COGENERATION SUSTAINABILITY STUDY FOR THE IZMIR INSTITUTE OF TECHNOLOGY

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ABSTRACT

COGENERATION SUSTAINABILITY STUDY FOR THE IZMIR INSTITUTE OF TECHNOLOGY

In this study, feasibility of Cogeneration/Combined Cycle System will be evaluated for the Izmir Institute of Technology. Turkish Energy Policy lacks some key factors which need to be highlighted for achieving Energy targets. The first aim of this study is to compare the policies and implementation of combined cycle systems of Turkey with Europe and to analyze the steps carried out by European Countries to achieve sustainability.

The main objective of this study includes the implementation of a combined cycle system based on the data collection from the authorities of the Institute to analyze the deficiencies of existing system and to propose a more efficient system for meeting the energy demand. Two systems were taken in consideration, a gas turbine and a reciprocating engine based combined cycle system, detailed energy analysis with emissions and cost analysis were presented to determine what case provides the best solution to meet the energy demand.

ÖZET

İZMİR YÜKSEK TEKNOLOJİ ENSTİTÜSÜ İÇİN KOJENERASYON SÜRDÜRÜLEBİLİRLİK ÇALIŞMASI

Bu çalışmada İzmir Yüksek Teknoloji Enstitüsü için kojenerasyon / kombine çevrim sisteminin fizibilitesi değerlendirilmiştir. Bu çalışma, sürdürülebilirliği sağlama kapsamındaki başlıklardan biri olan kombine çevrim sistemlerinin uygulamalarında, Avrupa ülkeleri ile Türkiye'nin politikalarını karşılaştırmaktır. Ayrıca, enstitü için tasarlanan kombine çevrim santralinde kullanılacak alt sistemlerin kısa bir tarifi de verilmiştir.

Ana hedef, mevcut sistemdeki eksiklikleri analiz etmek ve İzmir Yüksek Teknoloji Enstitüsünün enerji talebini daha verimli bir sistem tasarlayarak karşılamak için, enstitü yetkililerinden alınan verilere dayanan bir kombine çevrim sisteminin uygulamasını içermektedir. Kombine çevrim santrali için gaz türbini ve pistonlu motor (ısı geri kazanım ünitesi ve buhar türbini üretimi olan) olmak üzere iki farklı durum değerlendirilmiştir. Veri analizi, tesisin kapasitesi hakkında bilgi sağlamanın yanı sıra, elektrik tüketimi ve toplam tüketimin gelecekteki değişimi hakkında da fikir vermektedir. Enerji analizi ise, her bir durum için toplam enerji üretimini vermektedir. En son olarak, tasarlananan sistem ile mevcut sistem kıyaslanarak, toplam enerji tüketimi ve atık salınımı açısından ne mertebede bir iyileştirme yapıldığı değerlendirilmiştir.

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LIST OF ABBREVIATION

CHP..Combined heat and power

IEA.. .International Energy Agency

GWP.. ....Global Warming Potential

G 13... ....Great 13 Countries

MENR.............................Republic of Turkey Ministry of Energy and Natural Resources

MIT...Massachusetts Institute of Technology

HRSG..Heat Recovery Steam Generator

LHV...Lower Heating Value

EPA...Environmental Protection Agency

IPCC..Intergovernmental Panel on Climate Change

GE... General Electric

DEFRA.......................................Department of Environmental, Food and Rural Affairs

DECC... Department of Energy and Climate Change

UNFCCC..............................United Nations Framework Convention on Climate Change

LIST OF SYMBOL

m_{in}..Mass flow rate input

m_{out}...Mass flow rate out

P_2...Pressure at stage1 outlet

P_1...Inlet Pressure

W_{net}..Net Work Ouput

T_4..OutletTemperature at stage 4

m_{fuel}...mass flow rate of fuel

T_{2s}...Isentropic Temperature at stage 1 outlet

k...Specific heat ratio

W_{sc}...Isentropic compressor work

W_{ac}..Actual compressor work

h_{2a}...Enthalpy at T_{2a}

$W_{turbine}$..Overall work output turbine

$m_{f,s}$..stoichiometric fuel mass flow rate

$m_{air,s}$..stoichiometric air mass flow rate

$(F/A)_{stoichiometric}$...stoichiometric fuel to air ratio

$(F/A)_{actual}$...stoichiometric fuel to air ratio

(A/F)..air to fuel ratio

ǿ...Equivalence ratio

$Cp_{N.G}$...Specific of natural gas

Cp_{gas}...Specific heat of gaseous mixture

W_{gt}...Work output of Gas turbine

m_g...Mass flow rate of gaseous mixture

Q_{in}...Heat input rate

Q_{fuel}..Fuel heat rate

η_{th}...Thermal efficiency

$m_{gt\ exhaust}$...Gas turbine exhaust mass flow rate

Cp_{gas}...Specific heat of gaseous mixture

Tg_1...HRSG input temperature of input gas

T_s...Saturation Temperature

$T_{eco,\ out}$..Economizer outlet temperature water side

Tg_3...Evaporator exit temperature gas side

ΔT_{pp}...Pinch point temperature

ΔT_{app}...Approach point temperature

E...Enthalpy absorbed by steam

h_{sh}...Enthalpy of gas at superheater

h_{s1}..Enthalpy of water at economizer exit

W_s...Steam generation rate

h_{fw}..Enthalpy of feed water

η_{HRSG}...HRSG efficiency

W_p...Pump Work

η_{is}...Isentropic efficiency

η_a...Actual efficiency

$\eta_{C.C}$..Combined Cycle efficiency

W_{gt}...Gas turbine work output

W_{st}...Steam turbine work output

r_c...Compression ratio

B...Cut off ratio

C_v..Specific heat at constant volume

CHAPTER 1

INTRODUCTION

One of the most important aspects of our life is Energy. It has played an important role towards the development of society. Today large amount of the energy resources is consumed by the world. This increase in the demand of energy is due to rapid increase of population, increased living standards and rapid industrialization. The fossil fuels have a major share for providing the world's energy demand, as a result a reduction has been seen in these reserves which are discovered until now. This depletion is highly favored by inefficient generation, transmission and distribution system. Not only this, but these inefficiencies are leading to the emission of harmful pollutants to the environment. These concerns can only be eliminated by following strategic plans. One of them is to generate renewable energy sources to exploit a never ending resource of energy while the other is the development of more efficient systems.

