

An-Najah National University

Faculty of Graduate Studies

Optimal Utilization of Biogas from Western Wastewater Treatment Plant of Nablus City

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Wastewater Treatment Plant of Nablus City**

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This Thesis was defended successfully on and approved by

Defense Committee Members

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Dedication

To anybody beleives in serving the humanity.

Acknowledgments

Thanks to God at the beginning and the end and every time. Thanks for my father, mother , brother and sister for supporting me along my life.

Special thanks to my supervisor dr. Abdelrahim abusafa for his patience and my friend eng. Ashraf Hijazi Imraish for his support.

v
الإقرار

إننا الموقع أدناه مقدم الرسالة التي تحمل عنوان

Optimal Utilization of Biogas from Western Wastewater Treatment Plant of Nablus City

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Declaration

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List of Abbreviations

AS	Annual savings
AWC	Annual worth of cost
AWE	Annual worth of energy
AW_{INVEST}	Annual worth of investment
$AW_{SALVAGE}$	Annual worth of salvage value
$^{\circ}C$	Degrees Celsius
CC_{ICE}	Capital cost of MGT per kW
CC_{MGT}	Capital cost of MGT
CH_4	Methane gas
CHP	Combined heat and power
$CO\&M_{MGT}$	Operating and maintenance cost of MGT
$CO_{2,ICE}$	Carbon dioxide production from ICE
$CO_{2,MGT}$	Carbon dioxide production from MGT
CO_2	Carbon dioxide
$CO_{2,BIOGAS}$	Carbon dioxide production from burning biogas
$CO_{2,CHP}$	Carbon dioxide from CHP
$CO_{2,G}$	Carbon dioxide from grid
$CO_{2,S}$	Carbon dioxide savings
$CO_{2,SHP}$	Carbon dioxide from SHP
$C_{U,E}$	Cost of unit of electrical energy
EC	Electrical capacity
E_{demand}	Electrical energy demand
EF	Emission factor
E_{in}	Input energy
$E_{out,elec}$	Output electrical energy
$E_{out,ther}$	Output thermal energy
E_p	Annual produced energy
H.V	Heat value
H_2O	Water
$\zeta_{elec,ave}$	Average electrical efficiency
$\zeta_{individual}$	Electrical efficiency of a device
H_2S	Hydrogen sulphide
HAP	Hazardous air pollutant
HRSG	Heat recovery steam generator
ICE	Internal combustion engine
ISO	International Organization for Standardization conditions

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kWH	Kilowatt hour
M_{biogas}	Annual production of biogas
$\zeta_{\text{elec., PL}}$	Electrical efficiency at partial load
$\zeta_{\text{elec., Nom}}$	Nominal electrical efficiency
m_{BIOGAS}	Monthly biogas production
m_{exh}	Mass flow rate of exhaust gases
MGT	Micro-gas turbine
Mtoe	Mega ton of equivalent
Mtons	Mega tons
MW	Mega watt
n	Number of days
$\Phi 1$	Thermal efficiency 1
N	Number of devices
N_2	Nitrogen gas
Φ_{average}	Average thermal efficiency
NH_3	Ammonia
NO_x	Nitrogen oxides
$NO_{x,ICE}$	Nitrogen oxides from ICE
$NO_{x,MGT}$	Nitrogen oxides from MGT
NPW	Net present worth
$O\&M_F$	Operating and maintenance factor
O.S	Operating strategy
O_2	Oxygen
P/H	Power to heat ratio
P_C	Power capacity
$P_{\text{elec.net}}$	Net electrical power
$P_{F.L,MGT}$	Full load power production
P_{in}	Input power
PL	Partial load
PM_{MGT}	Particulate matter from MGT
$P_{\text{out},1}$	Output electrical power 1
$P_{\text{out,one MGT}}$	Output electrical power if one MGT at PL
$P_{\text{therm.net}}$	Output thermal power
rpm	Revolution per minute
S.P.B.P	Simple payback period
SHP	Separate heat and power production
$SO_{x,ICE}$	Sulfur oxides from ICE

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SO_{xMGT}	Sulfur oxides from MGT
t	Time(hours)
T_{exh}	Exhaust gases temperature
VOC_{MGT}	Volatile organic compunds
WWTP	Waste water treatment plant
Φ_2	Thermal efficiency 2

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**Optimal Utilization of Biogas from Western Wastewater Treatment
Plant of Nablus City**

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Abstract

Wastewater treatment plants with anaerobic digesters produce sufficient quantities of biogas. One of the best methods to utilize biogas in such plants is the cogeneration technologies CHP, where two types of energy are produced from one fuel, i.e. electrical and thermal energy are produced on-site to be consumed in the same facility, and it is known that wastewater treatment plants are consumers of electrify and thermal power.

In this study; for Western Wastewater Treatment Plant of Nablus city as a case study; optimal unit sizing and arrangement of CHP units which were Micro-Gas turbines and Internal Combustion Engines was studied by conducting an energy, economic and environmental calculations and analysis.

The number of units to be operated every month was selected using four commercial Micro-Gas Turbines C30/30kW, C65/65kW, T100/100kW, C200/200kW from CAPSTONE manufacturer and three Internal Combustion Engines G3306/143kWe, G3406/235 kWe, CG132-8/400kWe from CATERPILLAR manufacturer, depending on the data of biogas production rates since there is instantaneous variation in these rates, but this variation is being regulated to a monthly level, using Biogas storage technology already being used.

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The number of Micro-Gas turbines or internal combustion engines that must be operated every month was calculated depending on the fact that these engines give the maximum efficiency when operated at full load or near it.

Some of the alternatives can produce the needed annual thermal energy of **2137MWh** as a total, but may have shortage during some months.

It was found that the alternative which produced the maximum electrical energy was using one unit of the Internal Combustion engine **CG132-8/400kWe** with yearly energy production of **2442 MWh**.

Economic analysis were done using annual worth of cost calculation and finding the levelized cost of electrical energy, also, the total yearly saving from each alternative was also calculated. It was concluded that the using one unit of the Internal Combustion engine **CG132-8/400kWe** has the lowest value of unit energy cost of **0.09\$/kWh** and annual savings of **195,243\$/year**.

Environmental analysis were conducted to investigate the total CO₂ emissions and other pollutional emissions, and was found that the alternative of using one unit of the Internal Combustion engine **CG132-8/400kWe** produced the maximum saving of CO₂ production with a value of **2,203 Ton/year** instead of the current situation of separate heat and electricity generation with CO₂ production of **3,912Ton/year** Achieving a total CO₂ saving of **1,709Ton/year**.

1. Chapter One – Energy Overview

Energy is the fuel of our life; it drives everything beginning from single cell creations up to huge factories and vehicles. The conservation of energy law states that the total amount of energy is conserved, it is being converted from one type to another, but several types of it are not useful in state they are on; so our mission is to convert energy into useful types, and this is the challenge.

Energy is one of the main drivers of economic and social development. The main dependence nowadays is mainly on conventional energy sources i.e. the fossil fuels: oil, coal and natural gas, these sources cover about 80% of the world's total energy consumption. Just few years ago, the only uncertainty about energy was the prices of oil. Nowadays it extends to include several factors. The world's energy demand is increasing in a rate that is faster than the population's increasing. [1]

As shown in figure 1.1, the world is consuming about 13 966 Mtoe of energy and this value is increasing dramatically and expected to be doubled in 2050.

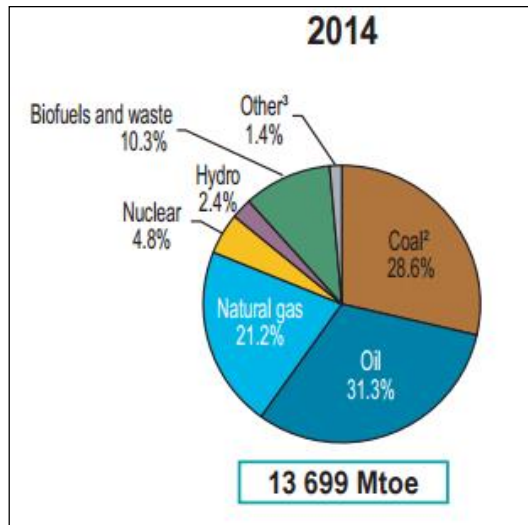


Figure 1.1: World's Energy Sources in 2014 [2]

The conventional energy sources are being depleted and the consumption is dramatically increasing. Also, the pollutional effect on these sources and the prices are going up affecting all of human life aspects.

Gases released by the burning and combustion of fossil fuels include carbon monoxide, nitrogen oxides, sulfur oxides and hydrocarbons. These gases cause many environmental effects such as acid rain and global warming. The world is producing about 32381 Mtons of CO₂ annually, registering a doubled quantity if compared to the year 1973 during which the world's CO₂ production was 15 458 Mton as shown in figure 1.2. [2]

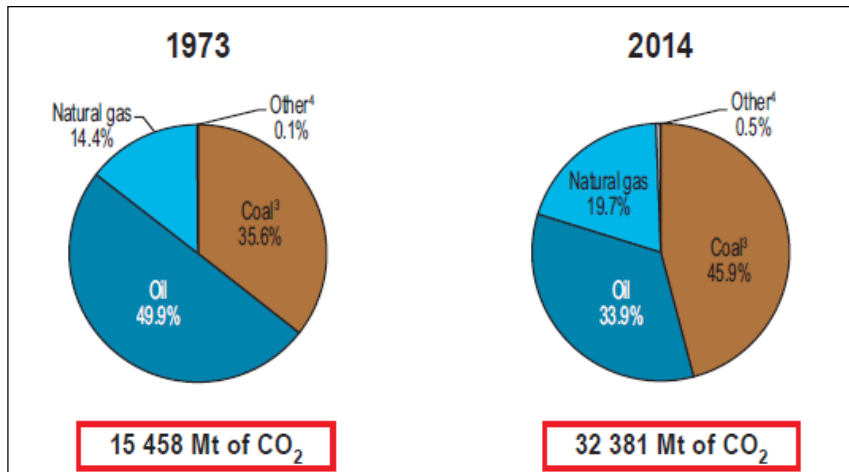


Figure 1.2: World's CO₂ production in 2014[2]

The Kyoto Protocol was adopted in Kyoto, Japan, on 11 December 1997 and entered into force on 16 February 2005. There are currently 192 parties; it is aimed at reducing greenhouse gases especially CO₂.

This leads us to find alternative renewable sources of energy that can meet the increasing demand and is not being depleted while being used, and not affecting the environment.

1.1 Renewable Energy

Renewable energy is energy that is derived from natural processes (e.g. sunlight and wind) that are replenished at a higher rate than they are consumed. Actually, they all originate from sun. Solar, wind, geothermal, hydropower, ocean power and bioenergy are sources of renewable energy, they can offer continuous and sustainable sources of energy.

Renewable energy sources derive their energy from sun directly or indirectly such as hydro and wind, are expected to be capable of supplying energy for almost another 1 billion years.

Renewable energy resources exist over wide geographical areas, in contrast to other energy sources, which are concentrated in a limited number of countries.

Climate change and global warming concerns, coupled with high oil prices, peak oil, and increasing government support, in addition to energy security concerns, are driving increasing renewable energy legislation, incentives and commercialization.

Figure 1.3 shows the total world dependence on renewables, which is planned to increase on the coming years.

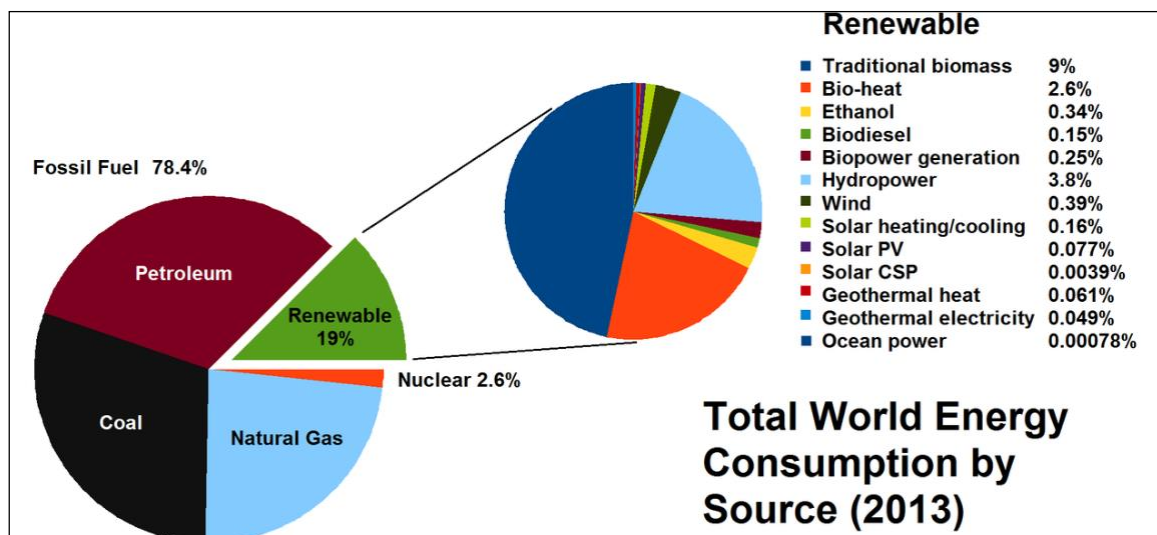


Figure 1.3: World's Renewable Energy Sources in 2013. [2]

1.2 Energy Sustainability

Sustainable energy is energy that is consumed at insignificant rates compared to its supply and with manageable collateral effects, especially environmental effects. Another common definition of sustainable energy is energy system that serves the needs of the present without compromising the ability of future generations to meet their needs. Figure 1.4 shows the components which that integrate to give the energy sustainability, which are: social, environmental and economic development.

The energy sustainability can be achieved by several strategies starting from energy efficiency policies and ending with using renewable energy resources where they are available and feasible.



Figure 1.4: Energy Security Factors

One new modern concept in energy sustainability is the distributed energy generation which depends on generating the needed energy on-site, eliminating the needs for power transition saving the losses of power

transportation which accounts for at least 10% of the generated value, and letting every area to produce the energy which is suitable to its resources.

Biomass is considered as one of the most important sustainable and distributed energy generation sources.

Biomass is one of the faces of renewable energy sources, it can be derived from multiple sources; municipal solid waste, wastewater treatment plants, energy crops, green residuals.

1.3 Biomass

Biomass is biological material derived from living, or recently living organisms. As an energy source, biomass can be directly combusted to produce heat, or indirectly used after converting it into biofuels. Conversion of biomass to biofuel can be achieved by different methods which are broadly classified into: *thermal*, *chemical*, and *biochemical* methods.

Biomass is a renewable energy source not only because the chemical energy in it originates from the sun, but also because biomass can re-grow over a relatively short period of time and convert the carbon dioxide in the atmosphere to organics again through photosynthesis process compared with the hundreds of millions of years that it took for fossil fuels to form. When these carbohydrates are burned, the bonds between hydrocarbons are broken; they turn back into carbon dioxide and water and release the

energy they captured from the sun resulting in zero-carbon short cycle.

Figure 1.5 shows the main types of biomass. [3]

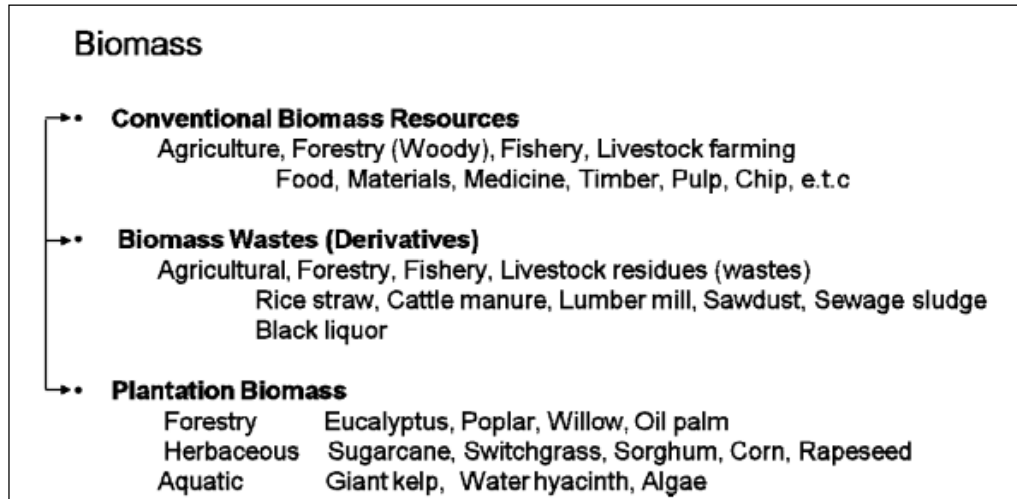


Figure 1.5: Biomass sources [3]

1.4 Biomass to Energy Conversion Methods

Biomass resources include three levels; level one which is the biomass directly taken from land such as woody crops and agricultural residues. The second level includes the biomass result from processing the first level physically, chemically or biologically. The third level includes post-consumer residues.

Biomass to energy can pass through several alternative processes as shown in figure 1.6 depending on the type of desired energy output, the type of biomass and its quantity, economic and environmental considerations.[4]

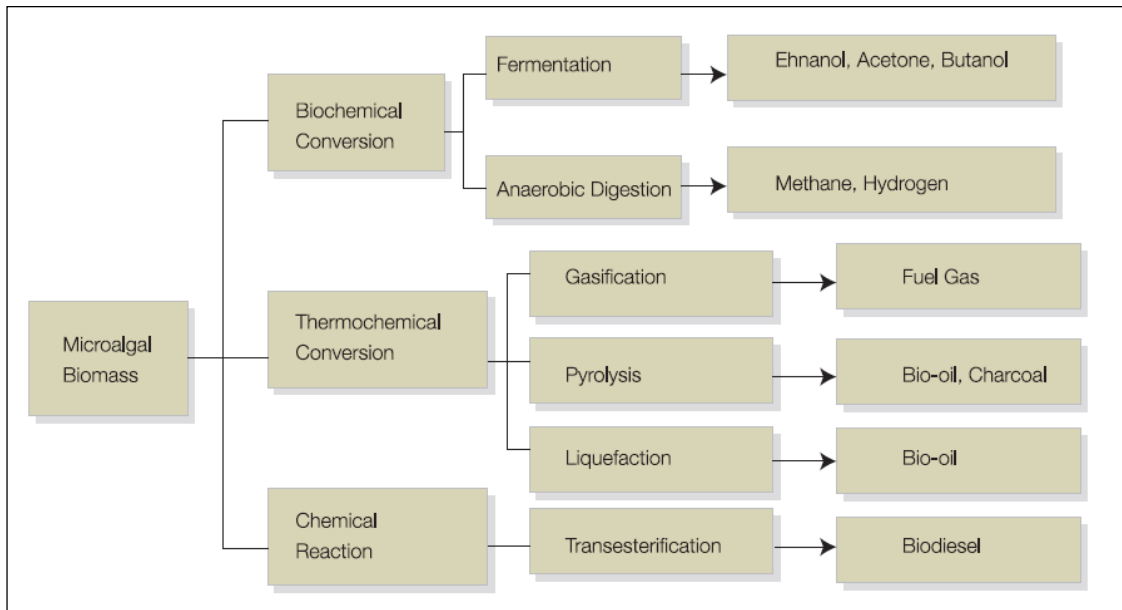


Figure 1.6: Biomass to energy pathways

1.5 Anaerobic Digestion

Anaerobic digestion is the degradation of organic material contained in sewage sludge, municipal solid waste, manure and agricultural residues in the absence of oxygen. Anaerobic digestion is achieved through three or four stages: hydrolysis, acidogenic and methanogenic by bacteria that can operate on two ranges of temperature and called mesophilic or thermophilic. Anaerobic digestion can convert about 90% of organic material into biogas and leaving digestate that can be stabilized into soil fertilizer. [4]

1.6 Biogas

Biogas is produced from some wastes such as manure, organic fraction of municipal solid waste, food and agricultural waste and sewage sludge by anaerobic bacteria in the absence of oxygen. Biogas is a mixture

of gases produced thorough different stages of digestion process. The composition of biogas is shown in figure 1.7. Biogas can be used for same applications of natural gas in cogeneration arrangement with some treatment needs or without depending on the desired application. Treatment is generally removing biogas CO_2 content to raise its heating value and H_2S removal for preventing the utilization device from corrosion.

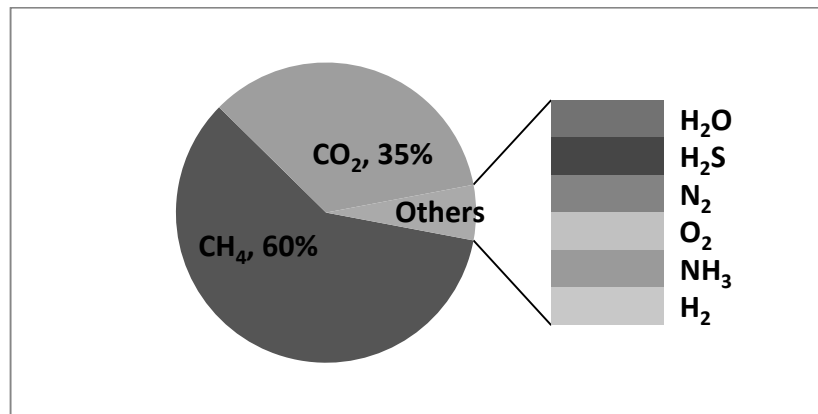


Figure 1.7: Biogas composition. [10]

1.7 Wastewater Treatment Plants

Wastewater treatment depends on removing contaminants from wastewater by physical means that removes bulky objects and grit, biological treatment that employs aerobic organisms to consume the dissolved organics in wastewater and chemical treatment; to produce environmentally-safe stream of water or to be reused. Figure1.8 shows the stages of wastewater treatment.[5]

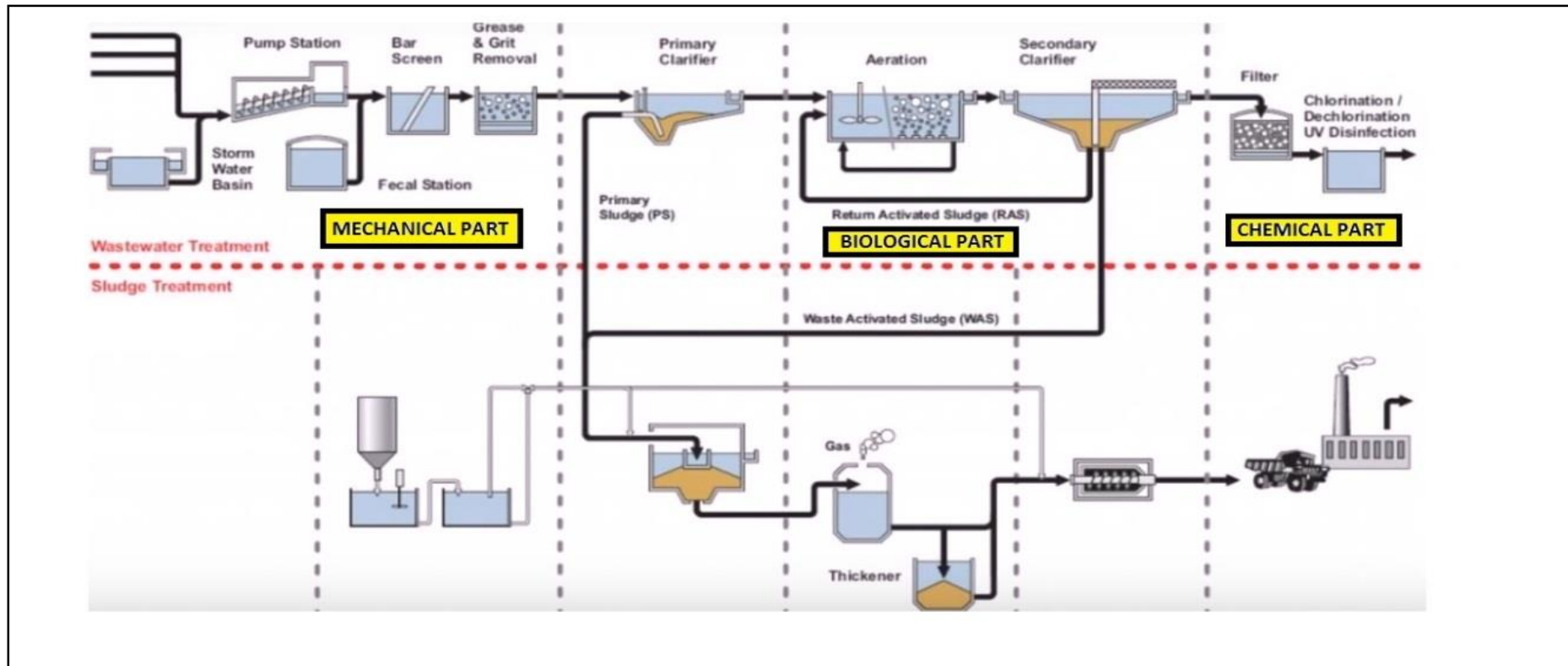


Figure 1.8: The sewage treatment Plants process

1.8 Problem Statement

Palestine has no natural sources of energy, no power generation stations, and imports all of its energy from the neighboring countries.

One of the solutions of this lack of energy sources is the dependence on renewable energy sources available in Palestine such as solar energy and biomass energy.

Biomass can be considered as the oil of Palestine, since we have mass quantities of agricultural wastes, municipal wastes and wastewater treatment facilities.

In the last few years, wastewater treatment facilities started to be a well-known tradition in Palestine; several municipalities have constructed their own wastewater treatment plants and started to produce enough quantities of biogas.

One of the constructed facilities is the western wastewater treatment plant of Nablus municipality.

The wastewater treatment plant consumes large amount of energy for its activities resulting in a large electricity bill monthly.

1.9 Strategy to Solve the Problem

The scenarios to deal with this problem may be one of the following:

- Utilizing all of the produced biogas: this strategy will be used in this study since our target is optimizing the biogas to electricity energy conversion process.
- Meeting dominantly the electrical energy demand of the facility: the electrical energy demand of the facility is higher than the electrical energy expected to be produced from this plant so no energy conversion process can produce enough electricity from the produced biogas to drive the plant electrical demand.
- Meeting dominantly the heat energy demand of the facility: the waste heat from any energy conversion process is more than electrical energy and usually contains 60 – 70% of the input fuel energy, so we always have excess heat from any energy conversion process that can cover the plant's energy needs and more.
- Meeting both the electrical and the heat demand of the facility.

Figure 1.9 shows the suggested situation; in which the cogeneration strategy will be utilized. In this strategy, the electricity will be generated on-site and the waste heat from this process will be used to heat the digester, in a process called combined heat and power, i.e. two types of energy will be produced from one fuel.

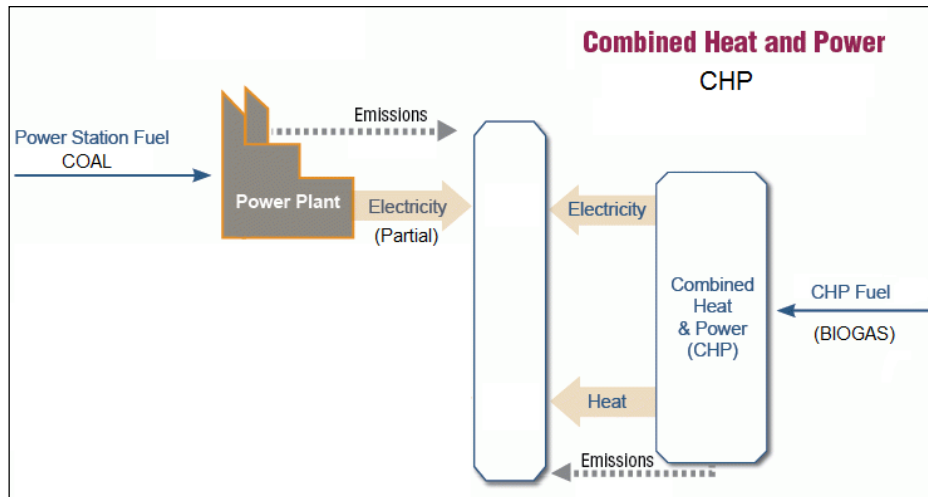


Figure 1.9: New situation model (CHP)

1.10 Objectives of This Thesis:

- The main objective of this work is utilizing the biogas produced from western waste water treatment plant of Nablus city.
- Compare between several alternatives to deal with the biogas potential produced from this plant from technical, economic and environmental point of view.
- Evaluate the technical, economic and environmental feasibility of utilizing biogas in internal combustion engine in CHP arrangement.
- Evaluate the technical, economic and environmental feasibility of utilizing biogas in micro-gas turbines in CHP arrangement.

2. Chapter Two - Wastewater Treatment Plants in West Bank

Palestinian territories (West Bank & Gaza strip) have no natural resources; it does not produce oil or natural gas. The dependence on energy supply in its two main types (electrical energy and fossil fuels) is from the neighboring countries especially Israel (88%). Small fractions are supplied by Jordan and Egypt to Jericho and Gaza strip. The cost of energy in these areas is one of the highest in the area especially when compared to low average income and high levels of poverty and unemployment. Under the pressure of economic considerations and energy security needs, untraditional sources of energy are desired. The renewable energy sources are available in Palestine in two major types: solar energy and biomass. Solar energy is already being utilized by Palestinians through solar water heaters to supply domestic water needs, and some PV systems for electrification of some rural areas. Biomass sources of energy are already utilized by direct combustion of woody crops (about 15%) of the total supply of energy in Palestinian territories. Other potential for biomass includes the organic fraction of municipal solid waste (1300Ton/day of municipal waste from Gaza strip), the agricultural residues from crops and livestock manure and dung since the Palestinian community is an agricultural one.

Recently, several wastewater treatment plants were established in West Bank and Gaza Strip, these plants act as a source of sewage sludge which is another type of biomass source. [6]

2.1 Waste Water Treatment Plants in The WB and Gaza Strip

About 45 Wastewater Treatment plants are present in West Bank and Gaza Strip, some are operating, some are under construction, and others are in the design phase. Table 2.1 shows that the plants' capacities range from 100 – 60,000 m³/day serving populations ranging from 1000 – 500,000 people with total costs of 0.5 – 38 Million \$ per plant. The plants consume electrical energy at a rate of 0.76 kWh/m³, and produce biogas with a rate of 0.29 kg/m³ of treated wastewater. The details of these plants are given in app. A.1 [7].

Table 2.1: Wastewater treatment plants in West Bank and GAZA Strip[7]

Area	Total Design Capacity	Total Estimated Cost		# of plants	Total Population Served	Estimated electricity consumption kWh/day	Expected Biogas Production kg/day
	(m ³ /day)	\$	[Million]				
Northern West Bank	58000	\$	232	19	446000	44,080	16,820
Middle of West Bank	22000	\$	59	13	234000	16,720	6,380
Southern West Bank	26000	\$	94	10	667000	19,760	7,540
Gaza Strip	103000	\$	124	3	1,011,232	78,280	29,870

The previous table shows that total biogas production and its energy content can supply enough portion of the energy demand of the wastewater treatment plants constructed or under construction.

2.2 Western Wastewater Treatment Plant of Nablus City

Nablus western wastewater treatment plant started its operation in July 2013 as one of the plants that were recently established in the west bank, with a total capital cost of 40Million euro. The treating capacity of the plant is 14,000 m³/day. It treats wastewater resulting from the Nablus western area and the nearby western villages of Deir sharaf, Beit Iba, Beit Wazan, Qusin and Zawata. This plant consists of concrete pipe line of sewage along 12 km extending from Tunis Street in western area of the Nablus city until in the treatment plant in Wade Alzumr. The plant is extendable to treat 15,000 m³/day. The effluent from the plant is released to a nearby valley. [7]

The wastewater treatment plants in the West Bank aim at:

- Reducing the environmental impact of wastewater stream.
- Saving the surface water and ground water and springs from contamination.
- Reuse water for agriculture and industrial activity which reserves the drinking water reserve.
- Prevent the use of wastewater on agricultural lands. [7]

Figure 2.1 shows the components of Western WWTP of Nablus city and explains the process and also shows the sources of sludge which is the source of biogas.

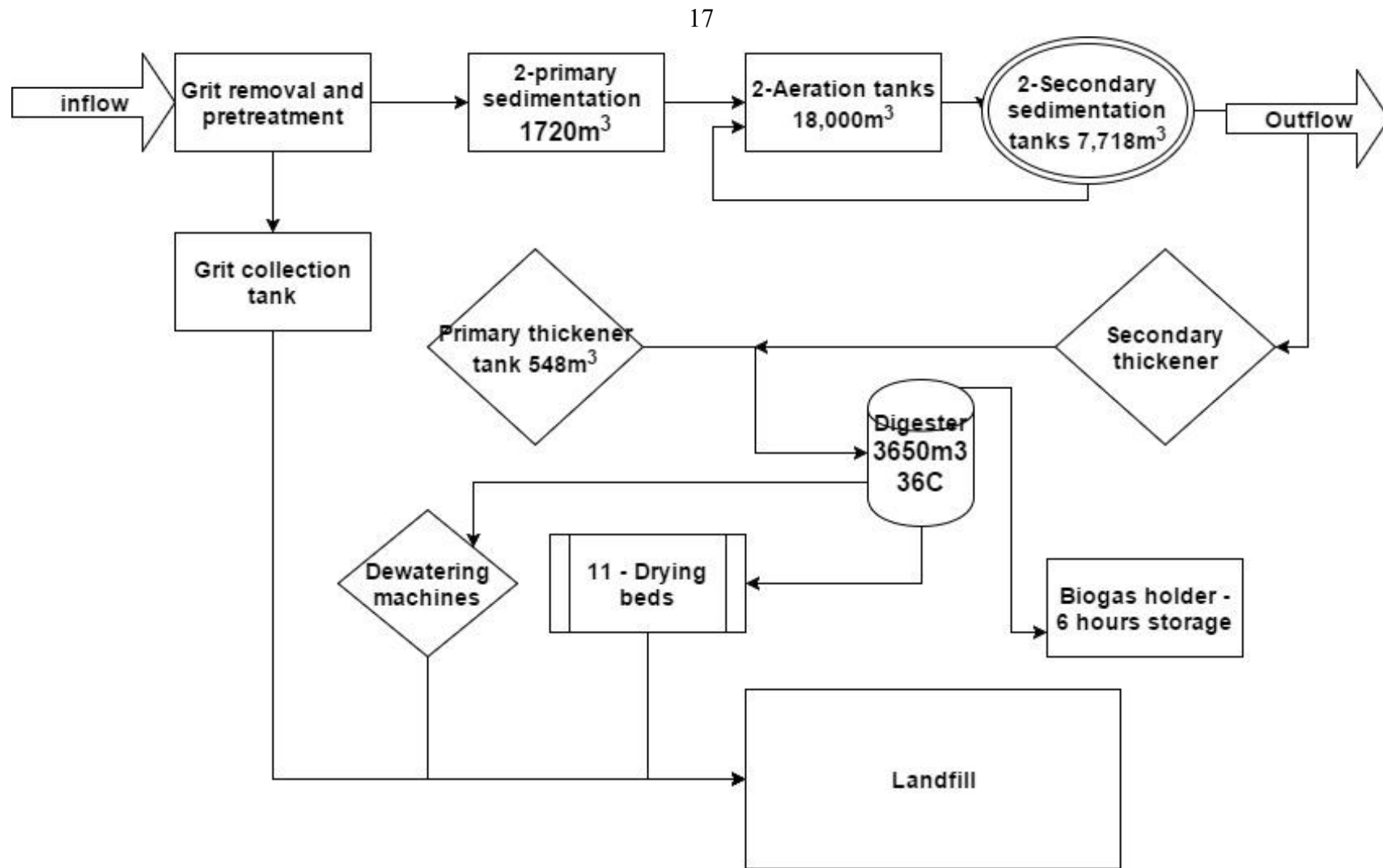


Figure 2.1 : The components of Western WWTP of Nablus city. [7]

2.2.1 Current Energy Situation in WWTP

Figure 2.2 shows the current situation in the plant, in which the electrical energy is supplied from the grid, and the thermal energy needed to attain suitable temperature in the anaerobic digester is supplied from a boiler combusting biogas produced from the digestion process. So we have separate heat and power generation situation.

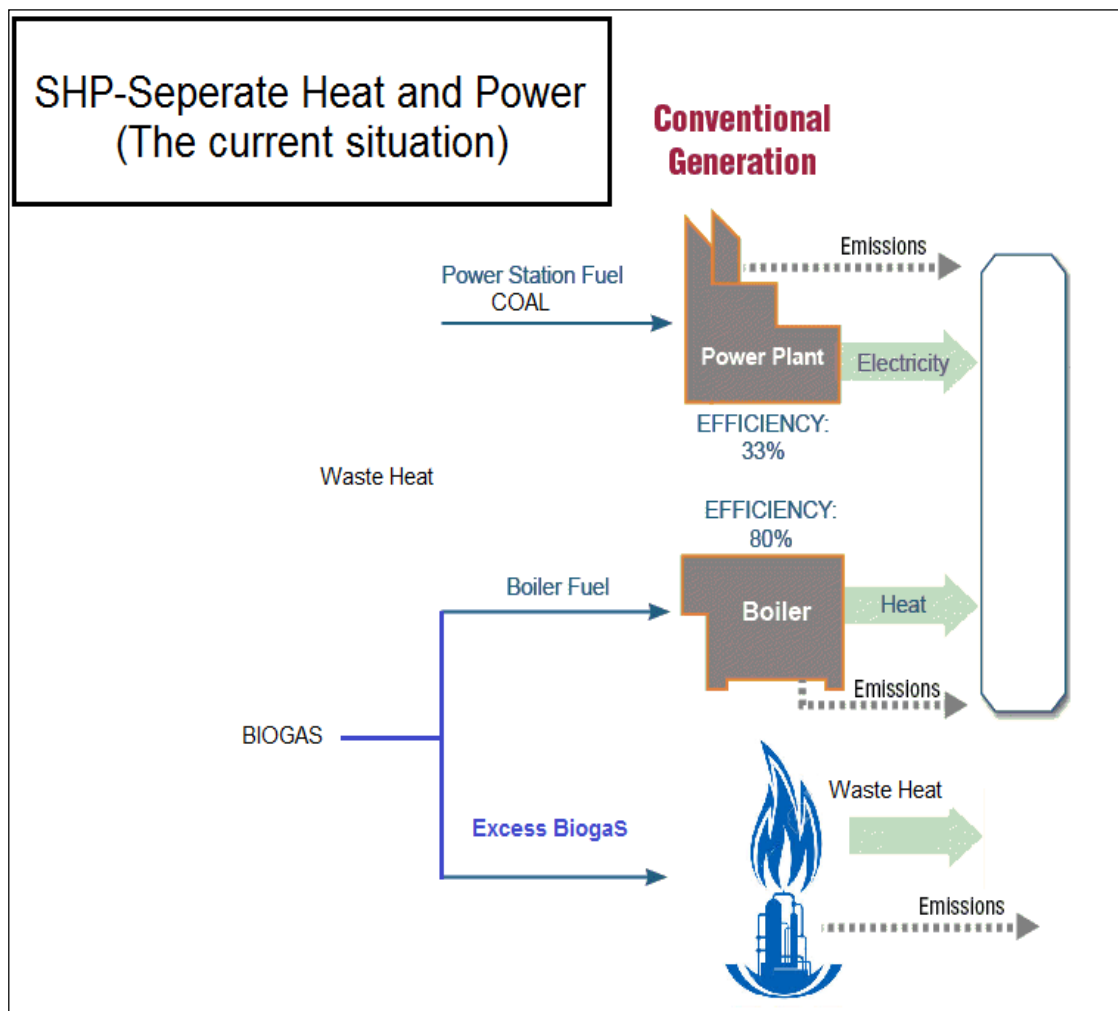


Figure 2.2: Current situation model (SHP)

The wastewater treatment plant processes an average flow of about 9,646 m³/day of wastewater and consumes an average value of 236,000 kWh/day of electricity and the digester produces an average value of 2,786 kg biogas daily as shown in figure 2.3.

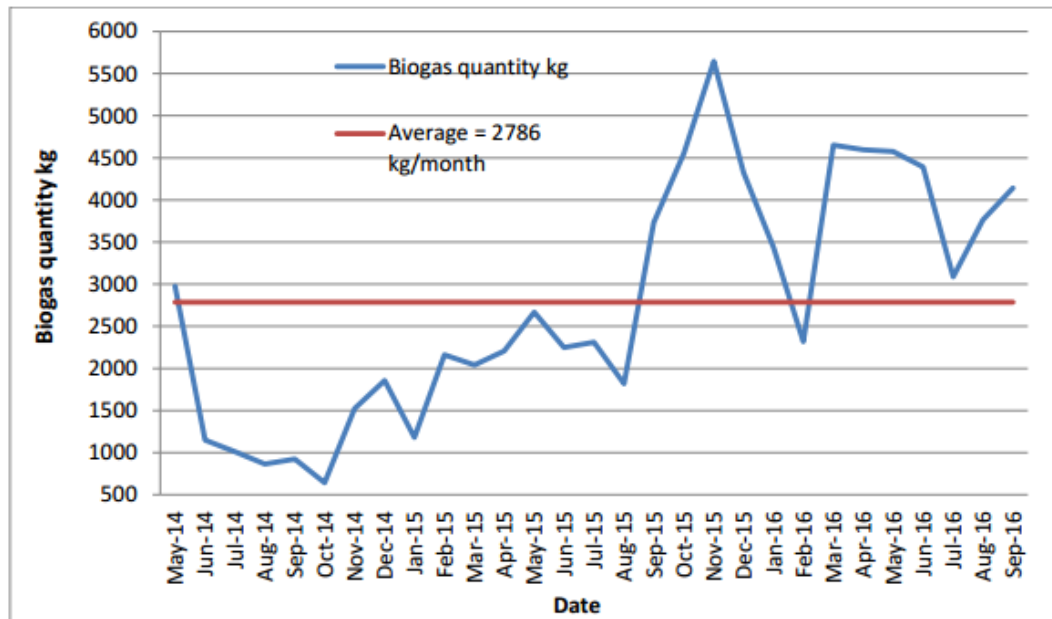


Figure 2.3: Average monthly quantities of Biogas [7]

Electricity consumption of plant varies daily depending on the wastewater influent. While the heat demand of the digester is almost constant .figure 2.4 shows the electrical and heat energy demand of the WWTP for the studied period.

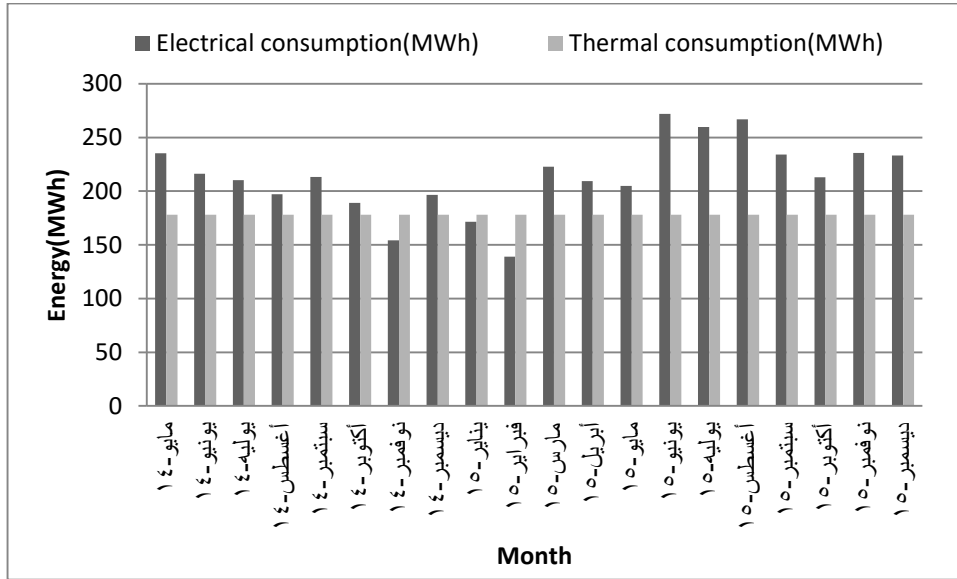


Figure 2.4: Monthly electrical and thermal loads of WWTP. [7]

Table 2.2 gives a brief description about the WWTP of Nablus showing its flow and biogas production and energy consumption.

