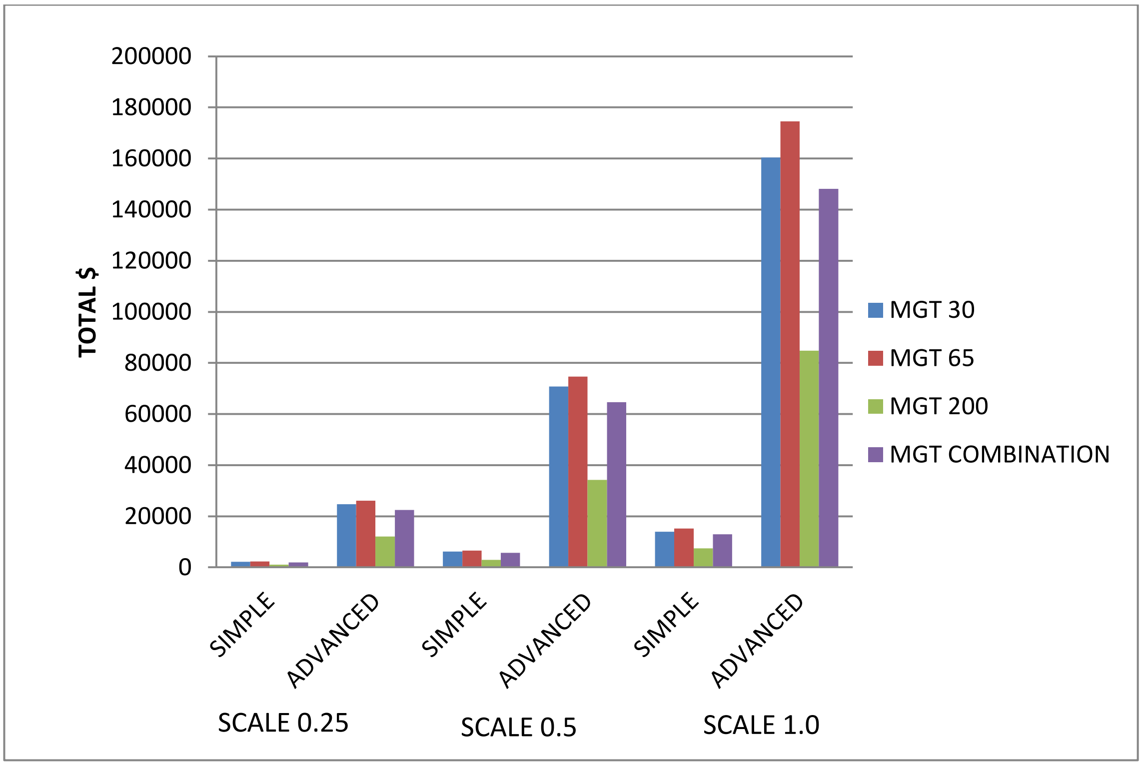

Figure 4.7: Result of total O&M cost of MGT-CGSs under low temperature condition.

From the graph the result of the operation & maintenance cost from simple economics analysis for all MGT-CGSs, the lowest operation and maintenance cost in every scale is MGT 200 and the highest cost for operation and maintenance in every scale is MGT 65. The graph pattern is same for every scale. This is based on the cost for O&M for MGT 200 is the cheapest compare to other MGT. The graph pattern for advanced economics analysis is the same for every scale. The highest NPV of O&M cost is from MGT 65 and the lowest NPV of O&M is from MGT 200. The cost range is from 12057.1818 $ to 26123.90 USD at scale 0.25. For scale 0.5 the cost range is from 34197.50 USD to 746644.12 USD and at scale the cost range is from 84802.78 USD to 174558.343 USD.

4.5.2 Medium temperature condition

Figure 4.8 shows the result of O&M cost of MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under medium temperature condition.

The graph show the total amount of O&M for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total value of O&M cost by simple economics calculation and followed by the total value of O&M cost for advanced economics calculation. From the graph, show that the result for advanced economics analysis has more greater value than the simple economic analysis, this is because the advanced economic analysis used of life cycle estimation calculation. Every value must be calculated with sum of estimation for 20 years with the time value of factor for every year. The advanced economic analysis graph show the estimation of total O&M cost by every MGT-CGSs for 20 years and the simple economics analysis graph show the total O&M cost for present year based on data collected.