Cogeneration is a terminology widely used to refer the technology, which generates heat and power at the same time from the same fuel source. This technology is not a new technology, but innovation in the integration of this technology in terms of heat and power has made it a very renowned, which allows increasing efficiency of the system and reduction of the emissions. Today, several combined heat and power (CHP/Cogeneration) technologies are being implemented all over the world in every sector like industrial, residential and commercial, etc. Benefits of the cogeneration in terms of sustainability, pollution and profitability are far greater than other techniques.

In Turkey, cogeneration has not received much importance. Several studies have been made on it, but still there is a lot of gap in the energy sector which can be overcome by cogeneration. In this study, the main theme is to provide an overview of cogeneration in Turkey. A comparison made between Turkey and World's cogeneration policies to point out the deficiencies, which can improve Turkey's economy, energy efficiencies and can lead to the decrease in heat and energy demand. A case study is involved, which motivates the investors and the policy makers to divert their intention from industrial cogeneration towards a relatively smaller scale like residential and institutional level. It also provides environmental and sustainability aspects of the cogeneration system and its importance towards national security and energy efficient systems. It supports the idea of implementing these technologies on institutional levels like universities, offices, big residential apartments and commercial complexes.

The main aim of the study is to find the most feasible solution from the gas turbine and reciprocating engine based combined cycle system which can be used to generate the utilities for the institute demand and to replace the old utility system with more efficient system.

Chapter 2 presents the literature survey used to gather the work done on combined cycle systems in different areas in order to analyze methodology to be used for thıs case study and chapter 3 provides a general overview of the methodology which is used for data collection, energy balance, cost and emission estimations.

Chapter 4, 5 and 6, 7 contains the energy and mass balance, emission estimation and cost analysis of the two cases considered for the institute. First case is gas turbine based combined cycle system and second one is based on reciprocating engine. The cost analysis is further classified into two general cases based on operating hour, first is 2880 hour per year only required for the Institute desired requirement and the second is 8000 hour with excess electricity sold on specified rate given by Turkish authorities. After this analysis, comparison made to analyze the system, which provides the best optimal solution for replacing the existing system for utility generation.

CHAPTER 2

LITERATURE SURVEY

Energy is the most important resource of this society. In the last decades, the energy has changed our societies to such an immense level that now we cannot see our future living without it. It has allowed countries to develop and grow in such a way that it has become a backbone of every country and the term energy, now directly determines the Gross domestic product (GDP) of a country. The more the energy use of a country, the better the growth of that country. Energy generation is linked with the aspects of economic, and economic development. The use of energy resources is not restricted to only one field, it includes the major sectors of our world like transportation, heat and electricity, industrial and residential sector. Today, there are more than 2 billion people on this earth who are deprived of energy and in the future it is going to increase. This shows that new ways or technologies are required that can meet the increasing energy demands without causing much harm to the environment (Rinkesh 2009).

2.1. Energy Crisis and World Economy

After arrival of the industrial revolution and the discovery of crude oil, the modern civilized standards have been changed dramatically. The use of the energy has become the most important factor for determining the economy of a country. It is now the essence of every country. During the last decade, the world's dependence on the non-renewable energy sources has increased to an enormous level, which has caused many adverse effects leading to an energy crisis. It has been estimated that during the next 30 years the electricity consumption will increase to 75-90 %. Fuels that are generally used globally are constituted by non-renewable sources like coal, oil, etc. After humongous exploitation of these resources now the world has realized that these resources will come to end (Haneef and Memon 2014).

Today, 80% of the world's total energy demand is met by fossil fuel including, crude oil, coal and natural gas, 5.8% from nuclear power, 2.3% from hydro power and the rest 12-13% is obtained from the renewable energy sources based on the report of the IEA. The reason is the energy generated by the non-renewable energy sources is cheaper than other sources and the technology is still developing for other resources. However huge consumption of these resources and few setbacks based on energy has made the world realize that they cannot depend on renewable resource completely (Höök and Tang 2013). Reasons for the energy crisis are many and some of them can be listed as:

1. Over consumption of resources due to many reasons, one of the most important reasons is the developing countries and developed countries. These countries, like China. India and the USA use the main part of the world's energy resources.
2. The increase in population has increased the use of energy resources nearly double fold.
3. Unexplored and costly energy that can be obtained from renewable sources.
4. A large amount of wastage of energy proportion in the world and cold approach to utilize the waste heat, has made the energy crisis more drastic.
5. Extremely poor distribution is also a main factor for the energy crisis.

The cheapest sources for the energy are fossil fuels and nuclear energy, but the effects associated with them are adverse. During last years, the dependence on nuclear energy was increasing to an immense amount until the Fukushima Daiichi incident in Japan happened, which lead to extremely harmful effects due to the structural damage of the nuclear power plant leading to radioactive emissions to the neighboring areas. Since then, the total power generation in European Union countries has decreased from 1008.4 thousand GWh (2004) to 876.8 thousand GWh (2013), which is 2.4% per year and total of 13% in 9 year period (ec.europa 2016) due to the lack of confidence in the nuclear energy and the risk associated with the nuclear energy.

The utilization of the fossil fuel is still increasing because of its wide versatility and use, but the effects associated with them are also harmful for the environment and humans. The energy predictions have been made that until 2040, 80% of the world energy demand will be met by fossil fuel and energy consumption from 2010 to 2040 will increase by 56% from 524 to 820 quadrillion British Thermal units, which shows a yearly increase of 2.5% (EIA 2013). For this reason, the organizations and researchers are trying to exploit natural, renewable and environmentally friendly sources like solar, wind and fuel cells to overcome the problems related to fossil fuel and to provide an everlasting source for energy, but still there is no efficient and cheaper way to produce energy than fossil fuel.