Table 2.2: WWTP Operating Characteristics [7,8]

Daily Average treated flow (September 2016)	9646 m ³ /day
Monthly Average treated flow (Sep2015-Sep2016)	332790 m ³ / month
Daily Average Biogas production rate	2786 kg / day
Digester Average Heat consumption	5739 KWh/day
Average monthly electrical consumption	236023 KWh / month
Electricity consumption per flow	0.76KWh/treated m ³

2.2.2 Fluctuations in Biogas Production

Due to the variation in wastewater flow during the day and during seasons, as shown in figure 2.5, in addition to the variation of the organic fraction contained in this flow; the production rate of biogas varies and so the energy content of it varies. Figure 2.6 shows a sample of the daily variation

of biogas production and its deviation from an average value. Biogas production quantities on hourly basis are shown in app. A.2.

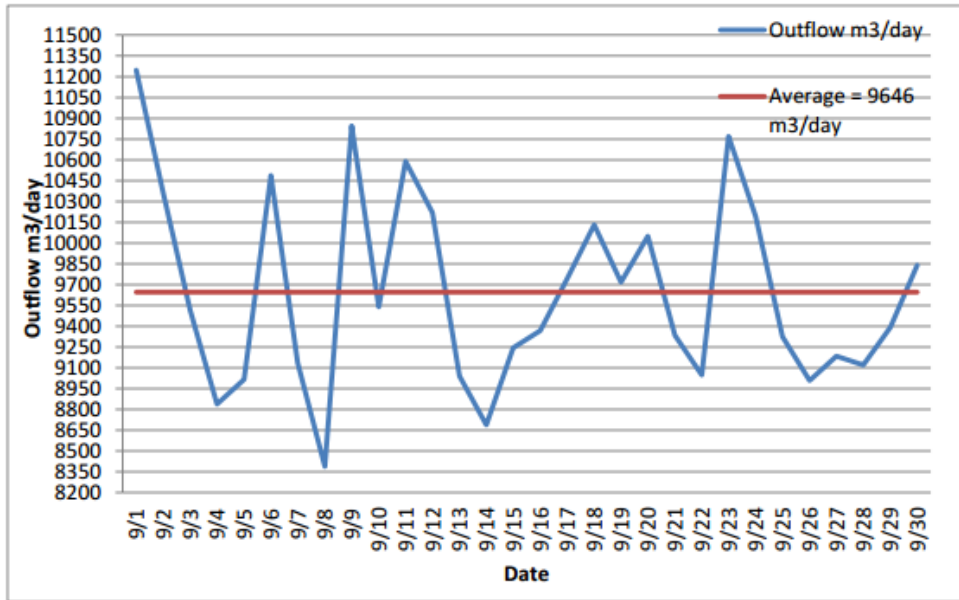


Figure 2.5: Influent Wastewater flowrate. [7]

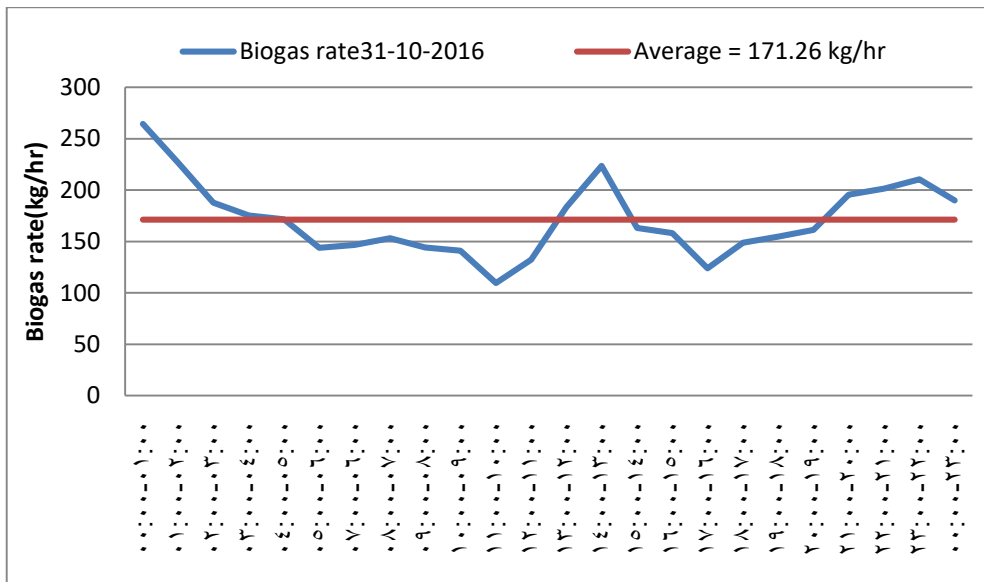


Figure 2.6: Daily biogas production rate. [7]

2.2.3 Photos Tour in the WWTP



Figure 2.7: General view of treatment facility



Figure 2.8: Biogas facilities (Digester , Boiler and CHP room , sludge dewatering, biogas holder).



Figure 2.9: Anaerobic Digester



Figure 2.10: Aeration Reservoirs



Figure 2.11: Primary Sedimentation Reservoir





Figure 2.12 : Secondary Sedimentation Reservoir

2.2.4 Recently Operated CHP unit

On 18/6/2017, an internal combustion engine of 400kW electrical capacity has been operated in the WWTP. The engine is fueled by biogas produced from the digester. It is being planned to operate the engine at 80% of its capacity. The engine is arranged to be a CHP (cogeneration) unit to produce electricity to feed the plant processes and thermal energy to heat the digester contents. The unit is still in testing stage and has produced 93,410kWh during July-2017 which represents about 34% of the plant electrical consumption.



Figure 2.13: Recently Operated CHP unit

3. Chapter Three - Literature Review

Wastewater treatments plants are using anaerobic digestion to degrade the sludge and produce biogas which is used through boilers to generate thermal energy needed by digesters with large portion of waste biogas. [9]

The rate of biogas production at WWTPs is not constant and may vary both on seasonal and hourly time bases. Depending on the magnitude and rate of fluctuations in biogas production, the operation of reciprocating engines, gas turbines or fuel cells could be disrupted. The two most commonly implemented strategies for mitigating the effect of biogas production fluctuations are (1) to introduce a biogas storage system or (2) to supplement biogas deficiency with natural gas. Biogas is typically stored only for short-terms and at low pressures. This is because long term storage requires biogas pressurization. The energy input for biogas compression to a typical storage pressure of 250 psi is equal to approximately 10% of the energy value of stored biogas.[10]

Several prime movers technologies suitable for biogas utilization at WWTPs. The most commonly employed are reciprocating engines, gas turbines, microturbines and fuel cells. The choice of the technology for a particular application is dependent on the size of the biogas source, biogas contaminants levels, required fuel pretreatment, local utility pricing, local emissions regulations and local incentives. [10]

Micro-gas turbines are new generation of prime movers that can be used on-site to produce energy and utilize the waste heat to supply the heat demand of waste water treatment plant .[9]

K.C Goli[16] revealed that the small size of microturbines is a major advantage that allows them to be situated right at the source of electricity demand. This eliminates energy losses that usually occur when transmitting electricity from power stations. Such transmission losses are quite significant and can easily amount 7% of the power generated. Microturbines are a new class of small gas turbines used for distributed generation of electricity. [11]

While the larger capacity micro-gas turbines are more efficient and have less capital costs; they have poor efficiency when they are operated at partial load, so when there is variable load in WWTP. Multiple units can be used and operated to achieve optimum efficiency. [9]

The optimum unit sizing and number of micro-gas turbine units to supply WWTPs have been studied by Firdaus Basrawi [9], who tried to find the optimal unit number and size of MGT fueled by WWTP biogas. Economic analysis were developed by Net Present Value comparison of several arrangements of 3 types of MGT in cogeneration operation, and used partial load relations to calculate the output power and energy in each case.[9]

Several connection modes including one-way, two-way, heat demand-following modes were studied by Mehdi Meybodi [12] to find the optimum arrangement and operating strategy of MGT in small scale CHP systems.

Mehdi has developed technical-economic approach depending on modeling the partial load performance by finding relations of partial load efficiency and exhaust temperature and flow rate and using Net Present Worth analysis to find objective function (NPW\$).

Thermodynamics was used by Sepher Sanaye [13] to develop thermal model to find electrical and thermal energy produced from MGT in small scale CHP systems. Then partial load relations were derived from manufacturers' tables. Objective function AP to find Annual worth of each case was developed.

Three strategies were studied by Sergio Camporeale [14] to operate micro turbine in CHP operation and match the electrical and thermal consumption of a residential building. The strategies depended on following the base-load, following the electrical load and following the thermal load. For this purpose; a techno – economic approach was developed.

The levelized cost of electrical energy was calculated by Konstantinos P. [15] by calculating the total annual economic cost which consists of the annual worth of capital coat and the O&M costs and dividing it by the annual electrical energy production from the project.

The effect of prime mover electrical capacity of MGT fueled by biogas in WWTP was studied by Firdaus Basrawi [16], by developing a techno economic model and considering the use of combinations of non-identical capacities of MGT units instead of identical units.

The performance of MGT in WWTP was studied by Takanobu [17] by considering different scales of WWTPs in different areas with different temperature ranges and so variable thermal consumption.

4. Chapter Four - Biogas Utilization Alternatives

Biogas can become a useful product only when it is converted into energy; Biogas energy is a renewable energy since it originates from sun and it is a part of short cycle that takes energy from sun and supplies us with it.

Biogas energy can be utilized using all techniques and equipment that are used in utilizing natural gas and fossil fuels with retrofit. Biogas has different composition and lower heat value and may also need upgrading to remove some undesired components such as H_2S before some types of utilization such as engines.

Since the biogas production process needs heat; many Biogas utilization strategies can be arranged in combined heat and power arrangements or what is called cogeneration; cogeneration is the production of two forms of energy from one source in a process. And this raises the total efficiency of the utilization system.

Four main utilization technologies are available for biogas:

- Engines (Internal combustion engines and turbines).
- Direct combustion in boilers.
- Fuel cells.
- Injections to natural gas pipelines and refuel stations.

The alternatives to deal with biogas are shown in figure 4.1, where the most suitable alternative is the use of internal combustion engines or gas turbines in cogeneration arrangement to produce electric power and heat energy for the digester.

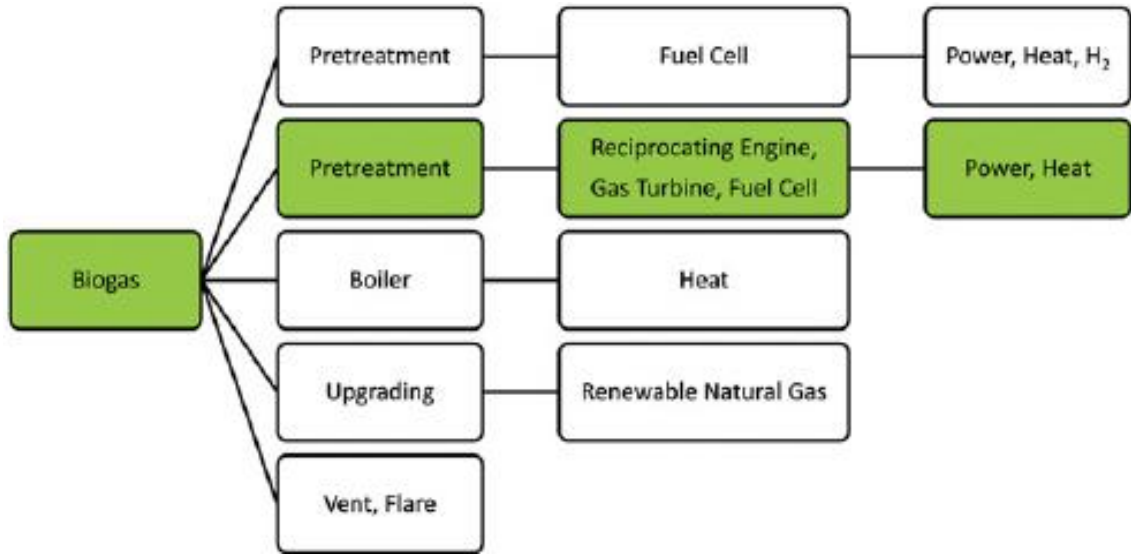


Figure 4.1: Biogas Utilization Alternatives. [10]

4.1 Cogeneration

Cogeneration is the production of two types of energy from single fuel, the concept is shown in figure 4.2. The produced energy is mechanical energy that is used to drive a mechanical application or electrical generator, the other type is heat or thermal energy that is used to produce hot water or low pressure steam for being used by another process. [18]

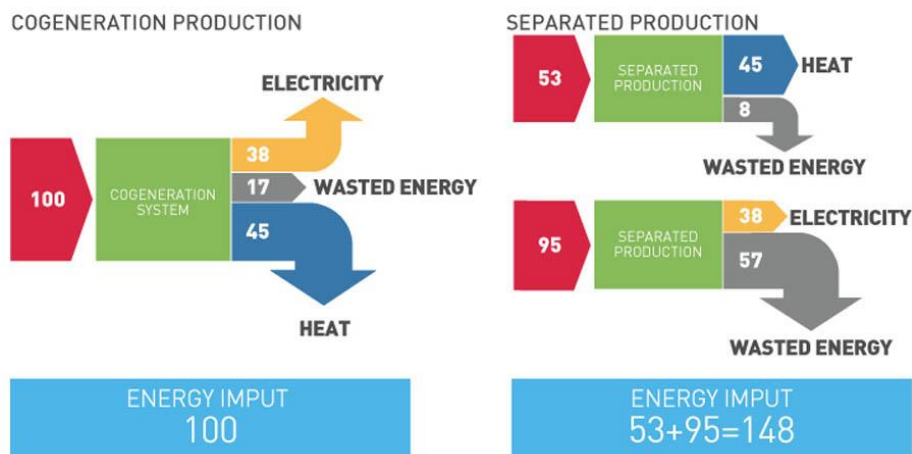


Figure 4.2 : Difference between combined heat and power and separate heat and power generation. [19]

4.1.1 Types of Cogeneration Systems

Two main types of cogeneration systems available, depending on the dominant output from the system:

1. **Topping cycle:** Power is the dominant product of this cycle and waste heat is used to drive another cycle that needs heat or hot water or steam. [18]
2. **Bottoming cycle:** Heat is the dominant product of this cycle and waste heat of the process is used to drive electricity generation cycle. This cycle is used in industrial applications that need high thermal energy and have high temperatures waste heat. An example of this cycle is the furnace in a metal factory that needs very high temperatures for melting; the waste heat from the furnace is used to produce steam for another application in the factory or hot water for buildings' heating. [18]

4.1.2 Types of Topping Cycles

Four types of cogeneration cycles are available to utilize biogas.

1. Heat Recovery to Drive Steam Turbine (Combined Cycle)

In this cycle, shown in figure 4.3, two power cycles are combined through a heat recovery steam generator (HRSG) which transfers waste exhaust heat from a gas turbine cycle to be used as input heat in a steam turbine power cycle. [20]

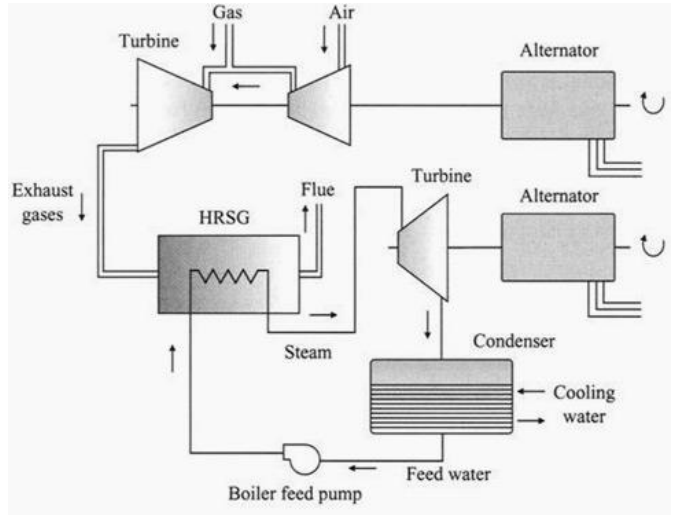


Figure 4.3: Combined cycle [21]

2. Heat Recovery in Micro-Gas Turbines

Exhaust gases exit from the recuperator of micro-gas turbines at about 260-315°C that allows more thermal energy to be recovered by additional heat exchanger (shown in figure 4.4 III-section), this energy can be used in processes that needs hot water or low pressure steam (2 bar) or even direct heating since microturbine exhaust is clean, also adsorption cooling can utilize this excess heat. [22, 23]

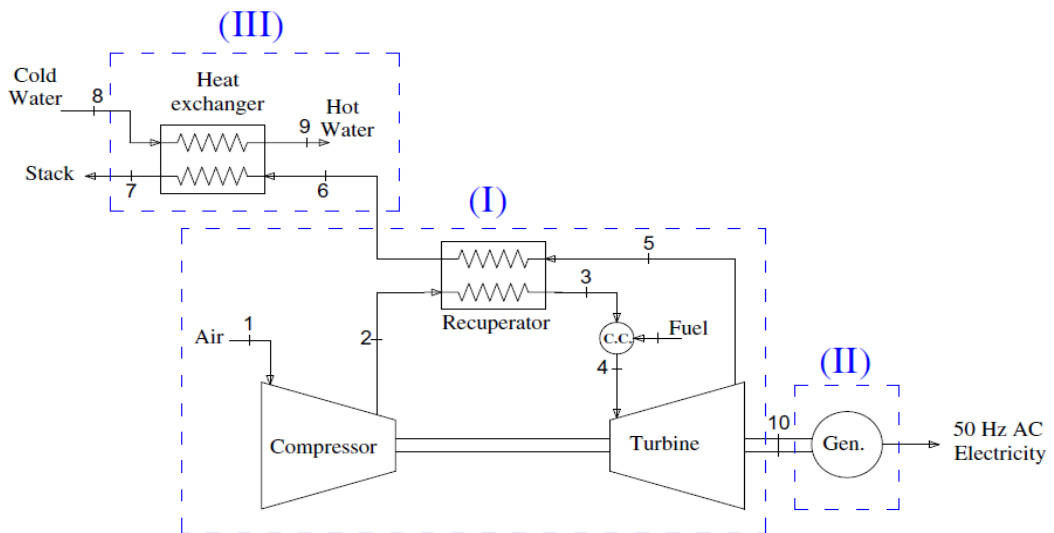


Figure 4.4: The schematic diagram of a microturbine in a combined heat and power system [10]

3. Heat Recovery in ICE

Internal combustion engines using cogeneration are mainly spark ignition engines fueled by natural gas and other gaseous fuels (biogas, landfill gas). They are commonly used in industrial facilities, water treatment facilities, universities, hospitals, commercial and residential buildings. Facility capacities range from 30 kW to 30 MW, with many larger facilities comprised of multiple units. [22]

The thermal energy contained in the exhaust gas and cooling systems of the internal combustion engines contains 60 -70 % of the input energy introduced to the engine as fuel. The economics of engines in distributed generation and on-site power generation applications depend on effective recovering of the waste heat is available in the engine exhaust and jacket coolant, while smaller amounts can be recovered from the lube oil cooler and the turbocharger's intercooler and after cooler. Jacket coolant and lube oil cooling systems contain 45 to 55 percent of the waste heat from engine. [22]

About 30 % of the energy input of the engine is contained in the jacket coolant and is capable of producing 90 to 110 °C hot water. Some engines, such as those with high pressure or ebullient cooling systems, can operate with water jacket temperatures of up to 130°C. 30 – 50% of the available waste heat is contained in the engine exhaust. Exhaust temperatures for the example systems range from 380 to 540°C. About 80% of the fuel's input energy can be effectively utilized to produce both power and useful thermal energy by recovering heat in the cooling systems and exhaust. [23]

Closed-loop cooling systems –These systems are the most common method of engine heat recovery and are designed to cool the engine by forced circulation of a coolant through engine passages and through an external heat exchanger. An excess heat exchanger transfers engine heat to a cooling tower or a radiator when there is excess heat generated. Closed-loop water cooling systems can operate at coolant temperatures from 88 to 120°C. The lube oil cooling and turbocharger after-cooling may be either separate or part of the jacket cooling system depending on the engine and cogeneration system requirements.[22]

Ebullient Cooling Systems –used in parallel with exhaust heat recovery to produce low-pressure steam by circulating a boiling coolant through the engine. [23]

Exhaust Heat Recovery – Energy in the exhaust is used to generate hot water of up to about 110°C or steam up to 28 bars. Because the exhaust temperature must be kept above temperatures thresholds in order to prevent corrosion due to condensation; only a portion of the exhaust heat can be recovered. [23]

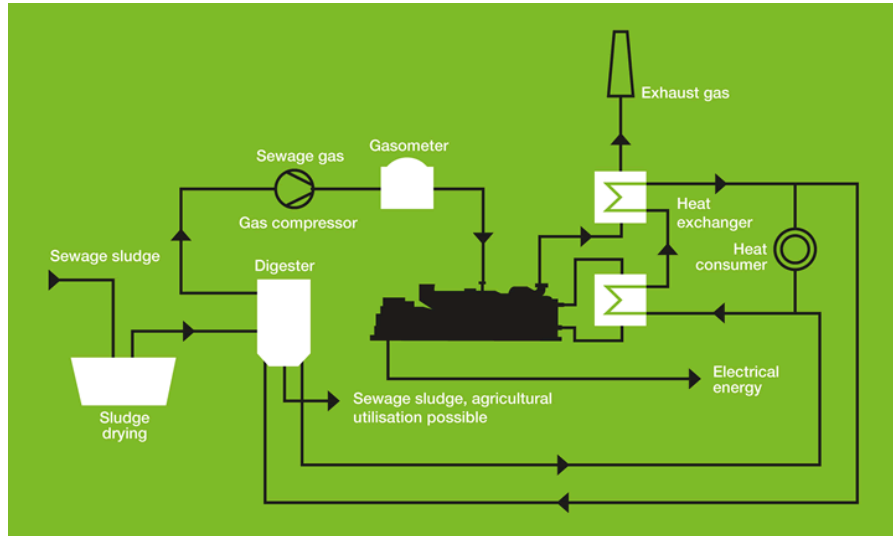


Figure 4.5: Internal Combustion Engine in CHP Arrangement [24]

4. Heat Recovery From Steam Turbine

Steam with high pressure is produced in a boiler and then expanded through a back-pressure steam turbine, as shown in figure 4.6, and then low-pressure steam is extracted from the turbine to be used in another process. [18,20]

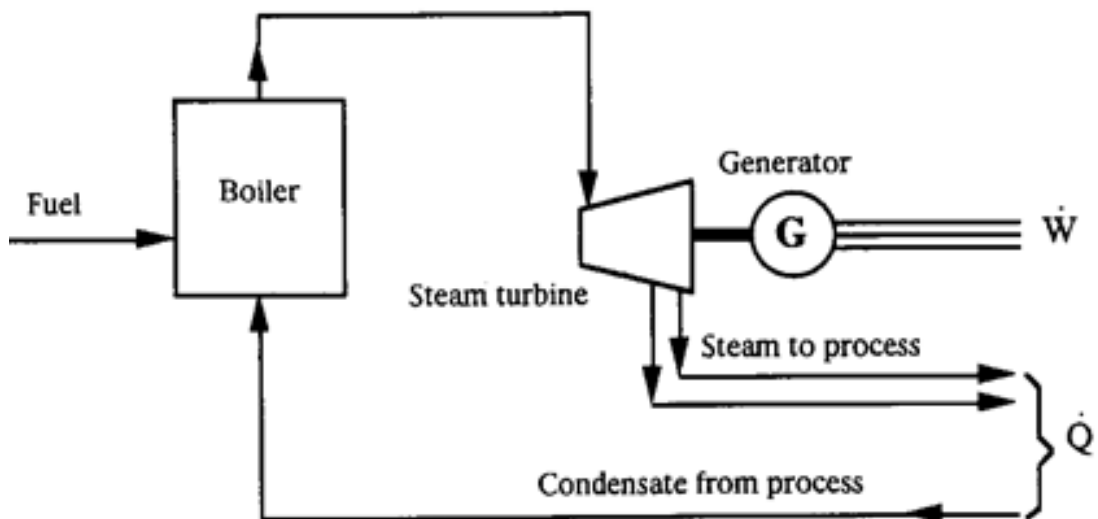


Figure 4.6: Cogeneration using low-pressure steam [25]

4.2 Reciprocating Internal combustion engines [22,23]

Internal combustion engines are used for both stationary and transportation uses with a power range from less than a kilowatt up to 80 MW capacities. Several types of fuels can be used in Internal reciprocating combustion engines with its two main types which are diesel (compression ignition) and gasoline or gas spark-ignition configurations.

Internal combustion engines are in operation for very long time and used in so many applications such as commercial, institutional and industrial facilities as stand-by power source or distributed generation applications in cogeneration arrangements.

The partial load efficiency of reciprocating engines is relatively high and their startup is quick. Internal combustion engines have lower net running costs than gas turbines since they have higher efficiency. Due to more moving parts; their maintenance costs are more than gas turbines but it can be done by local skilled persons.

4.3 Micro-Gas turbines

Micro-gas turbine is small scale gas turbines (30 kW to 1 MW) that operate at thermodynamic cycle called Brayton cycle. The process starts at the inlet of turbine where ambient air is introduced to the compressor to be pressurized then the compressed air enters a regeneration heat exchanger called recuperator where it is heated by the exhaust gases of the turbines, then air is mixed with fuel in the combustor to produce a heated mixture that is introduced to an expansion turbine that is on the same axis of the

compressor and driving an electric generator on the same shaft also. The components of MGT are shown in figure4.7. An external heat exchanger that recovers the exhaust gases energy can be used also to provide heat for on-site applications which raises the total efficiency of the plant using MGT.

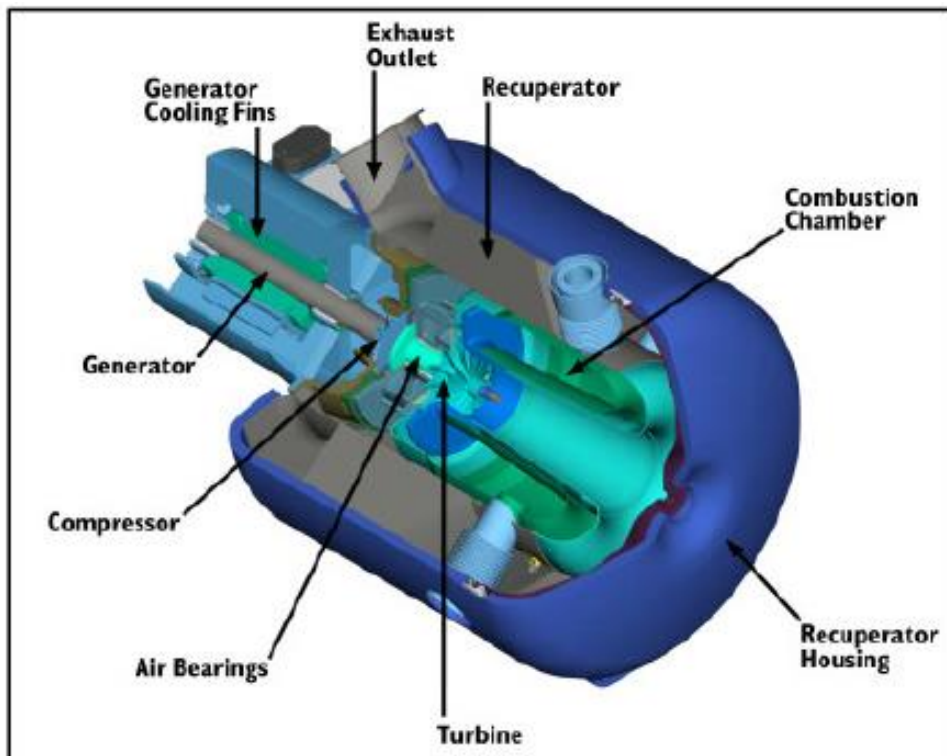


Figure 4.7: Sectional view of a microturbine and its components [26]

Turbine & compressor

The shaft on which the turbine and compressor are mounted is the core of the microturbine on which the generator is also mounted. One-shaft design has minimum number of moving parts that means minimum need for maintenance.

Microturbines operate on either air bearings or oil-lubricated that are used in microturbines to support the shaft. The exhaust from microturbines using

oil-lubricated bearings has the potential of air contamination so it may not be used for direct space heating in cogeneration configurations.

Air bearings allow the turbine to rotate in high rotational speed since the rotation is on a thin layer of air with low friction. No oil or oil pump is needed. Air bearings offer simplicity of operation minimum maintenance costs.

Generator

The microturbine may have a generator directly connected to the turbo compressor set on the same shaft or through a speed reduction gearbox driving a conventional 3,600 rpm generator. The high-speed generator single-shaft design produces variable voltage and high frequency so a power conditioning unit is used to regulate the output.

For on-grid arrangement, a single shaft design, the generator acts as a motor turning the turbo-compressor shaft until sufficient rotational speed is reached to start the combustor. For off- grid, battery is used to power the generator for starting.

Recuperator & Combustion

Recuperator is a built-in regeneration heat exchanger which recovers some of the waste heat in hot turbine exhaust gas (typically around 650°C) to preheat the compressed air (typically around 150°C) going into the combustor, in order to reduce the energy needed to heat the compressed air to the required turbine inlet temperature. Recuperators can increase machine efficiency but on the other hand, it has a noticeable pressure drop on its inlet and outlet, this will reduce the efficiency.

CHP Heat Exchanger

Microturbines have an external heat exchanger that collects the remaining heat in the turbine exhaust gases which exits at 260-315 ° C which can be used for space heating, potable water heating, adsorption cooling and dehumidification systems (absorption chillers, desiccant dehumidification).

Fuel Gas Compressors

Gaseous fuels such as biogas is produced in low pressures while microturbines needs higher pressure with a range between 4.5 to 6.5 bars range. Gas fuels may be compressed using several types of compressors including scroll, screw and rotary vane.

4.4 Comparison Between MGT and ICE

The following points summarize the main differences between internal combustion engines and micro turbines.

- 1. Electrical capacity range :** Microturbines power ranges from 30kW to 1 MW of electrical power capacities while internal combustion engines' power ranges from less than one kilowatt up to 8 MW of electrical power production.
- 2. Size and weight:** Microturbines have lower weight than internal combustion engines and smaller sizes.
- 3. Moving parts:** microturbines use fewer moving parts than reciprocating engines implies lower maintenance cost and lower frequent maintenance and low lubricating oil cost and consumption,

since they have only one shaft on which the compressor, turbine and generator are mounted.

- 4. Starting:** Microturbines startup needs longer time than internal combustion engines. Also, internal combustion engines can be started using battery that is available in the markets easily.
- 5. Maintenance simplicity and availability:** internal combustion engines are well-known technology and their maintenance can be achieved by local skills. On the other hand, microturbines have simple design and can be easily installed and have few moving parts.
- 6. Reliability and lifetime and availability:** Microturbines are a new technology and they are in market since few years, but the design value of lifetime ranges between 40,000 and 80,000 hours of operation.
- 7. Noise and vibration:** micro-gas turbines move in one direction only, with less vibration than internal combustion engines.
- 8. Flexibility to be paralled together:** Microturbines can be easily stacked together to supply large loads.
- 9. Heat recovery and thermal output:** in micro-gas turbines, all of the waste heat is contained in the exhaust while in internal combustion engines, it is contained in several outlets including the exhaust gases and cooling water jacket and oil. This leads to easier heat recovery in micro-gas turbines through external heat exchanger after the recuperator for combined heat and power applications.
- 10. Fuels:** both microturbines and internal combustion engines can operate on liquid or gaseous fuels including waste fuels such as biogas.

11. Efficiency and performance: the electrical efficiency of micro-gas turbines (24%-33%) is less than internal combustion engines (28-40%), but when the total efficiency is compared when there is a cogeneration (CHP) application, the micro-gas turbine offers higher CHP efficiency, making it suitable for applications where electricity and heat needs are coincident and at the same level of priority and occurs in parallel. Microturbines are highly affected by ambient conditions i.e. The output power production and efficiency are less when elevation or temperatures are increased.

12. Capital costs: capital costs of micro-gas turbines are higher than internal combustion engines.

13. Environmental impact: Microturbines produce less emission than reciprocating engines especially the NO_x and CO emissions and may produce about 15% of these emissions that produced from ICE's since the MGT can burn these gases.

4.5 Efficiency and Part – Load Performance

Internal combustion engines operating on gaseous fuels have electrical efficiencies ranging between 28-40% compared to 24-33% of micro-gas turbines.

The efficiency of larger electrical capacity units is higher than smaller ones for internal combustion engines and micro-gas turbines.

The part load performance of internal combustion engines is more stable than MGT, the electrical efficiency of MGT decreases dramatically during

partial load, for example, at 50% partial load the electrical efficiency of MGT decreases about 15-25% of nominal efficiency while it is stable in ICE. When partial load is expected in the power plant, multiple units of MGT can be used to avoid the electrical efficiency reduction of partial load.

Figure 4.8 shows a part load efficiency curve of some microturbines. The electrical efficiency is decreased from 30% to 15% at half load power output.

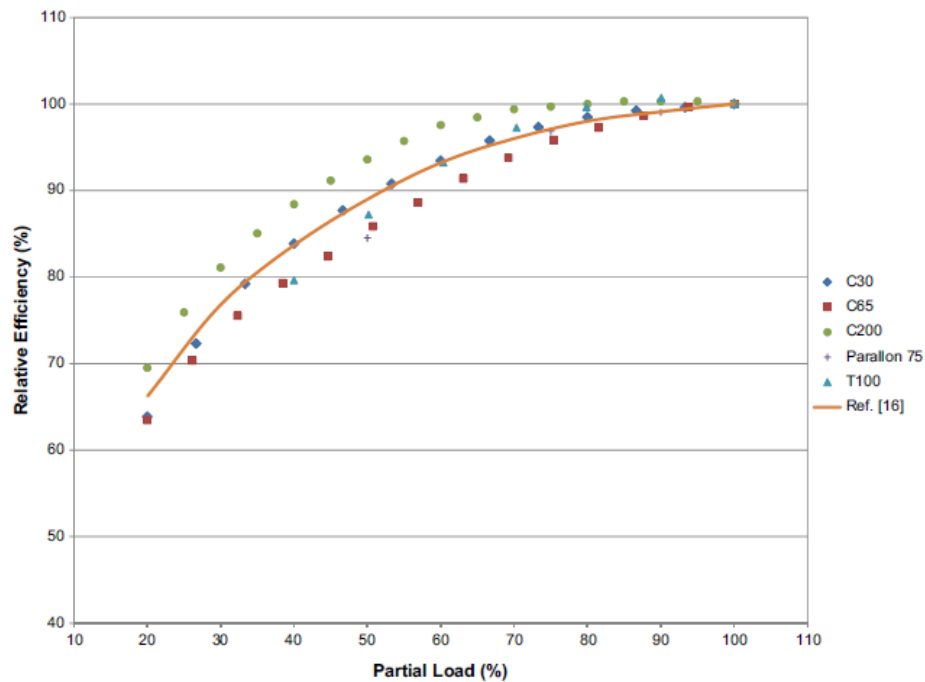


Figure 4.8: Part Load Efficiency of MGT's. [12]

Figure 4.9 shows the effect of partial load on mass flow rate of exhaust gases from MGT.

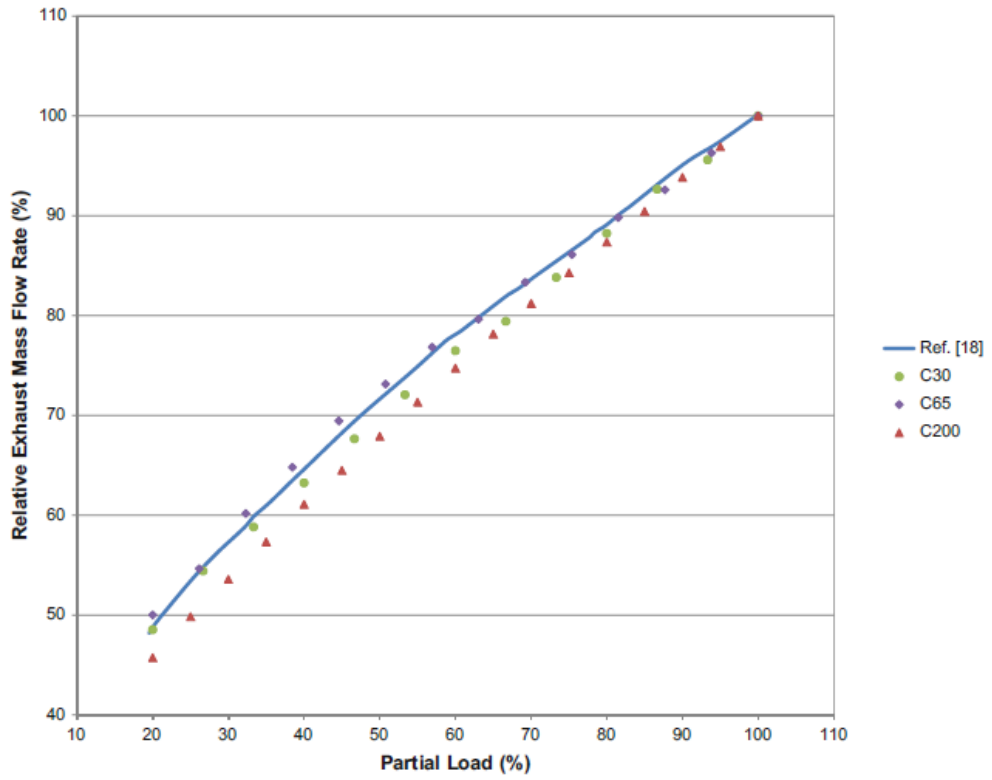


Figure 4.9: Part Load Exhaust Mass Flow Rate of MGT's [12]

Figure 4.10 shows the effect of partial load on temperature of exhaust gases from MGT.

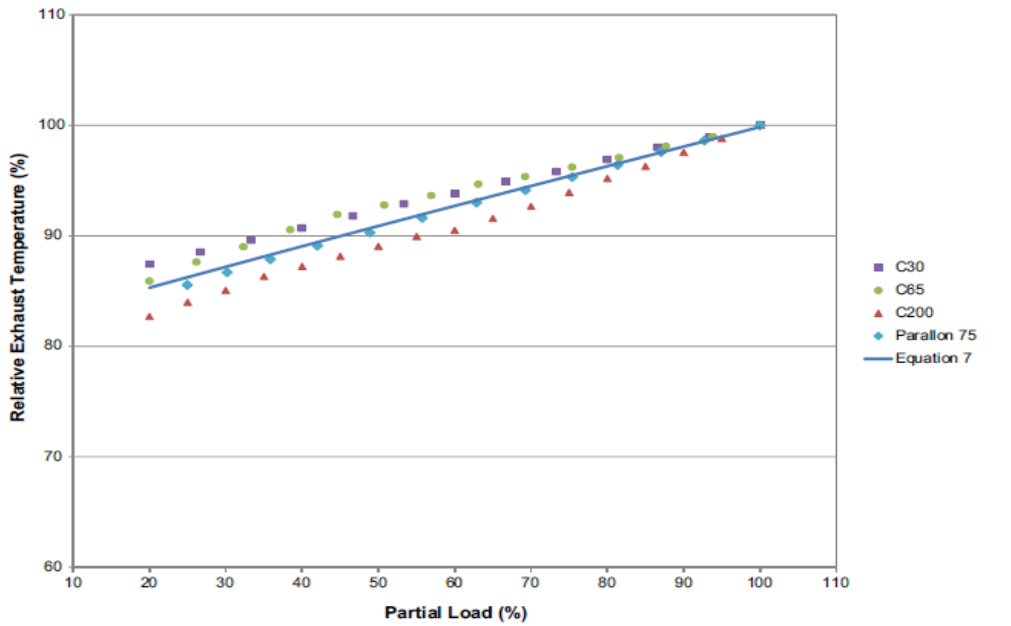


Figure 4.10: Part Load Exhaust Temperature of MGT's [12]

In order to produce steady alternating current, **reciprocating engines** generally drive synchronous generators at constant rotational speed. As the electrical load is reduced, the generated heat rate of spark ignition engines increases which decreases the efficiency. **Figure 4.11** shows the effect of the part load on engine's efficiency.

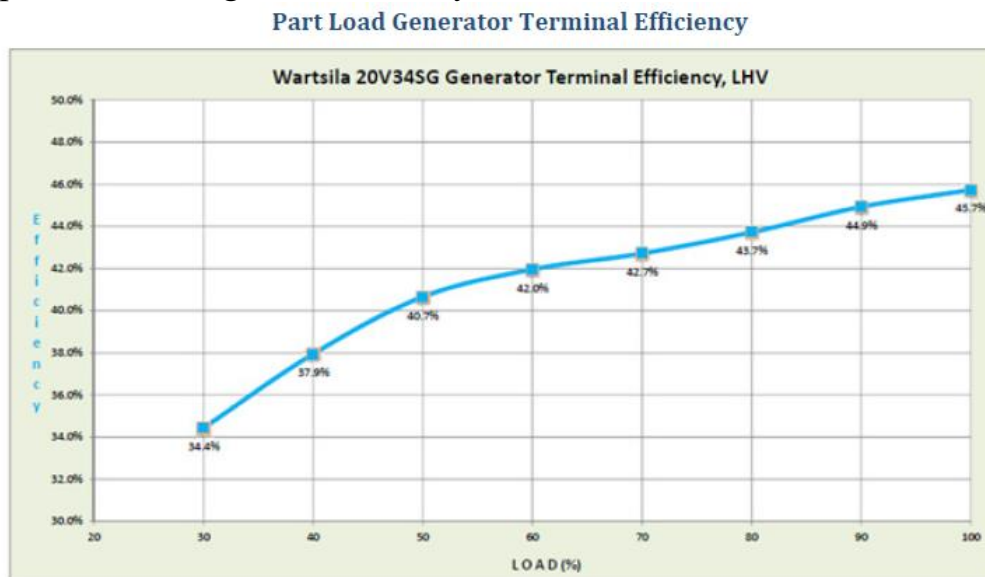


Figure 4.11: Part Load Efficiency of Internal Combustion Engines [23]

The efficiency of internal combustion engines decrease as the atmospheric temperature and elevation are higher. The effect of ambient conditions is less than that on microturbines and is usually rated at ISO conditions (25 °C and 1 bar). (Gas turbines are rated at 15 °F.).

Operating conditions of the microturbine such as temperature and pressure can have an observed influent on its efficiency and so, on its power production, as shown in figure 4.12 When the temperature of atmospheric air increases; its density decreases which leads to less flow rate into the turbine and leading to less power output and efficiency because the compressor requires more power to compress the low-density air.

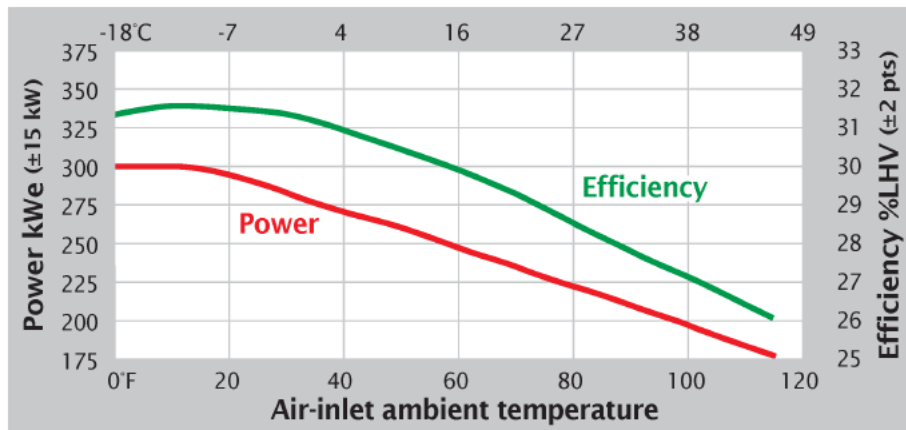


Figure 4.12: effect of ambient temperature of MGT performance. [23]

4.6 Micro-Gas Turbines and Internal Combustion Engines Economics

This section gives an overview of the capital costs for some micro-gas turbines from some manufacturers and depends them as a reference for estimating the capital costs of micro-gas turbines plants with the assumption that cogeneration arrangement is used for producing on-site heat.