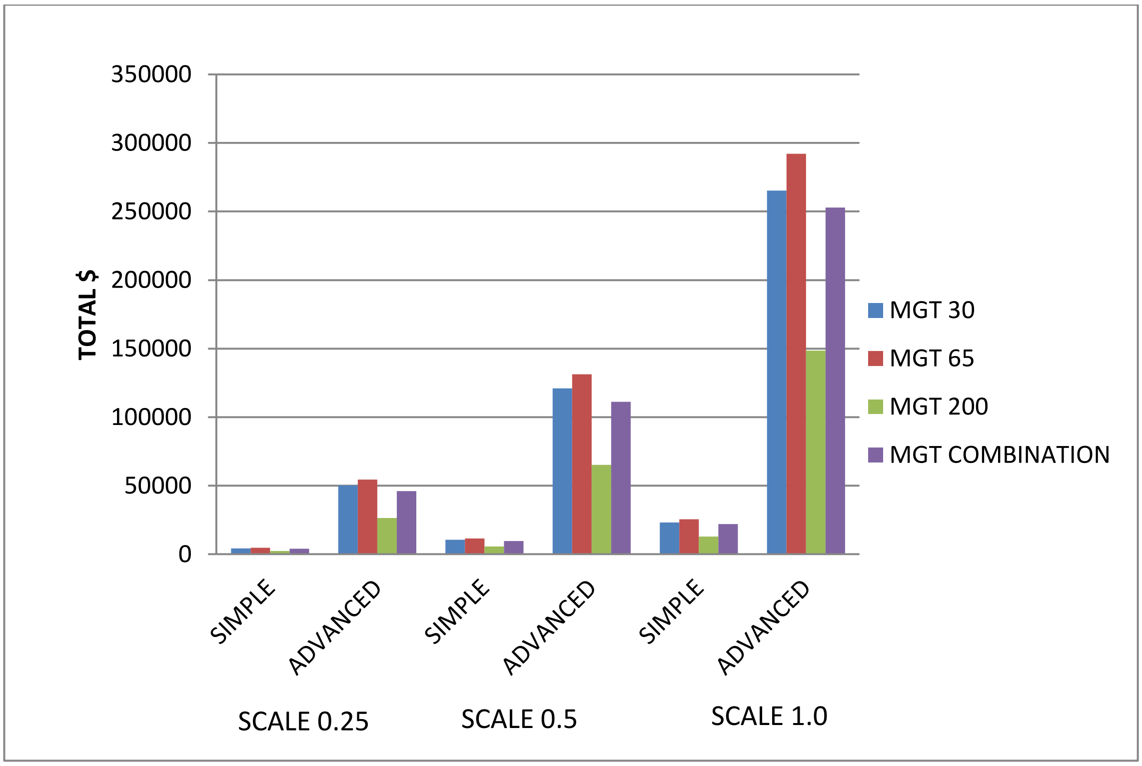

Figure 4.8: Result of total O&M cost of MGT-CGSs under medium temperature Condition

From the graph ,the graph pattern is also the same like graph pattern at low temperature condition, just the total operation and maintenance cost is greater. Range from the lowest 2314 USD to the highest 25462 USD.

From advanced economics analysis , NPV method The graph pattern is the same for every scale. The highest NPV of O&M cost is from MGT 65 and the lowest NPV of O&M is from MGT 200. The cost range is from 26551.42 USD to 54394.566 USD at scale 0.25. For scale 0.5 the cost range is from 65257.18 USD to 131205.09 USD and at scale the cost range is from 148585.14 USD to 292049.27 USD.

4.5.3 High temperature condition

Figure 4.9 shows the result of O&M cost of MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under high temperature condition. The graph show the total amount of O&M cost for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total value of O&M cost for simple economics calculation and followed by the total value of O&M cost for advanced economics calculation. From the graph, show that the result for advanced economics analysis has more greater value than the simple economic analysis, this is because the advanced economic analysis used of life cycle estimation calculation. Every value must be calculated with sum of estimation for 20 years with the time value of factor for every year. The advanced economic analysis graph show the estimation of total O&M cost by every MGT-CGSs for 20 years and the simple economics analysis graph show the total O&M cost for present year based on data collected.