2.2. Environmental Aspect

The world is moving towards a crucial climatic disaster, with the increase in energy production the risk to the environment is also increasing, which is not suitable with the international environment regulations and sustainability. Due to this grave situation, the international community is trying to convince and motivate investors to invest in the renewable and sustainable technologies that can produce less vulnerable effects to the society. In spite of the decreasing prices of oil and gas internationally, investments in renewable and sustainable technologies is increasing. At 2014, the total amount of energy production was estimated to be 128 GW (IEA 2015) from the renewable energy but still these technologies are costly with lower return and high cost of production per kilowatt hour which is a crucial barrier towards its development. Until new, more efficient and cheaper ways of utilizing these resources does not appear in the market, conventional and non-conventional fossil fuel sources will remain the key participators for energy production.

The effects associated with fossil fuels are quite harmful. There are several but some of the crucial ones are as follows:

1. Air pollution linked to the fossil fuel is huge, it is the cause of ozone depletion, the sulfur from the refineries and the coal plants can cause smog which in return is harmful for human health and causes cancer. Water and oxygen together produce nitrous oxide with nitrogen, which is responsible for the acid rain, which imparts disastrous effect to land, properties, aquatic life and humans.
2. Global warming is an issue of alarming importance and the reason behind it are fossil fuel specially coal, oil and the sectors associated with the emissions are mainly transportation and energy. As discussed earlier, fossil fuel provides 80% primary energy and responsible for 90% energy related emissions. The greenhouse gas (GHG) emissions from 1995 to 2012 increased to 435 ppm CO_{2eq}. According to the recent stats, the emissions from coal increased from 38-

44% due to the increase in consumption of coal. Oil emissions decreased from 42-35% due to the decrease in global consumption because of the increased utilization of the renewable energy sources worldwide, but natural gas provides energy, it is the cleanest energy source and the emissions are 20% flat and still decreasing due to improvement in technology and its usage is going to increase to 30 % by 2030 which is now around 23-25% (IEA 2015).

3. The third effect, which is crucial for the existence of many countries specially Scandinavian and European because of the rise in sea level. It has been said that every year world's temperature is increasing 2 °C. As a consequence of this increase, the sea level is increasing because the polar ice is melting. If it continues to happen like this then many countries will vanish in future from the face of earth.

After the steps or precautionary measures taken by the societies and organizations, the global carbon intensity is expected to decrease from 5238 g CO_2/ kWh (2013) to 370 g CO_2 / kWh in 2030 and the key for achieving this target is to invest in sustainable technologies and system improvements(IEA 2015). As the negative effects are irreversible that's why a serious, concise and fast approach is required to cope with the environmental effects before it is late.

2.3. Sustainable Energy

Sustainability is derived from the word "Sustain" which mean anything which can last longer. With respect to energy it means discovering, generating and utilizing of those resources, which are inexhaustible and can be generated again and again with the passage of time. As "Bionics" mean learning from the aspect of nature in such a way to motivate people in order to inspire the developments in the technology. The issue of energy is critical for the world and amongst various issues, it has been the most prominent issue faced by the world and people are getting inspired by nature to innovate technology. One can say that the reason behind suitability is bionics. It will help us in developing the world which can be termed as "A Greener World".

2.3.1. Sustainability and Renewable Technologies

Resources that best fit in the definition are the renewable energy sources. After some major technological discoveries, the world investor's intention has shifted towards these sources, after realizing that it is crucial for social economic development, creating opportunities, tackling with the climate change and providing energy to billions of people who are still living without it. Not only investors are the key players in decision making, there are several important key players' as this issue is affected by many factors. Usually, the main purpose of every investment is to get profit as much as they can because profit constitutes GDP and every country wants to increase their GDP, but there are also some barriers which are related to environmental and human health. The decision makers mainly policy makers, politicians and several big industrial stakeholders affect the policy making and after realizing their contribution towards Earth's destruction, they have changed their direction. As a result, their aim is to develop or invest in technologies that impose a less threat to the global environment and human health (Dorsey 2012).

Global awareness in renewable technology has made many countries to change its policies, yet there are many uncertainties associated with the renewable technology but still it is one of the most growing sectors in the world. In 2014, it gained importance and many factors were highlighted during an international meeting and several improvements were made in the policy for renewable energy. Now, there are 149 countries, which aims to strongly implement the renewable energy policy and 164 countries have set their targets for renewable energy to address their energy issues.

Table 2.1. Renewable Investments in Countries.
(Source: Renewables Global Status Report, REN21)

Ranking	1	2	3	4	5
Investment in renewable energy fuel	China	USA	Japan	UK	Germany
Investment per unit GDP	Burundi	Kenya	Honduras	Jordan	Uruguay
Geothermal	Kenya	Turkey	Indonesia	Philippines	Italy
Hydro Power	China	Brazil	Canada	Turkey	India
Solar PV Capacity	China	Japan	USA	UK	Germany
Wind Power	China	Germany	USA	Brazil	India
Solar Water Heating Capacity	China	Turkey	Brazil	India	Germany
Biodiesel	USA	Brazil	Germany	Indonesia	Argentine

Table 2.1 shows the leading countries in energy investments related with technology in which they are investing. In 2013, 19% of the total energy consumed by the world was obtained from renewable energy. This fact only justifies for electricity. The heating and cooling sector are still at the same level and there is not much variation in their efficient productivity. In 2015 or at the start of 2016, the total electricity generation reached to about 27.7% by renewable energy. While the investments made in 2014 is 17% higher than 2013 and it accounts for nearly $270.2 billion. The most thriving market for the renewable technology in the world is China, where there was a record investment of $83.3 billion, the second is the United States, accounting for $38.3 billion and the third most flourishing market is Japan constitutes $35.7 billion. While after that European Union, Malaysia, Indonesia, Turkey, Kenya, Mexico and South Africa are also in the billion dollar club in 2014.