The plant costs consist of capital and operating costs. Capital costs include equipment costs that are either basic or additional while the capital cost also include the installation costs that can vary depending on the scope of the plant equipment, geographical area of the plant, competition in the market, special location requirements, requirements of emissions control, prevailing labor rates, and whether the project is a new or a retrofit application.

The cost of equipment basically includes the cost of the compressor-turbine-generator, the external heat exchanger, the compressor of fuel gases and interconnection equipment cost.

Additional equipment may be required for micro-gas turbines power plants. A heat recovery system can be used; controllers and remote monitoring equipment can be used. Installation costs include materials such as piping, ductwork and wiring, labor for the mechanical, electrical and civil work, project management (including licensing, insurance, commissioning and startup) and engineering costs for the design of the system and integrating it functionally with the application's mechanical and electrical systems.

The operating and maintenance costs may include fixed and variable costs that mean the scheduled inspection and unscheduled replacement of spare parts. The maintenance needs depends on the special case of the project related to the atmosphere and location in addition to the size of the devices used and type of fuel and its contaminants in biogas case for example.

Figure 4.13 gives the micro-gas turbines capital and running costs and their components.

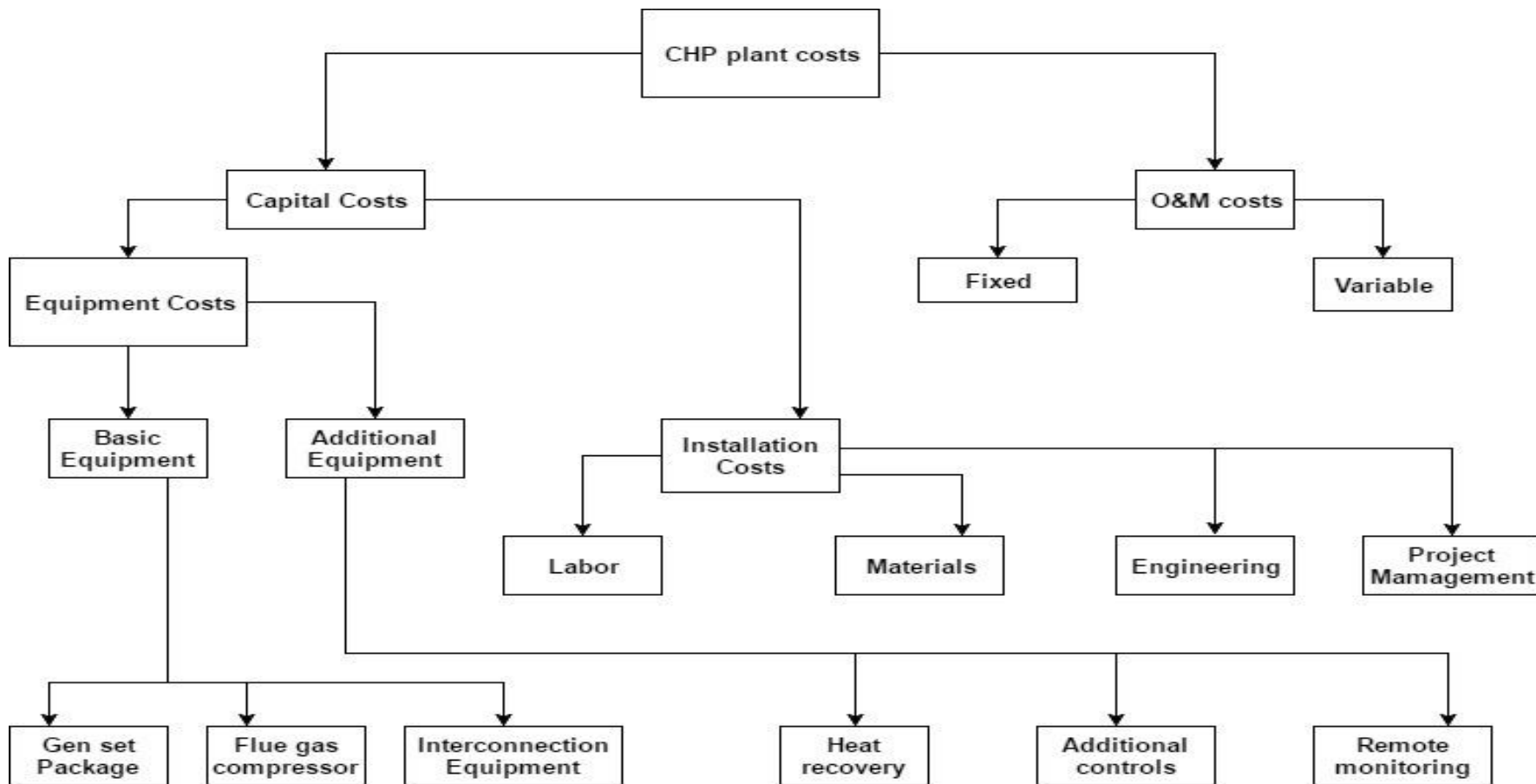


Figure 4.13: MGT Capital and running costs.

Table 4.2 shows the capital costs of some micro-gas turbines, including the equipment basic cost and the other installation costs.

Table 4.1: Capital Costs of Micro-Gas Turbines [23]

	System		
Nominal capacity (kW)	30	65	200
Net capacity(kW)	28	61	190
Equipment cost			
Gen set Package(\$)	53,100	112,900	359,300
Heat recovery(\$)	13,500	0	0
Fuel gas compression(\$)	8,700	16,400	42,600
Total equipment (\$)	75,300	129,300	401,900
\$/kW	2,689	2,120	2,115
Installation Costs			
Labor/Materials(\$)	22,600	28,400	80,400
Project &Construction(\$)	9,000	15,500	48,200
Engineering(\$)	9,000	15,500	44,200
Project management(\$)	3,800	6,500	20,100
Financing (\$)	700	1,200	3,700
Total other costs(\$)	45,100	67,100	196,600
\$/kW	1,611	1,100	1,035
Total installed cost\$	120,400	196,400	598,500
\$/kW	4,300	3,220	3,150

Costs of internal combustion engines with cogeneration have basically same components as micro-gas turbines as shown in figure 4.14 with some differences in the details. Engines may need a gearbox to be added to control the produced frequency. Catalyst may be used to control the emissions while the heat recovery system includes more than one heat exchanger to collect as much as possible from the waste heat from the genset.

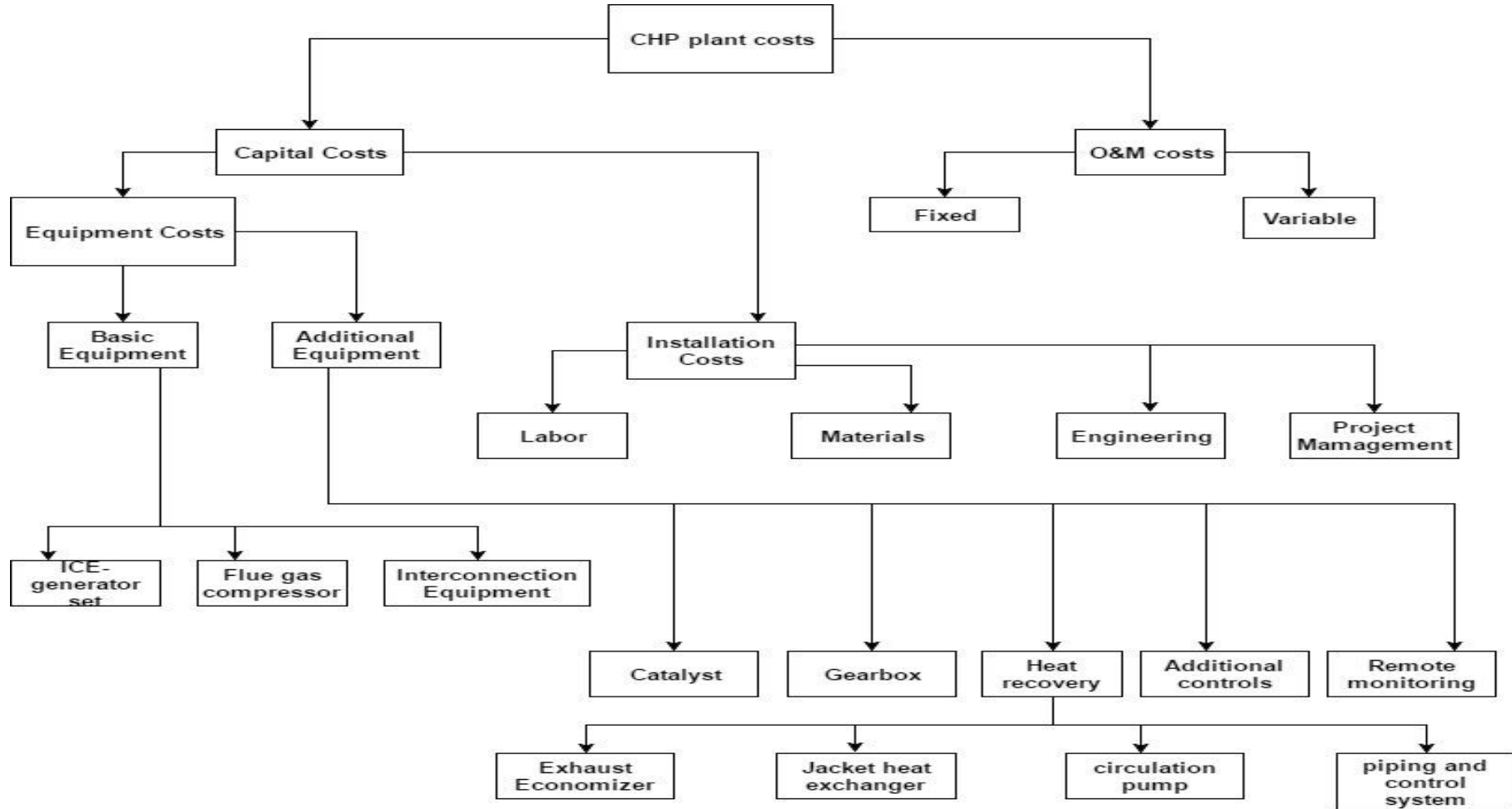


Figure 4.14: Capital Cost and running costs of Internal combustion engines.

Maintenance costs vary with size, type, speed, and number of cylinders of an engine. It may include scheduled activities such as inspection, monitoring and adjustment; it may include unscheduled activities such as replacement of spare parts. Internal combustion engine maintenance costs are relatively higher than MGT's since they have more moving parts such as pistons and crankshaft and more consumables such as coolants and oils. ICE's maintenance can be done on-site by local skilled people since it is a well-known technology.

4.7 Micro Turbine and Internal Combustion Engines Environmental Impact [22,23]

Some waste fuels have elements which can be considered as contaminants, specifically the acid gas components (H_2S , halogen acids, HCN, ammonia, salts and metal-containing compounds, halogens, nitrogen compounds, and silicon compounds) and oils. During the process of combustion, halogen and sulfur compounds form halogen acids, SO_2 , some SO_3 , and possibly H_2SO_4 emissions. Downstream corrosion can be caused by the acids. To prevent corrosion of turbine blades the solid particulates concentration must be kept low.

Various fuel scrubbing, droplet separation, and filtration steps are required if fuel contaminant levels exceed manufacturer specifications. Gas from landfills in particular often contains, sulfur compounds, organic acids, chlorine compounds, and silicon compounds which requires fuel treatment before use.

Siloxanes are an important contaminant in biogas. These compounds are widely used for a variety of industrial processes and are also commonly added to consumer products, including detergents, shampoos, cosmetics, paper coatings, and textiles. Siloxanes do not decompose in wastewater treatment plants or solid waste landfills.

In wastewater treatment plants siloxanes do not decompose but it volatilize under higher temperatures and become a component of biogas and then when it is heated in the engines or turbines they form hard deposits on engines components that causes corrosion and damage.

4.7.1 Emissions From Gas Turbines

Emissions from microturbines are relatively low and meet the emissions regulations; they include built-in controllers for emissions and need no external post-combustion emission controllers. They produce lower emissions when operated near full load conditions.

Nitrogen oxides are the main pollutants from micro-gas turbines since they use excess air and high temperatures in the combustion chamber, carbon monoxide is another main pollutant that can be produced because of incomplete combustion. Unburned organics in the fuel will produce volatile organic compounds. Hazardous air pollutants (HAP) are another result of incomplete combustion. Sulfur dioxide will be produced because of the sulfur components of the fuel especially H_2S in biogas.

1. Nitrogen Oxides (NO_x)

Three types of NO_x emissions occur in microturbines; the first type is called thermal NO_x which is formed due to reaction between air components which are oxygen and nitrogen.

Gas turbines operate with high overall levels of excess air, because turbines use combustion air dilution as the means to maintain the turbine inlet temperature below design limits.

The second type is called prompt NO_x; it is produced because of reaction between N₂ from the air and hydrocarbons of the biogas. The third type is fuel NO_x, which is produced because of reaction between nitrogen attached to the fuel with the oxygen.

2. Carbon Monoxide and Volatile Organic Compounds

Incomplete combustion will produce carbon monoxide and VOC emissions. Carbon monoxide is produced because the oxidation of it to carbon dioxide is slow in micro-turbines which lead to incomplete process at high temperatures. Quenching by excess air may result at failure to achieve CO burnout. Partial load condition will lead to incomplete combustion of fuel and reduced fuel efficiency and carbon monoxide and VOC higher emission rates.

3. Greenhouse Gases

The carbon content of biogas is turned mainly into carbon dioxide and relatively insignificant percentage to carbon monoxide during combustion in micro-turbines. The carbon conversion is relatively independent of firing

configuration. Methane (CH_4) is also present in the exhaust gas and is thought to be unburned fuel in the case of Biogas.

Nitrogen dioxide N_2O is also produced and is related to many factors is a result of series of reactions. High combustion temperatures and low excess air will reduce the formation of N_2O .

4. Hazardous Air Pollutants HAP Emissions

Micro-gas turbines produce lower HAP pollutants since they operate at high temperatures. These emissions are mainly Formaldehyde and other metallic HAP that originates from fuel components. Carbon monoxide emissions (CO) level is an indicator that reflects the HAP levels. As in CO; the partial load operating condition will lead to higher HAP levels.

5. Chapter five – Cogeneration Plant Sizing Methodology

This study aims at finding an optimum alternative to utilize the biogas which is being produced by local wastewater treatment plants in West Bank and Gaza Strip and especially the Western Wastewater Treatment Plant of Nablus city. Data about the gas quantities were collected and reviewed in chapter two which has shown that the biogas production rate is variable on a daily and seasonally basis. The scenario that can achieve optimum energy, economic and environmental outputs will be studied. Energy sustainability of the plant is targeted mainly.

The problem of this study can be summarized by two components: we have a biogas produced from the wastewater treatment plant with variable flow rate. And an electricity and heat consumed locally in the facility.

The methodology to be conducted is shown in figure 5.1 and will include the following sections:

1. The biogas utilization alternatives will be studied, compared and explained in order to find the suitable processes that can convert biogas energy into useful types of energy i.e. electricity and heat.
2. Two biogas utilization alternatives will be selected and the optimum sizing, arrangement and operating strategy will be studied.
 - Several cases with different sizing and arrangements of utilization devices will be selected.
 - The expected electrical and heat energy production will be calculated for each case.

3. The economic and financial calculations will be carried out to evaluate each case economically and the levelized energy cost will be calculated.
4. The emissions of each case will be evaluated to recognize the environmental impact of it.

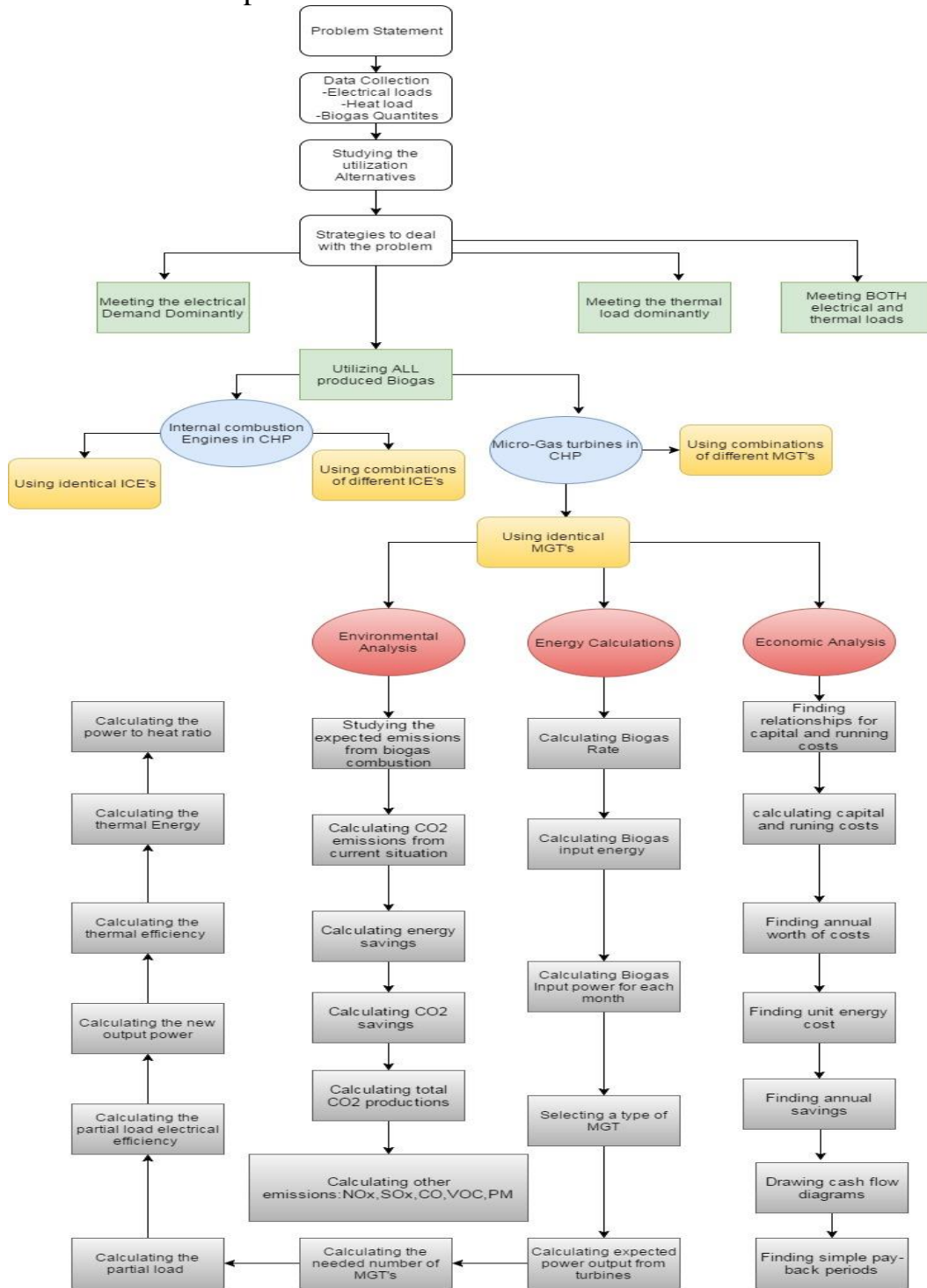


Figure 5.1: Methodology flowchart

Design assumptions and considerations are:

- The biogas production rate from sludge digester is variable and its rate is changing instantly.
- The biogas production rate will be regulated to have a constant daily rate during every month.
- The heat value and density of biogas are considered at NTP conditions.
- The ambient conditions are considered at NTP conditions (20°C and 1 atm).
- The biogas is considered to contain 60% CH₄ and 35% CO₂.
- The electrical load of the plant was considered to vary monthly.
- The thermal load of the digester was considered constant since we have constant loading and discharge rates.

5.1 Gas turbine equations and calculations

5.1.1 Average Biogas production rate

The biogas production rate will be studied. The variation in production will be noticed to find the average value of daily production and maximum and minimum values. These values will be used to make sure that biogas storage can make a biogas rate regulation on a daily – base.

Then, an average value of biogas production rate will be calculated for every month of the studied period, assuming that this rate is constant for

every month and varies monthly as it is regulated using biogas buffer storage tank.

$$m_{Biogas,ave} = \frac{\sum_{n=1}^{n=30} m_n}{t} \dots\dots\dots 5.1$$

Where:

m_{Biogas,ave} = monthly average of biogas production(kg/day).

n = number of the day.

m_n = the daily biogas production(kg/day), from Appendix.

t = number of operating hours in month (hour/month).

5.1.2 Monthly energy content in biogas and average power

The power content of biogas for every month will be calculated depending on the average flow rate value of every month multiplied by the heat content of biogas (lower heat value):

$$E_{in} = \sum_{n=1}^{n=t} m_n \times H.V \dots\dots\dots 5.2$$

Where:

E_{in} = monthly energy content of biogas (MWh/month).

m_n = the daily biogas production(kg/day), given in appendix.

L.H.V= Heating value of biogas (lower heating value) (MWh/kg).

$$P_{in} = \frac{E_{in}}{t} \dots\dots\dots 5.3$$

Where:

P_{in} = Input power from biogas to turbines/engines (kW).

E_{in} = monthly energy content of biogas (kWh/month), from eqn. 5.2.

t = number of operating hours in the month (hour/month).

5.1.3 Monthly expected power output from micro-turbines

Some micro-gas turbines/engines will be selected based on the range of output power that is suitable for the power content of the produced biogas. Assuming that all biogas is utilized, average efficiency will be calculated as:

$$\zeta_{elec,ave} = \frac{\sum \zeta_{individual}}{N} \dots\dots\dots 5.4$$

Where:

$\zeta_{elec,ave}$ = Average electrical efficiency of micro-turbines/engines.

$\zeta_{individual}$ = electrical efficiency of each individual microturbine/engine, from table5.1.

N = number of micro-turbines/engines.

Table 5.1: MGT's and ICE's nominal efficiencies[27-29]

Turbine type	Efficiency	Engine type	Efficiency
C30/30kW	26%	G3306/143kW	32%
C65/65kW	29%	G3406/235kW	38%
T100/100kW	30%	GC132-8/400kW	42%
C200/200kW	33%		

The expected power output from the micro-gas turbines/engines can be found by multiplying the input power from biogas by the efficiency of the selected micro-gas turbines/engines in each arrangement or by the average efficiency of micro turbines/engines for combined arrangements of non-identical micro turbines.

$$P_{out,1} = \zeta_{elec,ave} \times P_{in} \quad \dots\dots\dots 5.5$$

Where:

$P_{out,1}$ = First estimation of power output from micro-turbines/engines(kW).

$\zeta_{elec,ave}$ = Average electric efficiency of micro-turbines/engines, from eqn. 5.4.

P_{in} = input power from biogas (kW), from eqn. 5.3

5.1.4 Number of turbines in operation every month

After finding the expected power output from the micro turbines/engines, the number of micro turbines/engines to be used for every month is found by dividing the expected power output by the capacity of one unit.

$$O.S = \frac{P_{out,1}}{P_c} \quad \dots\dots\dots 5.6$$

O.S = Operating strategy (number of turbines in operation).

$P_{out,1}$ = First estimation of power output from micro-turbines/engines(kW).from eqn. 5.5.

P_C = Power capacity of turbines/engines (kW), from table 5.1.

5.1.5 Partial load calculation

The partial load value (PL) for every month will be calculated by dividing the expected power output by the capacity of the turbines in operation for that month.

$$PL = \frac{P_{out,1}}{P_{C,tot}} \dots\dots\dots 5.7$$

Where:

PL = Partial load.

$P_{out,1}$ = First estimation of power output from micro-turbines/engines (kW)from eqn. 5.5.

$P_{C,tot}$ = Total power capacity of operating micro turbines/engines (kW) from table 5.1.

5.1.6 Partial load electrical efficiency

The electrical efficiency of micro-gas turbines goes down dramatically when it is operated at partial load, so we must always try to attain full load or almost full load of the turbines.

While the partial load value for internal combustion engines must be more than 50% to attain electrical efficiency near the full load efficiency.

The electrical efficiency of micro turbines can be calculated using the following equation:

$$\frac{\zeta_{elec,PL}}{\zeta_{elec,Nom}} = 109.7e^{-0.000519 PL} - 75.61e^{-0.0291 PL} \dots\dots\dots 5.8 [12]$$

Where:

$\zeta_{elec,PL}$ = Electrical efficiency at partial load.

$\zeta_{elec,Nom}$ = Electrical efficiency at nominal load, from table 5.1.

PL = Partial load value, from eqn. 5.7.

5.1.7 New electrical output power from micro-turbines using PL efficiency

The output power of turbines can be recalculated using the partial load efficiency of the partially-loaded turbines, by multiplying the part-load efficiency by the input power of biogas produced for every month.

$$P_{elec,net} = \zeta_{elec,PL} \times P_{in} \dots\dots\dots 5.9$$

Where:

$P_{\text{elec, net}}$ = Net electric output power (kW).

$\zeta_{\text{elec, PL}}$ = Electrical efficiency at partial load, from eqn. 5.8.

P_{in} = input power from biogas (kW), from eqn. 5.3.

5.1.8 Output power if all MGT's are in full load and one MGT in PL

Using the control package that is supplied with every gas-turbine, the flow of biogas can be controlled and the supply of this gas can be distributed to the turbines in operation for each month in a way that only one turbine will be in partial load operation and the others are in full load operation and so, the full load efficiency can be obtained using eqn. 5.10.

$$P_{\text{out, one MGT}} = P_{F.L.MGT} + \zeta_{\text{elect.PL}} \times (P_{\text{out,1}} - P_{F.L.MGT}) \quad 5.10$$

Where:

$P_{F.L.MGT}$ = summation of output power from fully loaded MGTs (kW).

$\zeta_{\text{elect.PL}}$ = relative electric efficiency of one partially loaded MGT, from eqn. 5.8

$P_{\text{out,1}}$ = First estimation of power output from micro-turbines (kW).

5.1.9 Partial load thermal efficiency

The energy that is contained in biogas is converted partially into electricity, the remaining energy is flared out with the exhaust gases going out from turbine exhaust, and this heat energy is captured in micro turbines and recovered by a heat exchanger incorporated with the micro-gas turbine set.

The mass flow rate of exhaust gases and the temperature of exhaust gases varies with the variation of load on the micro turbines.

A formula can be used to find the exhaust mass flow rate:

$$\frac{\dot{m}_{exh,PL}}{\dot{m}_{exh,Nom}} = 4.507PL^{0.6261} + 19.35 \quad \dots\dots\dots (5.11)[12]$$

Where:

$\dot{m}_{exh,PL}$ = exhaust mass flow rate at partial load (kg/sec).

$\dot{m}_{exh,Nom}$ = exhaust mass flow rate at nominal load (kg/sec).

PL = Partial load (%).

Another formula can be used to find the exhaust gases temperature at partial load:

$$\frac{T_{exh,PL}}{T_{exh,PL}} = 0.232PL^{0.9515} + 81.29 \quad \dots\dots\dots (5.12)[12]$$

$T_{exh,PL}$ = exhaust temperature at partial load (Kelvin).

$T_{exh,Nom}$ = exhaust temperature at nominal load (Kelvin).

PL = Partial load (%).

Other formulas were found using mathematical regression of data from some manufacturers' manuals in App B.1 and B.2 to find expressions for micro-gas turbines thermal efficiency, as shown in figure 5.2.

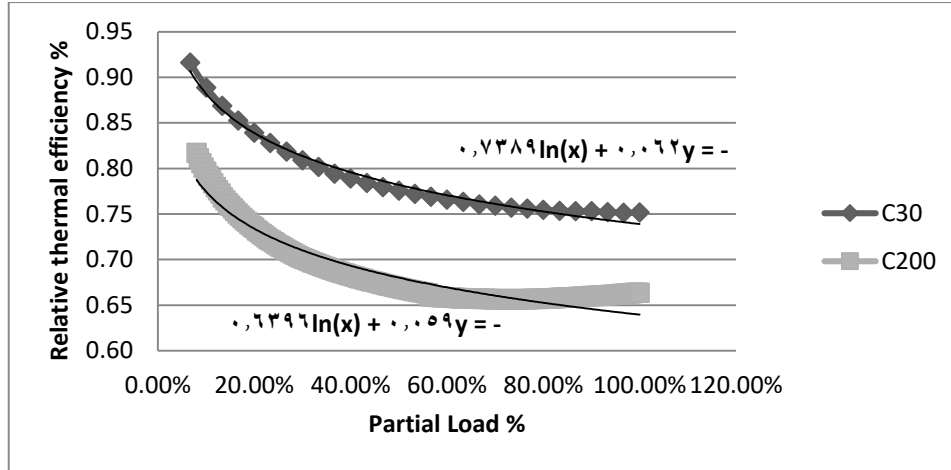


Figure 5.2: Relation between MGT part load and relative thermal efficiency [27]

The thermal efficiency, which is the efficiency of recovering energy contained in the exhaust gases of the microturbine was found by plotting data from two types of MGT and finding the following relationships:

$$\Phi_1 = -0.06 \times \ln PL + 0.7385 \dots\dots\dots 5.13$$

Φ_1 =Partial load thermal efficiency 1

PL = partial load, from eq5.7.

$$\Phi_2 = -0.05 \times \ln PL + 0.639 \dots\dots\dots 5.14$$

Φ_2 =Partial load thermal efficiency2.

PL = partial load, from eqn. 5.7.

$$\Phi_{average} = \frac{\Phi_1 + \Phi_2}{2} \dots\dots\dots . 5.15$$

$\Phi_{average}$ =Average partial load thermal efficiency

5.1.10 Output thermal power

The output thermal power output of turbines/engines can be calculated using the partial load thermal efficiency of the partially- loaded turbines, by multiplying the part-load efficiency by the input power of biogas produced for every month.

$$P_{thermal,net} = \Phi_{average} \times P_{in} \quad \text{5.16}$$

Where:

$P_{thermal, net}$ = Net thermal output power (kW).

$\Phi_{average}$ = Average thermal efficiency at partial load, from eqn. 5.15.

P_{in} = input power from biogas (kW), from eqn. 5.3.

5.1.11 Electrical and thermal energy calculation

The electrical energy that can be produced from the micro-gas turbines for every month is calculated by multiplying the power value on which the micro-turbines that will operate for that month by the time during which the micro turbines are operating

$$E_{out,elec} = P_{elec,net} \times t \quad \text{5.17}$$

Where:

$E_{out,elec}$ = Monthly electrical energy output (kWh/month).

$P_{elec,net}$ = Net electric output power(kW), from eqn. 5.9.

t = Number of operating hours.

The thermal energy that can be produced from the microturbines every month will be calculated by multiplying the input energy by the micro turbines' thermal efficiency then by the time of operation

$$E_{out,thermal} = P_{thermal,net} \times t \dots \dots \dots (5.18)$$

$E_{out,thermal}$ = Monthly thermal energy output (kWh/month).

$P_{thermal,net}$ = Net thermal output power(kW), from eq5.16.

t = Number of operating hours.

5.1.12 Power – to – heat ratio

The power to heat ratio of the micro-turbine will be calculated by dividing the electrical power that can be produced from the micro turbine every month by the thermal power that can be produced from that micro turbine for the same month:

$$P/H = \frac{P_{elec,net}}{P_{thermal,net}} \dots \dots \dots 5.19$$

Where:

P/H = Power – to – heat ratio.

$P_{elec,net}$ = Net electric output power(kW), from eqn. 5.9.

$P_{thermal,net}$ = Net thermal output power(kW), from eqn. 5.16.

5.1.13 Energy savings

Energy saving from each case of turbines will be equal to the electrical energy displaced from the grid, the total electrical energy that will be produced yearly will be:

$$E_P = \sum E_{out,elec} \quad \text{5.20}$$

Where:

E_P = Annual produced electrical energy (MWh/yr).

$E_{out,elec}$ = monthly output electrical energy(MWh/month),from eqn. 5.17.

5.2 Economoc Analysis of Using Micro-Gas Turbines and Internal Combustion Engines to Utilize Biogas

Wastewater treatment plants are electrical and thermal energy consumers, generally, these plants consumes electricity from grid and have on-site boiler to produce heat from the generated Biogas from the anaerobic digesters that treat the sludge or using another fuel. But this case has a lot of waste energy since the thermal load will not consume all of the produced Biogas, so the remaining of biogas is flared and wasted away.

In cogeneration plants, electricity is generated from the produced Biogas and the waste heat of electricity generation is being used to supply the thermal needs of the facility, and so; having two outputs from the same fuel: the electricity and heat.

The cogeneration technology will lead to large savings in electricity and the boiler fuel since it will use a wasted energy source to supply its energy needs.

This section discusses the economic aspects of utilizing Micro-Gas turbines and Internal Combustion engines in cogeneration arrangement to supply electrical and thermal energy needed for the Western Wastewater Treatment Plant of Nablus city.

5.2.1 Micro gas turbines capital and running costs calculation

The capital cost of Micro-Gas Turbines consists of equipment and installation costs, while the running costs consist of operating and maintenance costs.

The relation between basic equipment cost and equipment electrical capacity of micro-gas turbines was concluded from manufacturers’ values in table 4.2 and shown in figure 5.3 below.

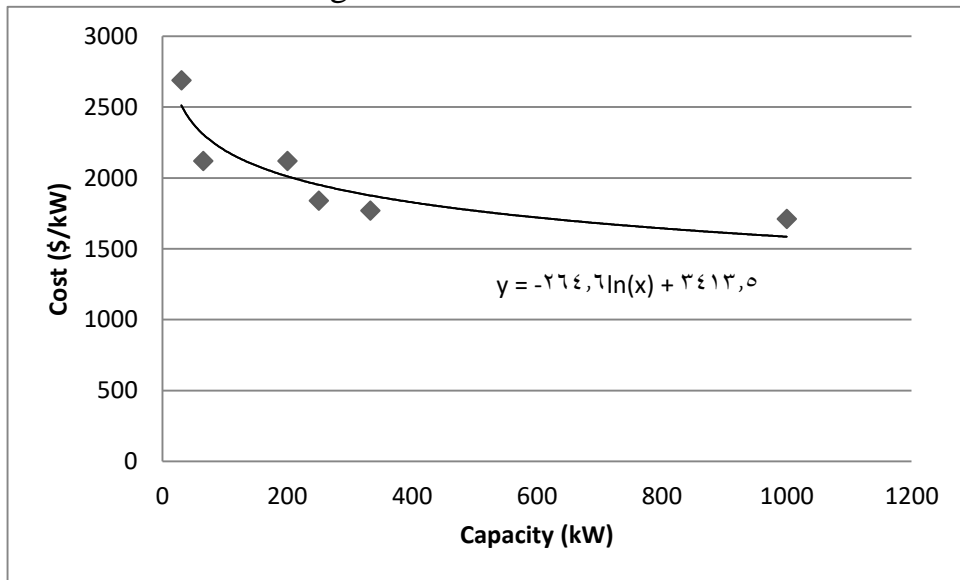


Figure 5.3: Relation between MGT capacity and unit power cost[22,23]

From figure 5.3, we conclude the following relationship between unit of power capital cost of microturbines and their capacities:

$$CC_{MGT} = -264.6 \ln (EC) + 3413.5..... 5.21$$

Where:

CC_{MGT} = capital cost of MGT per unit power capacity (\$/kW)

EC = Electrical power capacity of MGT (kW), from table 5.1.

The total capital cost of MGT can be calculated from equation 5.22:

$$C_{MGT} = CC_{MGT} \times EC \dots \dots \dots (5.22)$$

Where:

C_{MGT} = Total capital cost of MGT (\$).

CC_{MGT} = Capital cost of MGT per unit of power (\$/kW) from eqn. 5.21.

EC = Electric power capacity (kW), from table 5.1.

The cost of maintenance services are outlined in Table 5.2, including replacement or rebuild of the main turbo-compressor engine components.

The relation between the electric power capacity of MGT and its annual maintenance costs is according to the following relation:

$$C_{O\&M,MGT} = E_P \times O\&M_F \dots \dots \dots 5.23$$

Where:

$C_{O\&M,MGT}$ = Annual operating and maintenance costs (\$/yr).

E_P = Annual produced electrical energy (kWh/yr), from eqn. 5.20.

$O\&M_F$ = operating and maintenance costs factor, from table 5.2.

Table 5.2: Maintenance Costs for Micro-Gas Turbines [23]

Maintenance costs	System					
Nominal Electricity Capacity (kW)	30	65	200	250	333	1000
Average@6,000hrs/year operation(\$/kWh)	0.010	0.013	0.016	0.011	0.009	0.012

5.2.2 Internal Combustion Engines Capital and Running costs calculation

The capital cost of internal combustion engines consists of equipment and installation costs, while the running costs consist of operating and maintenance costs.

A relation between ICE capacity and unit power cost has been developed depending on some manufacturers' data for a range of engines and as shown in figure 5.4.

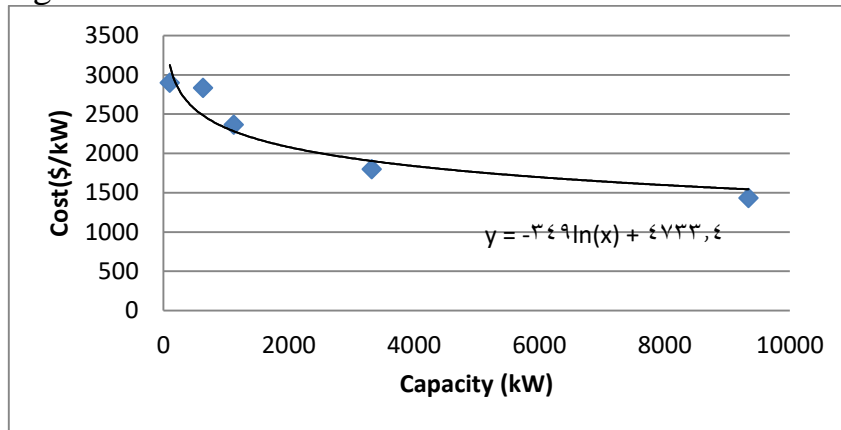


Figure 5.4: Relationship between ICE capacity and unit power cost. [22, 23]

From the figure above, we conclude the following relation between the ICE capacity and unit power capacity:

$$CC_{ICE} = -349\ln (EC) + 4733.45.24$$

Where:

CC_{ICE} = Capital cost per unit power capacity of ICE (\$/kW)

EC = Electric power capacity of ICE (kW), from table 5.1.

The total capital cost of ICE can be calculated from equation 5.25:

$$C_{ICE} = CC_{ICE} \times EC.....5.25$$

Where:

C_{ICE} = Total capital cost of ICE (\$).

CC_{ICE} = Capital cost of ICE per unit of power (\$/kW), from eqn. 5.24.

EC = Electric power capacity (kW), from table 5.1.

A relationship for maintenance costs was concluded as shown in figure 5.5 which is based on engine manufacturer estimates for service contracts consist of routine inspections and scheduled overhauls of the engine-generator set in appendix 7.

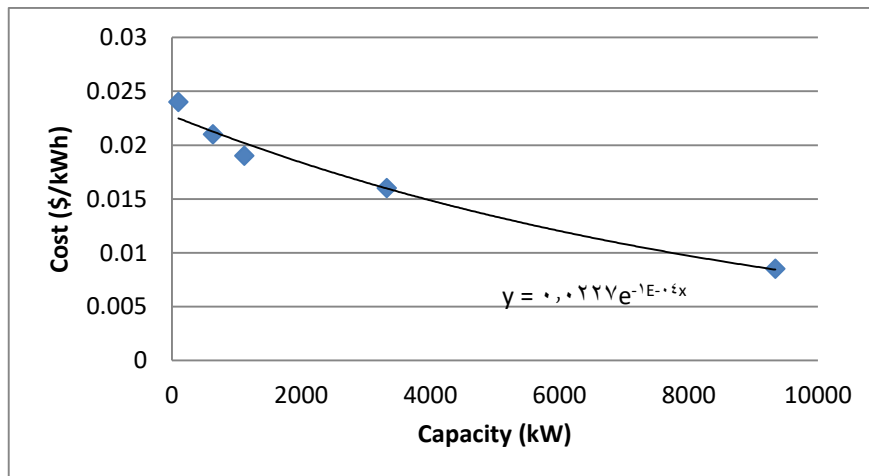


Figure 5.5 : ICE’s operating and maintenance costs [22, 23]

The relation between the electric power capacity of ICE and its maintenance costs is according to the following relation:

$$C_{O\&M} = E_P \times 0.0227e^{-(10^{-4}EC)} \dots\dots\dots 5.26$$

Where:

$C_{O\&M}$ = Annual operating and maintenance costs (\$/yr).

E_P = Annual produced electrical energy (kWh/yr), from eqn. 5.20.

EC=Electric power capacity of ICE (kW), from table 5.1.

5.2.3 Unit energy cost

The CHP systems produces two types of energy; electrical and thermal, while the thermal energy needed for the system is already produced from the biogas boiler on-site; the electrical energy is the recovered energy from the gas which was wasted by flaring. The CHP system will add electrical energy to the plant and heat energy which is already produced, so the cost of electrical energy from the system will be the same cost as the whole system i.e. the cost of electrical energy unit will be the annual cost of the system divided by the annual electrical energy production of it.

$$AW_C = AW_{C,Investment} + C_{O\&M} + - AW_{Salvage\ Value} \dots \dots \dots 5.27$$

Where:

AW_c = Annual worth of the cost (\$/yr).

$AW_{C,Investment}$ = Annual worth value of the investment (C_{MGT} or $C_{ICE} \times (A/P, 7\%, 10)$), from eqn. 5.22 And eqn. 5.25, A/P : from app. C.1.

$C_{O\&M}$ = Annual worth value of the operating and maintenance costs, from eqn. 5.23 eqn. 5.26.

$C_{Salvage\ Value}$ = Annual worth value of the end-life salvage value of the equipment which equals 10% of the total plant capital cost= S (A/F, 7%, 10).

Assumed Interest rate = 7%.

Lifetime of the project = 10 years.

The calculations of the cost per unit energy can be done using the equation

5.28:

$$C_{U.E} = \frac{AW_c}{E_p} \dots \dots \dots 5.28$$

Where:

$C_{U.E}$ = Unit energy cost (\$/kWh).

AW_c = Annual worth of project cost (\$/yr), from eqn. 5.27.

E_p = Produced electrical energy from the project (MWh/yr), from eqn. 5.20

5.2.4 Total Annual Saving of CHP Systems

The CHP alternatives will produce two types of energy; electrical and thermal, the thermal energy is already produced on-site by a boiler which utilize biogas, but the electrical energy will be produced by the CHP systems, so the main saving from these systems is the electrical energy produced on-site which will displace some of the electrical energy load consumed from grid.

The value of displaced electrical energy equals the cost of electrical energy produced if it was consumed from the grid:

$$AW_E = E_p \times C_{U.E,G} \dots \dots \dots 5.29$$

Where:

AW_E = Annual worth of produced energy (\$/yr).

E_p = Produced annual energy (MWh/yr), from eqn. 5.20.

$C_{U.E,G}$ = unit energy cost from grid (0.17\$/kWh, the cost from Nablus municipality).

The annual saving can be calculated by subtracting the annual worth of the alternative cost from the current cost of displaced electrical energy savings

$$AS = AW_E - AW_C \dots \dots \dots 5.30$$

Where:

AS = Annual saving (\$/yr).

AW_E = Annual value of produced electrical Energy (\$/yr), from eqn. 5.29.

AW_C = Annual worth of Cost (\$/yr), from eqn. 5.27.

5.2.5 Cash Flow Diagrams

Cash-flow diagram is a financial representation used to show the income and outcome cash during the period of a project life. This diagram can include the capital costs of the project in addition to running costs and savings in addition to the end of life value of the project. This financial tool can be used later in economic evaluation of the project through some evaluation calculations of it such as net present value or annual worth value or future worth value or internal rate of return value of the project.