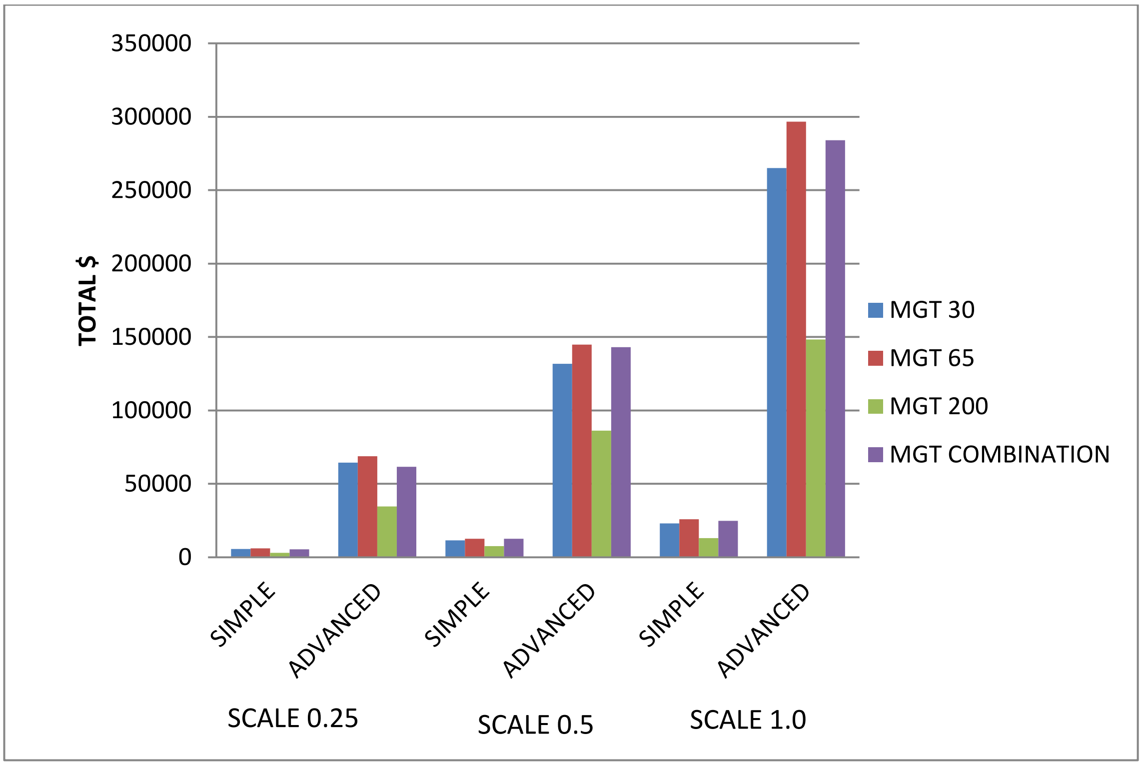

Figure 4.9: Result of total O&M cost of MGT-CGSs under high temperature condition.

. The graph pattern is also the same like graph pattern at low temperature condition, just the total operation and maintenance cost is greater. Range from the lowest 3014 USD at scale 0.25 from MGT 200 to the highest 25862 USD at scale 1.0 from MGT 65. For the advanced economics analysis The highest NPV of O&M cost is from MGT 65 and the lowest NPV of O&M is from MGT 200. The cost range is from 34576 USD to 68679.32 USD at scale 0.25. For scale 0.5 the cost range is from 86163.88 USD to 144798 USD and at scale the cost range is from 148358.64 USD to 296717.28 USD. The O&M cost increases when the power demand increases from the increasing of scales size and ambient temperature condition.

4.6 PAYBACK PERIOD OF MGT-CGSs IN ALL SCALES AND UNDER ALL AMBIENT TEMPERATURE CONDITIONS

4.6.1 Low temperature condition

Figure 4.10 shows the result of payback period of MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under low temperature condition. The graph show the total payback period for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total payback period based on simple economics calculation and followed by the payback period based on advanced economics calculation.

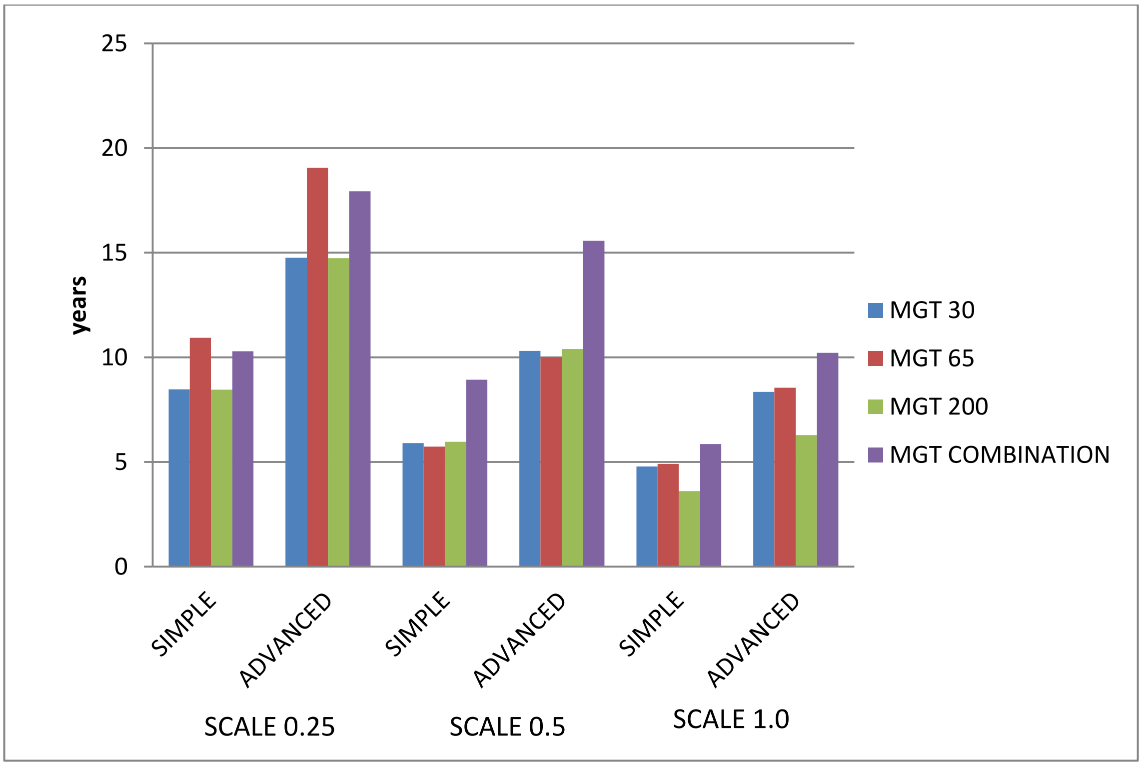

Figure 4.10: Result of payback period of MGT-CGSs under low temperature condition

From the graphbased on the simple economic analysis in scale 0.25, the shortest payback period is from MGT 200 is about 8.5 years and the longest is from MGT 65 about 11 years. In scale 0.5 the shortest payback period is from MGT 65 about 6 years and the longest is from MGT combination about 9 years.