Table 2.2. Renewable Energy Investments.
(Source: Renewable Global Status Report 2015, REN21.)

		Start 2004	2013	2014
Investments				
New Investments (annual)	Billion USD	45	232	270
Power				
Renewable Power Capacity (without hydro)	GW	35	560	657
Renewable Power Capacity (Including Hydro)	GW	800	1578	1712
Hydro Power Capacity	GW	715	1018	1055
Bio Power Capacity	GW	<36	88	93
Geothermal	GW	8.9	12.1	12.8
Solar Capacity	GW	3	141.4	182.4
Wind Capacity	GW	48	319	370

There are several renewable technologies and their use differs from the location or the preference of the country. Many countries are using these technologies depending upon the resources they can get easily in their countries. Some of the countries are investing in geothermal energy like Turkey, Indonesia, Philippines and Italy. While the expensive technologies are mostly implemented by the most powerful economies in the world like China, United States, Germany and the United Kingdom (Sawin and Sovacool 2015). The most important sector on which renewable energy has a huge impact is the power generation but there are several other sectors needing more attention like transportation which utilizes half of the world energy sources and makes vast contribution towards the GDP of every country. Apart from the electricity sector, the heating and cooling sector also need importance, but still no serious and constructive contributions made in this field (UNEP 2016)

The immense growth in the renewable energy can only be seen in the most developed countries, there are several barriers associated with renewable technologies and some uncertainties as well. These barriers are as follows:

1. Mature and less costly technologies which can be termed as commercialization barrier.
2. The distortion of subsidies and the unequal burden of the taxes is the major hurdle towards its growth.
3. The high transmission cost associated with it.

4. Lack of information and incentives
5. Lack of high capital required to set up these plants.
6. Poor efficiency regarding these technologies as compared to the previous technology makes them more inferior (ucsusa 1999).

2.3.2. Sustainability and Mature Technologies

The concept of sustainable energy is not only restricted to the renewable energy resources. Energy is a wide field and several technologies are being used widely for energy generation. The sustainability can also be used to help, innovate and modify the existing technologies to get higher efficiencies, lower emissions and help to reduce the use of fossil fuel. The main aspects to improve mature technology is energy and its management. Mature technologies provide better efficiency, less cost and less maintenance cost. There are several areas of sustainability which are as follows.

A. Energy Conservation
    a. Cogeneration
    b. Energy Efficiency
    c. Heat Pump
    d. Green Building
    e. Low carbon power
    f. Micro generation
B. Sustainable Transport
    a. Electric vehicle
    b. Carbon neutral fuel
    c. Fossil fuel phase out
    d. Green Vehicle
    e. Plug in hybrid

It has been said that buildings constitute nearly 40% of the total energy consumption and with the increase in population and living standards, their consumption is going to increase rapidly, but the waste heat and negative potential hazards associated with the buildings are also great. The need of the hour for energy efficiency in building is to implement sustainable and green architecture practices and use of integrated energy systems inside the building's heating and cooling requirements.

Apart from that energy efficiency also includes appliances which require less energy and services. The IEA vision is that if we can increase the energy efficiency in transportation, building and other sectors in order to reduce the global energy demand by one third until 2050 and also can help to tackle the problem of global emissions and fossil fuel conservation.

Waste heat is one of the most crucial aspect in energy efficiency. As the second thermodynamics law states that there is no engine which converts heat into work with an efficiency of 100%, there will always be a loss of heat from the system and it will be a waste and will participate in increasing the entropy of our world., This results in global warming, increase in sea levels and many diseases. The United States department of energy claims that, from the energy we get from fossil fuel, 50% of it is wasted as waste heat, but in some cases it can be as high as 70-80%. As a result greater utilization of fossil fuel leads to loss of energy and financial loss. The waste emissions are also related to carbon emissions, but through process integration the amount of waste heat recovered is 9-20%, which generally reduces 60% of the carbon emissions. For waste heat recovery solution, many options are considered, but the most suitable technology is the cogeneration or combine heat and power (CHP), which integrates the system in such a way that it achieves an overall efficiency of 90%. micro-cogeneration is also part of cogeneration which is implemented on a small scale, including residential, commercial and public buildings.

Another technology is the use of thermal storage techniques that allow better optimization and integration of the process. It is usually suitable for small or medium scale setups like residential or commercial. Many of the technologies are also gaining importance like underground thermal storage for homes and public buildings. Not only individual technologies, but a combination of renewable and mature technologies are also gaining importance, for example integration of solar and cogeneration. All these steps are being taken to tackle the problems related to socio-economics, environment and sustainability, to reduce the hazards in the environment to make the concept of Green Earth into reality. All the stakeholder and the countries are eager and committed for better results (Nordell and Gervet 2009). Table 2.3 shows the target set by different countries in order to reduce pollution.

Table 2.3. GHG emission reduction goals.
(Source: IEA)

UNFCCC Party	Intended National Determined Contribution (INDC)
Switzerland	Reduce GHG by 50% below 1990 levels by 2030 (30% below 2025).
European union	Reduce EU domestic GHG emissions by 40% below 1990 by 2030.
Norway	Reduce GHG Emissions atleast 40% by 2030 as compared to 1990.
Mexico	Reduce GHG emissions and short lived climate pollutant emissions unconditionally to 25% by 2030 with respect to business as usual aspect ratio.
United States	Reduce net GHG emissions from 26-28% below 2005 by 2030
Gabon	Reduce CO_2, CH_4, N_2O atleast 50% with respect to reference sceanerio by 2025.
Russia	Reduce anthropogenic GHG emissions by 25-30% below 1990 by 2030.
Andorra	Reduce GHG emissions by 37% with respect to business as usual scenario by 2030.