5.2.6 Simple Pay-Back Period

The payback period is the length of time required to recover the cost of an investment. Payback period intuitively measures how long something takes to "pay for itself." The payback period of a given investment or project is an important determinant of whether to undertake the position or project, as longer payback periods are typically not desirable for investment positions. The payback period ignores the time value of money, unlike other methods

of capital budgeting, such as net present value, internal rate of return or discounted cash flow.

$$\mathbf{S.P.B.P} = \frac{\mathbf{C_{MGT\ or\ C_{ICE}}}}{\mathbf{AS}} \dots\dots\dots\mathbf{5.31}$$

Where:

S.P.B.P = Payback period of the project (year).

C_{MGT or C_{ICE}} = capital cost of the project, (\$), from eqn. 5.22 & eqn. 5.25.

AS = annual worth of saving, (\$/yr) from eq5.30.

5.3 Environmental analysis of using micro turbines and internal combustion engines to utilize biogas

Biogas consists of approximately 60% methane (CH₄) and 35% carbon dioxide (CO₂), and other components such as nitrogen (N₂), oxygen O₂, and hydrogen sulfide (H₂S).

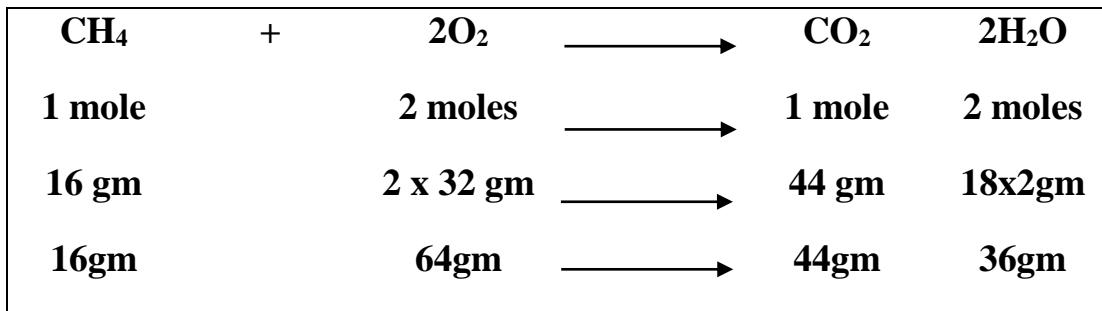
The combustion of biogas results in greenhouse gases which are carbon dioxide (CO₂), nitrous oxide (N₂O) and unburned methane (CH₄) in addition to emissions of criteria pollutants (carbon monoxide, (CO); oxides of nitrogen, (NO_x); oxides of sulfur (SO_x), unburned volatile organic compounds, (VOC), particulate matter (PM).

The emissions from biogas combustion can be similar to natural gas combustion emissions if it has low concentrations of impurities. However, the emissions concentrations will depend on the device of combustion and

the components of the gas itself, and whether the device is equipped with pollution-controllers or not. [30]

5.3.1 Combustion equation

The main component of Biogas is methane (CH₄), which contains the energy value of it. During combustion; methane is oxidized to form carbon dioxide. The other main component of biogas is carbon dioxide (CO₂) which does not react and turns into combustion reaction products. Biogas combustion equation (methane oxidation) is as follows:



This equation supposes complete burning of biogas, although that the combustion of biogas is sometimes not complete, this depends on the combusting device, and for example, in the Micro-Gas Turbines the methane destruction efficiency is 95%.

We conclude that the combustion of one kilogram of CH₄ will produce 2.75kilograms of CO₂. One kilogram of biogas contains 0.6 kg CH₄ and 0.35 kg CO₂; the CO₂ will not react and will go out as a combustion product. The total CO₂ production from burning one kilogram of biogas will be 2 kg of CO₂.

The total biogas production can be calculated from the following equation:

$$M_{Biogas} = \sum_{N=1}^{N=12} \sum_{n=1}^{n=t} m_n \dots \dots \dots 5.32$$

Where:

M_{Biogas} = Annual biogas production (kg/yr).

m_n = Daily biogas production(kg/day)from appendix.

N = number of month.

n= number of day.

t= number of operating days in one month.

The total yearly CO₂ production from burning biogas can be calculated from the following equation concluded from the biogas combustion equation:

$$CO_{2, Biogas} = 2 M_{Biogas} \dots \dots \dots 5.33$$

Where:

CO_{2, Biogas} = CO₂ production because of biogas combustion (kg/yr).

M_{Biogas} = mass of biogas production (kg/yr), from eqn. 5.32.

5.3.2 Effect of partial load on emissions

When microturbines operate at partial load, they consume less fuel, this leads to variation in emissions depending on combustion equation that relates the quantities of inputs and outputs of the biogas combustion. An equation that relates the mass flow rate of fuel during full load and partial load is:

$$\frac{m_{f,PL}}{\dot{m}_{f,Nom}} = 37.67e^{0.009828(PL)} 33.29 - e^{-0.03738(PL)} \dots \dots \dots 5.34[12]$$

Where:

$\dot{m}_{f,PL}$ = fuel mass flow rate at partial load

$\dot{m}_{f,NOM}$ = fuel mass flow rate at full load

5.3.3 Calculating Yearly CO₂ Emissions from Micro-Gas Turbines

The carbon dioxide production in the current situation (SHP) is caused by two sources; the carbon dioxide because of the grid that generates electricity using coal, and the on-site combustion of biogas in the WWTP through boiler and gas flare.

The carbon dioxide emission from grid can be calculated using emission factor of the Israelian electricity company.

$$\text{CO}_{2,G} = G_f \times E_{\text{demand}} \dots\dots\dots 5.35$$

Where:

$\text{CO}_{2,G}$ = CO₂ production from grid(kg/yr).

G_f = Grid CO₂ factor = 0.7 kg/kWh (Israelian electricity factor for CO₂).

E_{demand} = Electrical energy demand of the WWTP (MWh/yr).

$$\text{Total CO}_{2, \text{SHP}} = \text{CO}_{2, \text{G,SHP}} + \text{CO}_{2, \text{Biogas}} \dots\dots\dots 5.36$$

Where:

$\text{CO}_{2, \text{SHP}}$ = CO₂ production during separate heat and power production in the current situation.(kg/yr)

$\text{CO}_{2, \text{G,SHP}}$ = CO₂ produced because of grid, from eqn. 5.35 (kg/yr)

$\text{CO}_{2, \text{Biogas}}$ = CO₂ produced from burning biogas on-site, from eqn. 5.33 (kg/yr).

The electrical energy demand from grid will be lower in CHP case than in SHP case and its CO₂ emissions will be lower.

The carbon dioxide production during the suggested cogeneration situation is caused by the combustion of biogas and the electricity demand from the grid which is partial of the electricity demand from grid in SHP situation.

$$\text{Total CO}_2, \text{ CHP} = \text{CO}_2 \text{ G,CHP} + \text{CO}_2, \text{Biogas} \dots \dots \dots \mathbf{5.37}$$

Where:

$\text{CO}_2 \text{ CHP}$ = CO_2 production during combined heat and power production in the suggested situation.

$\text{CO}_2 \text{ G,CHP}$ = CO_2 produced because of grid, from eqn. 5.35.

$\text{CO}_2, \text{Biogas}$ = CO_2 produced from burning biogas on-site, from eqn. 5.33.

The new suggested situation expects that the cogeneration plant will replace some of electricity demand from the grid while producing all of the needed heat for the operation of digester, so CHP will result in savings of CO_2 because of the electricity demand reduction from grid. Equation 5.38 gives a relation between the saved electrical energy and CO_2 savings.

$$\text{CO}_2, \text{S} = \text{CO}_2, \text{SHP} - \text{CO}_2, \text{CHP} = \text{CO}_2, \text{GSHP} - \text{CO}_2 \text{G,CHP} \dots \dots \dots \mathbf{5.38}$$

Where:

CO_2, S = saved CO_2 (kg/yr)

CO_2, SHP = CO_2 production during current situation (kg/yr), from eqn. 5.36.

CO_2, CHP = CO_2 production during suggested situation CHP(kg/yr), from eq5.37.

$\text{CO}_2 \text{ G,SHP}$ = CO_2 production from grid in current situation(kg/yr), from eq5.35.

$\text{CO}_2 \text{G, CHP}$ = CO_2 production from grid during suggested situation CHP, (kg/yr), from eqn. 5.35.

5.3.4 Other Emissions from Burning Biogas

The emissions from burning Biogas other than CO₂ and greenhouse gases depends on the combustion device in which it is burned, the US Environmental Protection Agency gave the rate of emissions from burning Biogas depending on the burning device as shown in table 5.3.

The following set of equations will be used to calculate the annual emissions from burning biogas using micro-gas turbines and internal combustion engines:

$$NO_{x,MGT} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{NO_x} \dots \dots \dots 5.39$$

$$CO_{,MGT} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{CO} \dots \dots \dots 5.40$$

$$VOC_{MGT} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{VOC} \dots \dots \dots 5.41$$

$$PM_{MGT} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{PM} \dots \dots \dots 5.42$$

$$SO_{x,MGT} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{SO_x} \dots \dots \dots 5.43$$

$$NO_{x,ICE} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{NO_x} \dots \dots \dots 5.44$$

$$CO_{ICE} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{CO} \dots \dots \dots 5.45$$

$$SO_{x,ICE} = \frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}} \times M_{Biogas} \times EF_{SO_x} \dots \dots \dots 5.46$$

Where:

$\frac{\dot{m}_{f,PL}}{\dot{m}_{f,Nom}}$ = relative mass flow rate of biogas due to partial load, from eqn.

5.34.

M_{biogas} = Annual mass of produced biogas (kg/yr) from eqn. 5.32.

EF = Emission factor, from table 5.3.

Table 5.3: Emission Factors from Burning Biogas in Micro-Gas Turbines [3]

Technology Emission	lb/MMscf (lb/MMscf = $\frac{1}{21}$ ppm OR 3.66 mg/m ³ * 0.0624279606 = 0.2285 lb/MMcf)				
	NO _x	CO	VOC	PM	SO _x
MGT	96.0	10.2	3.48	NA	3.9
ICE	324	546	NA	NA	870

6. Chapter Six – Comparison Between Cogeneration Alternatives

6.1 Introduction

Any design model always depends on optimization; since we have so many outputs that we are targeting on having some range or specific values to attain; including technical, economic and environmental measures.

In this chapter the alternatives that will be selected and sized will depend on utilizing all of the biogas being produced from the wastewater treatment plant, and covering all of the heat demands of the digester.

6.2 Fluctuations in biogas production

Biogas production rate from digester varies instantaneously and so the electrical and thermal energy production will vary if this biogas is introduced to the cogeneration plant directly. This problem can be overcome by using a biogas holder to store the produced gas and regulate its flow rate to the engines or turbines.

Biogas is typically stored only for short-terms (hours) at low pressures. This is because long term energy storage of biogas requires biogas pressurization. The energy input for biogas compression to a typical pressure of 17 bars is equal to approximately 10% of the energy value of stored biogas [11].

Figures 6.1a, b and c show the fluctuation of biogas production for three months of the studied period. It is observed that the daily production fluctuates around an average value, this value will be used as the design

value as shown in figure 6.1- d. It is assumed that the system saves the excess gas in the holder. The stored quantity is to be used if there is a deficiency in the gas production. The average values of each month are given in app A.3.

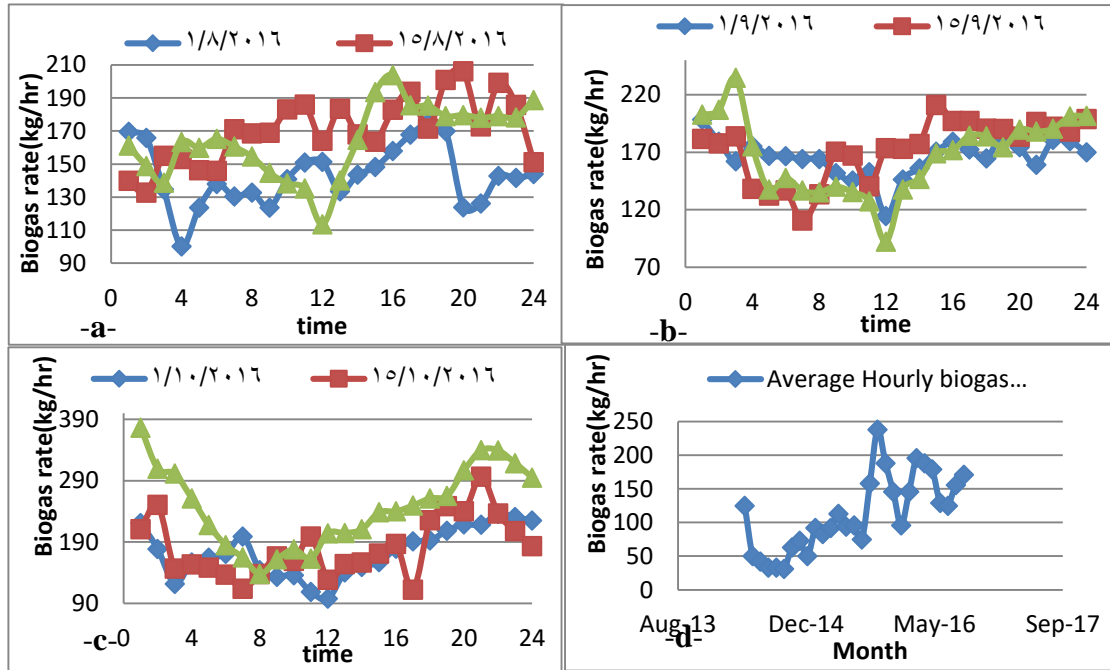


Figure 6.1: a-c: Fluctuations in biogas production for three selected months, d: the average values of biogas production for the studied period

6.3 Monthly energy content in biogas

The biogas energy content which was calculated using the lower heat value of biogas ($23\text{MJ}/\text{m}^3$) for every month, depending on the idea that Biogas flow rate is regulated using the Biogas holder for every day is shown in figure 6.2 which also shows the electrical energy demand for some months for comparison.

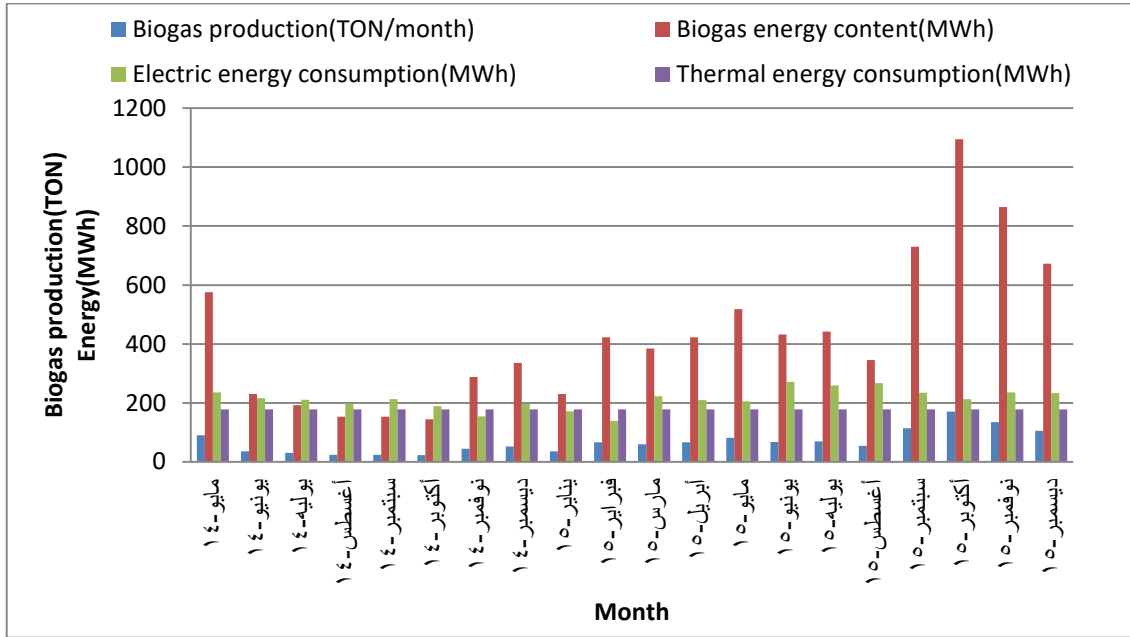


Figure 6.2: Biogas monthly quantities and its energy content

Due to the variation of organic content introduced to the digester; the biogas quantity varies. The utilization alternatives of biogas and their sizing will aim at maximizing energy recovery.

6.4 Microgas Turbines' Alternatives

Four types of Micro-Gas turbines were selected to be investigated, they were from CAPSTONE manufacturer: C30/30kW, C65/65kW, T100/100kW, C200/200kW.

For microturbine, the efficiency increases as the capacity increases since there is fixed operating losses for every turbine.

The average efficiency of the microturbines mentioned above is 30% and this value will be used to find a starting value of output power from the turbines for suitable sizing.

6.4.1 Expected output power depending on average efficiency

The output power from MGTs was calculated using the average value of MGT efficiency which was 30% depending on manufacturers' experimental values.

The expected power generation from MGT's is shown in figure 6.3 below as a first iteration. The power was considered to be constant during every month, since the buffer storage of biogas makes regulation for the supply flow rate.

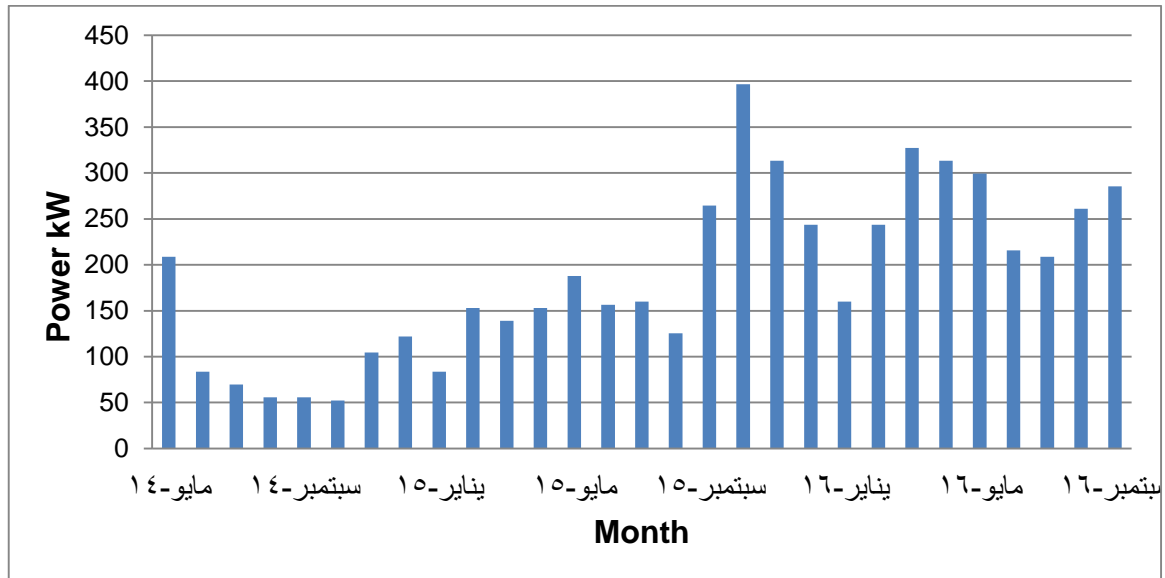


Figure 6.3: Expected Monthly power output from MGTs

It is observed from the previous figure that the output power that can be produced from the gas turbines varies monthly due to variation in gas flow rate, and this will affect the electrical energy supply to the plant, which will sometimes need to have supplemental supply from the electricity grid to compensate the difference between production and demand.

The electrical efficiency of microturbines is low; it can be increased by recovering some of the exhaust energy. Cogeneration is the ideal solution

in wastewater plants while there are coincident electrical and thermal consumption.

6.4.2 Number of turbines in operation

Four types of MGT were used to deal with this facility from CAPSTONE MGT manufacturer, C30 which has 30 kW capacity, C65 – 65 kW capacity, T100 – 100 kW capacity, C200 -200 kW capacity.

Five arrangements of the turbines were used to get benefit from and utilize all the produced Biogas to generate electricity and heat.

The total number of MGTs was calculated depending on the full load utilization approach, since the MGT is most efficient when operated near full load and its efficiency goes down dramatically when operated at partial load as discussed in chapter 4, table 6.1 shows the number of turbines needed for each case.

Table 6.1: Number of CHP Units for every case of MGT Arrangements.

Case Name MGT type	C30	C65	T100	C200	COMBINATION
C30	12 unit				1 unit of C30
C65		6 units			1 unit of C65
T100			4 units		2 units of T100
C200				2 units	1 unit of C200

The alternative cases that can be used to utilize the produced biogas with its variable production rates are discussed in the upcoming sections.

6.4.3 Case1- C30

In this case, 12 MGTs of C30 MGT were used to utilize the biogas produced from the digester; this number was selected depending on the maximum power output that can be achieved which was calculated in the previous section, the output power from these turbines was calculated depending on 26% efficiency of this type and assuming full load operating condition.

The schematic diagram of the system is shown in figure 6.4, showing the array of MGTs and explaining the cogeneration arrangement.

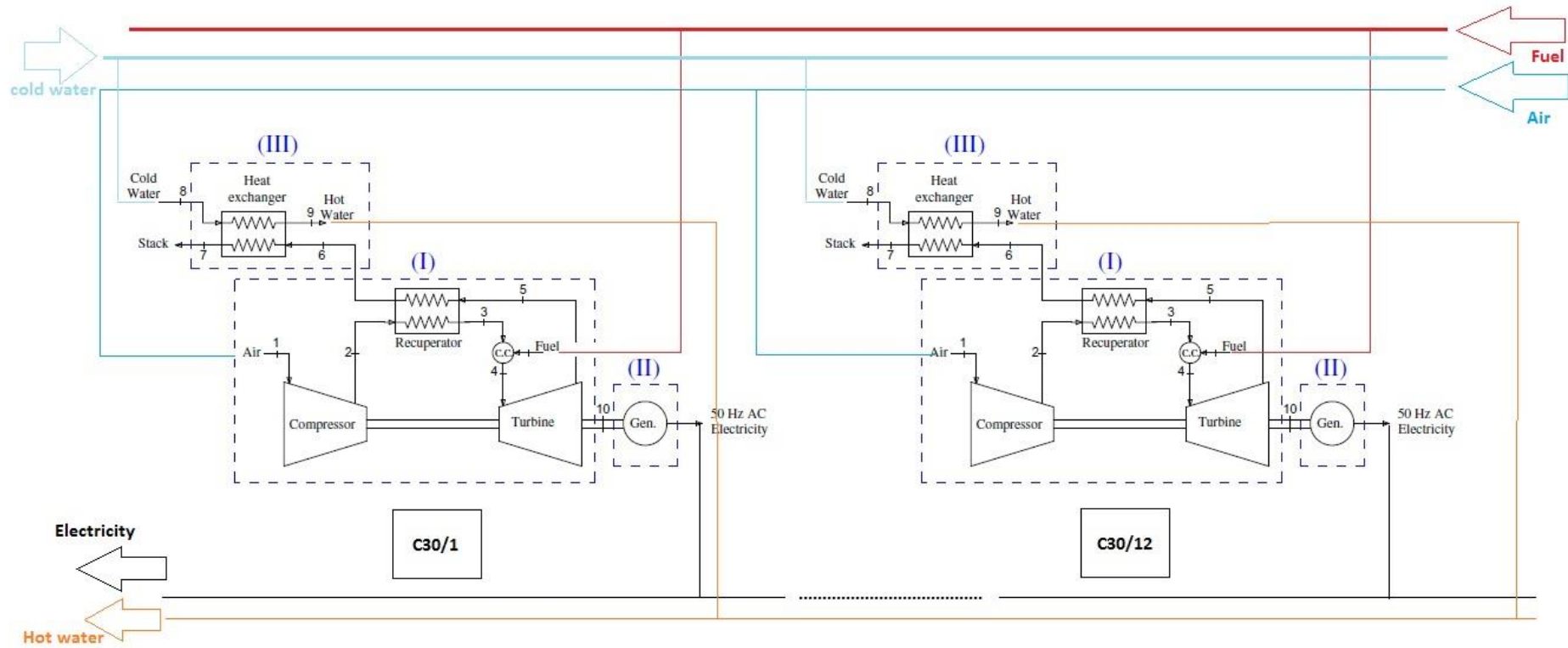


Figure 6.4 : Schematic diagram of the C30 case CHP arrangement

6.4.3.1 Output power from turbines

The output power of Micro-Gas Turbines in this case was calculated by multiplying the input power of biogas by the Electrical efficiency of C30 micro turbine which is 26%; figure 6.5 shows the expected output power for each month. This value is a first iteration value, which is not the actual output since the turbines are not operating at full load exactly, so we use this value as a first starting value to calculate the number of turbines that have to be operated during every month, then finding the actual output power using the efficiency of the turbine at its actual partial load value.

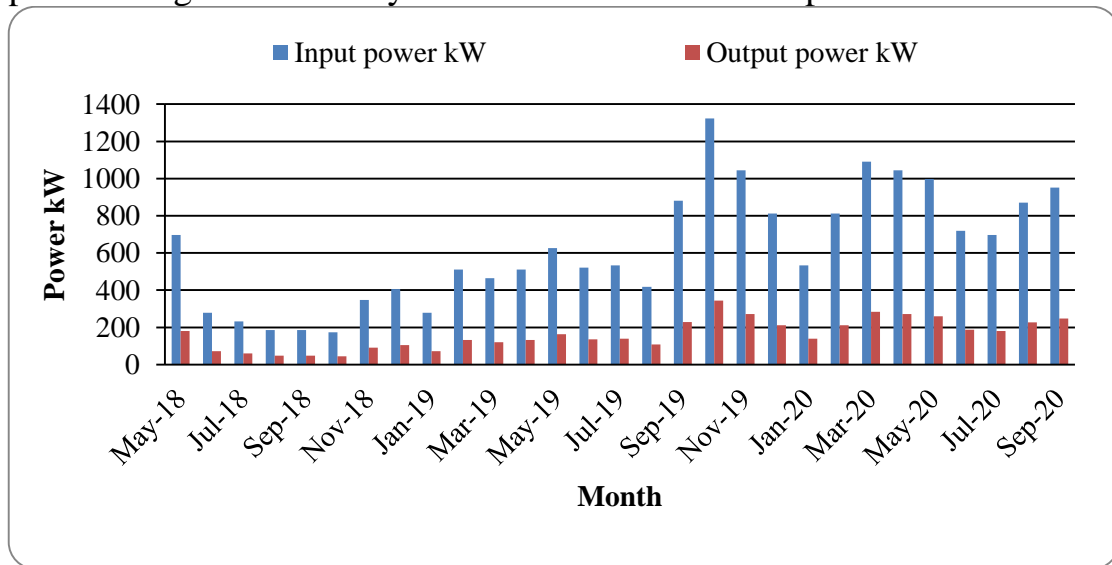


Figure 6.5: Expected output electrical power from turbines using C30 device

The electrical efficiency of the system is low and so the idea of having another additional energy conversion technology comes again. This can be seen in October 2015 for example which has a biogas quantity that can produce a power of 1322 kW while the expected electrical power output from C30 MGT is 343kW.

Also, the produced electrical energy does not meet the plant's electrical demand, so the plant must be connected to grid to compensate this shortage.

6.4.3.2 Number of turbines in operation and the partial load efficiency

The operating strategy of MGTs was planned depending on the idea of operating the turbines at full load condition, to attain the maximum efficiency of the devices.

The number of turbines to be operated every month was found by dividing the expected power output by the capacity of one turbine, and then the number was approximated to an integer.

As discussed in chapter 4, the efficiency of MGT goes down when it is operated at partial load; the effect of this on the output power of MGTs array was calculated.

The output power from MGTs was calculated again, taking the partial load efficiency in consideration,

Table 6.2 shows the number of turbines to be operated every month (operating strategy). It also shows the partial load efficiency for each month.

Table 6.2: The Monthly number of Turbines in Operation for C30 Arrangement and the partial load efficiency

Month	Power output kW	# of turbines in operation	Power Capacity kW	Partial load	P.L Electrical Efficiency%
May-14	181	7	210	0.86	25.8
Jun-14	72	3	90	0.80	25.6
Jul-14	60	3	90	0.67	24.9
Aug-14	48	2	60	0.80	25.6
Sep-14	48	2	60	0.80	25.6
Oct-14	45	2	60	0.75	25.4
Nov-14	90	4	120	0.75	25.3
Dec-14	105	4	120	0.88	25.8
Jan-15	72	3	90	0.80	25.6
Feb-15	133	5	150	0.88	25.8
Mar-15	121	5	150	0.80	25.6
Apr-15	133	5	150	0.88	25.8
May-15	163	6	180	0.90	25.8
Jun-15	136	5	150	0.90	25.8
Jul-15	139	5	150	0.92	25.9
Aug-15	109	4	120	0.90	25.8
Sep-15	229	8	240	0.96	26
Oct-15	344	12	360	0.96	26
Nov-15	272	10	300	0.90	25.8
Dec-15	211	8	240	0.88	25.8
Jan-16	139	5	150	0.92	25.9
Feb-16	211	8	240	0.88	25.8
Mar-16	284	10	300	0.95	26
Apr-16	272	10	300	0.90	25.8
May-16	259	9	270	0.96	26
Jun-16	187	7	210	0.89	25.8
Jul-16	181	7	210	0.86	25.8
Aug-16	226	8	240	0.94	25.9
Sep-16	247	9	270	0.92	25.8

The micro turbines will not operate at full load exactly, and so all or one of them will operate at partial load, this will lower the efficiency, on the other

hand, it will elongate the life of the turbine since it is not fully loaded and decrease the need for maintenance, so we have to operate in a range that considers achieving the optimum efficiency with the minimum need for maintenance.

It is observed that the partial load on MGT is not less than 70% which attains the efficiency in an accepted range.

6.4.3.3 Electrical Power Output Using Partial Load Efficiency and The Electrical Energy output

The electrical power output from turbines was calculated using the partial load efficiency while all MGT's were at partial load, then the electrical power output and energy for each month were calculated while all the MGT's were at full load and one turbine is at partial load operating condition, table 6.3 gives the results of these calculations.

Table 6.3: MGT new output power taking partial load efficiency in consideration

Month	All MGT are partially-loaded				One MGT is partially-loaded	
	Average input power(kW)	New output power(kW)	E _{elec.} (MWh)		P _{out}	E (MWh)
May-14	696	179.57	129.29		180.18	129.73
Jun-14	278.4	71.27	51.31		69.86	50.30
Jul-14	232	57.77	41.59		59.98	43.18
Aug-14	185.6	47.51	34.21		46.20	33.27
Sep-14	185.6	47.51	34.21		46.20	33.27
Oct-14	174	44.20	31.82		42.88	30.87
Nov-14	348	88.04	63.39		90.01	64.81
Dec-14	406	104.75	75.42		103.22	74.32
Jan-15	278.4	71.27	51.31		69.86	50.30
Feb-15	510.4	131.68	94.81		130.19	93.74
Mar-15	464	118.78	85.52		120.06	86.44
Apr-15	510.4	131.68	94.81		130.19	93.74
May-15	626.4	161.61	116.36		160.36	115.46
Jun-15	522	134.68	96.97		133.40	96.05
Jul-15	533.6	138.20	99.51		136.74	98.46
Aug-15	417.6	107.74	77.57		106.56	76.73
Sep-15	881.6	229.22	165.04		227.29	163.65
Oct-15	1322.4	343.82	247.55		341.36	245.78
Nov-15	1044	269.35	193.93		270.41	194.70
Dec-15	812	209.50	150.84		210.26	151.38
Jan-16	533.6	138.20	99.51		136.74	98.46
Feb-16	812	209.50	150.84		210.26	151.38
Mar-16	1090.4	283.50	204.12		281.03	202.34
Apr-16	1044	269.35	193.93		270.41	194.70
May-16	997.6	259.38	186.75		257.47	185.38
Jun-16	719.2	185.55	133.60		184.62	132.93
Jul-16	696	179.57	129.29		180.18	129.73
Aug-16	870	225.33	162.24		223.92	161.22
Sep-16	951.2	245.41	176.69		244.91	176.34

The electrical power output of turbines decreases slightly due to the partial load operating of MGTs in some of the months, but the percentage of decrease is in the accepted range.

Again, the electrical energy produced varies; this will lead us to think about using a supplemental source to compensate the shortage in electrical energy, which is the electrical grid.

The produced electrical energy from one partially loaded MGT sometimes more and sometimes less than the produced energy from it when all of MGT were partially loaded since the ratio of partial load of one MGT may be more when it is alone partially loaded. If we have a look to figure 6.6 we can see that for example July 2014, the expected electrical energy output if all MGT's are partially loaded is 41.6 MWh while it is 43.18MWh if one MGT is partially loaded and the others are at full load. But, if we take October 2015, the electrical energy output is 247.5MWh if all MGT's are partially loaded, while it is 245.8MWh if one MGT is partially loaded and the others are at full load.

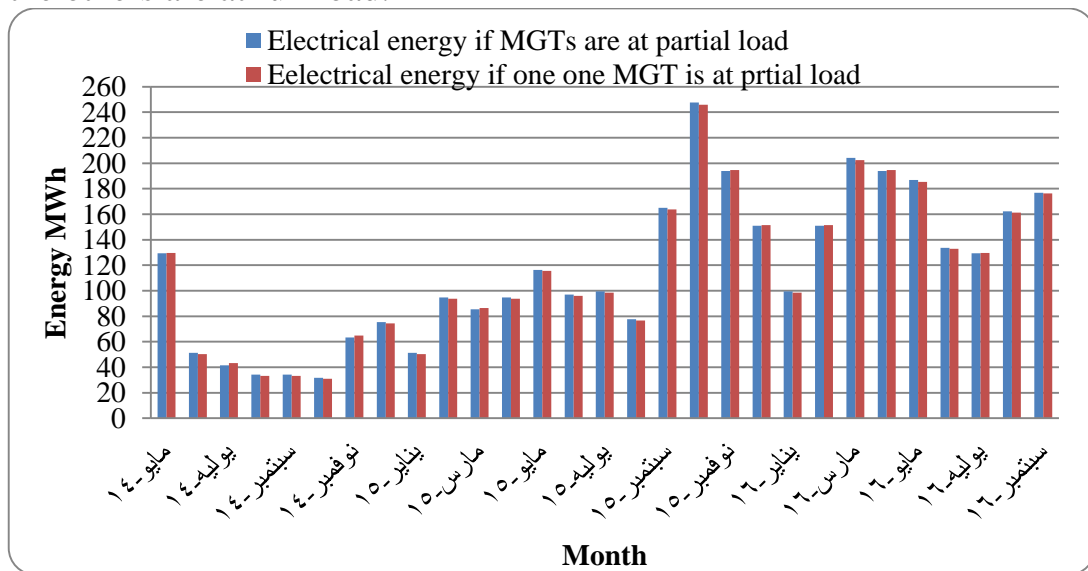


Figure 6.6: Comparison between electrical energy when all or one MGT are at full load

6.4.3.4 Partial load thermal efficiency and thermal energy

As discussed in chapter 4, the exhaust gases flow rate and exhaust gases temperature goes down dramatically while the microturbine is partially loaded same as the electrical efficiency, this will lead in a decrease in the thermal efficiency of MGT when it is in the CHP configuration, the partial load thermal efficiency was calculated.

The thermal energy from cogeneration processes was calculated taking in consideration the partial load thermal efficiency; table 6.4 gives the thermal efficiency at each partial load while figure 6.7 shows the thermal power results for each month.

Table 6.4: Partial load thermal efficiency and thermal power output of MGT

Month	P.L.	P. L. thermal Efficiency%	Thermal power output (kW)	E _{therm} (MWh)
May-14	0.86	75.00	529.99	382
Jun-14	0.80	75.00	215.04	155
Jul-14	0.67	76.00	184.96	133
Aug-14	0.80	75.00	143.36	103
Sep-14	0.80	75.00	143.36	103
Oct-14	0.75	75.00	136.15	98
Nov-14	0.75	75.00	271.23	195
Dec-14	0.88	75.00	307.15	221
Jan-15	0.80	75.00	215.04	155
Feb-15	0.88	75.00	385.43	278
Mar-15	0.80	75.00	358.39	258
Apr-15	0.88	75.00	385.43	278
May-15	0.90	74.00	469.69	338
Jun-15	0.90	74.00	391.41	282
Jul-15	0.92	74.00	398.89	287
Aug-15	0.90	74.00	313.13	225
Sep-15	0.96	74.00	654.96	472
Oct-15	0.96	74.00	982.44	707
Nov-15	0.90	74.00	782.81	564
Dec-15	0.88	75.00	614.29	442
Jan-16	0.92	74.00	398.89	287
Feb-16	0.88	75.00	614.29	442
Mar-16	0.95	74.00	812.77	585
Apr-16	0.90	74.00	782.81	564
May-16	0.96	74.00	739.79	533
Jun-16	0.89	74.00	542.00	390
Jul-16	0.86	75.00	529.99	382
Aug-16	0.94	74.00	646.53	466
Sep-16	0.92	74.00	710.48	512

The values of thermal energy is higher than the corresponding electrical energy values since the energy conversion of the waste heat energy is being done in a heat exchanger and so, it is energy transfer technology i.e., the energy type is heat and remains heat, and it is only transferred.

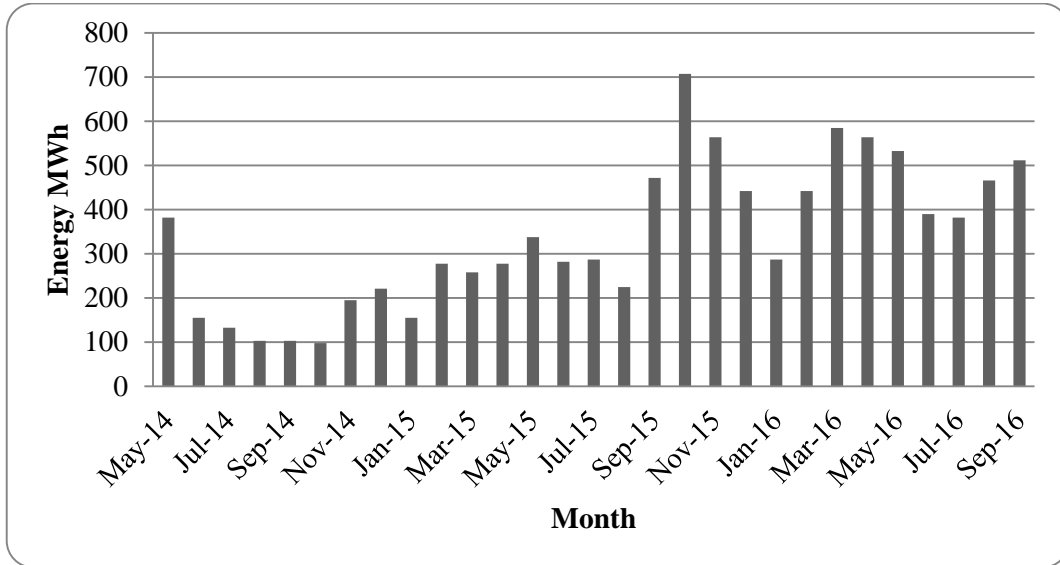


Figure 6.7: Thermal energy output from MGT array in C30 case

6.4.3.5 Total energy output and Power to heat ratio

Table 6.5 gives a summary for the electrical and thermal energy output produced from C30 MGT's array for each month. It also gives the total efficiency of cogeneration plant and the power to heat ratio, which shows the ratio between electrical and thermal outputs of the cogeneration plant.

Table 6.5: Output characteristics of MGTs array in case1

Case1- C30						
Month	E_{in} (MWh)	E_{elec} (MWh)	E_{therm} (MWh)	E_{total} (MWh)	Total CHP Efficiency %	Power/Heat Ratio
May-14	576	129.29	382	511	88.69	0.34
Jun-14	230.4	51.31	155	206	89.47	0.33
Jul-14	192	41.59	133	175	91.02	0.31
Aug-14	153.6	34.21	103	137	89.47	0.33
Sep-14	153.6	34.21	103	137	89.47	0.33
Oct-14	144	31.82	98	130	90.17	0.32
Nov-14	288	63.39	195	259	89.82	0.32
Dec-14	336	75.42	221	297	88.26	0.34
Jan-15	230.4	51.31	155	206	89.47	0.33
Feb-15	422.4	94.81	278	372	88.14	0.34
Mar-15	384	85.52	258	344	89.47	0.33
Apr-15	422.4	94.81	278	372	88.14	0.34
May-15	518.4	116.36	338	455	87.68	0.34
Jun-15	432	96.97	282	379	87.68	0.34
Jul-15	441.6	99.51	287	387	87.57	0.35
Aug-15	345.6	77.57	225	303	87.68	0.34
Sep-15	729.6	165.04	472	637	87.25	0.35
Oct-15	1094.4	247.55	707	955	87.25	0.35
Nov-15	864	193.93	564	758	87.68	0.34
Dec-15	672	150.84	442	593	88.26	0.34
Jan-16	441.6	99.51	287	387	87.57	0.35
Feb-16	672	150.84	442	593	88.26	0.34
Mar-16	902.4	204.12	585	789	87.47	0.35
Apr-16	864	193.93	564	758	87.68	0.34
May-16	825.6	186.75	533	719	87.14	0.35
Jun-16	595.2	133.60	390	524	88.01	0.34
Jul-16	576	129.29	382	511	88.69	0.34
Aug-16	720	162.24	466	628	87.19	0.35
Sep-16	787.2	176.69	512	688	87.43	0.35

It is observed that:

- The total CHP system efficiency is always about 90%.
- The electric power to heat ratio is always about 0.33, that means that the system produces heat three times the electrical energy which

makes the cogeneration arrangement very useful for onsite uses where heat energy is needed for the same facility.

Figure 6.8 shows the input and output energies for the MGT's array as an expression for the system efficiency.

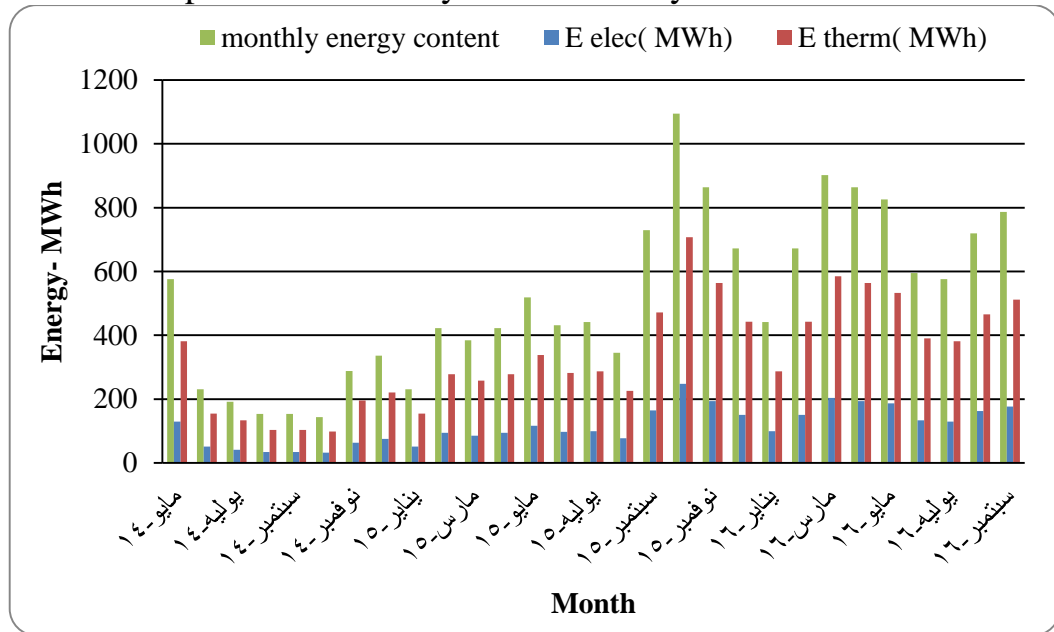


Figure 6.8: Comparison between energy input and two energy outputs of CHP MGTs

6.4.3.6 Meeting the electrical and thermal energy demand

The electrical load of the facility varies and thermal load has approximately constant value, while the produced electrical and thermal energy varies monthly.