Lastly at scale 1.0 the shortest payback period is from MGT 200 with payback period about 3.6 years and the longest from MGT combination about 6 years. From the advanced economic analysis, in scale 0.25 the longest payback period is from MGT 65 that take time about 19 years and the shortest is from MGT 30 about 14.8 years. For scale 0.5 the longest payback period is from MGT combination about 16 years and the shortest payback period is from MGT 200 bout 5.2 years. For scale 1.0 the longest payback period is from MGT combination about 10 years and shortest payback is fom MGT 200 about 6.3 years.

4.6.2 Medium temperature condition

Figure 4.11 shows the result of payback period of MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under medium temperature condition. The graph show the total payback period for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total payback period based on simple economics calculation and followed by the payback period based on advanced economics calculation.

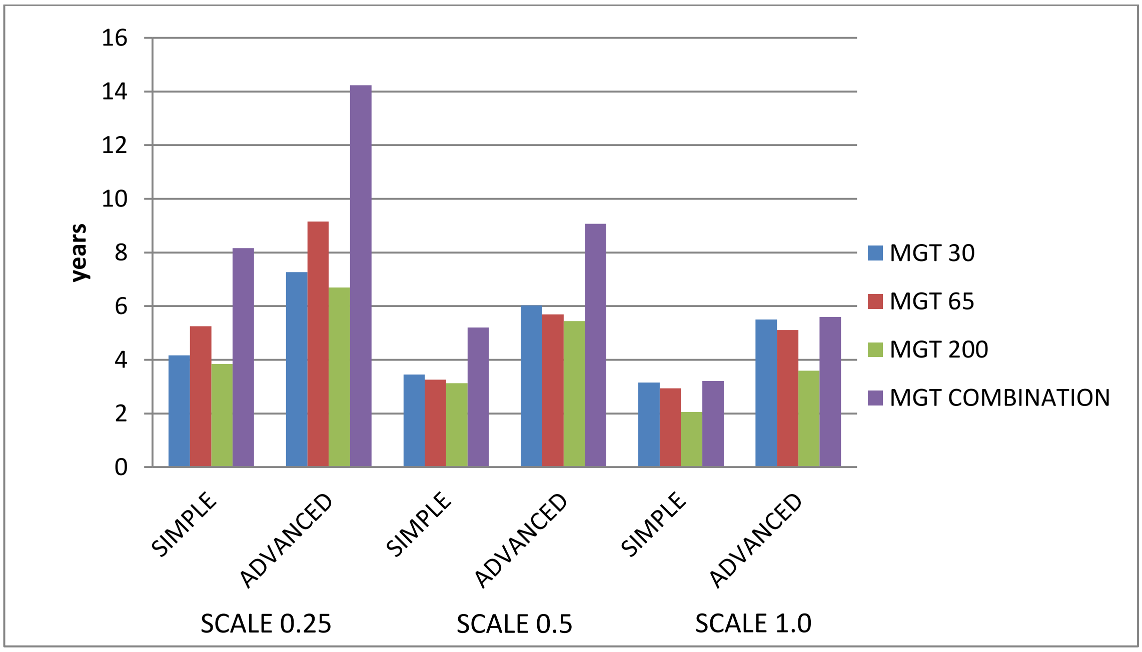

Figure 4.11: Result of payback period of MGT-CGSs under medium temperature condition

From the graph at scale 0.25, the shortest payback period is from MGT 65 is about 2.7 years and the longest is from MGT combination about 8.2 years. At scale 0.5 the shortest payback period is from MGT 200 about 3 years and the longest is from MGT combination about 5.2 years. Lastly at scale 1.0 the shortest is from MGT 200 with payback period about 2 years and the longest from MGT combination about 3.2 years. For advanced economics analysis, from the graph in scale 0.25 the longest payback period is from MGT combination that take time about 14 years and the shortest is from MGT 65 about 4.6 years. For scale 0.5 the longest payback period is from MGT combination about 9 years and the shortest payback period is from MGT 200 bout 5.4 years. For scale 1.0 the longest payback period is from MGT combination about 5.6 years and shortest payback is fom MGT 200 about 3.6 years. From the graph conclude that the MGT combination has the longest payback period, this is because MGT combination has high capital cost.

4.6.3 High temperature condition.

Figure 4.12 shows the result of payback period of MGT-CGSs in scale 0.25, scale 0.5 and scale 1.0 under high temperature condition. The graph show the total payback period for every MGT-CGSs based on the simple economics analysis calculation and advanced analysis calculation. From the left, the graph show the total payback period based on simple economics calculation and followed by the payback period based on advanced economics calculation.