2.4. Role of Cogeneration in Sustainability

The cogeneration is basically a term used to describe a methodology, which mean that is not a fixed process. The main purpose is to synchronize the production of heat and electricity from the same fuel source. There are several technologies to implement cogeneration, which are described later in this thesis. The main source for generating electricity has been thermal power plants. These plants are a serious threat to the environment and the human health, but still some developing and developed countries like India, China, the United States, Russia, South Africa is increasing their production by risking human health and environmental threats. China is the world's biggest producer as well as consumer, it has produced 3.6 billion tons of coal in 2012 and consumed about half of its coal for power production, which accounts for 80% of china electricity production. Then it comes America generating 37% of its country power from it. Coal accounts for 60% of India's power generation (Europe 2015). Still the power generation capacity of these plants is nearly 35% and the other goes into waste heat. This 35% efficiency, reduces to 30% when it goes through the transmission and distribution systems of the national grid system (Polimeros 1981). To overcome these kinds of losses associated with power generation plants, cogeneration is preferred with combined heat and power technology to increase the overall efficiency of the system. Currently worldwide only 10% of the electricity generation is based on CHP. It has been predicted that the total share of CHP in the G13 will rise to 24% at the end of 2030. The cogeneration systems provide a large amount of benefits:.

- Reduction in pollutants and carbon footprints.
- Increased overall efficiency of a system.
- Reduce fossil fuel consumption.
- Use of local energy resources.
- Reduction in transmission and distribution cost.

By recognizing the benefits of CHP, the Obama administration has set up a new goal to achieve 40 GW of generation capacity by 2020 from CHP and the goals to be achieved for the United States are defined by the Unite State department of energy:

- Total capacity of CHP will be increased up to 50% in less than a decade.
- It will provide a saving of $10 billion per year as compared to current energy use.
- It will participate in saving 1 Quadrillion Buts of Energy.
- It will help in reducing emission to about 150 million metric tons of CO_2 per year (emissions Exhausted by 25 million vehicles.)

The cogeneration comes in various forms, and with different types of fuels, depending upon the location and resources present near the plant location. Apart from cogeneration, based on the same bionics, another term, which is known as trigeneration refers to the production of cooling, heating and electricity simultaneously. The increase of the trigeneration in domestic and commercial system in the world speaks about its success. Another term is Quadgeneration, which refers to purification of carbon dioxide at the end of the cycle from the engine outlet, which in return increases efficiency and also reduces the release of CO and CO_2 into the environment. It generates a byproduct to increase productivity and profitability. The growing importance of energy and its production goals are helping policy makers and scientists to generate different ways to achieve goals. The cogeneration is considered as one of the most important contributors for the accomplishment of the energy and the environment targets.

2.5. Policy and Directives for Cogeneration.

Most of the western and especially European countries have a very specific and clear policy about cogeneration. The EU Directive of 2004/8/CE highlights the benefit of cogeneration coupled with the district heating system. The main purpose of this directive is to establish and implement a proper framework for the development of cogeneration in the member states (Inforse 2012). The European parliament has urged its member states to involve cogeneration in their national energy efficiency plans to promote its implementation. While the conference in Brussels ended with the consensus to develop and expand the cogeneration markets by implementing cogeneration policies in the member state by 2020, it was also recognized that there is still 120 GWe that can be exploited by cogeneration in the member states (Europe 2009)**.**

Not only at the international level, but countries are also implementing cogeneration policies at national level to address the national energy affairs. As in Spain, the framework of cogeneration is known by Special Regime by Royal Decree 661/2007. It involves the promotion of both renewable energy and cogeneration. Through this, it has been estimated that in Spain only in the building there is a potential of 9703 MW, which can be exploited by highly efficient cogeneration (Celador et al. 2011).

Germany was awarded the COGEN European Recognition Award in 2009, which shows that cogeneration is playing an important role in Germany's economy. In CHP Law 2012 (KWK-2012), Germany is going to increase the share of cogeneration to 25% by 2020. It has the biggest CHP market in the Europe and the implementation of new policies is motivating investors to invest in cogeneration (Europe 2013).

There are several countries, which tops the list in implementing CHP technologies specially Denmark and Netherland. The Managing Director of COGEN Europe said that by 2050 the total world annual saving will reach up to 500 billion euros, equivalent to 57% percent energy reduction in demand. In industry, the savings will reach to 9 Mtoe (Million tons of oil equivalent), while improving district heating and CHP can lead to savings to an amount of 10 Mtoe and technical savings can reach at the level of 95 Mtoe by 2050 (Phillips 2012).

The success factors responsible for sudden and effective success of the cogeneration are described below, but these success factors are case dependent based on each country situation.

- Investment subsidies based on projects
- Feed in tariff scheme
- A green certificate scheme
- Third party financing
- Policy favoring use of other fuel sources.

2.6. World Cogeneration Markets

The cogeneration projects depict the effective implementation of policies and their outcomes in terms of productivity, efficiency and profitability. A number of case studies have been performed to identify the growth in different sectors and based on different systems. Among European countries, Germany is the most significant one where large projects have been implemented and huge outcomes have been obtained in term of heat and power integration and GDP growth.. The recent increase has been due to the decentralized, on site heating system integrated with power generation. Several reports from international energy agency show the potential that exists for further growth not in terms of non-renewable energy sources, but also CHP systems coupled with renewable energy sources.

The demand for CHP or cogeneration systems is affected by many reasons, policies are one of the major causes, on-site implementation of cogeneration systems, which reduces the transmission losses and the other is the fuel source. Usually, the CHP systems are quite versatile and can use different types of fuel sources like biomass, solar, fossil fuel and many others, but in the most developed countries like USA, European countries and China still natural gas is the most effective fuel because of its reliability, efficient conversion and its environmentally friendly nature. The European Union achieved a total 382 megatons of GHG reduction goal based on different sector and CHP technologies contributed to 15% of them.