We have excess heat and shortage in electrical energy production, as shown in figure 6.9 this will lower the real total CHP efficiency of the system since we use the thermal energy produced for the on-site use only to heat the digester.

If we take the total expected electrical energy that can be produced during 2015, it will be 1475MWh while the electrical demand was 2661 MWh,

that means that the CHP plant can cover about 55% of the electrical needs of the wastewater plant. On the other hand, if we compare the thermal energy production during the year 2015 to the thermal energy consumption, we see that the expected output will be 4285MWh while the consumption was 2137 MWh; that means that we have excess thermal energy that can be used for other applications.

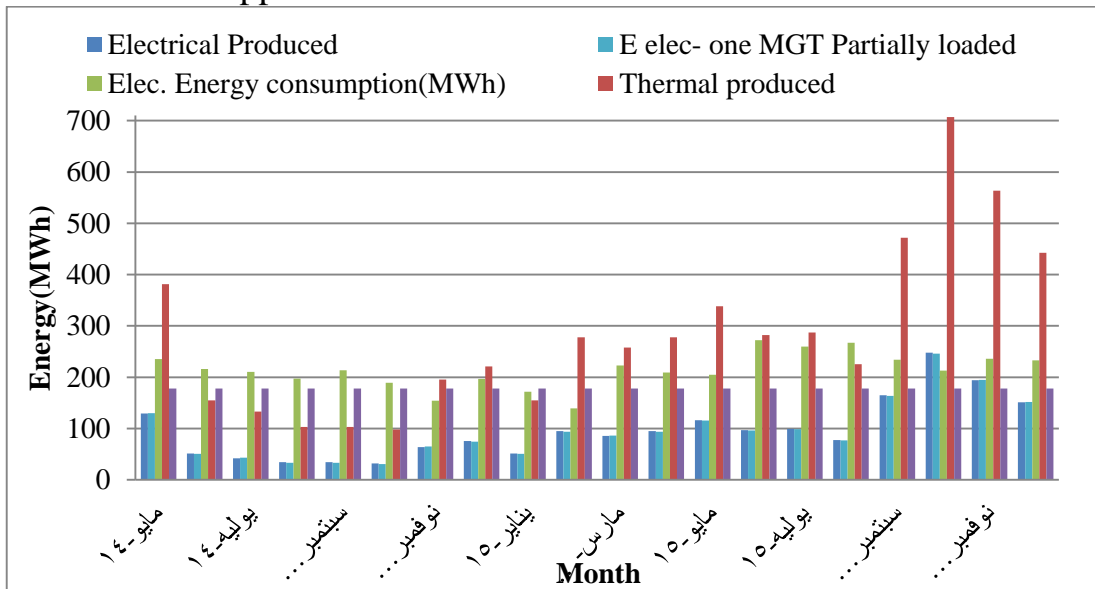


Figure 6.9: Comparison Between consumption and Electrical and Thermal energy production from C30 case

The shortage in electrical energy production can be substituted from the electricity grid, making the system as a primary power source with the grid as a backup. The detailed calculations of C30 are shown in App B.3.

6.4.4 Case2 - C65

In this case, 6 CHP units MGTs of C65 MGT were used to utilize the biogas produced from the digester, this number was selected depending on the maximum power output that can be achieved which was calculated in

the previous section, the output power from these turbines was calculated depending on 29% efficiency of this type and assuming full load operating condition. The schematic diagram of the system is similar to that of C30 case but the array contains 6 units of C65 turbines instead of 12 turbines used in C30 case.

The operating strategy of MGTs was planned depending on the idea of operating the turbines at full load condition, to attain the maximum efficiency of the devices.

The number of turbines to be operated every month was found by dividing the expected power output by the capacity of one turbine, and then the number was approximated to an integer.

Operating one or all MGT at partial load have the same output electrical energy, table 6.6 shows the operating strategy and outputs of this case.

Table6.6: Produced Electrical and Thermal Energy for C65 case

Case2- C65						
Month	E _{in} (MW)	# of turbines in operation	E _{elec} (MW)	E _{therm} (MWh)	Tot. CHP Efficiency %	Power/Heat Ratio
May-14	576	4	137	419	96.61	0.33
Jun-14	230.4	2	52	170	96.46	0.30
Jul-14	192	2	41	144	96.32	0.29
Aug-14	153.6	1	37	111	96.65	0.33
Sep-14	153.6	1	37	111	96.65	0.33
Oct-14	144	1	34	105	96.61	0.33
Nov-14	288	2	69	210	96.61	0.33
Dec-14	336	2	83	242	96.70	0.34
Jan-15	230.4	2	52	170	96.46	0.30
Feb-15	422.4	3	100	308	96.60	0.33
Mar-15	384	3	89	282	96.53	0.32
Apr-15	422.4	3	100	308	96.60	0.33
May-15	518.4	3	129	372	96.72	0.35
Jun-15	432	3	103	314	96.61	0.33
Jul-15	441.6	3	106	321	96.62	0.33
Aug-15	345.6	2	86	248	96.72	0.35
Sep-15	729.6	4	184	522	96.75	0.35
Oct-15	1094.4	6	276	783	96.75	0.35
Nov-15	864	5	215	620	96.72	0.35
Dec-15	672	4	166	483	96.70	0.34
Jan-16	441.6	3	106	321	96.62	0.33
Feb-16	672	4	166	483	96.70	0.34
Mar-16	902.4	5	227	646	96.75	0.35
Apr-16	864	5	215	620	96.72	0.35
May-16	825.6	5	204	595	96.69	0.34
Jun-16	595.2	4	143	432	96.63	0.33
Jul-16	576	4	137	419	96.61	0.33
Aug-16	720	4	181	515	96.74	0.35
Sep-16	787.2	5	192	569	96.67	0.34

-It is observed that the number of turbines to be operated varies monthly, so sometimes we need to operate one turbine and sometimes we must operate the power plant at full capacity with 6 turbines.

-It is also observed that we cannot meet the full load exactly since we don't have unity capacities of CHP units, but still we are operating about the full load.

-The maximum Electrical energy in this case occurs at October with a value of 276 MWh / Month.

-It is observed that there is a linear relation between the variation of biogas power content and the variation of electrical energy production.

The Produced electrical energy is always less than the electrical load, as shown in figure 6.10, while the produced thermal energy is always more than the thermal load, shortage in electrical energy can easily be compensated from the grid, so we have electrical energy savings, i.e. the CHP plant acts as a parallel source with the electrical grid.

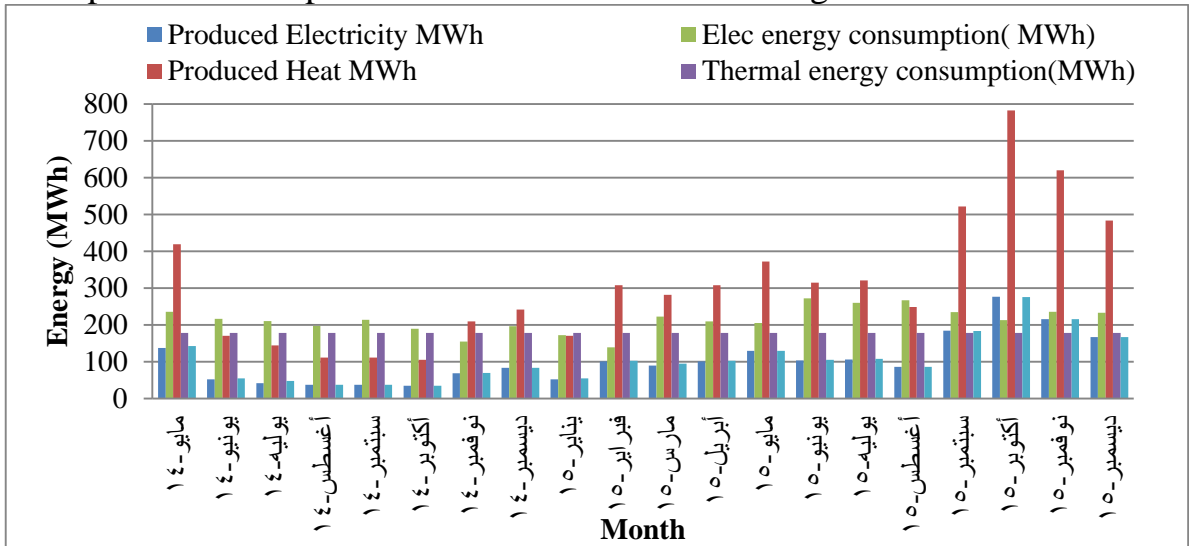


Figure 6.10: Comparison Between consumption and Produced Energy fom C65 Arrangement

If we take the total expected electrical energy that can be produced during 2015, it will be 1608MWh while the electrical demand was 2661 MWh that means that the CHP plant can cover about 60% of the electrical needs of

the wastewater plant. On the other hand, if we compare the thermal energy production during the year 2015 to the thermal energy consumption, we see that the expected output will be 4731MWh while the consumption was 2137MWh. These values are more than those of the C30 case since C65 has higher efficiency.

The electrical energy is always less than the thermal energy since the electrical efficiency is low, and so the heat energy contains all of the remaining energy of the exhaust except the losses in the recovering heat exchanger which is about 20% of the exhaust energy. The detailed calculations of C65 are given in App B.4.

6.4.5 Case 3- T100

In this case, 4 CHP units MGTs of T100 MGT were used to utilize the biogas produced from the digester, this number was selected depending on the maximum power output that can be achieved which was calculated in the previous section, the output power from these turbines was calculated depending on 30% efficiency of this type and assuming full load operating condition.

The schematic diagram of the system is similar to that of C30 case but the array contains 4 units of T100 instead of 12 turbines used in C30 case.

The strategy to operate the turbines used in this case can be noticed from table 6.7; it depends on keeping the turbines operating near the full load point.

In this case, it is observed that operating all microturbines on full load and loading one turbine partially will improve the total efficiency of the plant and produce more energy every month. Actually the difference between the two cases is a small percentage, but if we compare the yearly accumulation of the excess energy that will be produced, we will get a noticeable quantity, table 6.7 shows the results of this case.

As can be concluded from table 6.7, the total CHP efficiency of this case is low, this is due to the lower thermal energy that can be produced from this type of microturbines.

Table 6.7: The expected output from T100 case

Case3-T100						
Month	E_{in} (MWh)	#MGT in operation	E_{elec} (MWh)	E_{therm} (MWh)	Tot. CHP Efficiency%	Power/Heat Ratio
May-14	576	3	138	265	69.98	0.52
Jun-14	230.4	1	58	107	71.35	0.54
Jul-14	192	1	46	88	69.98	0.52
Aug-14	153.6	1	35	70	68.19	0.50
Sep-14	153.6	1	35	70	68.19	0.50
Oct-14	144	1	32	65	67.65	0.49
Nov-14	288	2	64	131	67.65	0.49
Dec-14	336	2	78	154	68.92	0.51
Jan-15	230.4	1	58	107	71.35	0.54
Feb-15	422.4	2	104	195	70.71	0.53
Mar-15	384	2	92	177	69.98	0.52
Apr-15	422.4	2	104	195	70.71	0.53
May-15	518.4	2	134	240	72.21	0.56
Jun-15	432	2	107	199	70.88	0.54
Jul-15	441.6	2	110	204	71.04	0.54
Aug-15	345.6	2	81	158	69.15	0.51
Sep-15	729.6	3	186	338	71.75	0.55
Oct-15	1094.4	4	286	508	72.59	0.56
Nov-15	864	4	214	399	70.88	0.54
Dec-15	672	3	168	310	71.15	0.54
Jan-16	441.6	2	110	204	71.04	0.54
Feb-16	672	3	168	310	71.15	0.54
Mar-16	902.4	4	225	417	71.20	0.54
Apr-16	864	4	214	399	70.88	0.54
May-16	825.6	3	216	383	72.63	0.56
Jun-16	595.2	3	144	274	70.23	0.53
Jul-16	576	3	138	265	69.98	0.52
Aug-16	720	3	183	333	71.65	0.55
Sep-16	787.2	3	204	365	72.29	0.56

The power to heat ratio in this case is more than C30 and C65 cases; i.e. the produced thermal energy is less than other cases.

As in the other cases in this study, it is shown in figure 6.11 that the expected electrical energy that can be produced from this case is less than the electrical demand.

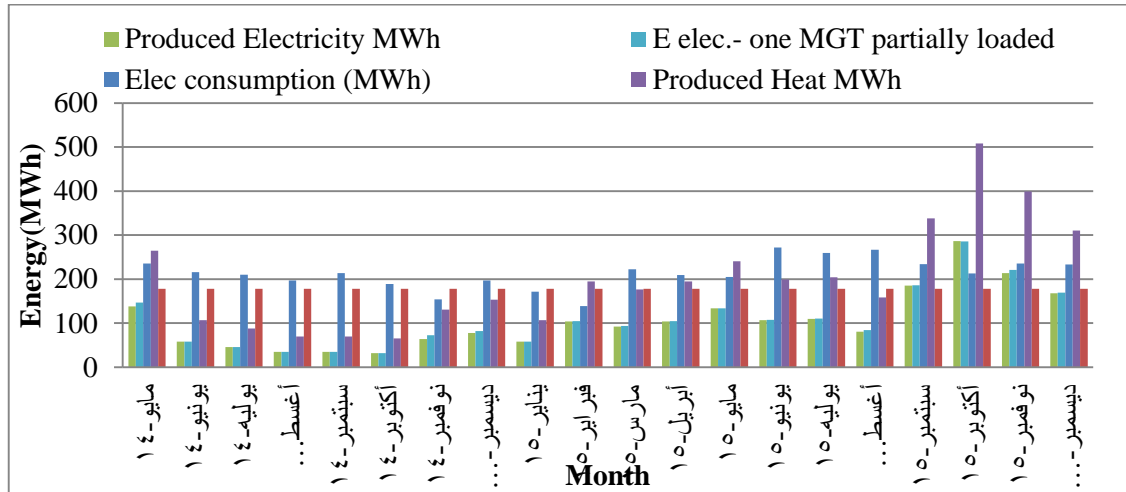


Figure 6.11: The Electrical and Thermal Production and consumption of T100 Arrangement

The difference between this case and the other cases is that the expected thermal energy production is less than the thermal load of the plant, this can be seen in the months may2014 to January 2015, if we take the minimum value of thermal energy production, it will be during October 2014 with a shortage of 113MWh that means that we need to use external source of heat such as boiler, this will affect the feasibility of using this alternative because of the increase in capital cost due to the need of boiler and operating costs due to the need of fuel. The detailed calculations of T100 are given in App. B.5.

6.4.6 Case 4- C200

In this case, 2 CHP units MGTs of C200 MGT were used to utilize the biogas produced from the digester, this number was selected depending on the maximum power output that can be achieved which was calculated in the previous section, the output power from these turbines was calculated depending on 33% efficiency of this type and assuming full load operating condition and then the operating strategy was planned and so, the capacities to be operated each month was found, then the partial load percentage for every month was calculated to find the partial load efficiency and the actual electrical and thermal power and energy outputs.

The schematic diagram of the system is similar to that of C30 case but the array contains 2 units of C200 turbines instead of 12 turbines used in C30 case.

The operating strategy of C200 turbines was planned and shown in table 6.8 below, in this case it is observed that some months of the studied period were at observable partial load, so this leads us to think about using non-identical microturbines to overcome this shortage, this is discussed in the next section which depends on using a combination of variable capacities of micro-gas turbines.

It was observed in this Arrangement that operating ALL MGTs at partial load produces more electrical energy than operating one MGT at partial load.

Table 6.8: Produced Thermal and Electrical Energy for C200 Arrangement

Case4- C200						
Month	E_{in} (MWh)	E_{elec} (MWh)	E_{therm} (MWh)	# of turbines in operation	Tot. CHP Eff. %	Power/Heat Ratio
May-14	576	141	288	2	74.41	0.49
Jun-14	230.4	53	114	1	72.26	0.46
Jul-14	192	42	93	1	70.39	0.45
Aug-14	153.6	31	73	1	67.95	0.42
Sep-14	153.6	31	73	1	67.95	0.42
Oct-14	144	28	68	1	67.20	0.42
Nov-14	288	70	144	1	74.41	0.49
Dec-14	336	86	169	1	75.81	0.51
Jan-15	230.4	53	114	1	72.26	0.46
Feb-15	422.4	114	214	1	77.78	0.53
Mar-15	384	101	194	1	76.97	0.52
Apr-15	422.4	114	214	1	77.78	0.53
May-15	518.4	147	264	1	79.43	0.56
Jun-15	432	117	219	1	77.96	0.54
Jul-15	441.6	121	224	1	78.14	0.54
Aug-15	345.6	89	174	1	76.06	0.51
Sep-15	729.6	190	368	2	76.53	0.52
Oct-15	1094.4	315	559	2	79.85	0.56
Nov-15	864	235	439	2	77.96	0.54
Dec-15	672	171	338	2	75.81	0.51
Jan-16	441.6	121	224	1	78.14	0.54
Feb-16	672	171	338	2	75.81	0.51
Mar-16	902.4	248	459	2	78.32	0.54
Apr-16	864	235	439	2	77.96	0.54
May-16	825.6	222	419	2	77.59	0.53
Jun-16	595.2	147	298	2	74.71	0.49
Jul-16	576	141	288	2	74.41	0.49
Aug-16	720	187	363	2	76.42	0.51
Sep-16	787.2	209	399	2	77.18	0.52

The electrical energy expected to be produced from this case is as all the cases of microturbines is not enough to cover the electrical load of the plant

as shown in figure 6.12, another source of electrical energy is needed to compensate this shortage which will be mainly the electricity grid.

If we take the total expected electrical energy that can be produced during 2015, it will be 1768 MWh while the electrical demand was 2661 MWh, that means that the CHP plant can cover about 65% of the electrical needs of the wastewater plant, and this value is more than those of the previous cases; since C200 has the highest efficiency and the effect of partial load is minimized since the partial load percentage will always be more than 70%. On the other hand, if we compare the thermal energy production during the year 2015 to the thermal energy consumption, we see that the expected output will be 3223MWh while the consumption was 2137MWh; which is less than the previous cases since the electrical energy is higher that means that thermal energy is lower and this situation is desired as we have excess thermal energy and shortage in electrical.

M. Aghaei. et al. [12] has studied the optimum arrangements for MGT's and investigated same CHP units used in this study. They tested several connection modes with identical and non-identical MGT's and found that the optimum arrangement is using two units of C200 MGT. The reason behind this choice was the relatively high nominal efficiency of this unit.

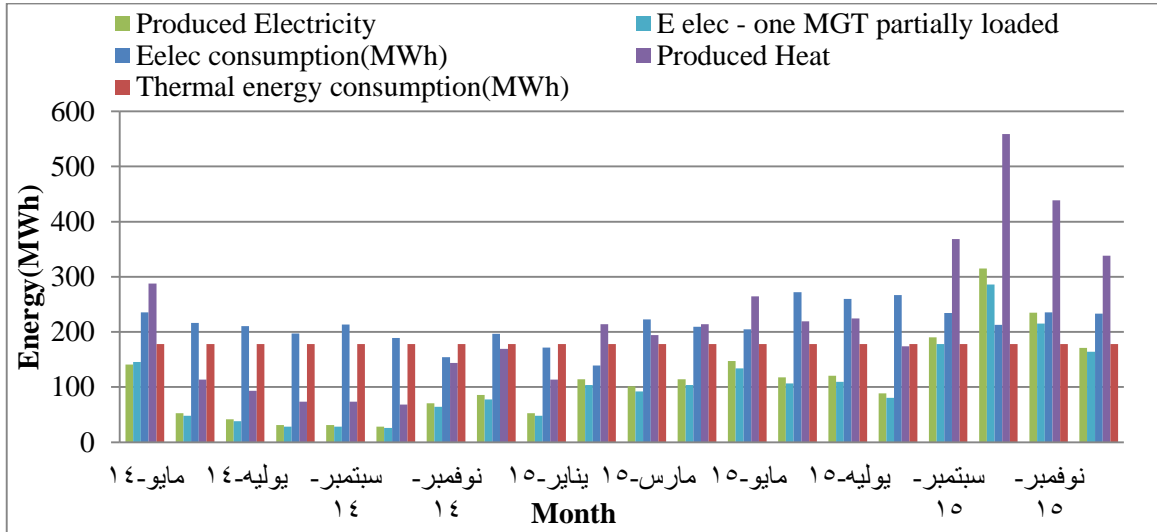


Figure 6.12: Comparison Between Electrical and Thermal Production And consumption in C200 CHP Arrangement

Again, as in T100 case, the thermal energy expected to be produced from this case is less than C30 and C65 cases, but generally it is enough to cover thermal load of the plant in most of the months of the studied period. The detailed calculations of C200 are given in App. B.6.

6.4.7 Case 5- Combined MGTs

In this arrangement, non – identical MGTs were used, which are C30, C65, 2-T100 and C200, all are in CHP operating condition. For every month of operation, combinations of two or three microturbines were used.

The expected output power from each month was calculated using a first iteration value of efficiency which is the average efficiency of the used turbines, this value was 30%, then after expecting the output power, the suitable combinations of turbines were selected, at this point, we have new average electrical efficiency of the turbines used in each month. Table 6.9 gives the results of these calculations for each month of the studied period.

After finding the average efficiency of the combinations of turbines we have a new value of expected output power, this value is also not the actual value, it is another iteration towards finding a value very near to the reality, this value was divided by the power capacity of the turbines combination for each month to find the partial load factor. For each partial load value, the partial load efficiency was calculated to find the actual efficiency on which the combinations of turbines are operating and then calculation the power and so the output electrical energy for each month of the studied period. Table 6.9 gives the results of the explained calculations.

Table 6.9: Monthly Combinations of MGT to be operated

Combined MGTs case							
Month	Power output	Turbines in operation	Average elec. Efficiency %	output power @ full load	partial load %	P.L. output power	P.L. average thermal efficiency
May-14	229.68	C200+30	29.50	205	89	191	0.69
Jun-14	91.87	C65+C30	27.50	77	81	72	0.70
Jul-14	76.56	C65+C30	27.50	64	67	57	0.71
Aug-14	61.25	C65	29.00	54	83	52	0.70
Sep-14	61.25	C65	29.00	54	83	52	0.70
Oct-14	57.42	C65	29.00	50	78	48	0.70
Nov-14	114.84	T100+C30	28.00	97	75	95	0.70
Dec-14	133.98	T100+C30	28.00	114	87	116	0.70
Jan-15	91.87	C65+C30	27.50	77	81	72	0.70
Feb-15	168.43	T100+C65+C30	28.30	144	74	139	0.71
Mar-15	153.12	T100+C65	29.00	135	82	123	0.70
Apr-15	168.43	T100+C65+C30	28.30	144	74	139	0.71
May-15	206.71	C200+C30	29.50	185	80	179	0.70
Jun-15	172.26	T100+C65+C30	28.30	148	76	143	0.70
Jul-15	176.09	T100+C65+C30	28.30	151	77	147	0.70
Aug-15	137.81	C100+C65	29.50	123	75	120	0.70
Sep-15	290.93	C200+T100	29.50	260	87	256	0.70
Oct-15	436.39	C200+T100 +C100+C65	30.50	403	87	384	0.70
Nov-15	344.52	C200+T100+C65	31.00	324	89	299	0.70
Dec-15	267.96	C200+T100	29.50	240	80	231	0.70
Jan-16	176.09	C200	33.00	176	88	147	0.70
Feb-16	267.96	C200+T100	29.50	240	80	231	0.70
Mar-16	359.83	C200+T100+C65	31.00	338	93	316	0.69
Apr-16	344.52	C200+T100+C65	31.00	324	89	299	0.70
May-16	329.21	C200+T100+C30	30.00	299	91	283	0.69
Jun-16	237.34	C200+C65	31.00	223	84	199	0.70
Jul-16	229.68	C200+C30	29.50	205	89	191	0.69
Aug-16	287.10	C200+T100	29.50	257	86	252	0.70
Sep-16	313.90	C200+T100+C30	30.00	285	86	267	0.70

Figure 6.13 shows a comparison between the expected electrical energy production if all the MGT's were partially loaded or one MGT of smallest capacity of each combination was partially loaded, it is observed that

loading one MGT partially will have more efficiency and produce more electrical energy.

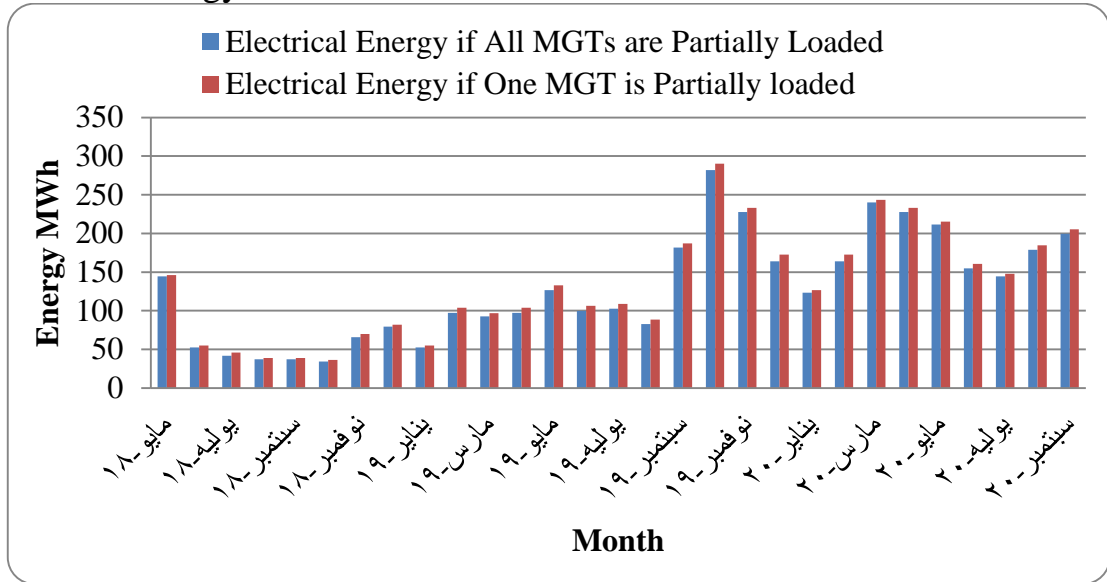


Figure 6.13: Electrical energy produced if One or All MGTs are Partially Loaded

Table 6.10 gives the expected outputs from the combined MGT's case in which the expected output of electrical and thermal energies is shown and the total efficiency and power to heat ratio were calculated.

Table 6.10: Electrical and Thermal Energy production for Case5

Case5- Combined MGTs						
Month	E_{in} (MWh)	E_{elec} (MWh)	E_{therm} (MWh)		CHP Eff. %	Power/Heat Ratio
May-14	576	145	329		82.23	0.44
Jun-14	230.4	53	123		76.17	0.43
Jul-14	192	42	103		75.25	0.41
Aug-14	153.6	37	86		80.46	0.43
Sep-14	153.6	37	86		80.46	0.43
Oct-14	144	34	81		80.13	0.42
Nov-14	288	66	157		77.19	0.42
Dec-14	336	80	182		77.95	0.44
Jan-15	230.4	53	123		76.17	0.43
Feb-15	422.4	97	232		77.95	0.42
Mar-15	384	93	216		80.38	0.43
Apr-15	422.4	97	232		77.95	0.42
May-15	518.4	127	297		81.69	0.43
Jun-15	432	100	237		78.07	0.42
Jul-15	441.6	103	243		78.18	0.42
Aug-15	345.6	83	198		81.30	0.42
Sep-15	729.6	182	417		82.08	0.44
Oct-15	1094.4	282	647		84.87	0.44
Nov-15	864	228	519		86.38	0.44
Dec-15	672	164	385		81.66	0.43
Jan-16	441.6	124	282		91.91	0.44
Feb-16	672	164	385		81.66	0.43
Mar-16	902.4	240	541		86.60	0.44
Apr-16	864	228	519		86.38	0.44
May-16	825.6	212	480		83.70	0.44
Jun-16	595.2	155	358		86.09	0.43
Jul-16	576	145	329		82.23	0.44
Aug-16	720	179	412		82.01	0.43
Sep-16	787.2	199	458		83.46	0.44

No change was observed in total efficiency seen in this case, as shown in figure 6.14; this means that no need to use non-identical units of microturbines. The use of identical turbines is better since it is easier to

stack them in parallel array and using same spare parts while making maintenance. The detailed calculations of combined MGT are given in App. B.7.

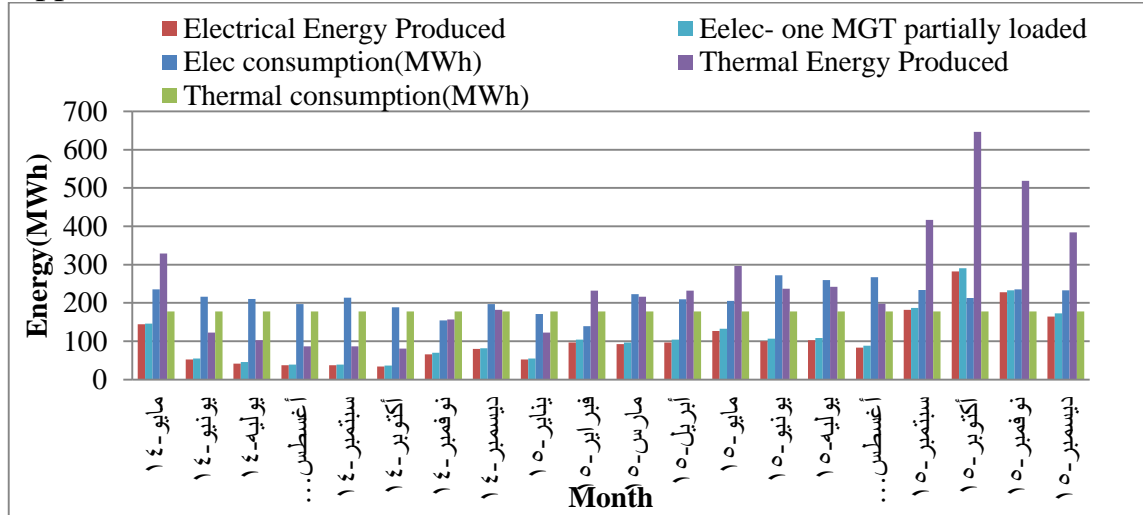


Figure 6.14: Comparison Between Electrical and Thermal Production And consumption in Combined MGT CHP Arrangement

6.4.8 Comparison between all cases of MGT

The comparison between the produced electrical and thermal energy from the micro-gas turbines alternatives for the period of study as shown in figure 6.15 was done on energy basis so as to test which of the alternatives can meet the electrical and thermal demands of the plant or what is the percentage of its share of these demands.

The comparison was also done to find the alternative that supplies the maximum quantity of energy production in its two types electrical and thermal, and so finding the saving of energy that can be achieved by these cogeneration alternatives.

We see from the figure 6.15 that the output energy from C200 MGT is higher than the other alternatives, since the nominal efficiency (full load

efficiency) is higher than them. Although the C200 turbines are partially loaded, i.e. sometimes 40% partially loaded, but the partial load efficiency remains higher than other alternatives. let's take the efficiency of February 2015, the partial load of this month is 76.5%, the efficiency of this load is 31% which is higher than all the other types of micro-gas turbines used in this study which range from 26%-30%, this leads us to a conclusion that we can load the micro-gas turbine partially until some limit, and still have higher electrical efficiency which means that we can use less number of generating units, and have longer life for the operating unit since it is not fully loaded and have less need for frequent maintenance and spare parts.

F. Basrawi et al. [9] has used the same MGT's and found that the most efficient alternative is using a combination of C30, C65 and C200 which produced the maximum energy of 1,630 MWh of electrical energy while C30 has produced the minimum electrical energy output of 1,430 MWh because of its low nominal efficiency although it is operated at full load.

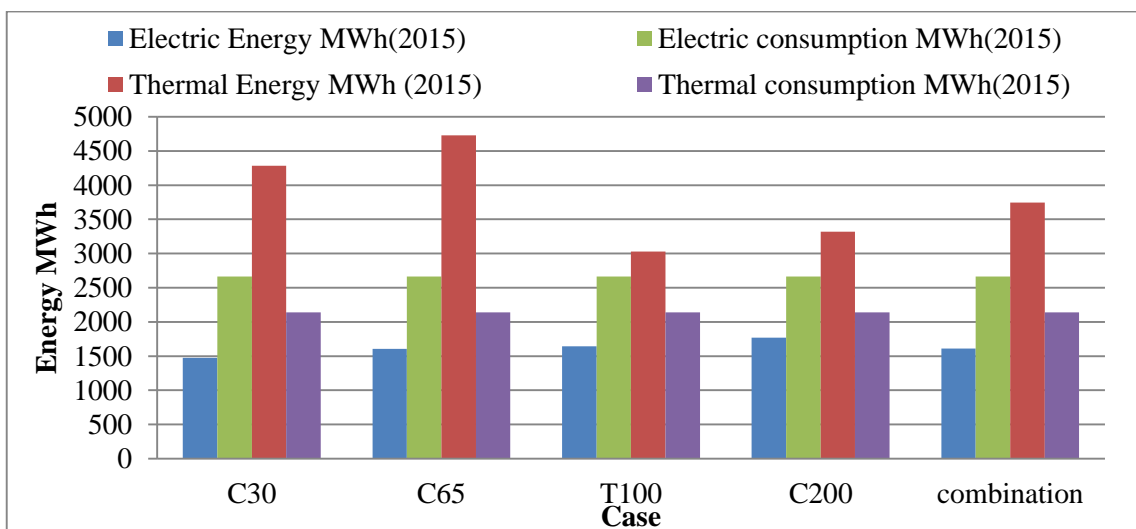


Figure 6.15 : Comparison between Electrical and thermal output energy for MGT cases

6.5 Internal combustion Engines

6.5.1 Expected power from internal combustion engines

The Power output from ICE's was calculated depending on the average electrical efficiency of the selected gas engines from CATERPILLAR manufacturer which were: C3306/143kW, C3406/235kW and CG132-8/400kW. Figure 6.1 shows the expected power output that can be produced from internal combustion engines depending on the average efficiency of 38% of the used engines.

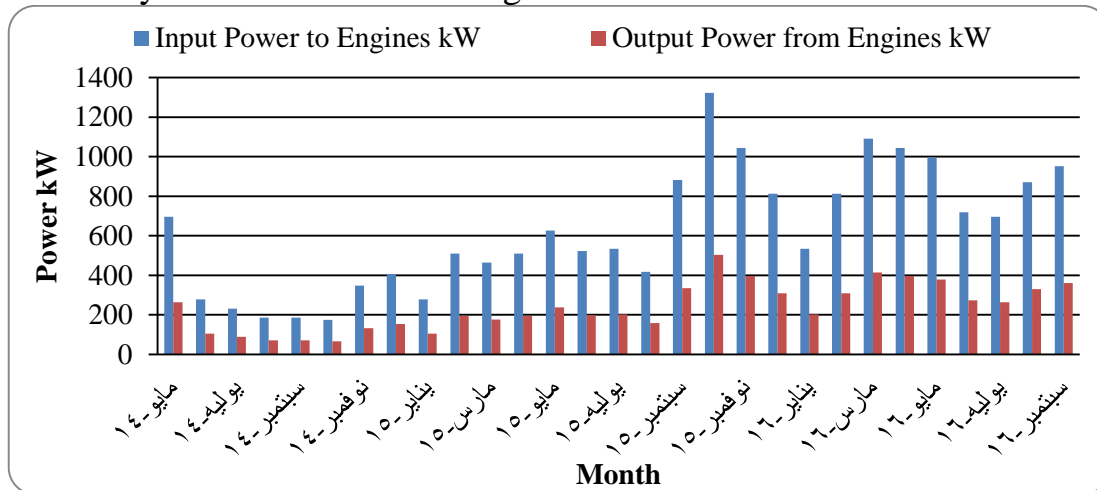


Figure 6.16: Expected electrical power output from internal combustion engines

Depending on the production chart given in figure 6.16, the maximum electrical power output will be 502kW in October 2015, the sizes of engines were selected and 4 scenarios were suggested, the analysis in the proceeding sections investigates the efficiencies and electrical and thermal energies outputs expected from each scenario.

The number of combined heat and power internal combustion engines units that was used in each of the suggested arrangements are shown in table 6.11.

Table 6.11: Number of CHP units in Each of Internal Combustion Engine Arrangements

Case Name Engine Type	G3306		G3406		CG132-8		COMBINED	
	ICE No.	Tot. capacity	ICE No.	Tot. capacity	ICE No.	Tot. capacity	ICE No.	Tot. capacity
G3306-143kW	3units	429					1unit	778
G3406-235kW			2units	470			1unit	
CG132-8 400kW					1	400	1unit	

In the first scenario; G3306 case, three engines of 143kW were selected so we have a total capacity of 429 kW. While in the second scenario; G3406 case, two engines of 235kW were selected so we have a total capacity of 470 kW. In the third scenario; CG132-8 case, one engine of 400kW was selected so we have a total capacity of 400 kW. In the fourth scenario; combined ICE case, three engines of different power capacities of 143kW, 235kW and 400kW were selected so we have a total capacity of 778 kW.

6.5.2 Case 6- G3306

Three internal combustion engines from CATERPILLAR manufacturer were selected to utilize biogas in this case, these engines are of G3306 type with electrical capacity of 143kW and electrical efficiency of 32 %.The engines are prepared to operate in cogeneration process that will produce electrical energy for on-site use in the plant and thermal energy that will supply the needed heat for the digester. The schematic diagram of this power plant is shown in figure 6.17.

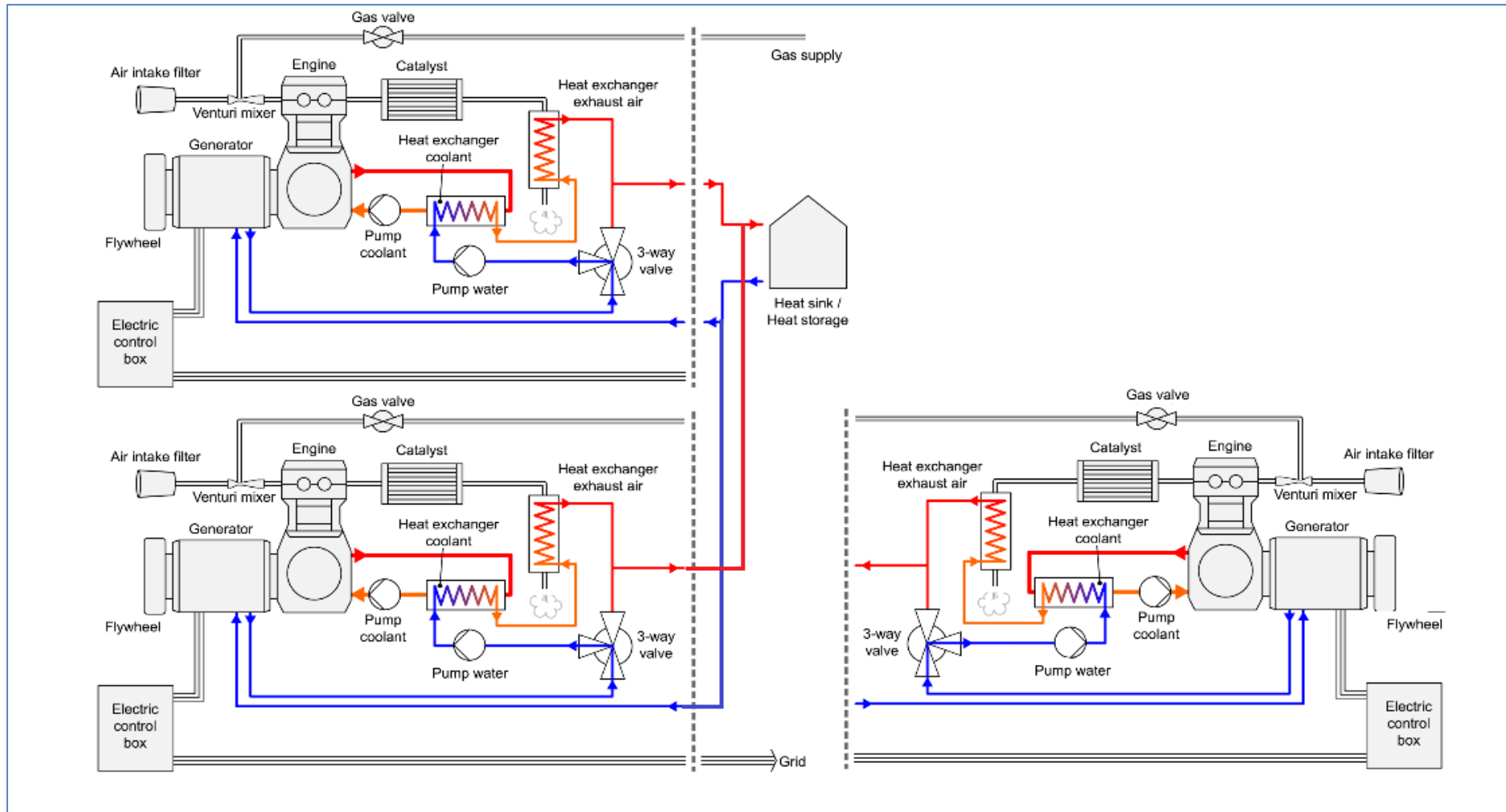


Figure 6.17: Schematic diagram of G3306 case

As the load on internal combustion engines is reduced, the waste heat increases and electrical efficiency decreases. The partial load efficiency of internal combustion engines at load factor of 50% is about 8 – 10 % below the full load efficiency. When the load factor becomes less than 50%, the electrical efficiency of the engine becomes less and the efficiency curve becomes steeper under this point. Depending on this fact, the internal combustion engine can be partially loaded until 50% of its full load with negligible amounts of efficiency decrease if compared to saving due to the fact that full load efficiency of the engines of larger capacities is more than that of smaller capacities.

We can see from table 6.12 that during the period of study, sometimes we need to operate only one engine, other times we need two, others we need three. This operating strategy is suggested to lower the losses that happen when operating small load on large capacities since there is fixed losses on the engine regardless to its load. In the other sections we will evaluate if this strategy is really feasible or not; since the efficiency of larger capacity engines is higher and the partial load efficiency is almost near the full load efficiency while the load factor on the engine is higher than 50%. Table 6.12 gives the output energy output that can be produced from G3306 scenario.

Table 6.12: Energy Outputs from Case 6

Case6- G3306										
Month	Power output	# of Engines	power capacity	P.L. % (must be > 50%)		E_{in} (MWh)	E_{elec} (MWh)	E_{therm} (MWh)	CHP Eff. %	Power/Heat Ratio
May-14	222.02	2	286	78		576	160	192	70	0.83
Jun-14	88.81	1	143	62		230.4	64	77	70	0.83
Jul-14	74.01	1	143	52		192	53	64	70	0.83
Aug-14	59.21	1	143	41		153.6	43	51	70	0.83
Sep-14	59.21	1	143	41		153.6	43	51	70	0.83
Oct-14	55.51	1	143	39		144	40	48	70	0.83
Nov-14	111.01	1	143	78		288	80	96	70	0.83
Dec-14	129.51	1	143	91		336	93	112	70	0.83
Jan-15	88.81	1	143	62		230.4	64	77	70	0.83
Feb-15	162.82	2	286	57		422.4	117	141	70	0.83
Mar-15	148.02	2	286	52		384	107	128	70	0.83
Apr-15	162.82	2	286	57		422.4	117	141	70	0.83
May-15	199.82	2	286	70		518.4	144	173	70	0.83
Jun-15	166.52	2	286	58		432	120	144	70	0.83
Jul-15	170.22	2	286	60		441.6	123	147	70	0.83
Aug-15	133.21	1	143	93		345.6	96	115	70	0.83
Sep-15	281.23	2	286	98		729.6	202	243	70	0.83
Oct-15	421.85	3	429	98		1094.4	304	365	70	0.83
Nov-15	333.04	3	429	78		864	240	288	70	0.83
Dec-15	259.03	2	286	91		672	187	224	70	0.83
Jan-16	170.22	2	286	60		441.6	123	147	70	0.83
Feb-16	259.03	2	286	91		672	187	224	70	0.83
Mar-16	347.84	3	429	81		902.4	250	301	70	0.83
Apr-16	333.04	3	429	78		864	240	288	70	0.83
May-16	318.23	3	429	74		825.6	229	275	70	0.83
Jun-16	229.42	2	286	80		595.2	165	198	70	0.83
Jul-16	222.02	2	286	78		576	160	192	70	0.83
Aug-16	277.53	2	286	97		720	200	240	70	0.83
Sep-16	303.43	3	429	71		787.2	218	262	70	0.83

The power to heat ratio in the internal combustion engines is higher than in micro-gas turbines, this mainly mean that the heat that can be recovered from the engine is lower since that there are mutiple outlets of heat losses

in the internal combustion engines which are the exhaust gases and cooling systems represented by jacket coolant and the oil cooling system.