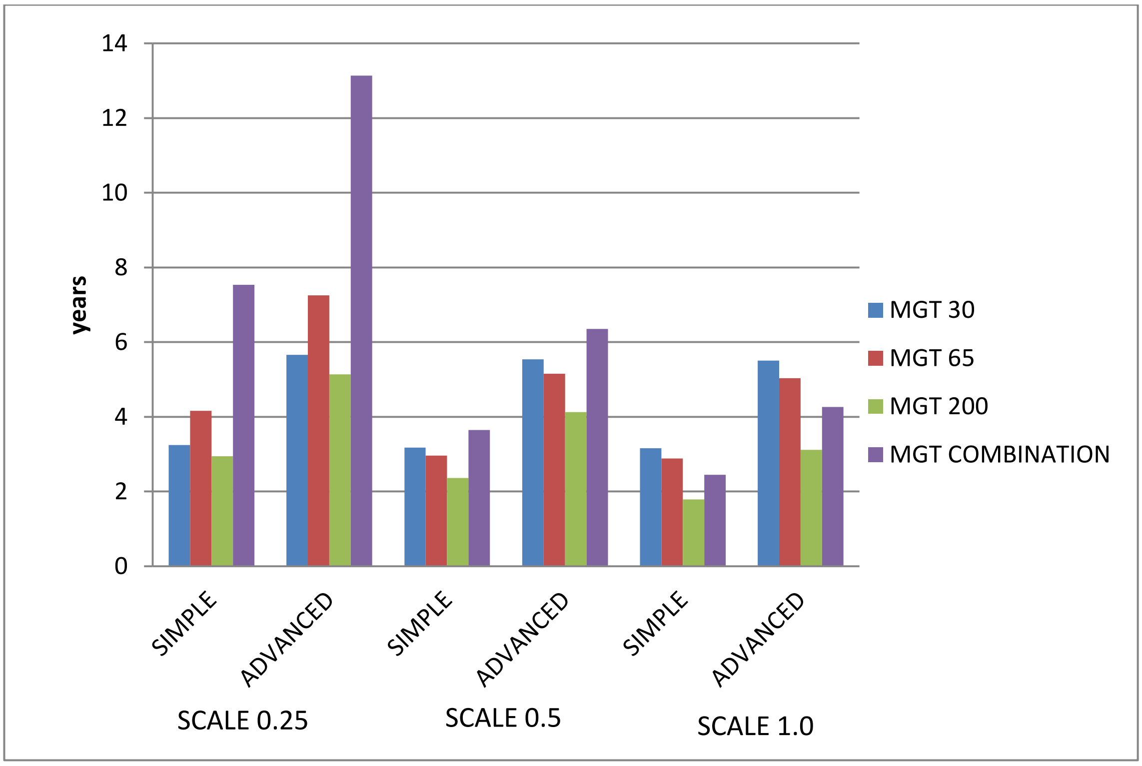

Figure 4.12: Result of payback period of MGT-CGSs under high temperature condition

From the graph at scale 0.25, the shortest payback period is from MGT 200 is about 3 years and the longest is from MGT combination about 7.5 years. At scale 0.5 the shortest payback period is from MGT 200 about 2.4 years and the longest is from MGT 30 about 3.2 years. Lastly at scale 1.0 the shortest is from MGT combination with payback period about 2 years and the longest from MGT combination about 3.2 years. From the advanced economic analysis for the payback period, in scale 0.25 the longest payback period is from MGT combination that take time about 13 years and the shortest is from MGT 200 about 5.1 years. For scale 0.5 the longest payback period is from MGT 30 about 5.6 years and the shortest payback period is from MGT 200 about 4.1 years. For scale 1.0 the longest payback period is from MGT 30 about 5.5 years and shortest payback is fom MGT 200 about 3.1 years. NPV of profit of MGT-CGSs in all scales and under all ambient temperature conditions

4.7 NPV OF PROFIT OF MGT-CGSs IN ALL SCALES AND UNDER ALL AMBIENT TEMPERATURE CONDITIONS

4.7.1 Low temperature condition

Figure 4.13 shows the result of NPV of total profit for all MGT at scale 0.25, scale 0.5 and scale 1.0 at low temperature condition.

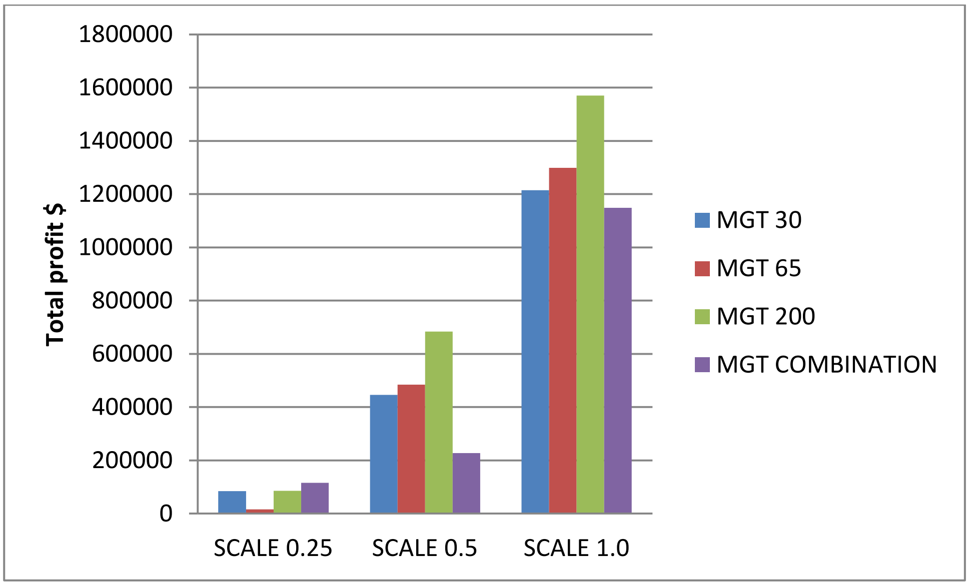

Figure 4.13: NPV of profit of MGT-CGSs under low temperature condition

From the graph at scale 0.25 the lowest NPV of profit is from MGT 65 with the value 15910.60 USD and the highest is from MGT combination 115829.20 USD. At scale 0.5 the lowest NPV of profit is from MGT combination with the value 226938.25 USD and the highest is from MGT 200 with value 683331.87 USD. Lastly from scale 1.0 the lowest NPV of profit is from MGT combination with the value 1148641.43 USD and the highest is from MGT 200 with the value 1569674.98 USD.