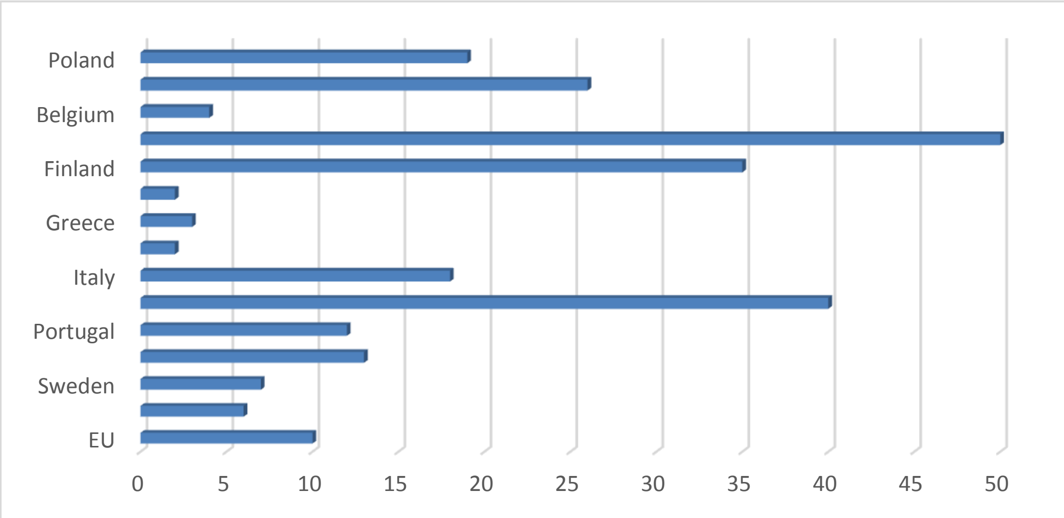

Figure 2.1.Policy in the EU, Cogeneration share in national production.
(Source: Cogen Europe.)

The data suggest that there are only five countries which have successfully implemented cogeneration technologies in the range of 30-50% like Denmark, Finland, Russia, Latvia and Netherland. Each of these countries has implemented technology in their own way, but from the overall perspective reduction in GHG emissions was observed.

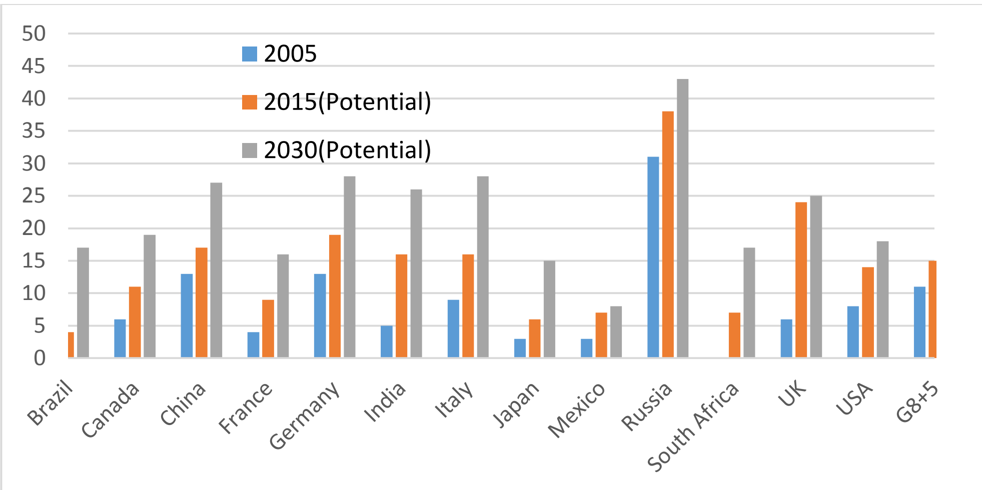

Figure 2.2. CHP share of total electricity generation in percentage.
(Source: IEA, 2008a.)

Figure 2.2 illustrates the potential of saving energy in different countries by implementing CHP. Russia is considered to be the most important stakeholder of CHP technology. It accounts for one third of the installed electricity potential. In 2007, the evaluation suggested that Russia had 700 plants with a capacity of 215 GW. Thermal electricity and CHP plants had a share of 68% in it. It is expected that by 2030, Russia will increase its CHP and District Heating and Cooling (DHC) capacity to 43% (Kerr, 2008 #74).

The rapid industrialization has increased the use of CHP technology in Japan. While the fastest growing economies like China and India will also increase their CHP capacity. The expected increase is from 17 to 27% in China while in India it is from 16 to 26%. The CHP implementation increase is based on its environmental and economic effects. Apart from the transmission and distribution network systems, the average capital investment for CHP plants is less than the central power generation and the development of new infrastructure is saved (IEA 2009).

By employing CHP technologies the overall capital saving varies with respect to different power investments. For the years of 2005-2030 is shown as in Figure 2.3.

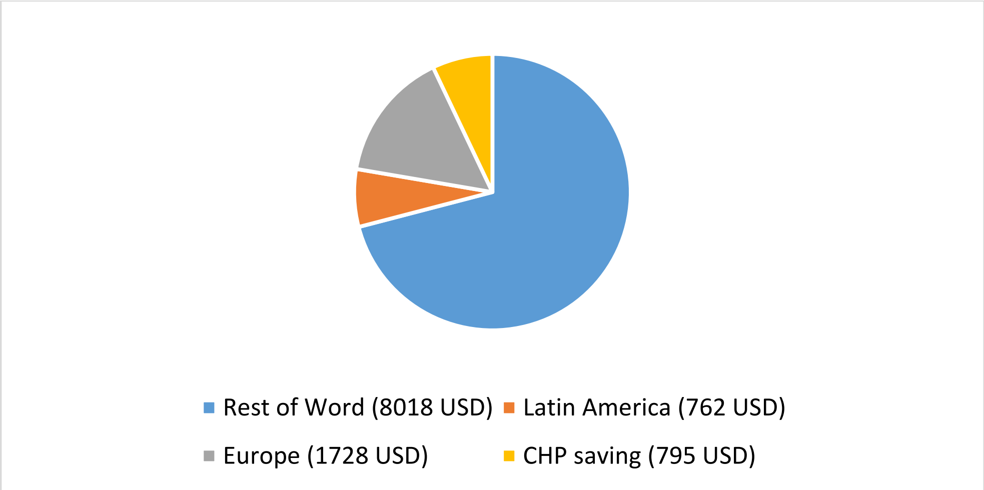

Figure 2.3. CHP cost saving as total power investment 2005-2030.
(Source: IEA.)