As in the micro-gas turbines, the internal combustion engines will not cover the electrical energy demand of the facility; for example, during the year 2015 the total expected electrical energy production will be 1820 MWh while the electrical energy consumption was 2661MWh, i.e. covering 70% of the demand. This leads us to keep the facility on grid for shortage consumption. On the other hand, it is observed from figure 6.18 that the thermal energy that can be produced is not always sufficient to supply the heat demand of the facility during some months such as January 2015 , it was 77 MWh while the consumption is 178MWh . This is because the thermal energy that can be recovered in internal combustion engines is lower than that from micro-gas turbines because of the variation of waste heat outlets, this will lead us to investigate another alternative of internal combustion engines in order to try achieving total thermal energy covering and as much electrical energy as possible . The detailed calculations of G3306 are given in App. B.8.

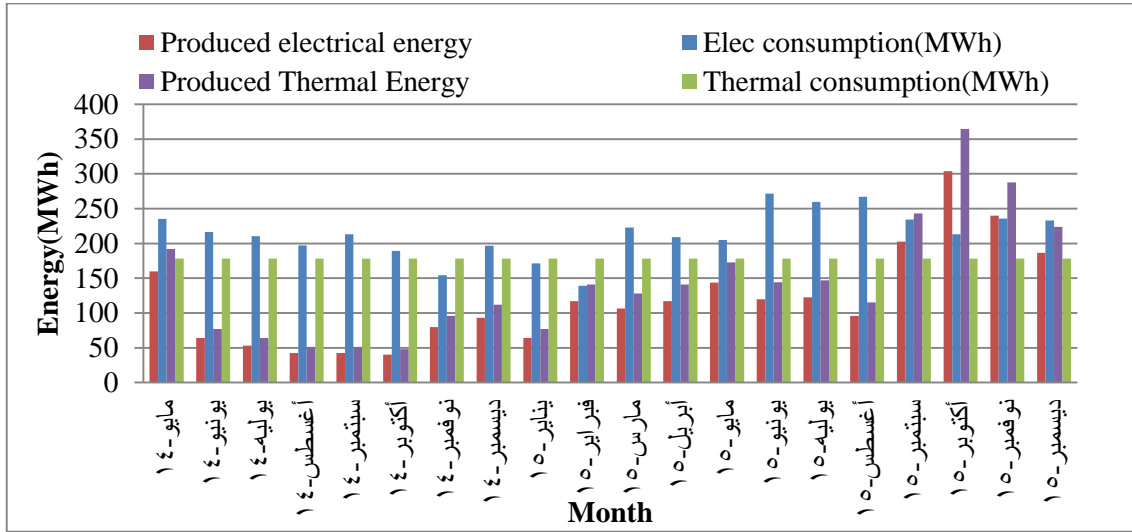


Figure 6.18: Electrical and thermal energy outputs and consumption in G3306 case

6.5.3 Case 7- G3406

Two internal combustion engines from CATERPILLAR manufacturer were selected to utilize biogas in this case. These engines are of G3406 type with electrical capacity of 235kW and electrical efficiency of 37 %. The engines are prepared to operate in cogeneration process that will produce electrical energy for on-site use in the plant and thermal energy that will supply the heat needed for the sludge digester.

The operating strategy of the engines in G3406 case shown in table 6.13 and depends on operating one engine or two engines and few months three engines to keep the load factor at higher values.

Table 6.13: Energy output, efficiency and power/heat ratio of G3406 case

Case7- G3406						
Month	E_{in} (MWh)	E_{elec}(MWh)	E_{therm}(MWh)	# of engines in operation	Tot. CHP Eff. %	Power/Heat Ratio
May-14	576	187	225	2	82.10	0.83
Jun-14	230.4	75	90	1	82.10	0.83
Jul-14	192	62	75	1	82.10	0.83
Aug-14	153.6	50	60	1	82.10	0.83
Sep-14	153.6	50	60	1	82.10	0.83
Oct-14	144	47	56	1	82.10	0.83
Nov-14	288	93	112	1	82.10	0.83
Dec-14	336	109	131	1	82.10	0.83
Jan-15	230.4	75	90	1	82.10	0.83
Feb-15	422.4	137	165	1	82.10	0.83
Mar-15	384	125	150	1	82.10	0.83
Apr-15	422.4	137	165	1	82.10	0.83
May-15	518.4	168	202	1	82.10	0.83
Jun-15	432	140	168	1	82.10	0.83
Jul-15	441.6	143	172	1	82.10	0.83
Aug-15	345.6	112	135	1	82.10	0.83
Sep-15	729.6	237	284	2	82.10	0.83
Oct-15	1094.4	355	427	3	82.10	0.83
Nov-15	864	280	337	2	82.10	0.83
Dec-15	672	218	262	2	82.10	0.83
Jan-16	441.6	143	172	1	82.10	0.83
Feb-16	672	218	262	2	82.10	0.83
Mar-16	902.4	293	352	2	82.10	0.83
Apr-16	864	280	337	2	82.10	0.83
May-16	825.6	268	322	2	82.10	0.83
Jun-16	595.2	193	232	2	82.10	0.83
Jul-16	576	187	225	2	82.10	0.83
Aug-16	720	234	281	2	82.10	0.83
Sep-16	787.2	255	307	2	82.10	0.83

The total CHP efficiency of G3406 case is high relatively as an internal combustion engine.

The power to heat ratio is also high, the electrical energy that can be produced during 2015 is 2128 MWh of the demand which was 2661 MWh that means that the engines in this case produce electrical energy that can meet 80% of the electrical loads of the plant at higher percentage when compared to G3306 case which was 70%, as shown in figure 6.19. the thermal energy production is also not sufficient to cover the thermal consumption during some months such as January – April 2015, that means the need for external source of thermal energy such as a boiler; leading to additional costs for the boiler and fuel. The detailed calculations of G3406 are given in App. B.9.

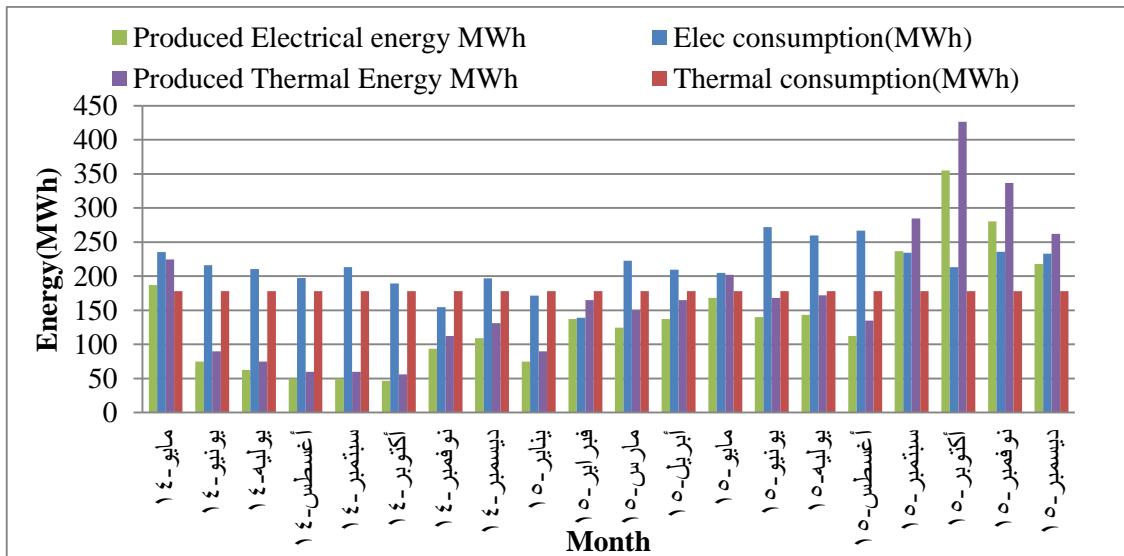


Figure 6.19: The electrical and thermal energy output from G3406 case compared with consumption.

6.5.4 Case 8-CG132-8

Two internal combustion engines from CATERPILLAR manufacturer were selected to utilize biogas in this case; these engines are of CG132-8 type

with electrical capacity of 400kW and electrical efficiency of 43 %. The engines are prepared to operate in cogeneration process that will produce electrical energy for on-site use in the plant and thermal energy that will supply the heat needed for the sludge digester.

One internal combustion engine of CG132-8 type will be kept operating while another engine of similar capacity will be operated during some months of the studied period.

The load factor is not a unity any time, but it is kept at a value over 50% which means that the efficiency will be kept near full load value, while not loading the engine at its full capacity to avoid frequent need for maintenance and spare parts.

This type of engine has the highest electrical efficiency among other alternatives as shown in table 6.14; it has the largest capacity. The power to heat ratio is high since the heat recovery of the internal combustion engines is lower than that in microturbines for example since that there is waste heat that can't be recovered. The detailed calculations of CG132-8 are given in App. B.10.

This case has the highest expected electrical energy output of 2441 MWh, that means it can cover a percentage of 90% of the electrical energy of the wastewater plant .The monthly demand can be covered by higher percentage than the other cases.

Thermal energy that can be produced in this case can cover the thermal needs of the wastewater plant, if we take the year of 2015, as shown in figure 6.20, the total expected energy production will be 2931MWh while

the total consumption was 2137 MWh. Also, not only the yearly total demand is covered; but the monthly demand can be covered without shortage in thermal energy.

Table 6.14: Energy output, efficiency and power/heat ratio of GC132-8 case

Case7- GC132-8						
Month	E_{in} (MWh)	E_{elec}(MWh)	E_{therm} (MWh)	# of engines in operation	Tot. CHP Efficiency %	Power/Heat Ratio
May-14	576	214	258	1	94.20	0.83
Jun-14	230.4	86	103	1	94.20	0.83
Jul-14	192	71	86	1	94.20	0.83
Aug-14	153.6	57	69	1	94.20	0.83
Sep-14	153.6	57	69	1	94.20	0.83
Oct-14	144	54	64	1	94.20	0.83
Nov-14	288	107	129	1	94.20	0.83
Dec-14	336	125	150	1	94.20	0.83
Jan-15	230.4	86	103	1	94.20	0.83
Feb-15	422.4	157	189	1	94.20	0.83
Mar-15	384	143	172	1	94.20	0.83
Apr-15	422.4	157	189	1	94.20	0.83
May-15	518.4	193	232	1	94.20	0.83
Jun-15	432	161	193	1	94.20	0.83
Jul-15	441.6	164	197	1	94.20	0.83
Aug-15	345.6	129	155	1	94.20	0.83
Sep-15	729.6	272	326	1	94.20	0.83
Oct-15	1094.4	408	489	2	94.20	0.83
Nov-15	864	322	386	2	94.20	0.83
Dec-15	672	250	301	1	94.20	0.83
Jan-16	441.6	164	197	1	94.20	0.83
Feb-16	672	250	301	1	94.20	0.83
Mar-16	902.4	336	404	2	94.20	0.83
Apr-16	864	322	386	2	94.20	0.83
May-16	825.6	307	369	2	94.20	0.83
Jun-16	595.2	222	266	1	94.20	0.83
Jul-16	576	214	258	1	94.20	0.83
Aug-16	720	268	322	1	94.20	0.83
Sep-16	787.2	293	352	2	94.20	0.83

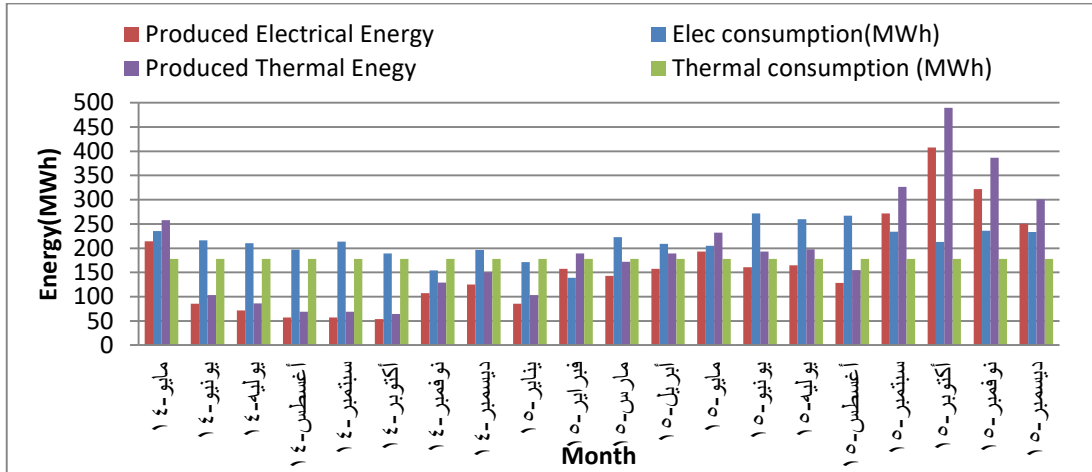


Figure 6.20: Energy output of CG132-8 case compared to load

6.5.5 Combined ICE case:

Three internal combustion engines from CATERPILLAR manufacturer were selected to utilize biogas in this case, these engines are not identical and are of G3306, G3406 and GC132-8 types with electrical capacity of 143kW, 235 kW, 400kW and electrical efficiencies of 32%, 38 % and 42%. The engines are prepared to operate in cogeneration process that will produce electrical energy for on-site use in the plant and thermal energy that will supply the heat needed for the sludge digester.

The operation of this power plant was planned and the engines that have to be used every month are shown in table 6.15, this table also gives the expected outputs of this case. The detailed calculations of combined ICE are given in App. B.11.

Table 6.15: Energy output, efficiency and power/heat ratio of combined ICE case

Month	Engines in operation	E_{in} (MWh)	E_{elec} (MWh)	E_{therm} (MWh)	Total Energy	Total CHP Efficiency %	Power/Heat Ratio
May-14	CG132-8	576	214	225	439	87.60	0.96
Jun-14	G3306	230.4	64	77	141	70.20	0.83
Jul-14	G3306	192	53	64	117	70.20	0.83
Aug-14	G3306	153.6	43	51	94	70.20	0.83
Sep-14	G3306	153.6	43	51	94	70.20	0.83
Oct-14	G3306	144	40	48	88	70.20	0.83
Nov-14	G3306	288	80	96	176	70.20	0.83
Dec-14	G3406	336	109	112	221	75.60	0.97
Jan-15	G3306	230.4	64	77	141	70.20	0.83
Feb-15	G3406	422.4	137	165	302	82.10	0.83
Mar-15	G3406	384	125	150	274	82.10	0.83
Apr-15	G3406	422.4	137	165	302	82.10	0.83
May-15	G3406	518.4	168	202	370	82.10	0.83
Jun-15	G3406	432	140	168	309	82.10	0.83
Jul-15	G3406	441.6	143	172	315	82.10	0.83
Aug-15	G3406	345.6	112	115	227	75.60	0.97
Sep-15	CG132-8	729.6	272	272	543	85.60	1.00
Oct-15	G3306 & CG132-8	1094.4	355	355	710	74.60	1.00
Nov-15	G3306 & CG132-8	864	322	322	643	85.60	1.00
Dec-15	CG132-8	672	250	250	500	85.60	1.00
Jan-16	G3406	441.6	143	143	287	74.60	1.00
Feb-16	CG132-8	672	250	250	500	85.60	1.00
Mar-16	G3306 & CG132-8	902.4	293	336	629	80.10	0.87
Apr-16	G3306 & CG132-8	864	322	322	643	85.60	1.00
May-16	G3306 & CG132-8	825.6	307	307	615	85.60	1.00
Jun-16	CG132-8	595.2	222	193	415	80.10	1.15
Jul-16	CG132-8	576	214	187	401	80.10	1.15
Aug-16	CG132-8	720	268	268	536	85.60	1.00
Sep-16	G3306 & CG132-8	787.2	293	293	586	85.60	1.00

The total electrical energy that can be produced in this case is 2225MWh during the year 2015, which is lower than using one unit of CG-132-8 engine, that leads to avoiding the use of multiple non-identical engines which is more complex and needs different spare parts and maitenace.

The total thermal energy production is 2412 MWh which is less than that of the CG132-8 case which was 2931 MWh.

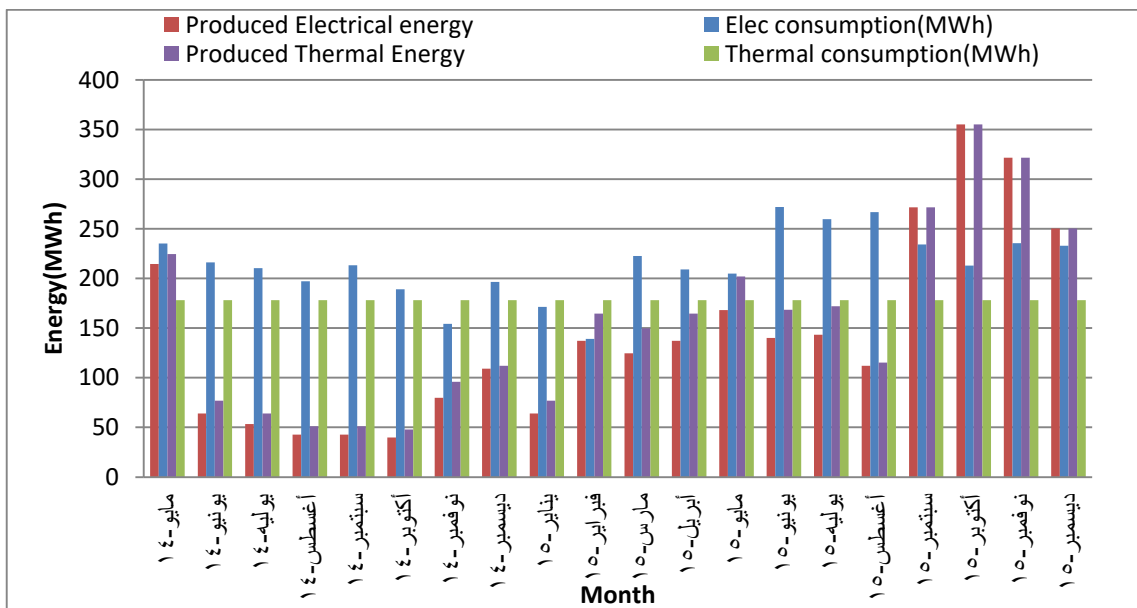


Figure 6.21: Output energy of combined ICE case compared to consumption

6.5.6 Comparison between internal combustion engine cases

As can be concluded from figure 6.22; the internal combustion engines can supply electrical energy higher than microturbines since they have higher efficiency; they supply the majority of the electrical load of the facility and increase the savings. On the other hand, they produce less recoverable thermal energy, some of the ICE alternatives can't cover the plant thermal needs .but still others can cover the thermal needs of the facility, that means

more total real CHP efficiency; i.e. they produce electrical and thermal energy that both are useable and find their outlet and consumed in the facility while in microturbines; there is excess heat that is recovered and has no on-site use.

The most efficient alternative to utilize biogas among ICE cases is the G132-8 case with about 2441 MWh of expected electrical energy production per year of 2015 and 2931 MWh of expected thermal energy production during that year, with full covering of thermal load of the plant.

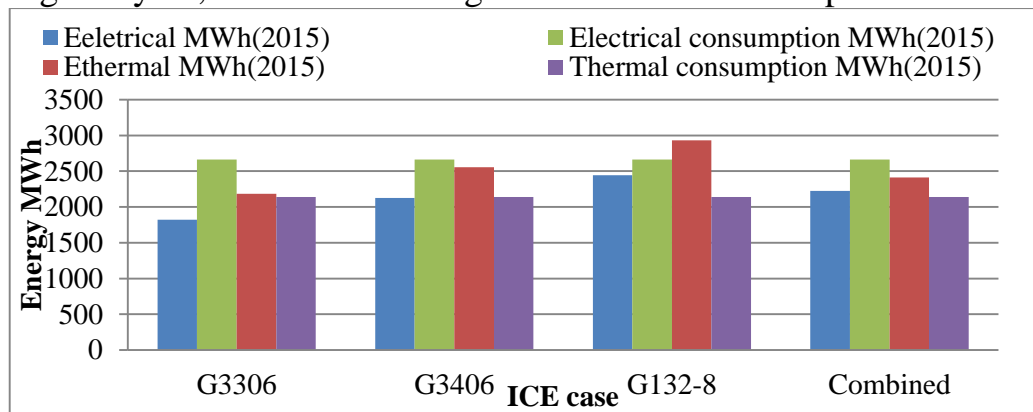


Figure 6.22: Comparison between ICE's cases for the year 2015

6.6 Economic evaluation of alternatives

6.6.1 Capital and running costs of CHP cases

Fixed and running costs of MGT's were calculated using eq. 5.22 and eq. 5.23, the results are shown in table 6.16.

The equipment costs were taken 2000 – 2700\$/kW depending on the capacity of the system. While the installations costs were considered 1000 – 1600 \$/kW depending on the system capacity. The operating and

maintenance costs were considered 0.010-0.016\$/kWh depending on the capacity of the system.

Table 6.16: Fixed and Running Costs of Micro-Gas Turbines Cases

	C30	C65	T100	C200	Combined
Electricity Capacity(kW)	30	65	100	200	495
Equipment cost (10³\$)	80.7	138	205	400	1,028.5
Installations cost (10³\$)	48.3	71.5	107	207	540.8
Number of units	12	6	4	2	C30 – 1, C65 – 1 T100 – 2, C200 – 1
Total Plant Capital Cost 10³ \$	1,547.6	1,256	1,248	1,214	1,569
E_p (MWh)	1474	1608	1642	1768	1608
O&M costs (10³\$)	14.8	20.9	24.6	28.3	24.1

The alternative that has the lowest capital cost is C200 in which two units of C200 MGT were used, this is due to the low cost of unit of power for this capacity, because as the capacity increases the cost of unit of power capacity decreases.

Fixed and running costs of ICE's were calculated using eq. 5.25 and eq. 5.26, the results are shown in table 6.17.

The equipment costs was taken 1800 – 1900\$/kW depending on the capacity of the system. The installations was considered 1000\$/kW. The operating and maintenance costs were considered 0.023-0.025\$/kWh [22,23] depending on the capacity of the system.

Table 6.17: Fixed and Running Costs of ICE's cases

	G3306	G3406	CG132-8	Combined
Electricity Capacity(kW)	143	235	400	778
Equipment cost (10³ \$)	272	435	720	1,426
Installations cost (10³\$)	143	235	400	778
Number of units	3	2	1	G3306-1,G3406-1, CG132-8-1
Total Capital cost (10³\$)	1,244	1,339.5	1,120	2,204.5
EP (MWh/yr)	1,820	2,128	2,441	2,225
O&M costs (10³\$/yr)	45500	51072	56143	53400

The alternative that has the lowest capital cost is CG132-8 in which one unit of CG132-8 ICE was used, this is due to the low cost of unit of power for this capacity, because as the capacity increases the cost of unit of power capacity decreases, same as in MGT's. This alternative has the lowest capital cost among all the cases with a value of 1.12M\$

6.6.2 Unit energy cost of CHP cases

The annual worth of cost was found using eq. 5.27 and then the unit of energy cost was found using eq. 5.28, table 6.18 and 6.18 show the results.

Table 6.18: Unit Energy Cost from MGTs arrangements

	C30	C65	T100	C200	Combined
Electricity Capacity(kW)	30	65	100	200	495
E_p (MWh/yr)	1,474	1,608	1,642	1,768	1,608
Salvage Value(10³\$)	154.7	125.5	124.8	121.4	156.9
Annual cost(10³\$/yr)	223.9	190.6	193.3	192.3	236.2
Unit energy cost (\$/kWh)	0.15	0.12	0.12	0.11	0.15

It is observed that the alternative that has the minimum unit energy cost among MGT systems is the C200 system with unit cost of 0.11\$/KWh.

Table 6.19: ICE's Unit Energy Cost

Value Case	G3306	G3406	CG132-8	Combined
Electricity Capacity(kW)	143	235	400	778
Salvage value(10³\$)	124.4	133.9	112.0	220.4
Annual Energy Produced by MGTs (MWh/yr)	1,820	2,128	2,441	2,225
Annual Cost (10³\$/yr)	213.6	232.1	207.5	351.3
Unit energy cost(\$/kWh)	0.12	0.11	0.09	0.16

It is observed that the alternative that has the minimum unit energy cost among ICE systems is the **CG132-8** system with unit cost of 0.09\$/kWh

Figure 6.23 compares the unit energy cost for all alternatives considered in this study including Micro-Gas Turbines and Internal Combustion engines.

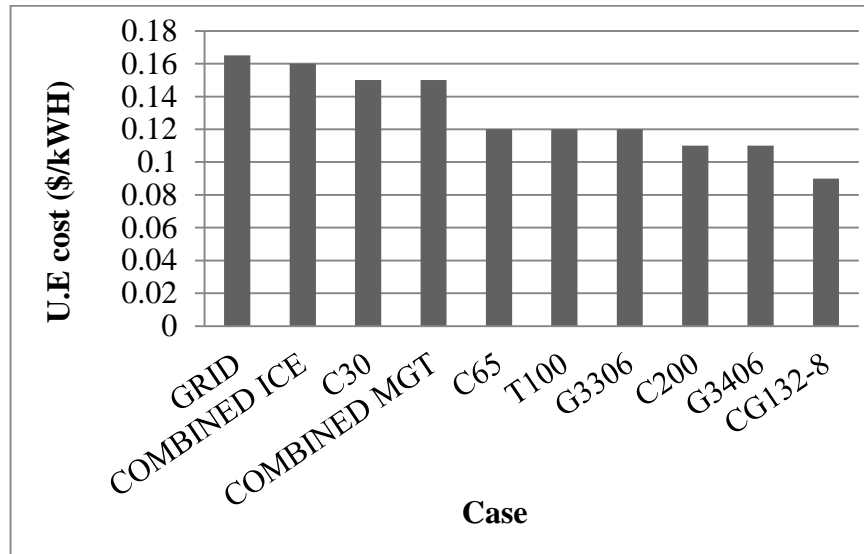


Figure 6.23: Unit energy cost comparison

It is observed that the CHP system with minimum unit energy cost is CG132-8 Internal Combustion Engine with unit cost of 0.09\$/kWh.

6.6.3 Annual savings from CHP cases

The annual savings were calculated using eq. 5.29 and eq. 5.30, table 6.20 shows the results.

Table 6.20: Annual savings of CHP alternatives

Alternative	Annual Value of Produced Electrical Energy (\$/yr)	Annual Worth of the Cost (\$/yr)	Annual Saving (\$/yr)
C30	243210	223919	19291
C65	265320	190637	74683
T100	270930	193309	77621
C200	291720	192372	99348
COMBINED MGT	265320	236222	29098
G3306	300300	213652	86648
G3406	351120	232118	119002
CG132-8	402765	207522	195243
COMBINED ICE	367125	351535	15590

The alternative with maximum value of annual saving is the CG132-8 system with total annual saving of 195,243 \$.

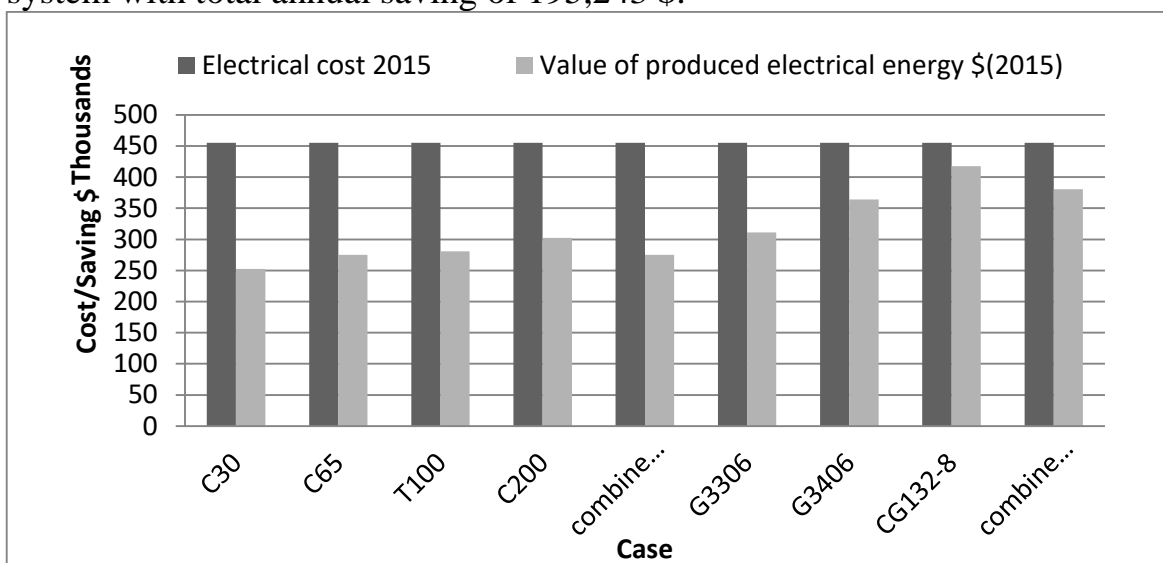


Figure 6.24: Comparison between Annual value of consumed and produced potential electrical (2015)

6.6.4 Cash flow diagrams of CHP cases

The cash flow diagrams for all the cases are shown in figures 6.25-6.33, showing all of the incomes and outcomes of cash during the lifetimes of alternatives which were considered 10 years, the equipment and installation costs are considered in the beginning of the project lifetime and the salvage value of 10% of the total capital cost was considered at the end of projects' lives.

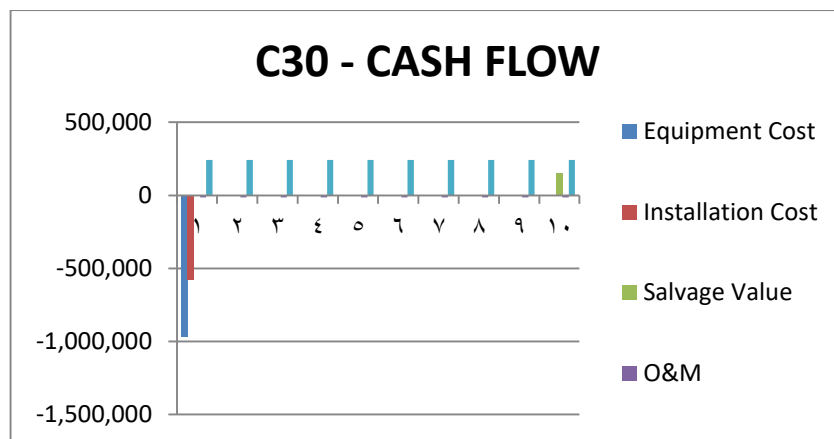


Figure 6.25: cash flow of case 1 – C30

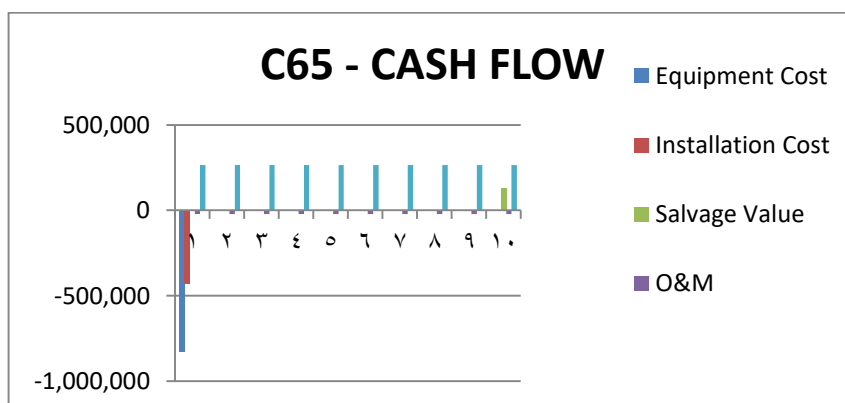


Figure 6.26: cash flow of case 2 – C65

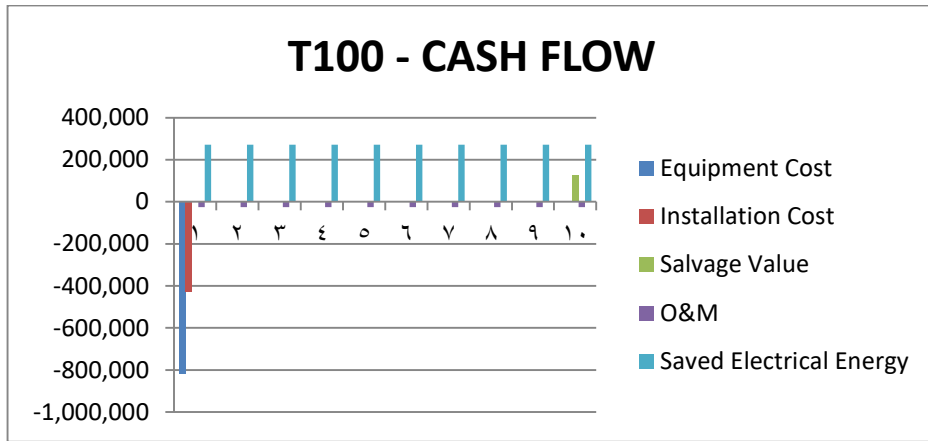


Figure 6.27: cash flow of case 3 – T100

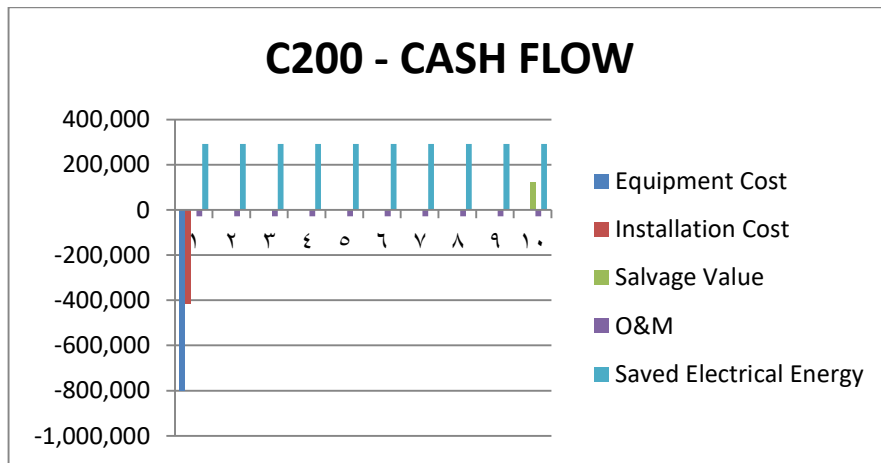


Figure 6.28: cash flow of case 4– C200

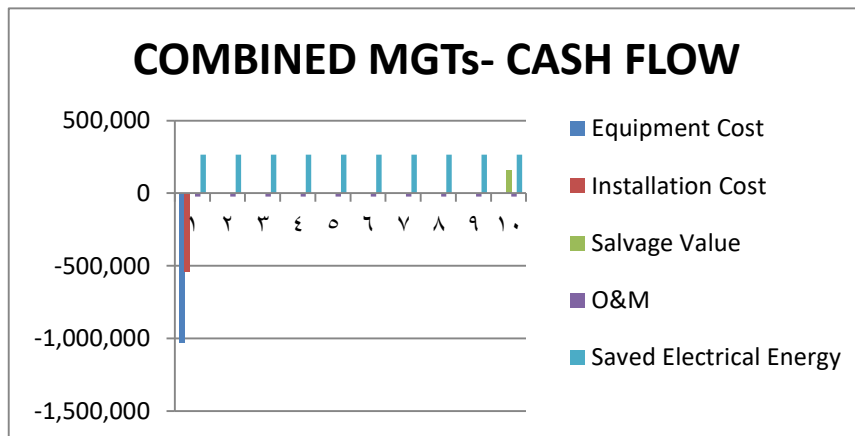


Figure 6.29: cash flow of case 5– Combined MGT

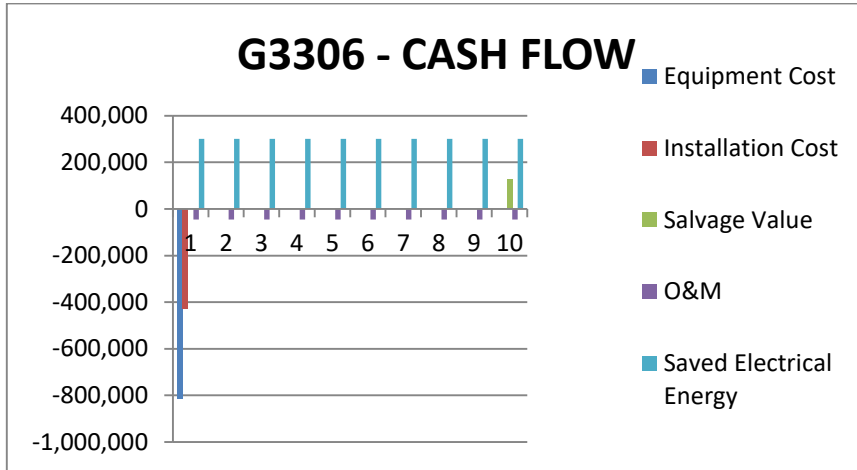


Figure 6.30: cash flow of case 6– G3306

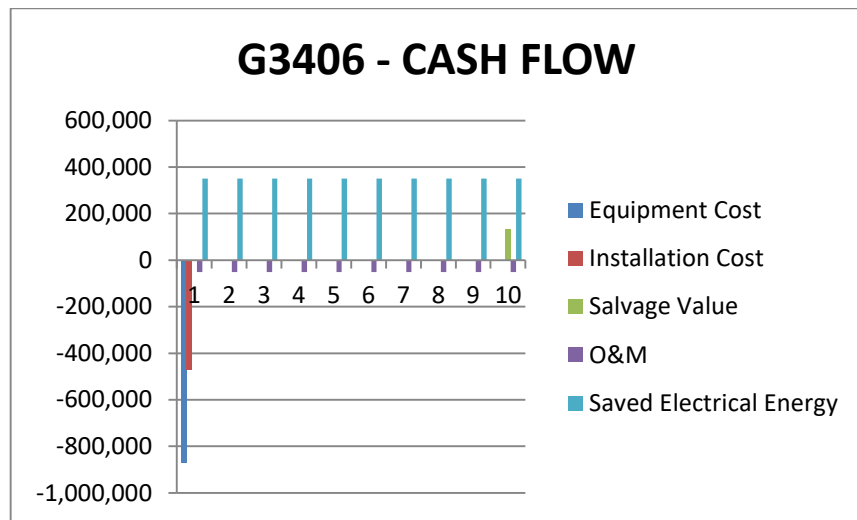


Figure 6.31: cash flow of case 7 – G3406

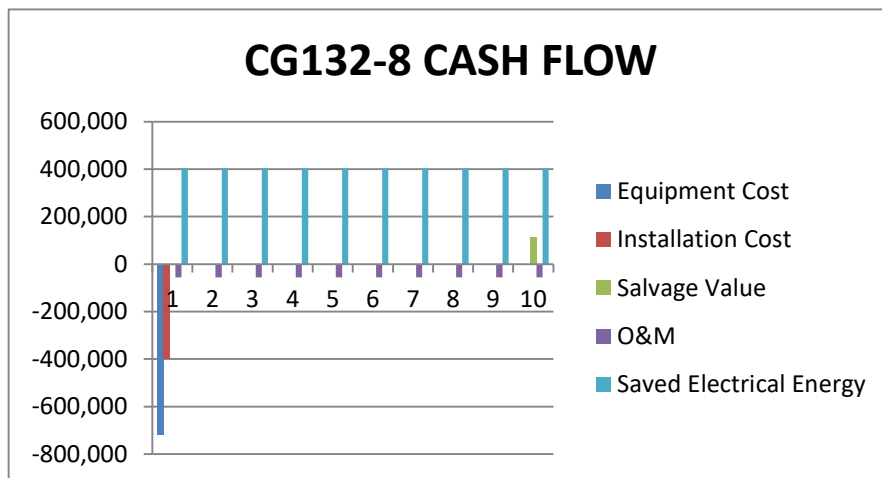


Figure 6.32: cash flow of case 8–CG132-8

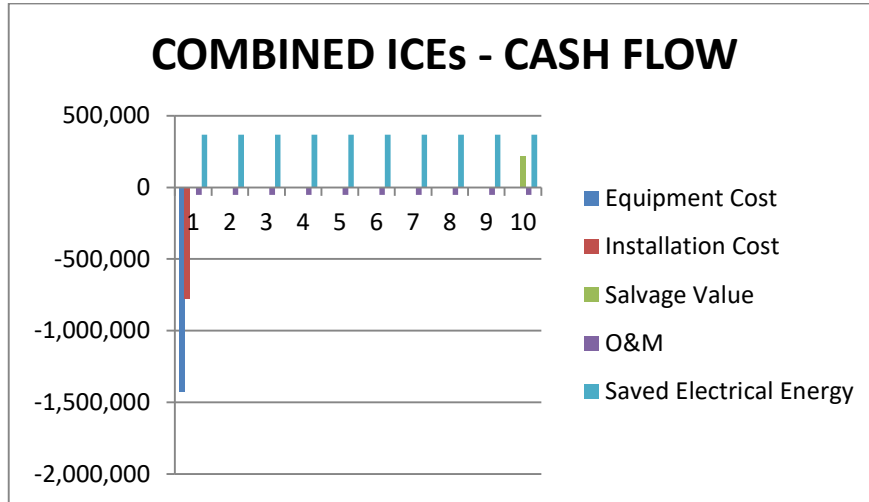


Figure 6.33: cash flow of case 9– Combined ICE

6.6.5 Simple pay back periods of CHP cases

Simple pay-back-periods of alternatives were calculated using eq 5.31; the results are shown in table 6.21.

As shown in figure 6.34, the alternative that has the minimum pay-back period was CG132-8 with 3.2 years to return back its investment which was also the lowest with a value of 1.12M\$ and highest total annual saving of 195,243 \$.

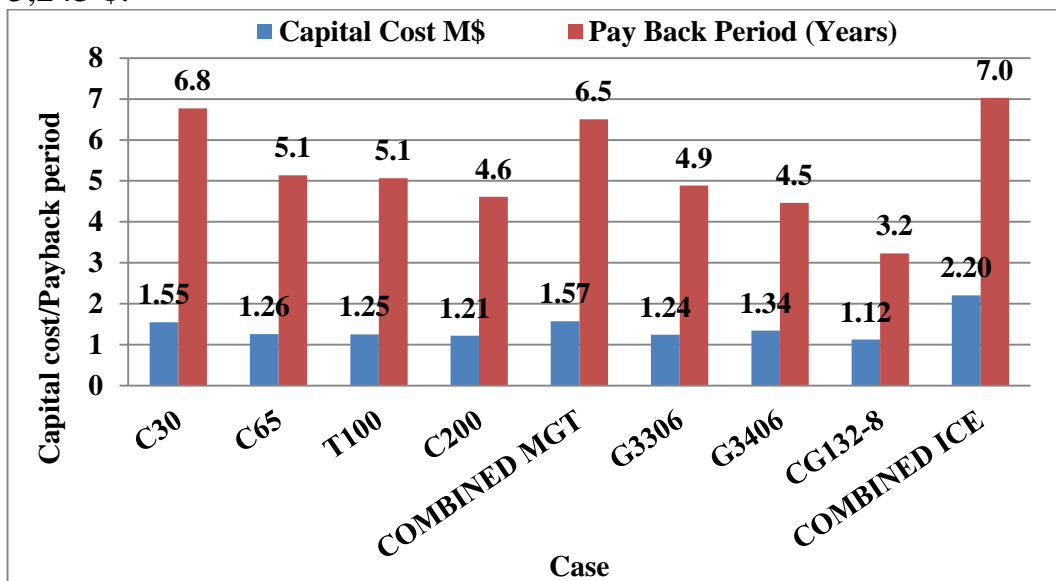


Figure 6.34 : Capital Costs and Pay-Back Periods

6.7 Environmental impact of alternatives

6.7.1 CO₂ emissions from current SHP situation

Carbon dioxide emissions from the current situation which utilizes a boiler to burn biogas and supply the digester with its heat demand were calculated using equation 5.32 and equation 5.33. The emissions are a result of burning biogas in the boiler and excess biogas in the flare. While the electric energy needed for the plant is consumed from the grid. The carbon dioxide emissions from grid were calculated using equation 5.35. Table 6.21 shows the total CO₂ production from separate heat and power situation which is the current situation.