4.7.2 Medium temperature condition.

Figure 4.14 shows the result of NPV of total profit for all MGT at scale 0.25, scale 0.5 and scale 1.0 at medium temperature condition.

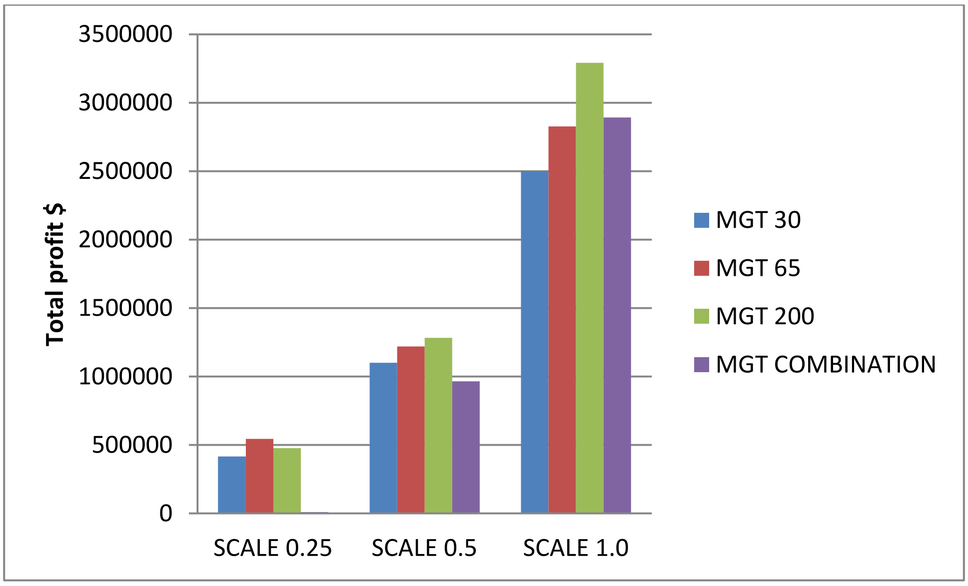

Figure 4.14: NPV of profit of MGT-CGSs under medium temperature condition

From the graph at scale 0.25 the lowest NPV of profit is from MGT combination with the value 9676.01 USD and the highest is from MGT 65 545279.37 USD. At scale 0.5 the lowest NPV of profit is from MGT combination with the value 964530.18 USD and the highest is from MGT 200 with value 1281943.9 USD. Lastly from scale 1.0 the lowest NPV of profit is from MGT 30 with the value 2499100.082 USD and the highest is from MGT 200 with the value 3291798.768 USD.

4.7.3 High temperature condition.

Figure 4.15 shows the result of NPV of total profit for all MGT at scale 0.25, scale 0.5 and scale 1.0 high temperature condition.

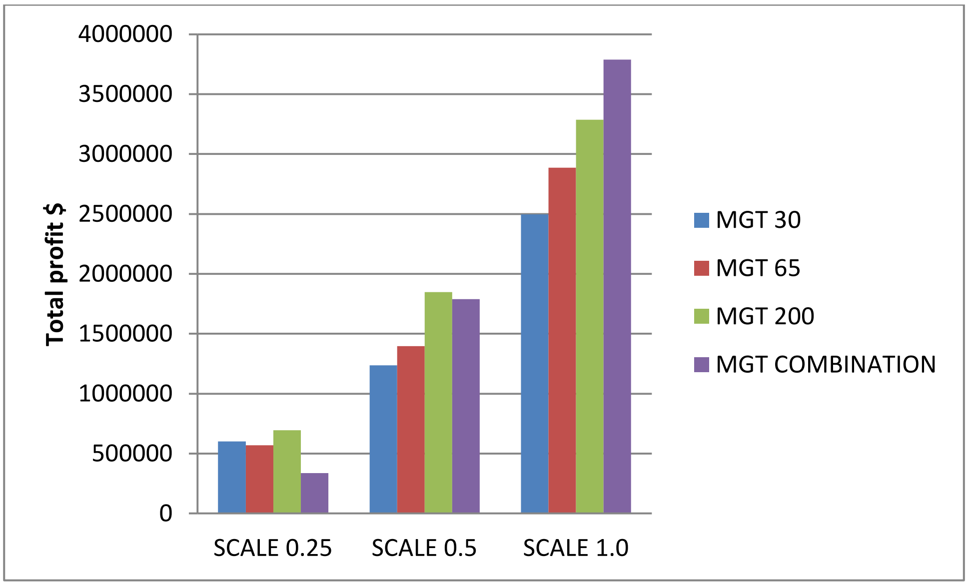

Figure 4.15: NPV of profit of MGT-CGSs under high temperature condition

From the graph at scale 0.25 the lowest NPV of profit is from MGT combination with the value 335957.66 USD and the highest is from MGT 200 with the value 6933552.05 USD. At scale 0.5 the lowest NPV of profit is from MGT 30 with the value 1237435.66 USD and the highest is from MGT 200 with value 1846424.82 USD. Lastly from scale 1.0 the lowest NPV of profit is from MGT 30 with the value 2496581.58 USD and the highest is from MGT combination with the value 3787686,84 USD.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

Biogas-fuelled micro gas turbine co-generation system (MGT-CGSs) with various output power were compared in different scales of sewage treatment plants under various ambient temperature condition and the following economics analysis result were obtained.