With the implementation of good and constructive cogeneration policies and the strategies necessary for convincing and motivating investors to improve existing technologies brings more profitability in the existing system and newer technologies. The recent policy modifications and incentives regarding cogeneration have had a huge impact on the investors and this is the reason for rapid growth of cogeneration technology while some Asian countries are also modifying their policies to get benefit from the cogeneration technologies at every level.

2.7. Turkish Cogeneration Policy, Barriers and Solution

Turkey is a country with a population of 75 million with an area of 800000 Km^2. It is the 17^{th} biggest economy in the world. In 2002, the total energy demand was 133 TWh, 2004 it increased to about 150 TWh, in 2005 it increased to about 160 TWh and in 2020 it is predicted to be near 566 TWh as mentioned by MENR. To meet the increased demand for electricity and heating, the Turkish government is trying to implement every resource to give a boost to its economy because of its inefficient energy resources, high energy prices, power quantity, and global climate conditions. In recent years, the Turkish government has made a deal with Russia to install nuclear power plants Turkish Policy makers are focusing on two aspects , firstly dealing with the energy security to decrease the dependence on imports and secondly sustainability, However Turkey has not made any significant improvements in this area. Some reasons are many like insufficient data availability, narrow focus on renewable energy, lack of information regarding some new methodologies and alternatives to achieve higher sustainability. During the last couple of years, researchers have analyzed the importance of energy efficiency data, several studies have been done to gather or estimate the data related to the inefficiencies of equipment's of systems in every country (eie). Two main sectors play an important role in Turkey for improving electricity and heating efficiency. One is the industrial sector, which constitutes 33% of electrical consumption, while the other is residential sector, which consumes 31% (Brahmanand 2007).

. Energy saving potential in Turkey is huge as Turkey's energy sector is humongous. As, the 11^{th} biggest iron and steel producer in the world, the estimated saving potential is 60 PJ/ year, Turkey could save large amounts of energy in the manufacturing industry: 36% of its heat from this sector, for cement production 46 PJ, the glass industry saving potential in heat is 16%, and in the textile sector, the saving potential is estimated is nearly 35% (OeEB 2013).

When it comes to the residential sector, the urban population consumes 75% of heat and electricity consumption, 75-80% of which comes from natural resources like natural gas ,which provides 30% of them. It has been predicted the saving potential to about 20-50% of this sector, but based on UNDP 2010 could be up 80%. In comparison with EU countries Turkey, consumes a lot more heat in buildings than normal EU consumption (OeEB 2013). For Denmark the consumption is 23 kwh/m^2.year, Netherland 34 kwh/m^2.year, UK 35 kwh/m^2.year and Turkey 100 kwh/m^2.year (OeEB 2013)**.** The reason for this drastic difference between heat and electricity consumption is due to better integration of systems and well monitored implementation of policies.

In Turkey, the cogeneration is only implemented on the large industrial scale. Turkish Policy makers are emphasizing on the electricity from renewable energy sources, but these technologies are still developing and will take years to produce a cost effective and more efficient system. Turkey is implementing more in wind and solar based projects, but there are also some negative impacts associated with these technologies. Disadvantages of wind energy are as follows.

- **a.** Wind Energy is an unreliable source of energy because it depends on wind and there are only some areas in most of the countries where huge generation capacities can be implemented because of high wind speed and it does not provide a constant source of energy because some time's there is no wind for days as a result there will be no energy generation
- **b.** This system is less efficient than conventional generation or Cogeneration.
- **c.** Requires a large amount of an open area to generate capacity in Mega Watt or Giga Watt.
- **d.** It is very dangerous for birds, large wind farm can affect the birds during migrations or even in normal days and. Not only birds the floating wind turbines are dangerous to aquatic life.
- **e.** Wind Turbines are generally expensive and the maintenance cost is quite huge.
- **f.** Noise pollution is the greatest factor for the nearby inhabitants, which makes their life uncomfortable. Sometimes the wind turbines occupy an agricultural land and makes it unfit for agricultural products (CEI 2016) .

During the recent years, huge investments in renewable energy have made Germany and many other countries to realize that they have invested billions of dollars in this technology but results are not relevant to the expectations. As in case of solar energy, its disadvantages are as follows.

a. It can only be harnessed when it is daytime, in sunny condition, this technology becomes quite inefficient in regions where winter conditions.

b. For now its cost is quite high installation, as well as maintenance and its payback time is longer as compared to other technologies.

c. Most of the photovoltaic cells are made up of silicon, some toxic materials like lead and cadmium. Environmental pollution can greatly reduce its efficiency and quality of the cell.

d. The maximum efficiency of a solar cell is nearly 40%, which makes the cost quite higher as compared to normal solar panels which is still less than the normal conventional systems.

e. Solar Energy need batteries to store energy. So, it can be used in the nigh time and these batteries need regular replacement after some time, which makes it more costly (Ryan 2009).

After realizing these aspects of the renewable energy, countries are forced to invest in technologies like cogeneration whose integrated efficiency reaches up to 85-90%, depending upon the system used, generating less pollution, more profit, decrease losses which decreases the overall electricity and heat demand due to increased efficiency.