Table 6.21: Current Situation CO₂ Yearly Emissions

M Biogas (TON/year)	CO₂,Biogas (TON/Year)	E_{demand} (MWh/Year)	CO₂ G,_{SHP} (TON/Year)	CO₂ ,_{SHP} (TON/Year)
1,024	2,049	2,661	1,863	3,912

6.7.2 CO₂ emissions from the suggested CHP cases

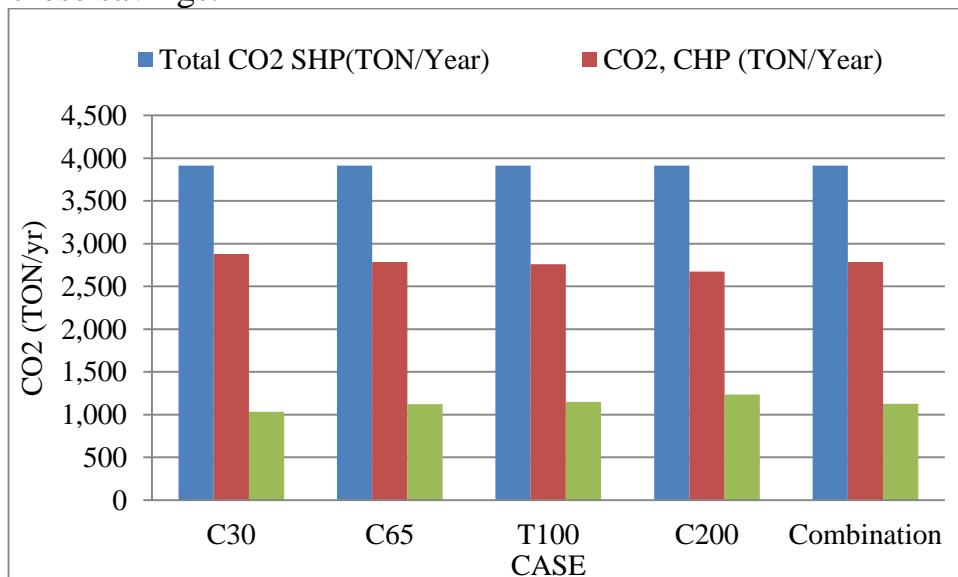
The new suggested situation depends on using the same quantity of biogas to produce part of the electricity needed for the plant and the thermal energy, equations 5.35 and eq5.37 was used to find the new carbon dioxide emissions that are expected to be produced from the suggested cases, table 6.22 gives the results.

Table 6.22:CO₂ Emissions from CHP cases

Alternative	CO _{2G,CHP} (TON/yr)	CO _{2,CHP} (TON/yr)	Alternative	CO _{2G,CHP} (TON/yr)	CO _{2,CHP} (TON/yr)
C30	830	2879	G3306	588	2637
C65	739	2788	G3406	374	2423
T100	712	2761	CG132-8	154	2203
C200	626	2675	Combination	306	2355
Combination	737	2786			

6.7.3 CO₂ savings from CHP cases

The difference between carbon dioxide emissions during SHP situation and during CHP cases equals the CO₂ savings that are expected from CHP cases of MGT's and ICE's as equation 4.38 reveals. Figures 6.35 and 6.36 show these savings.

**Figure 6.35:CO₂ Savings from MGT Arrangements**

As shown in figure 6.35 that the case C200 will have the largest saving of CO₂ production since it has the highest energy production and thus

electrical energy saving among micro-gas turbines alternative with total yearly CO₂ savings of 1237 Ton/yr.

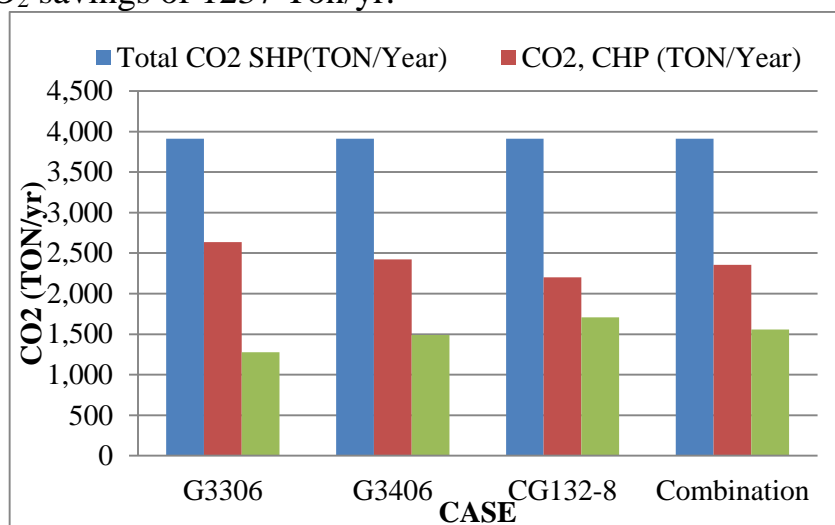


Figure 6.36: CO₂ Savings from ICE Arrangements

The case CG132-8 will have the largest saving of CO₂ production . as shown in figure 6.36; since it has the highest energy production and thus electrical energy saving among internal combustion engines alternatives with total yearly CO₂ savings of 1709 Ton/yr. This alternative has also the highest CO₂ yearly savings among all the cases studied in this project.

6.7.4 Other Emissions From Burning Biogas

The emissions are mainly NO_x, CO, and VOCs and other pollutants related to biogas such as PM and SO_x which are determined by the H₂S content of biogas especially SO₂.

Figure 6.37 shows the results of the calculated yearly emissions from burning biogas in micro-gas turbines and internal combustion engines by applying the factors in table 4.4 and using equations 5.39 – 5.46.

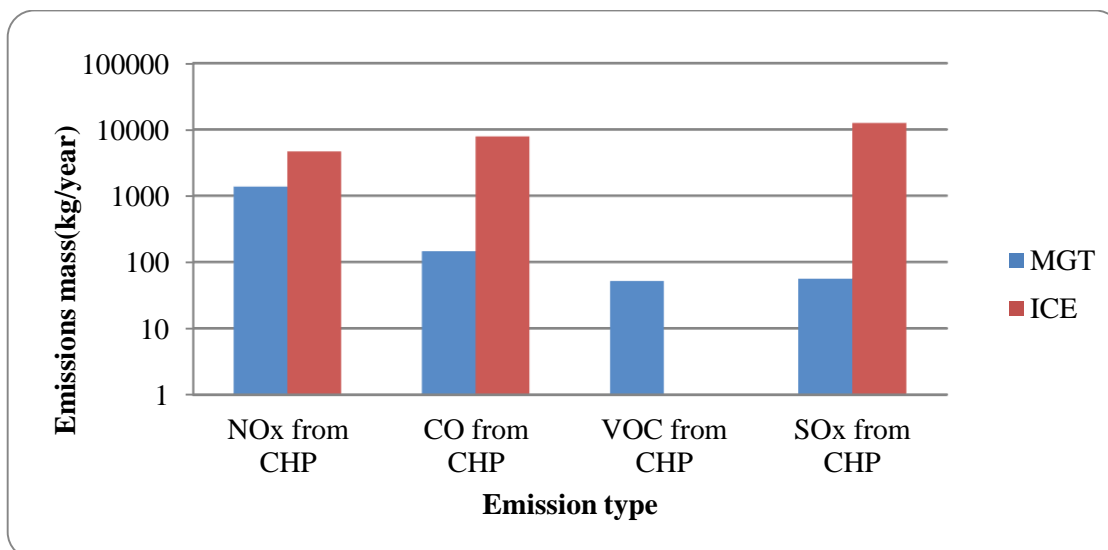


Figure 6.37: Other Emissions from Burning Biogas in MGTs and ICEs

The pollutants from micro-gas turbines are very low, as can be observed from figure 6.37. NO_x emissions from MGT accounts for about 30% of that from ICE while CO and SO_x account for 1.85% and 0.45%, respectively. This can be related to the high temperatures that MGT use and complete combustion while it is operating at high load.

The detailed environmental calculations of MGT cases are shown in Appendices D.1 to D.5.

7. Chapter Seven - Conclusions and Recommendations

7.1 Conclusion

Waste Water treatment plants with anaerobic digesters produce biogas which is a renewable source of energy. This biogas can be used as a source for electrical and thermal energy for on-site uses for the plant.

Many alternatives are available to deal with biogas; all are the same alternatives of utilizing biogas except some treatment technologies to upgrade biogas and remove some contaminants from it and modify its conditions. All of the available technologies to deal with biogas are of the CHP type which means combined heat and power, i.e. producing two types of energy from the same source: electricity and heat. Generally all of the utilization options of biogas produce enough heat energy, but the point to be studied is the electrical energy produced.

The micro-gas turbine alternatives have lower electrical efficiency than internal combustion engine alternatives. This low efficiency can be overcome by using the cogeneration where there is coincident electrical and thermal demand. Five cases of using MGT were discussed in this study; using C30/30kW, C65/65kW, T100/100kW , C200/200kW and a combination of these types. C30 was expected to produce 1475 MWh of electrical energy and 4285 MWh of thermal energy covering 55% of the electrical demand and all the thermal demand.

The second case C65 was expected to produce 1608 MWh of electrical energy annually and 4731MWh of thermal energy covering 60% of the electrical demand and the thermal demand.

Third case T100 was expected to produce 1642MWh of electrical energy and 3030MWh of thermal energy covering 62% of the electrical demand and the thermal demand as a total, but during some months there will be a shortage, this leads to the need of external boiler and fuel and so more capital and operating costs.

Fourth case C200 was expected to produce 1768MWh of electrical energy and 3223MWh of thermal energy covering 65% of the electrical demand and the thermal demand.

Fifth case Combined case was expected to produce 1608MWh of electrical energy and MWh of thermal energy covering 60% of the electrical demand and the thermal demand.

Internal combustion engines have higher electrical efficiency than micro turbines while having lower opportunity for recovering the waste heat of the engine, this has lead us to investigate the thermal energy that can be recovered from internal combustion engines; this is was done to be sure that engines can cover the thermal needs of the plant without any additional capital and operating costs that are using a boiler and fuel for it.

G3306 engine case was expected to produce 1820MWh of electrical energy annually while producing 2185MWh of thermal energy. G3406 engine case was expected to produce 2128 MWh of electrical energy annually and 2556MWh of thermal energy. These two cases have a problem that they

cannot cover the thermal energy demand completely while CG-132-8 case was expected to produce 2931MWh of thermal energy and can cover the thermal needs of all the months while producing 2441MWh of electrical energy, which is the highest among all alternatives. The combined engines case was expected to produce 2225 MWh of electrical energy and 2412 MWh of thermal energy which are lower than CG-132-8 case.

It was found that the alternative which produced the maximum electrical energy was using one unit of the Internal Combustion engine CG132-8/400KWe with yearly energy production of **2442 MWh/year**.

Economic analysis were done using annual worth of cost calculation and finding the levelized cost of electrical energy. Also, the total yearly saving from each alternative was also calculated. It was concluded that the using one unit of the Internal Combustion engine **CG132-8/400KWe** has the lowest value of unit energy cost of **0.09\$/KWh** and annual savings of **195,243\$/year**.

Environmental analysis were conducted to investigate the total CO₂ emissions and other pollutional emissions, and was found that the alternative of using one unit of the Internal Combustion engine CG132-8/400KWe gave the maximum saving of CO₂ production with a value of **3,483,447 KG/year** instead of the current situation of separate heat and electricity generation with CO₂ production of **5,192,847KG/year** Achieving a total CO₂ saving of **1,709,400 KG/year**.

7.2 Recommendations

The following recommendations may be implemented in any future work:

1. Monitoring the biogas production rate for longer period and on an instantaneous basis.
2. Analyzing biogas to recognize its components and their percentage and its heat value.
3. Studying sludge treatment to increase the biogas production rate.
4. Trying to design sludge incineration system.
5. Making a study of energy audit for the wastewater treatment plant to study the opportunities of energy management.
6. Studying more cases for the combinations of MGT's and ICE's and trying to combine MGT's with ICE's in the same cogeneration plant.
7. Studying the utilization of biogas in fuel cells with CHP arrangement.
8. Studying the opportunities to treat biogas to be distributed to propane gas stations.
9. Studying co-digestion of biogas and organic fraction of municipal solid waste.
10. Evaluate co-firing of biogas and sludge.
11. Since the target of this study was utilizing all of produced biogas; the situation can be revaluated to study meeting the electrical demand of the wastewater plant. Also, study can be done from another perspective in which the target can be following the heat demand of the wastewater plant.

12. The possibility to sell thermal energy (hot water or steam) to nearby facilities and factories can be studied since we have excess heat during the cogeneration processes.
13. A study of designing on-grid power plant may be done; and so the electrical energy production can be sold to the grid.

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A.Appendix A

Table A.1: Wastewater treatment plants in West Bank and GAZA strip [7]

#	WWTP Project	Donor	Design Capacity	Estimated Cost		Status	Population Served
			(m ³ /d)	€	[Million]		
1	Jenin city	KFW	9000	€	1.5	Completed	55000
2	Misilya village	AFD	400	€	2.8	Tendering phase	4000
3	Al-Yamun	USAID	3000	\$	20	Design phase completed	25000
4	Qabatiya	USAID	4000	\$	20	Design phase completed	25000
5	Ya'abad	USAID	5000	\$	20	Design phase completed	25000
6	Anza village	EU	346	€	3	operational	3460
7	Barta` Sharqieh	EU	400		N.A	N.A	4000
8	Tubas, Tayaseer	EU	3000	€	22	under construction	25000
9	Nablus West WWTP	KFW	15000	€	30	Operational	110000
10	Nablus East WWTP	KFW	10000	€	30	F.S& EIA &Design phase	80000
11	Beit Dajan town	EU	540	€	3	operational	5400
12	Surra village	EU	224	€	3	operational	3108
13	Tulkarm city	KFW	2660		N.A	upgraded	26600
14	Anabta, Bala`, Shwaike,	KFW		€	19	N.A	75000
15	Baqa Alsharqieh	EU			N.A	sewerage complete	5000
16	Qalqilia city	EU			N.A	N.A	35000
17	Azzoun	USAID	4000	€	22	Design completed	15000
18	Habliah town	EU			N.A		3000
19	Salfit city	KFW				Tendering phase	20000
20	Al-Bireh WWTP	KFW	5500	€	7	Operational	59000

21	Ramallah city WWTP	KFW	2720	€	0.5	Overloaded	26110
22	Altirah sub-urb	Private	2000	\$	3.8	Operational	20000
23	Alrihan housing compound	Private	500		N.A	Operational	5000
24	Birzeit University campus	Private	200		N.A	Operational	2000
25	Dipolmatic housing compound	Private	500	\$	1.5	Operational	5000
26	Rawabi city	USTDA	-	\$	0.5	Operational	20000
27	At-Taybah-Rammun	EU	350	€	9	Operational	7550
28	Ramallah-Betunia Ein Jarlot	KFW				Design Phase	
29	Jericho sewerage project	Japan	9600	\$	32	Operational	22000
30	Jericho hospital WWTP	USAID	150	\$	0.69	Operational	36000
31	Intercontinantal hotel WWTP	Private	250	\$	3	Operational	1200
32	North East Jerusalem WW project	Finland	-		N.A	Baseline Study	30000
33	West Bethlehem sanitation project	World Bank	-	\$	3.65	TOR-feasibility study	25000
34	Bethlehem Industrial Zone WWTP	AFD	100	€	0.5	Operational	1000
35	Hebron city	World Bank, AFD	15000	\$	38	Detailed design phase	300000
36	Dura	USAID	3000	\$	22	Design completed	150000
37	Tarqumiya	USAID	5000	\$	25	Design completed	150000
38	Al'Aroub WWTP project	Spain	1200	€	1.5	Design Phase	25000
39	Artas sewage project	BTC		€	0.6	completed	5000

40	Beit Hasan sewerage project	Spain	1000	\$	0.31	Design Phase	8000
41	Kharras village	EU	135		N.A	Overloaded	2200
42	Industrial area WW project	USAID		\$	1.5	Implementation phase	
43	North Gaza Beit Lahia	World Bank, AFD..	23000	\$	75	Start-up phase	238500
44	Gaza Central	KFW	60000	€	19	Operational	492263
45	Rafah-Khan Yunis South	KFW	20000	€	19	Under Construction	280469

Table A.2: Biogas production data for one day on hourly basis [7]

Date	Time	Biogas production(kg)
01.08.2016	00:00-01:00	169.55
01.08.2016	01:00-02:00	165.87
01.08.2016	02:00-03:00	134.53
01.08.2016	03:00-04:00	100.15
01.08.2016	04:00-05:00	123.57
01.08.2016	05:00-06:00	137.95
01.08.2016	06:00-07:00	130.35
01.08.2016	07:00-08:00	132.78
01.08.2016	08:00-09:00	123.65
01.08.2016	09:00-10:00	140.81
01.08.2016	10:00-11:00	150.93
01.08.2016	11:00-12:00	151.21
01.08.2016	12:00-13:00	133.54
01.08.2016	13:00-14:00	143.54
01.08.2016	14:00-15:00	148.12
01.08.2016	15:00-16:00	157.85
01.08.2016	16:00-17:00	167.81
01.08.2016	17:00-18:00	174.73
01.08.2016	18:00-19:00	169.85
01.08.2016	19:00-20:00	123.69
01.08.2016	20:00-21:00	126.02
01.08.2016	21:00-22:00	142.76
01.08.2016	22:00-23:00	141.5
01.08.2016	23:00-00:00	143.91

Table A.3: Biogas average production rate for each month

Month	Average Daily biogas quantity (kg/day)	Average Hourly biogas quantity(kg/hr) (design value)	Monthly biogas quantity(kg)
May-14	3000	125	90000
Jun-14	1200	50	36000
Jul-14	1000	42	30000
Aug-14	800	33	24000
Sep-14	800	33	24000
Oct-14	750	31	22500
Nov-14	1500	63	45000
Dec-14	1750	73	52500
Jan-15	1200	50	36000
Feb-15	2200	92	66000
Mar-15	2000	83	60000
Apr-15	2200	92	66000
May-15	2700	113	81000
Jun-15	2250	94	67500
Jul-15	2300	96	69000
Aug-15	1800	75	54000
Sep-15	3800	158	114000
Oct-15	5700	238	171000
Nov-15	4500	188	135000
Dec-15	3500	146	105000
Jan-16	2300	96	69000
Feb-16	3500	146	105000
Mar-16	4700	196	141000
Apr-16	4500	188	135000
May-16	4300	179	129000
Jun-16	3100	129	93000
Jul-16	3000	125	90000
Aug-16	3750	156	112500
Sep-16	4100	171	123000

B. Appendix B

Table B.1: C30 MGT thermal output [26]

Net power(KW)	PL	Net effici%	E _{exhaust} (Btu/hr)	E _{exhaust} (KW)	Therma effici%
2	6.67%	8.8	74700	21.8871	0.92
3	10.00%	11.5	81900	23.9967	0.89
4	13.33%	13.6	90200	26.4286	0.87
5	16.67%	15.2	98700	28.9191	0.85
6	20.00%	16.6	107000	31.351	0.84
7	23.33%	17.7	115000	33.695	0.83
8	26.67%	18.8	123000	36.039	0.82
9	30.00%	19.8	130000	38.09	0.81
10	33.33%	20.6	138000	40.434	0.80
11	36.67%	21.2	145000	42.485	0.79
12	40.00%	21.8	153000	44.829	0.79
13	43.33%	22.3	161000	47.173	0.78
14	46.67%	22.8	169000	49.517	0.78
15	50.00%	23.2	177000	51.861	0.78
16	53.33%	23.6	185000	54.205	0.77
17	56.67%	24	193000	56.549	0.77
18	60.00%	24.3	201000	58.893	0.77
19	63.33%	24.6	209000	61.237	0.76
20	66.67%	24.9	217000	63.581	0.76
21	70.00%	25.1	226000	66.218	0.76
22	73.33%	25.3	234000	68.562	0.76
23	76.67%	25.4	243000	71.199	0.76
24	80.00%	25.6	252000	73.836	0.75
25	83.33%	25.7	261000	76.473	0.75
26	86.67%	25.8	271000	79.403	0.75
27	90.00%	25.8	281000	82.333	0.75
28	93.33%	25.9	290000	84.97	0.75
29	96.67%	26	299000	87.607	0.75
30	100.00%	26	310000	90.83	0.75

Table B.2:C200 MGT thermal output [26]

Net power(KW)	Partial load	Exhaust Energy (KW)	Thermal efficiency%
16	8.00%	71.4	0.82
17	8.50%	73	0.81
18	9.00%	74.7	0.81
19	9.50%	76.5	0.80
20	10.00%	78.2	0.80
21	10.50%	79.9	0.79
22	11.00%	81.6	0.79
23	11.50%	83.3	0.78
24	12.00%	84.9	0.78
25	12.50%	86.6	0.78
26	13.00%	88.2	0.77
27	13.50%	89.6	0.77
28	14.00%	91.2	0.77
29	14.50%	92.9	0.76
30	15.00%	94.5	0.76
31	15.50%	96.2	0.76
32	16.00%	97.8	0.75
33	16.50%	99.4	0.75
34	17.00%	101.1	0.75
35	17.50%	102.7	0.75
36	18.00%	104.3	0.74
37	18.50%	105.9	0.74
38	19.00%	107.4	0.74
39	19.50%	109	0.74
40	20.00%	110.8	0.73
41	20.50%	112.1	0.73
42	21.00%	113.7	0.73
43	21.50%	115.2	0.73
44	22.00%	116.8	0.73
45	22.50%	118.2	0.72
46	23.00%	119.7	0.72
47	23.50%	121.3	0.72
48	24.00%	122.8	0.72
49	24.50%	124.4	0.72
50	25.00%	125.9	0.72
51	25.50%	127.4	0.71
52	26.00%	129	0.71
53	26.50%	130.5	0.71
54	27.00%	132	0.71
55	27.50%	133.5	0.71

56	28.00%	135	0.71
57	28.50%	136.4	0.71
58	29.00%	137.9	0.70
59	29.50%	139.5	0.70
60	30.00%	141.1	0.70
61	30.50%	142.6	0.70
62	31.00%	144.2	0.70
63	31.50%	145.8	0.70
64	32.00%	147.3	0.70
65	32.50%	148.9	0.70
66	33.00%	150.5	0.70
67	33.50%	152	0.69
68	34.00%	153.6	0.69
69	34.50%	155.1	0.69
70	35.00%	156.7	0.69
71	35.50%	158.2	0.69
72	36.00%	159.8	0.69
73	36.50%	161.3	0.69
74	37.00%	162.9	0.69
75	37.50%	164.4	0.69
76	38.00%	165.9	0.69
77	38.50%	167.5	0.69
78	39.00%	169	0.68
79	39.50%	170.5	0.68
80	40.00%	172	0.68
81	40.50%	173.5	0.68
82	41.00%	175.1	0.68
83	41.50%	176.6	0.68
84	42.00%	178.1	0.68
85	42.50%	179.8	0.68
86	43.00%	181.2	0.68
87	43.50%	182.7	0.68
88	44.00%	184.2	0.68
89	44.50%	185.7	0.68
90	45.00%	187.3	0.68
91	45.50%	188.8	0.67
92	46.00%	190.3	0.67
93	46.50%	191.8	0.67
94	47.00%	193.3	0.67
95	47.50%	194.7	0.67
96	48.00%	196.2	0.67
97	48.50%	197.7	0.67
98	49.00%	199.2	0.67
99	49.50%	200.7	0.67

100	50.00%	202.2	0.67
101	50.50%	203.7	0.67
102	51.00%	205.2	0.67
103	51.50%	206.7	0.67
104	52.00%	208.2	0.67
105	52.50%	209.7	0.67
106	53.00%	211.2	0.67
107	53.50%	212.7	0.67
108	54.00%	214.2	0.66
109	54.50%	215.7	0.66
110	55.00%	217.2	0.66
111	55.50%	218.7	0.66
112	56.00%	220.3	0.66
113	56.50%	219.1	0.66
114	57.00%	220.8	0.66
115	57.50%	222.5	0.66
116	58.00%	224.3	0.66
117	58.50%	226	0.66
118	59.00%	227.8	0.66
119	59.50%	229.6	0.66
120	60.00%	231.4	0.66
121	60.50%	233.2	0.66
122	61.00%	235	0.66
123	61.50%	236.8	0.66
124	62.00%	238.5	0.66
125	62.50%	240.3	0.66
126	63.00%	242.2	0.66
127	63.50%	244	0.66
128	64.00%	245.8	0.66
129	64.50%	247.6	0.66
130	65.00%	249.4	0.66
131	65.50%	251.3	0.66
132	66.00%	253.1	0.66
133	66.50%	255	0.66
134	67.00%	256.8	0.66
135	67.50%	258.6	0.66
136	68.00%	260.4	0.66
137	68.50%	262.2	0.66
138	69.00%	264	0.66
139	69.50%	265.8	0.66
140	70.00%	267.6	0.66
141	70.50%	269.5	0.66
142	71.00%	271.4	0.66
143	71.50%	273.3	0.66

144	72.00%	275.2	0.66
145	72.50%	277.1	0.66
146	73.00%	279	0.66
147	73.50%	280.9	0.66
148	74.00%	282.9	0.66
149	74.50%	284.8	0.66
150	75.00%	286.8	0.66
151	75.50%	288.7	0.66
152	76.00%	290.7	0.66
153	76.50%	292.7	0.66
154	77.00%	294.6	0.66
155	77.50%	296.6	0.66
156	78.00%	298.6	0.66
157	78.50%	300.6	0.66
158	79.00%	302.7	0.66
159	79.50%	304.7	0.66
160	80.00%	306.7	0.66
161	80.50%	308.8	0.66
162	81.00%	310.8	0.66
163	81.50%	312.9	0.66
164	82.00%	314.9	0.66
165	82.50%	317	0.66
166	83.00%	319.2	0.66
167	83.50%	321.4	0.66
168	84.00%	323.5	0.66
169	84.50%	325.6	0.66
170	85.00%	327.8	0.66
171	85.50%	329.9	0.66
172	86.00%	332	0.66
173	86.50%	334.1	0.66
174	87.00%	336.3	0.66
175	87.50%	338.4	0.66
176	88.00%	340.6	0.66
177	88.50%	342.8	0.66
178	89.00%	344.9	0.66
179	89.50%	347.1	0.66
180	90.00%	349.3	0.66
181	90.50%	351.5	0.66
182	91.00%	353.7	0.66
183	91.50%	355.9	0.66
184	92.00%	358.1	0.66
185	92.50%	360.3	0.66
186	93.00%	362.6	0.66
187	93.50%	364.8	0.66

188	94.00%	367.1	0.66
189	94.50%	369.3	0.66
190	95.00%	371.6	0.66
191	95.50%	373.9	0.66
192	96.00%	376.3	0.66
193	96.50%	378.6	0.66
194	97.00%	381	0.66
195	97.50%	383.3	0.66
196	98.00%	385.7	0.66
197	98.50%	388	0.66
198	99.00%	390.4	0.66
199	99.50%	392.8	0.66
200	100.00%	394.6	0.66

Table B.3: CASE 1 – C30 calculations

P_{in}	Month	P_{out}	# MGT	P_C	PL%	PL effi.%	P_{out,new}	PL thermal efficiency	P_{out,thermal}	E_{elec} (MWh)	E_{therm} (MWh)	E MWh(one MGT is PL)
696	May-14	180.96	7	210	0.86	25.8	179.57	0.75	529.99	129.29	382	129.73
278.4	Jun-14	72.38	3	90	0.80	25.6	71.27	0.75	215.04	51.31	155	50.30
232	Jul-14	60.32	3	90	0.67	24.9	57.77	0.76	184.96	41.59	133	43.18
185.6	Aug-14	48.26	2	60	0.80	25.6	47.51	0.75	143.36	34.21	103	33.27
185.6	Sep-14	48.26	2	60	0.80	25.6	47.51	0.75	143.36	34.21	103	33.27
174	Oct-14	45.24	2	60	0.75	25.4	44.20	0.75	136.15	31.82	98	30.87
348	Nov-14	90.48	4	120	0.75	25.3	88.04	0.75	271.23	63.39	195	64.81
406	Dec-14	105.56	4	120	0.88	25.8	104.75	0.75	307.15	75.42	221	74.32
278.4	Jan-15	72.38	3	90	0.80	25.6	71.27	0.75	215.04	51.31	155	50.30
510.4	Feb-15	132.70	5	150	0.88	25.8	131.68	0.75	385.43	94.81	278	93.74
464	Mar-15	120.64	5	150	0.80	25.6	118.78	0.75	358.39	85.52	258	86.44
510.4	Apr-15	132.70	5	150	0.88	25.8	131.68	0.75	385.43	94.81	278	93.74
626.4	May-15	162.86	6	180	0.90	25.8	161.61	0.74	469.69	116.36	338	115.46
522	Jun-15	135.72	5	150	0.90	25.8	134.68	0.74	391.41	96.97	282	96.05
533.6	Jul-15	138.74	5	150	0.92	25.9	138.20	0.74	398.89	99.51	287	98.46
417.6	Aug-15	108.58	4	120	0.90	25.8	107.74	0.74	313.13	77.57	225	76.73
881.6	Sep-15	229.22	8	240	0.96	26	229.22	0.74	654.96	165.04	472	163.65
1322.4	Oct-15	343.82	12	360	0.96	26	343.82	0.74	982.44	247.55	707	245.78

1044	Nov-15	271.44	10	300	0.90	25.8	269.35	0.74	782.81	193.93	564	194.70
812	Dec-15	211.12	8	240	0.88	25.8	209.50	0.75	614.29	150.84	442	151.38
533.6	Jan-16	138.74	5	150	0.92	25.9	138.20	0.74	398.89	99.51	287	98.46
812	Feb-16	211.12	8	240	0.88	25.8	209.50	0.75	614.29	150.84	442	151.38
1090.4	Mar-16	283.50	10	300	0.95	26	283.50	0.74	812.77	204.12	585	202.34
1044	Apr-16	271.44	10	300	0.90	25.8	269.35	0.74	782.81	193.93	564	194.70
997.6	May-16	259.38	9	270	0.96	26	259.38	0.74	739.79	186.75	533	185.38
719.2	Jun-16	186.99	7	210	0.89	25.8	185.55	0.74	542.00	133.60	390	132.93
696	Jul-16	180.96	7	210	0.86	25.8	179.57	0.75	529.99	129.29	382	129.73
870	Aug-16	226.20	8	240	0.94	25.9	225.33	0.74	646.53	162.24	466	161.22
951.2	Sep-16	247.31	9	270	0.92	25.8	245.41	0.74	710.48	176.69	512	176.34

Table B.4:CASE 2 – C65 calculations

P_{in}	Month	P_{out}	#MGT	P_C	PL%	PL efficiency%	$P_{out,new}$	PL effi.	output thermal power	$E_{elec.}(MWh)$	$E_{therm}(MWh)$	E_{tot}	CHP effi.	P/H
696	May-14	201.84	4	260	77.63	27.41%	191	0.75	582.12	137	419	556	96.61%	0.33
278.4	Jun-14	80.74	2	130	62.10	25.88%	72	0.77	236.62	52	170	222	96.46%	0.30
232	Jul-14	67.28	2	130	51.75	24.63%	57	0.78	199.71	41	144	185	96.32%	0.29
185.6	Aug-14	53.82	1	65	82.81	27.85%	52	0.75	154.50	37	111	148	96.65%	0.33
185.6	Sep-14	53.82	1	65	82.81	27.85%	52	0.75	154.50	37	111	148	96.65%	0.33
174	Oct-14	50.46	1	65	77.63	27.41%	48	0.75	145.53	34	105	139	96.61%	0.33
348	Nov-14	100.92	2	130	77.63	27.41%	95	0.75	291.06	69	210	278	96.61%	0.33
406	Dec-14	117.74	2	130	90.57	28.46%	116	0.74	335.73	83	242	325	96.70%	0.34
278.4	Jan-15	80.74	2	130	62.10	25.88%	72	0.77	236.62	52	170	222	96.46%	0.30
510.4	Feb-15	148.02	3	195	75.91	27.25%	139	0.75	427.59	100	308	408	96.60%	0.33
464	Mar-15	134.56	3	195	69.01	26.60%	123	0.76	391.41	89	282	371	96.53%	0.32
510.4	Apr-15	148.02	3	195	75.91	27.25%	139	0.75	427.59	100	308	408	96.60%	0.33
626.4	May-15	181.66	3	195	93.16	28.65%	179	0.74	516.90	129	372	501	96.72%	0.35
522	Jun-15	151.38	3	195	77.63	27.41%	143	0.75	436.59	103	314	417	96.61%	0.33
533.6	Jul-15	154.74	3	195	79.36	27.56%	147	0.75	445.58	106	321	427	96.62%	0.33
417.6	Aug-15	121.10	2	130	93.16	28.65%	120	0.74	344.60	86	248	334	96.72%	0.35
881.6	Sep-15	255.66	4	260	98.33	29.02%	256	0.74	724.54	184	522	706	96.75%	0.35
1322.4	Oct-15	383.50	6	390	98.33	29.02%	384	0.74	1086.81	276	783	1059	96.75%	0.35
1044	Nov-15	302.76	5	325	93.16	28.65%	299	0.74	861.50	215	620	836	96.72%	0.35
812	Dec-15	235.48	4	260	90.57	28.46%	231	0.74	671.46	166	483	650	96.70%	0.34

533.6	Jan-16	154.74	3	195	79.36	27.56%	147	0.75	445.58	106	321	427	96.62%	0.33
812	Feb-16	235.48	4	260	90.57	28.46%	231	0.74	671.46	166	483	650	96.70%	0.34
1090.4	Mar-16	316.22	5	325	97.30	28.95%	316	0.74	896.86	227	646	873	96.75%	0.35
1044	Apr-16	302.76	5	325	93.16	28.65%	299	0.74	861.50	215	620	836	96.72%	0.35
997.6	May-16	289.30	5	325	89.02	28.34%	283	0.74	826.00	204	595	798	96.69%	0.34
719.2	Jun-16	208.57	4	260	80.22	27.63%	199	0.75	600.09	143	432	575	96.63%	0.33
696	Jul-16	201.84	4	260	77.63	27.41%	191	0.75	582.12	137	419	556	96.61%	0.33
870	Aug-16	252.30	4	260	97.04	28.93%	252	0.74	715.72	181	515	697	96.74%	0.35
951.2	Sep-16	275.85	5	325	84.88	28.02%	267	0.75	790.37	192	569	761	96.67%	0.34

Table B.5: CASE 3 – T100 calculations

P_{in}	Month	P_{out}	# MGT	P_c	PL%	PL eff. %	$P_{out,new}$	PL thermal efficiency	$P_{thermal}$	E_{elec} (MWh)	E_{therm} (MWh)	E_{tot}	Effi. CHP	P/H ratio
696	May-14	208.80	3	300	69.60	27.58%	191.95	0.66	367.86	138	265	403	69.98%	0.52
278.4	Jun-14	83.52	1	100	83.52	28.87%	80.37	0.65	147.96	58	107	164	71.35%	0.54
232	Jul-14	69.60	1	100	69.60	27.58%	63.98	0.66	122.62	46	88	134	69.98%	0.52
185.6	Aug-14	55.68	1	100	55.68	26.00%	48.25	0.67	97.21	35	70	105	68.19%	0.50
185.6	Sep-14	55.68	1	100	55.68	26.00%	48.25	0.67	97.21	35	70	105	68.19%	0.50
174	Oct-14	52.20	1	100	52.20	25.54%	44.44	0.67	90.85	32	65	97	67.65%	0.49
348	Nov-14	104.40	2	200	52.20	25.54%	88.89	0.67	181.70	64	131	195	67.65%	0.49
406	Dec-14	121.80	2	200	60.90	26.63%	108.13	0.66	213.49	78	154	232	68.92%	0.51
278.4	Jan-15	83.52	1	100	83.52	28.87%	80.37	0.65	147.96	58	107	164	71.35%	0.54
510.4	Feb-15	153.12	2	200	76.56	28.25%	144.21	0.65	270.60	104	195	299	70.71%	0.53
464	Mar-15	139.20	2	200	69.60	27.58%	127.97	0.66	245.24	92	177	269	69.98%	0.52
510.4	Apr-15	153.12	2	200	76.56	28.25%	144.21	0.65	270.60	104	195	299	70.71%	0.53
626.4	May-15	187.92	2	200	93.96	29.70%	186.06	0.64	333.83	134	240	374	72.21%	0.56
522	Jun-15	156.60	2	200	78.30	28.41%	148.31	0.65	276.94	107	199	306	70.88%	0.54
533.6	Jul-15	160.08	2	200	80.04	28.57%	152.44	0.65	283.27	110	204	314	71.04%	0.54
417.6	Aug-15	125.28	2	200	62.64	26.83%	112.05	0.66	219.85	81	158	239	69.15%	0.51
881.6	Sep-15	264.48	3	300	88.16	29.25%	257.89	0.65	469.18	186	338	523	71.75%	0.55
1322.4	Oct-15	396.72	4	400	99.18	30.09%	397.86	0.64	705.51	286	508	794	72.59%	0.56
1044	Nov-15	313.20	4	400	78.30	28.41%	296.63	0.65	553.87	214	399	612	70.88%	0.54
812	Dec-15	243.60	3	300	81.20	28.67%	232.80	0.65	431.23	168	310	478	71.15%	0.54

533.6	Jan-16	160.08	2	200	80.04	28.57%	152.44	0.65	283.27	110	204	314	71.04%	0.54
812	Feb-16	243.60	3	300	81.20	28.67%	232.80	0.65	431.23	168	310	478	71.15%	0.54
1090.4	Mar-16	327.12	4	400	81.78	28.72%	313.17	0.65	579.19	225	417	643	71.20%	0.54
1044	Apr-16	313.20	4	400	78.30	28.41%	296.63	0.65	553.87	214	399	612	70.88%	0.54
997.6	May-16	299.28	3	300	99.76	30.13%	300.55	0.64	532.28	216	383	600	72.63%	0.56
719.2	Jun-16	215.76	3	300	71.92	27.81%	200.02	0.66	380.55	144	274	418	70.23%	0.53
696	Jul-16	208.80	3	300	69.60	27.58%	191.95	0.66	367.86	138	265	403	69.98%	0.52
870	Aug-16	261.00	3	300	87.00	29.16%	253.68	0.65	462.86	183	333	516	71.65%	0.55
951.2	Sep-16	285.36	3	300	95.12	29.79%	283.37	0.64	507.06	204	365	569	72.29%	0.56

Table B.6: CASE 4 – C200 calculations

P_{in}	Month	P_{out}	#MGT	P_C	PL%	PL effi%	P_{out,new}	PL therm effi.	P_{out,therm}	E (MWh)	E^{therm} (MWh)	E_{tot}	CHP effi.	P/H
696	May-14	208.80	2	400	52.20	28.10%	195.55	0.67	399.74	141	288	429	74.41%	0.49
278.4	Jun-14	83.52	1	200	41.76	26.36%	73.38	0.68	157.86	53	114	166	72.26%	0.46
232	Jul-14	69.60	1	200	34.80	24.94%	57.86	0.69	129.86	42	93	135	70.39%	0.45
185.6	Aug-14	55.68	1	200	27.84	23.20%	43.06	0.70	101.89	31	73	104	67.95%	0.42
185.6	Sep-14	55.68	1	200	27.84	23.20%	43.06	0.70	101.89	31	73	104	67.95%	0.42
174	Oct-14	52.20	1	200	26.10	22.70%	39.49	0.71	94.91	28	68	97	67.20%	0.42
348	Nov-14	104.40	1	200	52.20	28.10%	97.77	0.67	199.87	70	144	214	74.41%	0.49
406	Dec-14	121.80	1	200	60.90	29.30%	118.94	0.66	234.84	86	169	255	75.81%	0.51
278.4	Jan-15	83.52	1	200	41.76	26.36%	73.38	0.68	157.86	53	114	166	72.26%	0.46
510.4	Feb-15	153.12	1	200	76.56	31.08%	158.63	0.65	297.66	114	214	329	77.78%	0.53
464	Mar-15	139.20	1	200	69.60	30.34%	140.76	0.66	269.77	101	194	296	76.97%	0.52
510.4	Apr-15	153.12	1	200	76.56	31.08%	158.63	0.65	297.66	114	214	329	77.78%	0.53
626.4	May-15	187.92	1	200	93.96	32.67%	204.67	0.64	367.22	147	264	412	79.43%	0.56
522	Jun-15	156.60	1	200	78.30	31.25%	163.15	0.65	304.63	117	219	337	77.96%	0.54
533.6	Jul-15	160.08	1	200	80.04	31.43%	167.68	0.65	311.59	121	224	345	78.14%	0.54
417.6	Aug-15	125.28	1	200	62.64	29.52%	123.26	0.66	241.83	89	174	263	76.06%	0.51
881.6	Sep-15	264.48	2	400	66.12	29.94%	263.93	0.66	511.61	190	368	558	76.53%	0.52
1322.4	Oct-15	396.72	2	400	99.18	33.09%	437.65	0.64	776.06	315	559	874	79.85%	0.56
1044	Nov-15	313.20	2	400	78.30	31.25%	326.29	0.65	609.26	235	439	674	77.96%	0.54
812	Dec-15	243.60	2	400	60.90	29.30%	237.89	0.66	469.69	171	338	509	75.81%	0.51
533.6	Jan-16	160.08	1	200	80.04	31.43%	167.68	0.65	311.59	121	224	345	78.14%	0.54

812	Feb-16	243.60	2	400	60.90	29.30%	237.89	0.66	469.69	171	338	509	75.81%	0.51
1090.4	Mar-16	327.12	2	400	81.78	31.59%	344.49	0.65	637.11	248	459	707	78.32%	0.54
1044	Apr-16	313.20	2	400	78.30	31.25%	326.29	0.65	609.26	235	439	674	77.96%	0.54
997.6	May-16	299.28	2	400	74.82	30.90%	308.26	0.65	581.38	222	419	641	77.59%	0.53
719.2	Jun-16	215.76	2	400	53.94	28.35%	203.90	0.67	413.73	147	298	445	74.71%	0.49
696	Jul-16	208.80	2	400	52.20	28.10%	195.55	0.67	399.74	141	288	429	74.41%	0.49
870	Aug-16	261.00	2	400	65.25	29.83%	259.56	0.66	504.62	187	363	550	76.42%	0.51
951.2	Sep-16	285.36	2	400	71.34	30.53%	290.39	0.66	553.49	209	399	608	77.18%	0.52