- The total capital cost increases when scale of the sewage treatment plant increases. This is because the total number of MGT used will be increase to support the heat demand and power demand from the sewage treatment plant.
- The electricity generated increases when the scale of the sewage treatment plant increase. This is because the power generated by MGT-CGSs in increases when the scale of the sewage treatment increases based on the power demand.
- The electricity generated also increase when the temperature changes from low to medium and to high. This is because more power demand at high temperature condition.
- The O&M cost increase when the scale of the sewage treatment plants increase. This is because the O&M cost is based on the power generated by the MGT-CGSs.
- The Payback period decreases when scale of the sewage treatment plant increases. The payback period also decrease from low temperature to high temperature. This is because MGT-CGSs will generated more power at high temperature and the total electricity generated will increase.

- In general MGT-CGSs generates more power in bigger scale sewage treatment plant. The power generated also increases when the ambient temperature is increase. This because greater scale has more power demand and need more electrical power.
- For NPV, the NPV of electricity sold, NPV of O&M and NPV of profit will increase when scale of the sewage treatment plants increase and ambient temperature condition increase. This is because the power demand and power generated increase when scale of the sewage treatment and ambient temperature condition increase.
- Based on the NPV method conclude that the MGT-suitable to operate at high temperature condition for power generation. MGT-CGSs also suitable to operate in large sewage treatment plant because it can operate in maximum capacity that will produce more income.
- Based on the result generally can conclude that MGT 200 is the best and has more economical value compare to others MGT, this is because MGT 200 has lower capital cost and maintenance cost compare to other MGT based on same scale. MGT 200 also give more profit compare to others MGT.

5.2 RECOMMENDATION

For further study, it is recommended to change the price of MGT-CGSs use, use newest price range of the MGT-CGSs that listed in the market. It will give more accurate result for the economics analysis and estimation about the system economic performance.

On the other hand, for the advanced economics analysis, other than Net Present Value method, net benefit method also can be used to do the advanced economic analysis.

Another suggestion for the further work is to use different output power of MGT to get more variety of result so the analysis can be done in

REFERENCES

1. Basrawi. F, Yamada T, Nakanishi K. Analysis of the performances of biogas-fuelled micro gas turbine co-generation systems (MGT-CGSs) in middle- and small-scale sewage treatment plants: Comparison of performances and optimization of MGTs with various electrical power outputs. 2011

2. J. V. Farr, Systems Life Cycle Costing. U.S,2011
3. Pilavachi PA. Mini- and micro-gas turbines for combined heat and power. Appl Ther Eng 2002.
4. Sovacool BK. The importance of comprehensiveness in renewable electricity and energy-efficiency policy. Energy Policy 2009.
5. Energy Nexus Group, Technology characterization -reciprocating engines. USA. Environ Protection Agency,2002.
6. Karellas S, Karl J, Kakaras E. An innovative gasification process and its coupling with microturbine and fuel cell systems. Energy 2008.
7. Basrawi F, Yamada T, Nakanishi K. Performance evaluation of a micro gas turbine co-generation system at a sewage treatment plant (performance analysis under various regions with different annual average temperature). Transactions of the Japan Society of Mechanical Engineers Series B 2010.
8. Advanced micro-gas turbine systems-Program plan for fiscal year 2000. USA: US Department of Energy ,2000
9. Greenhouse Gas Technology Center. Environmental technology verification report: capstone 60 kW microturbine CHP system. Greenhouse Gas Technology Center; 2003.
10. Basrawi F, Yamada T, Nakanishi K, Naing S. Effect of ambient temperature on the performance of micro gas turbine with co-generation system in cold region. Applied Thermal Engineering 2011.
11. Technology characterization-microturbine. Energy Nexus Group, USA Environmental Protection Agency; 2002.
12. Kim TS, Hwang SH. Part load performance analysis of recuperated gas turbines considering engine configuration and operation strategy. Energy 2006.

13. Marco ARN, Electo SL, Paulo SP, Rubenildo VA, Manuel AR, Osvaldo JV, et al. Biodiesel fuel in diesel micro-turbine engines: Modelling and experimental evaluation. Energy 2008.
14. Schicktanz MD,Wapler J, Henning HM. Primary energy and economic analysis of combined heating, cooling and power systems. Energy 2011.
15. Juha K, Jari B. Technical and economic performance analysis for a microturbine in combined heat and power generation. Energy 2007.
16. Basrawi F, Yamada T, Nakanishi K. Performance evaluation of a micro gas turbine co-generation system at a sewage treatment facility (2nd report,optimized configuration method of co-generation system). Transactions of the Japan Society of Mechanical Engineers Series B 2011.
17. Jurado F, Cano A, Carpio J. Biomass based micro-turbine plant and distribution network stability. Energy Conversion and Management 2004.
18. Bruno JC, Lopez VO, Coronas A. Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: case study of a sewage treatment plant. Applied Energy 2009.
19. Hur KB, Rhim SK, Park JK. Mechanical characteristics evaluation of biogas micro turbine power systems. Journal of Loss Prevention in the Process Industries 2009.
20. Basrawi F, Yamada T, Nakanishi K. Effect of ambient temperature on the energy Engineering 2010.

Appendix A

Temperature	Scale	MGT power	NPV for Electric sold
Low	0.25	MGT 30	346041.1
		MGT 65	365734.5
		MGT 200	337601.1
		MGT Combination	379242.9
	0.5	MGT 30	990994.6
		MGT 65	1045018
		MGT 200	957529.3
		MGT Combination	1089723
	1	MGT 30	2244873
		MGT 65	2443817
		MGT 200	2374478
		MGT Combination	2498635
Medium	0.25	MGT 30	702772.9
		MGT 65	761523.9
		MGT 200	743439.8
		MGT Combination	777638.9
	0.5	MGT 30	1695308
		MGT 65	1836871
		MGT 200	1827201
		MGT Combination	1875745
	1	MGT 30	3713295
		MGT 65	4088690
		MGT 200	4160384
		MGT Combination	4266746
High	0.25	MGT 30	902198.2
		MGT 65	961510.5
		MGT 200	968128
		MGT Combination	1040420
	0.5	MGT 30	1843601
		MGT 65	2027182
		MGT 200	2412589
		MGT Combination	2412589
	1	MGT 30	3710583
		MGT 65	4154042
		MGT 200	4154042
		MGT Combination	4791770

Appendix B

Temperature	Scale	MGT power	NPV for O&M
Low	0.25	MGT 30	24717.22
		MGT 65	26123.89
		MGT 200	12057.18
		MGT Combination	22483.69
	0.5	MGT 30	70785.33
		MGT 65	74644.12
		MGT 200	34197.48
		MGT Combination	64605.03
	1	MGT 30	160348.1
		MGT 65	174558.3
		MGT 200	84802.78
		MGT Combination	148133.3
Medium	0.25	MGT 30	50198.06
		MGT 65	54394.57
		MGT 200	26551.42
		MGT Combination	46102.88
	0.5	MGT 30	121093.4
		MGT 65	131205.1
		MGT 200	65257.18
		MGT Combination	111204.9
	1	MGT 30	265235.4
		MGT 65	292049.3
		MGT 200	148585.1
		MGT Combination	252957.1
High	0.25	MGT 30	64442.73
		MGT 65	68679.32
		MGT 200	34576
		MGT Combination	61682.02
	0.5	MGT 30	131685.8
		MGT 65	144798.7
		MGT 200	86163.88
		MGT Combination	143032
	1	MGT 30	265041.7
		MGT 65	296717.3
		MGT 200	148358.6
		MGT Combination	284083.5

Appendix C

Temperature	Scale	MGT power	NPV profit
Low	0.25	MGT 30	84083.88
		MGT 65	15910.6
		MGT 200	85543.89
		MGT Combination	36749.2
	0.5	MGT 30	445729.3
		MGT 65	484823.6
		MGT 200	443331.9
		MGT Combination	226938.3
	1	MGT 30	1214645
		MGT 65	1298158
		MGT 200	1569675
		MGT Combination	1148641
Medium	0.25	MGT 30	415334.8
		MGT 65	383429.4
		MGT 200	476888.3
		MGT Combination	211066
	0.5	MGT 30	1099735
		MGT 65	1220116
		MGT 200	1281944
		MGT Combination	964530.2
	1	MGT 30	2499100
		MGT 65	2825540
		MGT 200	3291799
		MGT Combination	2891008
High	0.25	MGT 30	600515.5
		MGT 65	569131.2
		MGT 200	693552
		MGT Combination	335957.7
	0.5	MGT 30	1237436
		MGT 65	1396833
		MGT 200	1846425
		MGT Combination	1548627
	1	MGT 30	2496582
		MGT 65	2886225
		MGT 200	3900103
		MGT Combination	3546757

Appendix D

Temperature	Scale	MGT power	Payback period
Low	0.25	MGT 30	14.76641
		MGT 65	19.06301
		MGT 200	14.74456
		MGT Combination	17.93983
	0.5	MGT 30	10.31244
		MGT 65	10.00749
		MGT 200	10.39713
		MGT Combination	15.57245
	1	MGT 30	8.346075
		MGT 65	8.558743
		MGT 200	6.289102
		MGT Combination	10.22641
Medium	0.25	MGT 30	7.27089
		MGT 65	9.155326
		MGT 200	6.695603
		MGT Combination	14.22951
	0.5	MGT 30	6.028149
		MGT 65	5.693377
		MGT 200	5.448527
		MGT Combination	9.067631
	1	MGT 30	5.504312
		MGT 65	5.115575
		MGT 200	3.589412
		MGT Combination	5.594615
High	0.25	MGT 30	5.663705
		MGT 65	7.251091
		MGT 200	5.141652
		MGT Combination	13.13488
	0.5	MGT 30	5.543264
		MGT 65	5.158886
		MGT 200	4.126503
		MGT Combination	6.353047
	1	MGT 30	5.508336
		MGT 65	5.035096
		MGT 200	3.116813
		MGT Combination	4.263517