Table B.7: CASE 5 – Combined MGT calculations

P_{in}	Month	P_{out}	MGT in operation	P_C	$\zeta_{elec,ave}$	$P_{out,new1}$	PL %	$\zeta_{elec,PL}$	$P_{out,new2}$	Φ_1	Φ_2	Φ_{ave}	P_{therm}	E (MWh)	E_{therm} (MWh)	E_{tot}	CHP effi	P/H
69.6	May-14	229.68	200+30	230	29.50%	205.32	89.27	28.85%	200.81	0.74	0.64	0.69	457.03	145	329	474	82.23%	0.44
278.4	Jun-14	91.87	65+30	95	27.50%	76.56	80.59	26.23%	73.03	0.75	0.65	0.70	170.70	53	123	175	76.17%	0.43
232	Jul-14	76.56	65+30	95	27.50%	63.8	67.16	25.05%	58.11	0.76	0.66	0.71	142.55	42	103	144	75.25%	0.41
185.6	Aug-14	61.25	65	65	29.00%	53.824	82.81	27.85%	51.69	0.75	0.65	0.70	119.96	37	86	124	80.46%	0.43
185.6	Sep-14	61.25	65	65	29.00%	53.824	82.81	27.85%	51.69	0.75	0.65	0.70	119.96	37	86	124	80.46%	0.43
174	Oct-14	57.42	65	65	29.00%	50.46	77.63	27.41%	47.69	0.75	0.65	0.70	112.57	34	81	115	80.13%	0.42
348	Nov-14	114.84	100+30	130	28.00%	97.44	74.95	26.23%	91.28	0.76	0.65	0.70	217.47	66	157	222	77.19%	0.42
406	Dec-14	133.98	100+30	130	28.00%	113.68	87.45	27.25%	110.63	0.75	0.65	0.70	253.14	80	182	262	77.95%	0.44
278.4	Jan-15	91.87	65+30	95	27.50%	76.56	80.59	26.23%	73.03	0.75	0.65	0.70	170.70	53	123	175	76.17%	0.43
510.4	Feb-15	168.43	100+65+30	195	28.30%	144.4432	74.07	26.43%	134.91	0.76	0.65	0.71	322.42	97	232	329	77.95%	0.42
464	Mar-15	153.12	100+65	165	29.00%	134.56	81.55	27.74%	128.73	0.75	0.65	0.70	299.97	93	216	309	80.38%	0.43
510.4	Apr-15	168.43	100+65+30	195	28.30%	144.4432	74.07	26.43%	134.91	0.76	0.65	0.71	322.42	97	232	329	77.95%	0.42
626.4	May-15	206.71	200+30	230	29.50%	184.788	80.34	28.12%	176.13	0.75	0.65	0.70	412.03	127	297	423	81.69%	0.43
522	Jun-15	172.26	100+65+30	195	28.30%	147.726	75.76	26.58%	138.76	0.75	0.65	0.70	329.66	100	237	337	78.07%	0.42

53 3.6	Jul-15	176.0 9	100+65+ 30	195	28.30%	151.00 88	77.44	26.73%	142.63	0.75	0.65	0.70	336.8 9	103	243	345	78.1 8%	0.42
41 7.6	Aug-15	137.8 1	100+65	165	29.50%	123.19 2	74.66	27.61%	115.29	0.76	0.65	0.70	274.9 6	83	198	281	81.3 0%	0.42
88 1.6	Sep-15	290.9 3	200+100	300	29.50%	260.07 2	86.69	28.65%	252.56	0.75	0.65	0.70	579.2 0	182	417	599	82.0 8%	0.44
13 22. 4	Oct-15	436.3 9	200+100 +100+65	465	30.50%	403.33 2	86.74	29.62%	391.73	0.75	0.65	0.70	898.2 4	282	647	929	84.8 7%	0.44
10 44	Nov-15	344.5 2	200+100 +65	365	31.00%	323.64	88.67	30.27%	316.01	0.75	0.65	0.70	720.4 9	228	519	746	86.3 8%	0.44
81 2	Dec-15	267.9 6	200+100	300	29.50%	239.54	79.85	28.08%	227.97	0.75	0.65	0.70	534.1 7	164	385	549	81.6 6%	0.43
53 3.6	Jan-16	176.0 9	200	200	33.00%	176.08 8	88.04	32.17%	171.65	0.75	0.65	0.70	392.0 6	124	282	406	91.9 1%	0.44
81 2	Feb-16	267.9 6	200+100	300	29.50%	239.54	79.85	28.08%	227.97	0.75	0.65	0.70	534.1 7	164	385	549	81.6 6%	0.43
10 90. 4	Mar-16	359.8 3	200+100 +65	365	31.00%	338.02 4	92.61	30.59%	333.53	0.74	0.64	0.69	751.9 0	240	541	782	86.6 0%	0.44
10 44	Apr-16	344.5 2	200+100 +65	365	31.00%	323.64	88.67	30.27%	316.01	0.75	0.65	0.70	720.4 9	228	519	746	86.3 8%	0.44
99 7.6	May-16	329.2 1	200+100 +30	330	30.00%	299.28	90.69	29.45%	293.82	0.74	0.64	0.69	665.9 8	212	480	691	83.7 0%	0.44
71 9.2	Jun-16	237.3 4	200+65	265	31.00%	222.95 2	84.13	29.89%	214.94	0.75	0.65	0.70	496.7 8	155	358	512	86.0 9%	0.43
69 6	Jul-16	229.6 8	200+30	230	29.50%	205.32	89.27	28.85%	200.81	0.74	0.64	0.69	457.0 3	145	329	474	82.2 3%	0.44
87 0	Aug-16	287.1 0	200+100	300	29.50%	256.65	85.55	28.56%	248.43	0.75	0.65	0.70	571.7 1	179	412	591	82.0 1%	0.43
95 1.2	Sep-16	313.9 0	200+100 +30	330	30.00%	285.36	86.47	29.12%	276.95	0.75	0.65	0.70	635.5 5	199	458	657	83.4 6%	0.44

Table B.8: CASE 6 –G3306 calculations

P_{in}	Month	P_{out}	# Engines	P_C	PL(must be > 50%)	E_{elec} (MWh)	P_{therm}	E_{therm} (MWh)	E_{tot}	CHP Effi.	P/H
696	May-14	222.02	2	286	0.78	160	266.57	192	352	70.20%	0.83
278.4	Jun-14	88.81	1	143	0.62	64	106.63	77	141	70.20%	0.83
232	Jul-14	74.01	1	143	0.52	53	88.86	64	117	70.20%	0.83
185.6	Aug-14	59.21	1	143	0.41	43	71.08	51	94	70.20%	0.83
185.6	Sep-14	59.21	1	143	0.41	43	71.08	51	94	70.20%	0.83
174	Oct-14	55.51	1	143	0.39	40	66.64	48	88	70.20%	0.83
348	Nov-14	111.01	1	143	0.78	80	133.28	96	176	70.20%	0.83
406	Dec-14	129.51	1	143	0.91	93	155.50	112	205	70.20%	0.83
278.4	Jan-15	88.81	1	143	0.62	64	106.63	77	141	70.20%	0.83
510.4	Feb-15	162.82	2	286	0.57	117	195.48	141	258	70.20%	0.83
464	Mar-15	148.02	2	286	0.52	107	177.71	128	235	70.20%	0.83
510.4	Apr-15	162.82	2	286	0.57	117	195.48	141	258	70.20%	0.83
626.4	May-15	199.82	2	286	0.70	144	239.91	173	317	70.20%	0.83
522	Jun-15	166.52	2	286	0.58	120	199.93	144	264	70.20%	0.83
533.6	Jul-15	170.22	2	286	0.60	123	204.37	147	270	70.20%	0.83
417.6	Aug-15	133.21	1	143	0.93	96	159.94	115	211	70.20%	0.83
881.6	Sep-15	281.23	2	286	0.98	202	337.65	243	446	70.20%	0.83
1322.4	Oct-15	421.85	3	429	0.98	304	506.48	365	668	70.20%	0.83
1044	Nov-15	333.04	3	429	0.78	240	399.85	288	528	70.20%	0.83
812	Dec-15	259.03	2	286	0.91	187	311.00	224	410	70.20%	0.83
533.6	Jan-16	170.22	2	286	0.60	123	204.37	147	270	70.20%	0.83

812	Feb-16	259.03	2	286	0.91	187	311.00	224	410	70.20%	0.83
1090.4	Mar-16	347.84	3	429	0.81	250	417.62	301	551	70.20%	0.83
1044	Apr-16	333.04	3	429	0.78	240	399.85	288	528	70.20%	0.83
997.6	May-16	318.23	3	429	0.74	229	382.08	275	504	70.20%	0.83
719.2	Jun-16	229.42	2	286	0.80	165	275.45	198	364	70.20%	0.83
696	Jul-16	222.02	2	286	0.78	160	266.57	192	352	70.20%	0.83
870	Aug-16	277.53	2	286	0.97	200	333.21	240	440	70.20%	0.83
951.2	Sep-16	303.43	3	429	0.71	218	364.31	262	481	70.20%	0.83

Table B.9: CASE 7 –G3406 calculations

P_{in}	Month	P_{out}	# engines	P_C	PL (> 50%)	E_{elec} (MWh)	P_{therm}	E_{th} (MWh)	E_{tot}	CHP Effi.	P/H
696	May-14	259.61	2	470	0.55	187	311.81	225	411	82.10%	0.83
278.4	Jun-14	103.84	1	235	0.44	75	124.72	90	165	82.10%	0.83
232	Jul-14	86.54	1	235	0.37	62	103.94	75	137	82.10%	0.83
185.6	Aug-14	69.23	1	235	0.29	50	83.15	60	110	82.10%	0.83
185.6	Sep-14	69.23	1	235	0.29	50	83.15	60	110	82.10%	0.83
174	Oct-14	64.90	1	235	0.28	47	77.95	56	103	82.10%	0.83
348	Nov-14	129.80	1	235	0.55	93	155.90	112	206	82.10%	0.83
406	Dec-14	151.44	1	235	0.64	109	181.89	131	240	82.10%	0.83
278.4	Jan-15	103.84	1	235	0.44	75	124.72	90	165	82.10%	0.83
510.4	Feb-15	190.38	1	235	0.81	137	228.66	165	302	82.10%	0.83
464	Mar-15	173.07	1	235	0.74	125	207.87	150	274	82.10%	0.83
510.4	Apr-15	190.38	1	235	0.81	137	228.66	165	302	82.10%	0.83
626.4	May-15	233.65	1	235	0.99	168	280.63	202	370	82.10%	0.83
522	Jun-15	194.71	1	235	0.83	140	233.86	168	309	82.10%	0.83
533.6	Jul-15	199.03	1	235	0.85	143	239.05	172	315	82.10%	0.83
417.6	Aug-15	155.76	1	235	0.66	112	187.08	135	247	82.10%	0.83
881.6	Sep-15	328.84	2	470	0.70	237	394.96	284	521	82.10%	0.83
1322.4	Oct-15	493.26	3	705	0.70	355	592.44	427	782	82.10%	0.83
1044	Nov-15	389.41	2	470	0.83	280	467.71	337	617	82.10%	0.83
812	Dec-15	302.88	2	470	0.64	218	363.78	262	480	82.10%	0.83
533.6	Jan-16	199.03	1	235	0.85	143	239.05	172	315	82.10%	0.83
812	Feb-16	302.88	2	470	0.64	218	363.78	262	480	82.10%	0.83

1090.4	Mar-16	406.72	2	470	0.87	293	488.50	352	645	82.10%	0.83
1044	Apr-16	389.41	2	470	0.83	280	467.71	337	617	82.10%	0.83
997.6	May-16	372.10	2	470	0.79	268	446.92	322	590	82.10%	0.83
719.2	Jun-16	268.26	2	470	0.57	193	322.20	232	425	82.10%	0.83
696	Jul-16	259.61	2	470	0.55	187	311.81	225	411	82.10%	0.83
870	Aug-16	324.51	2	470	0.69	234	389.76	281	514	82.10%	0.83
951.2	Sep-16	354.80	2	470	0.75	255	426.14	307	562	82.10%	0.83

Table B.10: CASE 8 –CG132-8 calculations

P_{in}	Month	P_{out}	#engines	P_C	PL (> 50%)	E (MWh)	P_{therm}	E_{therm} (MWh)	E_{tot}	CHP Effi	P/H
696	May-14	297.89	1	400	0.74	214	357.74	258	472	94.20%	0.83
278.4	Jun-14	119.16	1	400	0.30	86	143.09	103	189	94.20%	0.83
232	Jul-14	99.30	1	400	0.25	71	119.24	86	157	94.20%	0.83
185.6	Aug-14	79.44	1	400	0.20	57	95.39	69	126	94.20%	0.83
185.6	Sep-14	79.44	1	400	0.20	57	95.39	69	126	94.20%	0.83
174	Oct-14	74.47	1	400	0.19	54	89.43	64	118	94.20%	0.83
348	Nov-14	148.94	1	400	0.37	107	178.87	129	236	94.20%	0.83
406	Dec-14	173.77	1	400	0.43	125	208.68	150	275	94.20%	0.83
278.4	Jan-15	119.16	1	400	0.30	86	143.09	103	189	94.20%	0.83
510.4	Feb-15	218.45	1	400	0.55	157	262.34	189	346	94.20%	0.83
464	Mar-15	198.59	1	400	0.50	143	238.4	172	315	94.20%	0.83
510.4	Apr-15	218.45	1	400	0.55	157	262.34	189	346	94.20%	0.83
626.4	May-15	268.10	1	400	0.67	193	321.96	232	425	94.20%	0.83
522	Jun-15	223.42	1	400	0.56	161	268.30	193	354	94.20%	0.83
533.6	Jul-15	228.38	1	400	0.57	164	274.27	197	362	94.20%	0.83
417.6	Aug-15	178.73	1	400	0.45	129	214.64	155	283	94.20%	0.83
881.6	Sep-15	377.32	1	400	0.94	272	453.14	326	598	94.20%	0.83
1322.4	Oct-15	565.99	2	800	0.71	408	679.71	489	897	94.20%	0.83
1044	Nov-15	446.83	2	800	0.56	322	536.61	386	708	94.20%	0.83
812	Dec-15	347.54	1	400	0.87	250	417.36	301	551	94.20%	0.83
533.6	Jan-16	228.38	1	400	0.57	164	274.27	197	362	94.20%	0.83
812	Feb-16	347.54	1	400	0.87	250	417.36	301	551	94.20%	0.83

1090.4	Mar-16	466.69	2	800	0.58	336	560.46	404	740	94.20%	0.83
1044	Apr-16	446.83	2	800	0.56	322	536.61	386	708	94.20%	0.83
997.6	May-16	426.97	2	800	0.53	307	512.76	369	677	94.20%	0.83
719.2	Jun-16	307.82	1	400	0.77	222	369.66	266	488	94.20%	0.83
696	Jul-16	297.89	1	400	0.74	214	357.74	258	472	94.20%	0.83
870	Aug-16	372.36	1	400	0.93	268	447.18	322	590	94.20%	0.83
951.2	Sep-16	407.11	2	800	0.51	293	488.91	352	645	94.20%	0.83

Table B.11: CASE 9 –Combined ICE calculations

P_{in}	Month	P_{out}	Engines in operation	P_C	$P_{out,new}$	Engines in operation	PL (> 50%)	E_{elec} (MWh)	P_{therm}	E_{th} MWh	E_{tot}	CHP Effi.	P/H
696	May-14	264.48	CG132-8	400	297.89	CG132-8	0.74	214	311.81	225	439	87.60%	0.96
278.4	Jun-14	105.79	G3306	143	88.81	G3306	0.62	64	106.63	77	141	70.20%	0.83
232	Jul-14	88.16	G3306	143	74.01	G3306	0.52	53	88.86	64	117	70.20%	0.83
185.6	Aug-14	70.53	G3306	143	59.21	G3306	0.41	43	71.08	51	94	70.20%	0.83
185.6	Sep-14	70.53	G3306	143	59.21	G3306	0.41	43	71.08	51	94	70.20%	0.83
174	Oct-14	66.12	G3306	143	55.51	G3306	0.39	40	66.64	48	88	70.20%	0.83
348	Nov-14	132.24	G3306	143	111.01	G3306	0.78	80	133.28	96	176	70.20%	0.83
406	Dec-14	154.28	G3406	235	151.44	G3406	0.64	109	155.50	112	221	75.60%	0.97
278.4	Jan-15	105.79	G3306	143	88.81	G3306	0.62	64	106.63	77	141	70.20%	0.83
510.4	Feb-15	193.95	G3406	235	190.38	G3406	0.81	137	228.66	165	302	82.10%	0.83
464	Mar-15	176.32	G3406	235	173.07	G3406	0.74	125	207.87	150	274	82.10%	0.83
510.4	Apr-15	193.95	G3406	235	190.38	G3406	0.81	137	228.66	165	302	82.10%	0.83
626.4	May-15	238.03	G3406	235	233.65	G3406	0.99	168	280.63	202	370	82.10%	0.83
522	Jun-15	198.36	G3406	235	194.71	G3406	0.83	140	233.86	168	309	82.10%	0.83
533.6	Jul-15	202.77	G3406	235	199.03	G3406	0.85	143	239.05	172	315	82.10%	0.83
417.6	Aug-15	158.69	G3406	235	155.76	G3406	0.66	112	159.94	115	227	75.60%	0.97
881.6	Sep-15	335.01	CG132-8	400	377.32	CG132-8	0.94	272	377.32	272	543	85.60%	1.00
1322.4	Oct-15	502.51	G3306 & CG132-8	543	493.26	G3306 & CG132-8	0.91	355	493.26	355	710	74.60%	1.00
1044	Nov-15	396.72	G3306 & CG132-8	543	446.83	G3306 & CG132-8	0.82	322	446.83	322	643	85.60%	1.00
812	Dec-15	308.56	CG132-8	400	347.54	CG132-8	0.87	250	347.54	250	500	85.60%	1.00
533.6	Jan-16	202.77	G3406	235	199.03	G3406	0.85	143	199.03	143	287	74.60%	1.00

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812	Feb-16	308.56	CG132-8	400	347.54	CG132-8	0.87	250	347.54	250	500	85.60%	1.00
1090.4	Mar-16	414.35	G3306 & CG132-8	543	406.72	G3306 & CG132-8	0.75	293	466.69	336	629	80.10%	0.87
1044	Apr-16	396.72	G3306 & CG132-8	543	446.83	G3306 & CG132-8	0.82	322	446.83	322	643	85.60%	1.00
997.6	May-16	379.09	G3306 & CG132-8	543	426.97	G3306 & CG132-8	0.79	307	426.97	307	615	85.60%	1.00
719.2	Jun-16	273.30	CG132-8	400	307.82	CG132-8	0.77	222	268.26	193	415	80.10%	1.15
696	Jul-16	264.48	CG132-8	400	297.89	CG132-8	0.74	214	259.61	187	401	80.10%	1.15
870	Aug-16	330.60	CG132-8	400	372.36	CG132-8	0.93	268	372.36	268	536	85.60%	1.00
951.2	Sep-16	361.46	G3306 & CG132-8	543	407.11	CG132-8	0.75	293	407.11	293	586	85.60%	1.00

C.Appendix C

Table C.1: Compound interest factors for $i=7\%$

7%		Compound Interest Factors							7%
<i>n</i>	Single Payment		Uniform Payment Series				Arithmetic Gradient		<i>n</i>
	Compound Amount Factor Find <i>F</i> Given <i>P</i> <i>F/P</i>	Present Worth Factor Find <i>P</i> Given <i>F</i> <i>P/F</i>	Sinking Fund Factor Find <i>A</i> Given <i>F</i> <i>A/F</i>	Capital Recovery Factor Find <i>A</i> Given <i>P</i> <i>A/P</i>	Compound Amount Factor Find <i>F</i> Given <i>A</i> <i>F/A</i>	Present Worth Factor Find <i>P</i> Given <i>A</i> <i>P/A</i>	Gradient Uniform Series Find <i>A</i> Given <i>G</i> <i>A/G</i>	Gradient Present Worth Find <i>P</i> Given <i>G</i> <i>P/G</i>	
1	1.070	.9346	1.0000	1.0700	1.000	0.935	0	0	1
2	1.145	.8734	.4831	.5531	2.070	1.808	0.483	0.873	2
3	1.225	.8163	.3111	.3811	3.215	2.624	0.955	2.506	3
4	1.311	.7629	.2252	.2952	4.440	3.387	1.416	4.795	4
5	1.403	.7130	.1739	.2439	5.751	4.100	1.865	7.647	5
6	1.501	.6663	.1398	.2098	7.153	4.767	2.303	10.978	6
7	1.606	.6227	.1156	.1856	8.654	5.389	2.730	14.715	7
8	1.718	.5820	.0975	.1675	10.260	5.971	3.147	18.789	8
9	1.838	.5439	.0835	.1535	11.978	6.515	3.552	23.140	9
10	1.967	.5083	.0724	.1424	13.816	7.024	3.946	27.716	10

D.Appendix D

Table D.1: CASE 1 –C30 environmental calculations

Month	m _{biogas}	CO _{2,Biogas}	EP	E _{demand}	CO _{2G, SHP}	E _{demand,new}	CO _{2 G, CHP}	Co _{2,s}	NO _{x,CHP}	CO _{CHP}	VOC _{CHP}	SO _{x,CHP}
May-14	90000	292500	129	196.652	137656.4	67.652	47356.4	90300	120.6	12.78	4.545	4.914
Jun-14	36000	117000	51	154.362	108053.4	103.362	72353.4	35700	48.24	5.112	1.818	1.9656
Jul-14	30000	97500	42	189.057	132339.9	147.057	102939.9	29400	40.2	4.26	1.515	1.638
Aug-14	24000	78000	34	213.369	149358.3	179.369	125558.3	23800	32.16	3.408	1.212	1.3104
Sep-14	24000	78000	34	197.193	138035.1	163.193	114235.1	23800	32.16	3.408	1.212	1.3104
Oct-14	22500	73125	32	210.365	147255.5	178.365	124855.5	22400	30.15	3.195	1.13625	1.2285
Nov-14	45000	146250	63	216.232	151362.4	153.232	107262.4	44100	60.3	6.39	2.2725	2.457
Dec-14	52500	170625	75	235.323	164726.1	160.323	112226.1	52500	70.35	7.455	2.65125	2.8665
Jan-15	36000	117000	51	171.474	120031.8	120.474	84331.8	35700	48.24	5.112	1.818	1.9656
Feb-15	66000	214500	95	139.101	97370.7	44.101	30870.7	66500	88.44	9.372	3.333	3.6036
Mar-15	60000	195000	86	222.721	155904.7	136.721	95704.7	60200	80.4	8.52	3.03	3.276
Apr-15	66000	214500	95	209.234	146463.8	114.234	79963.8	66500	88.44	9.372	3.333	3.6036
May-15	81000	263250	116	204.99	143493	88.99	62293	81200	108.54	11.502	4.0905	4.4226
Jun-15	67500	219375	97	271.837	190285.9	174.837	122385.9	67900	90.45	9.585	3.40875	3.6855
Jul-15	69000	224250	100	259.617	181731.9	159.617	111731.9	70000	92.46	9.798	3.4845	3.7674
Aug-15	54000	175500	78	266.86	186802	188.86	132202	54600	72.36	7.668	2.727	2.9484
Sep-15	114000	370500	165	234.126	163888.2	69.126	48388.2	115500	152.76	16.188	5.757	6.2244

Oct-15	171000	555750	248	213	149100	-35	-24500	173600	229.14	24.282	8.6355	9.3366
Nov-15	135000	438750	194	235.684	164978.8	41.684	29178.8	135800	180.9	19.17	6.8175	7.371
Dec-15	105000	341250	151	233.102	163171.4	82.102	57471.4	105700	140.7	14.91	5.3025	5.733
Jan-16	69000	224250	100	171.474	120031.8	71.474	50031.8	70000	92.46	9.798	3.4845	3.7674
Feb-16	105000	341250	151	139.101	97370.7	-11.899	-8329.3	105700	140.7	14.91	5.3025	5.733
Mar-16	141000	458250	204	222.721	155904.7	18.721	13104.7	142800	188.94	20.022	7.1205	7.6986
Apr-16	135000	438750	194	209.234	146463.8	15.234	10663.8	135800	180.9	19.17	6.8175	7.371
May-16	129000	419250	187	204.99	143493	17.99	12593	130900	172.86	18.318	6.5145	7.0434
Jun-16	93000	302250	134	271.837	190285.9	137.837	96485.9	93800	124.62	13.206	4.6965	5.0778
Jul-16	90000	292500	129	259.617	181731.9	130.617	91431.9	90300	120.6	12.78	4.545	4.914
Aug-16	112500	365625	162	266.86	186802	104.86	73402	113400	150.75	15.975	5.68125	6.1425
Sep-16	123000	399750	177	234.126	163888.2	57.126	39988.2	123900	164.82	17.466	6.2115	6.7158

Table D.2: CASE 2 –C65 environmental calculations

Month	m _{biogas}	CO ₂ ,Biogas	EP	E _{demand}	CO ₂ G, SHP	E _{demand,new}	CO ₂ G, CHP	CO ₂ ,S	NO _x ,CHP	CO _{CHP}	VOC _{CHP}	SO _x ,CHP
May-14	90000	292500	137	196.652	137656.4	59.652	41756.4	95900	120.6	12.78	4.545	4.914
Jun-14	36000	117000	52	154.362	108053.4	102.362	71653.4	36400	48.24	5.112	1.818	1.9656
Jul-14	30000	97500	41	189.057	132339.9	148.057	103639.9	28700	40.2	4.26	1.515	1.638
Aug-14	24000	78000	37	213.369	149358.3	176.369	123458.3	25900	32.16	3.408	1.212	1.3104
Sep-14	24000	78000	37	197.193	138035.1	160.193	112135.1	25900	32.16	3.408	1.212	1.3104
Oct-14	22500	73125	34	210.365	147255.5	176.365	123455.5	23800	30.15	3.195	1.13625	1.2285
Nov-14	45000	146250	69	216.232	151362.4	147.232	103062.4	48300	60.3	6.39	2.2725	2.457
Dec-14	52500	170625	83	235.323	164726.1	152.323	106626.1	58100	70.35	7.455	2.65125	2.8665
Jan-15	36000	117000	52	171.474	120031.8	119.474	83631.8	36400	48.24	5.112	1.818	1.9656
Feb-15	66000	214500	100	139.101	97370.7	39.101	27370.7	70000	88.44	9.372	3.333	3.6036
Mar-15	60000	195000	89	222.721	155904.7	133.721	93604.7	62300	80.4	8.52	3.03	3.276
Apr-15	66000	214500	100	209.234	146463.8	109.234	76463.8	70000	88.44	9.372	3.333	3.6036
May-15	81000	263250	129	204.99	143493	75.99	53193	90300	108.54	11.502	4.0905	4.4226
Jun-15	67500	219375	103	271.837	190285.9	168.837	118185.9	72100	90.45	9.585	3.40875	3.6855
Jul-15	69000	224250	106	259.617	181731.9	153.617	107531.9	74200	92.46	9.798	3.4845	3.7674
Aug-15	54000	175500	86	266.86	186802	180.86	126602	60200	72.36	7.668	2.727	2.9484
Sep-15	114000	370500	184	234.126	163888.2	50.126	35088.2	128800	152.76	16.188	5.757	6.2244
Oct-15	171000	555750	276	213	149100	-63	-44100	193200	229.14	24.282	8.6355	9.3366
Nov-15	135000	438750	215	235.684	164978.8	20.684	14478.8	150500	180.9	19.17	6.8175	7.371
Dec-15	105000	341250	166	233.102	163171.4	67.102	46971.4	116200	140.7	14.91	5.3025	5.733
Jan-16	69000	224250	106	171.474	120031.8	65.474	45831.8	74200	92.46	9.798	3.4845	3.7674
Feb-16	105000	341250	166	139.101	97370.7	-26.899	-18829.3	116200	140.7	14.91	5.3025	5.733

Mar-16	141000	458250	227	222.721	155904.7	-4.279	-2995.3	158900	188.94	20.022	7.1205	7.6986
Apr-16	135000	438750	215	209.234	146463.8	-5.766	-4036.2	150500	180.9	19.17	6.8175	7.371
May-16	129000	419250	204	204.99	143493	0.99	693	142800	172.86	18.318	6.5145	7.0434
Jun-16	93000	302250	143	271.837	190285.9	128.837	90185.9	100100	124.62	13.206	4.6965	5.0778
Jul-16	90000	292500	137	259.617	181731.9	122.617	85831.9	95900	120.6	12.78	4.545	4.914
Aug-16	112500	365625	181	266.86	186802	85.86	60102	126700	150.75	15.975	5.68125	6.1425
Sep-16	123000	399750	192	234.126	163888.2	42.126	29488.2	134400	164.82	17.466	6.2115	6.7158

Table D.3:CASE3 –T100 environmental calculations

Month	m_{biogas}	CO₂,Biogas	E_P	E_{demand}	CO₂G, SHP	E_{demand,new}	CO₂ G, CHP	CO₂,S	NO_x,CHP	CO_{CHP}	VOC_{CHP}	SO_x,CHP
May-14	90000	292500	138	196.652	137656.4	58.652	41056.4	96600	120.6	12.78	4.545	4.914
Jun-14	36000	117000	58	154.362	108053.4	96.362	67453.4	40600	48.24	5.112	1.818	1.9656
Jul-14	30000	97500	46	189.057	132339.9	143.057	100139.9	32200	40.2	4.26	1.515	1.638
Aug-14	24000	78000	35	213.369	149358.3	178.369	124858.3	24500	32.16	3.408	1.212	1.3104
Sep-14	24000	78000	35	197.193	138035.1	162.193	113535.1	24500	32.16	3.408	1.212	1.3104
Oct-14	22500	73125	32	210.365	147255.5	178.365	124855.5	22400	30.15	3.195	1.13625	1.2285
Nov-14	45000	146250	64	216.232	151362.4	152.232	106562.4	44800	60.3	6.39	2.2725	2.457
Dec-14	52500	170625	78	235.323	164726.1	157.323	110126.1	54600	70.35	7.455	2.65125	2.8665
Jan-15	36000	117000	58	171.474	120031.8	113.474	79431.8	40600	48.24	5.112	1.818	1.9656
Feb-15	66000	214500	104	139.101	97370.7	35.101	24570.7	72800	88.44	9.372	3.333	3.6036
Mar-15	60000	195000	92	222.721	155904.7	130.721	91504.7	64400	80.4	8.52	3.03	3.276
Apr-15	66000	214500	104	209.234	146463.8	105.234	73663.8	72800	88.44	9.372	3.333	3.6036
May-15	81000	263250	134	204.99	143493	70.99	49693	93800	108.54	11.502	4.0905	4.4226
Jun-15	67500	219375	107	271.837	190285.9	164.837	115385.9	74900	90.45	9.585	3.40875	3.6855
Jul-15	69000	224250	110	259.617	181731.9	149.617	104731.9	77000	92.46	9.798	3.4845	3.7674
Aug-15	54000	175500	81	266.86	186802	185.86	130102	56700	72.36	7.668	2.727	2.9484
Sep-15	114000	370500	186	234.126	163888.2	48.126	33688.2	130200	152.76	16.188	5.757	6.2244
Oct-15	171000	555750	286	213	149100	-73	-51100	200200	229.14	24.282	8.6355	9.3366
Nov-15	135000	438750	214	235.684	164978.8	21.684	15178.8	149800	180.9	19.17	6.8175	7.371
Dec-15	105000	341250	168	233.102	163171.4	65.102	45571.4	117600	140.7	14.91	5.3025	5.733
Jan-16	69000	224250	110	171.474	120031.8	61.474	43031.8	77000	92.46	9.798	3.4845	3.7674

Feb-16	105000	341250	168	139.101	97370.7	-28.899	-20229.3	117600	140.7	14.91	5.3025	5.733
Mar-16	141000	458250	225	222.721	155904.7	-2.279	-1595.3	157500	188.94	20.022	7.1205	7.6986
Apr-16	135000	438750	214	209.234	146463.8	-4.766	-3336.2	149800	180.9	19.17	6.8175	7.371
May-16	129000	419250	216	204.99	143493	-11.01	-7707	151200	172.86	18.318	6.5145	7.0434
Jun-16	93000	302250	144	271.837	190285.9	127.837	89485.9	100800	124.62	13.206	4.6965	5.0778
Jul-16	90000	292500	138	259.617	181731.9	121.617	85131.9	96600	120.6	12.78	4.545	4.914
Aug-16	112500	365625	183	266.86	186802	83.86	58702	128100	150.75	15.975	5.68125	6.1425
Sep-16	123000	399750	204	234.126	163888.2	30.126	21088.2	142800	164.82	17.466	6.2115	6.7158

Table D.4:CASE4 –C200 environmental calculations

Month	m _{biogas}	CO _{2,Biogas}	E _P	E _{demand}	CO _{2G, SHP}	E _{demand,new}	CO _{2 G, CHP}	CO _{2,S}	NO _{x,CHP}	CO _{CHP}	VOC _{CHP}	SO _{x,CHP}
May-14	90000	292500	141	196.652	137656.4	55.652	38956.4	98700	120.6	12.78	4.545	4.914
Jun-14	36000	117000	53	154.362	108053.4	101.362	70953.4	37100	48.24	5.112	1.818	1.9656
Jul-14	30000	97500	42	189.057	132339.9	147.057	102939.9	29400	40.2	4.26	1.515	1.638
Aug-14	24000	78000	31	213.369	149358.3	182.369	127658.3	21700	32.16	3.408	1.212	1.3104
Sep-14	24000	78000	31	197.193	138035.1	166.193	116335.1	21700	32.16	3.408	1.212	1.3104
Oct-14	22500	73125	28	210.365	147255.5	182.365	127655.5	19600	30.15	3.195	1.13625	1.2285
Nov-14	45000	146250	70	216.232	151362.4	146.232	102362.4	49000	60.3	6.39	2.2725	2.457
Dec-14	52500	170625	86	235.323	164726.1	149.323	104526.1	60200	70.35	7.455	2.65125	2.8665
Jan-15	36000	117000	53	171.474	120031.8	118.474	82931.8	37100	48.24	5.112	1.818	1.9656
Feb-15	66000	214500	114	139.101	97370.7	25.101	17570.7	79800	88.44	9.372	3.333	3.6036
Mar-15	60000	195000	101	222.721	155904.7	121.721	85204.7	70700	80.4	8.52	3.03	3.276
Apr-15	66000	214500	114	209.234	146463.8	95.234	66663.8	79800	88.44	9.372	3.333	3.6036
May-15	81000	263250	147	204.99	143493	57.99	40593	102900	108.54	11.502	4.0905	4.4226
Jun-15	67500	219375	117	271.837	190285.9	154.837	108385.9	81900	90.45	9.585	3.40875	3.6855
Jul-15	69000	224250	121	259.617	181731.9	138.617	97031.9	84700	92.46	9.798	3.4845	3.7674
Aug-15	54000	175500	89	266.86	186802	177.86	124502	62300	72.36	7.668	2.727	2.9484
Sep-15	114000	370500	190	234.126	163888.2	44.126	30888.2	133000	152.76	16.188	5.757	6.2244
Oct-15	171000	555750	315	213	149100	-102	-71400	220500	229.14	24.282	8.6355	9.3366
Nov-15	135000	438750	235	235.684	164978.8	0.684	478.8	164500	180.9	19.17	6.8175	7.371
Dec-15	105000	341250	171	233.102	163171.4	62.102	43471.4	119700	140.7	14.91	5.3025	5.733
Jan-16	69000	224250	121	171.474	120031.8	50.474	35331.8	84700	92.46	9.798	3.4845	3.7674

Feb-16	105000	341250	171	139.101	97370.7	-31.899	-22329.3	119700	140.7	14.91	5.3025	5.733
Mar-16	141000	458250	248	222.721	155904.7	-25.279	-17695.3	173600	188.94	20.022	7.1205	7.6986
Apr-16	135000	438750	235	209.234	146463.8	-25.766	-18036.2	164500	180.9	19.17	6.8175	7.371
May-16	129000	419250	222	204.99	143493	-17.01	-11907	155400	172.86	18.318	6.5145	7.0434
Jun-16	93000	302250	147	271.837	190285.9	124.837	87385.9	102900	124.62	13.206	4.6965	5.0778
Jul-16	90000	292500	141	259.617	181731.9	118.617	83031.9	98700	120.6	12.78	4.545	4.914
Aug-16	112500	365625	187	266.86	186802	79.86	55902	130900	150.75	15.975	5.68125	6.1425
Sep-16	123000	399750	209	234.126	163888.2	25.126	17588.2	146300	164.82	17.466	6.2115	6.7158

Table D.5:CASE5 –Combined MGT environmental calculations

Month	m _{biogas}	CO ₂ ,Biogas	EP	E _{demand}	CO ₂ G, SHP	E _{demand,new}	CO ₂ G, CHP	CO ₂ ,S	NO _x ,CHP	CO _{CHP}	VOC _{CHP}	SO _x ,CHP
May-14	90000	292500	145	196.652	137656.4	51.652	36156.4	101500	120.6	12.78	4.545	4.914
Jun-14	36000	117000	53	154.362	108053.4	101.362	70953.4	37100	48.24	5.112	1.818	1.9656
Jul-14	30000	97500	42	189.057	132339.9	147.057	102939.9	29400	40.2	4.26	1.515	1.638
Aug-14	24000	78000	37	213.369	149358.3	176.369	123458.3	25900	32.16	3.408	1.212	1.3104
Sep-14	24000	78000	37	197.193	138035.1	160.193	112135.1	25900	32.16	3.408	1.212	1.3104
Oct-14	22500	73125	34	210.365	147255.5	176.365	123455.5	23800	30.15	3.195	1.13625	1.2285
Nov-14	45000	146250	66	216.232	151362.4	150.232	105162.4	46200	60.3	6.39	2.2725	2.457
Dec-14	52500	170625	80	235.323	164726.1	155.323	108726.1	56000	70.35	7.455	2.65125	2.8665
Jan-15	36000	117000	53	171.474	120031.8	118.474	82931.8	37100	48.24	5.112	1.818	1.9656
Feb-15	66000	214500	97	139.101	97370.7	42.101	29470.7	67900	88.44	9.372	3.333	3.6036
Mar-15	60000	195000	93	222.721	155904.7	129.721	90804.7	65100	80.4	8.52	3.03	3.276
Apr-15	66000	214500	97	209.234	146463.8	112.234	78563.8	67900	88.44	9.372	3.333	3.6036
May-15	81000	263250	127	204.99	143493	77.99	54593	88900	108.54	11.502	4.0905	4.4226
Jun-15	67500	219375	100	271.837	190285.9	171.837	120285.9	70000	90.45	9.585	3.40875	3.6855
Jul-15	69000	224250	103	259.617	181731.9	156.617	109631.9	72100	92.46	9.798	3.4845	3.7674
Aug-15	54000	175500	83	266.86	186802	183.86	128702	58100	72.36	7.668	2.727	2.9484
Sep-15	114000	370500	182	234.126	163888.2	52.126	36488.2	127400	152.76	16.188	5.757	6.2244
Oct-15	171000	555750	282	213	149100	-69	-48300	197400	229.14	24.282	8.6355	9.3366
Nov-15	135000	438750	228	235.684	164978.8	7.684	5378.8	159600	180.9	19.17	6.8175	7.371
Dec-15	105000	341250	164	233.102	163171.4	69.102	48371.4	114800	140.7	14.91	5.3025	5.733
Jan-16	69000	224250	124	171.474	120031.8	47.474	33231.8	86800	92.46	9.798	3.4845	3.7674

Feb-16	105000	341250	164	139.101	97370.7	-24.899	-17429.3	114800	140.7	14.91	5.3025	5.733
Mar-16	141000	458250	240	222.721	155904.7	-17.279	-12095.3	168000	188.94	20.022	7.1205	7.6986
Apr-16	135000	438750	228	209.234	146463.8	-18.766	-13136.2	159600	180.9	19.17	6.8175	7.371
May-16	129000	419250	212	204.99	143493	-7.01	-4907	148400	172.86	18.318	6.5145	7.0434
Jun-16	93000	302250	155	271.837	190285.9	116.837	81785.9	108500	124.62	13.206	4.6965	5.0778
Jul-16	90000	292500	145	259.617	181731.9	114.617	80231.9	101500	120.6	12.78	4.545	4.914
Aug-16	112500	365625	179	266.86	186802	87.86	61502	125300	150.75	15.975	5.68125	6.1425
Sep-16	123000	399750	199	234.126	163888.2	35.126	24588.2	139300	164.82	17.466	6.2115	6.7158

جامعة النجاح الوطنية

كلية الدراسات العليا

الاستخدام الامثل للغاز الحيوي الناتج من محطة معالجة المياه العادمة غرب مدينة نابلس

إعداد

معتز عدلي توفيق شهاب الدين

إشراف

د. عبد الرحيم أبو صفا

قدمت هذه الاطروحة استكمالاً لمتطلبات الحصول على درجة الماجستير في هندسة الطاقة النظيفة وترشيد الاستهلاك من كلية الدراسات العليا في جامعة النجاح الوطنية، نابلس، فلسطين

2017م

ب
الاستخدام الامثل للغاز الحيوي الناتج من محطة معالجة المياه العادمة غرب مدينة
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اشراف

د. عبد الرحيم ابو صفا

الملخص

محطات معالجة مياه الصرف الصحي مع الهضم اللاهوائي تنتج كميات كافية من الغاز الحيوي. واحدة من أفضل الطرق لاستخدام الغاز الحيوي في مثل هذه المحطات هي تكنولوجيات التوليد المشترك للطاقة، حيث يتم إنتاج نوعين من الطاقة من وقود واحد، أي يتم إنتاج الطاقة الكهربائية والحرارية في الموقع ليتم استهلاكها في نفس المنشأة، ومن المعروف أن محطات معالجة مياه الصرف الصحي هي مستهلكات الكهرباء والطاقة الحرارية.

في هذه الدراسة؛ لمحطة معالجة مياه الصرف الصحي الغربية لمدينة نابلس كدراسة حالة. تم دراسة التحجيم الأمثل للوحدات وترتيب وحدات التوليد المشترك للطاقة التي كانت عبارة عن توربينات غازية صغيرة ومحركات احتراق داخلي من خلال إجراء حسابات وتحليلات للطاقة وحسابات اقتصادية وبيئية.

تم اختيار عدد الوحدات التي سيتم تشغيلها كل شهر باستخدام أربعة توربينات غازية صغيرة تجارية C200 / 200kW و T100 / 100kW و C65 / 65kW و C30 / 30kW من مصنع كابستون وثلاثة محركات احتراق داخلي G3306 / 143kWe ، G3406 / 235 كيلوواط، CG132-8 / 400kWe من الشركة المصنعة كاتربيلار، اعتمادا على بيانات معدلات إنتاج الغاز الحيوي نظرا لوجود تباين فوري في هذه المعدلات، ولكن يتم تنظيم هذا الاختلاف إلى مستوى شهري، وذلك باستخدام تكنولوجيا تخزين الغاز الحيوي المستخدمة بالفعل.

ت

تم حساب عدد التوربينات الغازية الصغيرة أو محركات الاحتراق الداخلي التي يجب تشغيلها كل شهر اعتمادا على حقيقة أن هذه المحركات تعطي أقصى قدر من الكفاءة عند تشغيلها في حمولة كاملة أو قريبا منها.

بعض البدائل يمكن أن تنتج الطاقة الحرارية السنوية اللازمة من 2137 MWh كمجموع، ولكن قد يكون نقص خلال بعض أشهر.

وقد وجد أن البديل الذي ينتج الطاقة الكهربائية القصوى كان يستخدم وحدة واحدة من محرك الاحتراق الداخلي CG132-8 / 400kW مع إنتاج الطاقة السنوية من 2442 ميغاواط.

تم إجراء التحليل الاقتصادي باستخدام القيمة السنوية لحساب التكلفة وإيجاد التكلفة المعيارية للطاقة الكهربائية، كما تم حساب إجمالي التوفير السنوي من كل بديل. واستنتج أن وحدة واحدة من محرك الاحتراق الداخلي CG132-8 / 400kWe لديها أدنى قيمة لتكلفة الطاقة وحدة من \$ 0.09 / كيلواط ساعة والوفورات السنوية من \$ 195243 / السنة.

تم إجراء التحليل البيئي للتحقيق في إجمالي انبعاثات ثاني أكسيد الكربون وغيرها من الانبعاثات الملوثة، وتبين أن البديل من استخدام وحدة واحدة من محرك الاحتراق الداخلي CG132-8 / 400kWe أنتج الحد الأقصى من انبعاثات ثاني أكسيد الكربون بقيمة 2,203 طن / سنة بدلا من الوضع الحالي للحرارة الذي يتم فيه توليد الكهرباء والحرارة بشكل منفصل منتجا ثاني أكسيد الكربون بقيمة 3,912 طن / سنة محققا ما مجموعه توفير ثاني أكسيد الكربون بمقدار 1,709 طن / سنة.