In Turkey, the “Energy Efficiency and Saving law”, implemented in 2007, focused on the enforcement of cogeneration in all sectors. However, little improvements have been made. The capacity of cogeneration reached to about 5000 MW in 2009 but it has not increased as expected, perhaps due to the increasing natural gas prices.

The recent short term policy was introduced in Turkey by the Ministry of Development in July 2013, which focuses on all these aspects (Development 2014). The article 794 focuses on the energy efficiency strategy to be applied in all sectors. Article 789 focuses on increasing the network and resources of oil and gas will be increased with the help of transmission and distribution system (PEW 2011).

To increase strength of the Turkey ESCO market, current models need to be revised again. A more wide approach is required to deal with the energy, sustainability, including revision of policies for efficient systems based on renewable or non-renewable energy sources.

2.8. Type of Cogeneration Systems.

Cogeneration technologies can be classified into various setups according to the sector where they are used, but the two most basic divisions are “topping and bottom cycle”. One of the most reliable and readily used is the topping cycle in which the fuel is first used to generate electricity, then the waste heat is recovered to generate thermal energy which can be further used for heating, chilling or any desired operation. While in the bottom cycle the heat is produced from the fuel to generate thermal energy then waste is utilized to generate electricity. The application of bottom cycle can be observed in various high temperature industrial processes like furnaces for materials processing.

The potential for cogeneration is extremely high, as the renewable technology can only be used to overcome the electricity or power generation issue, but heat constitute a large part of our energy use and thus more efficient systems are required and cogeneration serves as one of them generating an efficiency of 85% unlike any other technology. The growing potential of this technology is due to its versatility that it can be used for any kind of application for small scale like residential, commercial to large scale industrial levels. The cogeneration is receiving more importance in the world because it can be applied to many building applications like hospitals, hotels, multi residential buildings, offices and many other sectors.

Several new technologies like fuel cell and Stirling engine are used for small scale application, but the most readily available at reasonable cost is the internal combustion engines. Only in the United States, there is a potential of 50.4GW until 2020 and at 2030 its further going to increase specially after the discovery of shale oil, the role of cogeneration on large scale is going to flourish (Durmaz). Cogeneration is classified into several types based on the capacity and its use.

Gas turbines are same as the jet engines. The process involved is combustion in which the high pressure gases are utilized to generate electricity. The general turbine shaft efficiency is 40-45%, while the exhaust temperature is 700-750 K and the thermal losses in gas turbines are estimated to be 50-55%. These losses are recovered by various heat recovery systems. The capacity of gas turbine varies from 500 KW to 250 MW, which shows that this system can be implemented for medium to large scale applications (Durmaz).

The steam turbine works, when the high pressure steam enters into the turbine and the energy of steam is converted into the mechanical energy of the blades which in return produces work through the shaft and this shaft can be coupled with any device like a generator to generate electricity. Steam and gas turbines are the prime movers and can be used to convert the mechanical energy into any useful work. The general capacity of steam turbines ranges from 50KW to 250 MW. The steam is generated with the help of the boiler. Apart from the work, there is also waste heat which is then utilized to meet high thermal load demand especially in institutions and industrial plants. The fuel, which is being used in can vary, like natural gas, coal, wood, solid waste and agricultural byproducts. Usually the combined cycle power generation is implemented across the globe because of its high efficiency. The efficiency of the steam turbine varies according to design, size and conditions but the general practical efficiency are about 35-45% (Onovwiona and Ugursal 2006).

The most widely used systems are Reciprocating engines. They can be found in small scale capacities as well as large scale capacities. Their capacity range is from 10 KW to 10 MW, these engines are quite reliable, follow load well and they have good efficiencies. These engines can be classified into two types based on the ignition.

The efficiency of the cogeneration system based on the reciprocating engines is usually 85-90% the most. For electric efficiency is in the range of 25-39 %, while the other is the thermal efficiency. Several case studies have been performed to evaluate the efficiency of cogeneration systems based on reciprocating engines and the outcome validates that the overall efficiency achieved is nearly 85% (Onovwiona and Ugursal 2006).

These micro turbine cogeneration systems are a downsize mode of turbines, they are light weight and small in size. Their capacity may range from 30-350 KW. The overall efficiency that can be achieved is nearly 80%, which is less than the reciprocating engines. This system is versatile with the ability to deal with multiple fuels, high heat recovery and generation. The first step involved in the operation is to intake the air into the compressor. Then the air fuel mixture is formed and burned in the combustion chamber, work is produced by the hot expanding gases in the turbine. A device known as a recuperator is used to preheat the incoming air into the compressor.

This micro turbine is also available in various shaft designs depending upon the work required. Various kinds of fuels can be used in it like gasoline, diesel, biofuel, landfill gases and others (Onovwiona and Ugursal 2006). The advantages of micro turbines are as follows.

a. Light Weight
b. Smaller in size
c. Moving parts which can allow ease of shifting from one place to another.
d. Low noise
e. High grade of heat evolution as waste heat
f. Lower maintenance cost
g. Low vibration problems
h. Delivery time is quite short

Fuel cell systems are also becoming popular in the field of energy, especially in transportation and power sector. For now they are generally used for small scale because of their environmentally friendly nature. Typically the most common fuel used is natural gas in it. The implementation of these systems can reduce carbon dioxide emission up to 49%, NO_x 91%, CO 68% and 93% reduction in volatile organic compounds. The barriers in the path are that this technology is still developing, the cost associated with it is quite high and the lifetime is short making it slightly unfavorable. The operating procedure is that the hydrogen reacts with oxygen with an electrolyte without combustion and mechanical work. The reaction works as oxidation of H_2 and reduction of oxygen occurs. As the whole process is exothermic, heat is released which is then used for heating purposes.

Anode: $H_2 \longrightarrow 2H^+ + 2e^-$

Cathode: $2H + \frac{1}{2} O_2 + 2e^- \longrightarrow H_2O$

Overall Reaction: $H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$

The overall reaction is exothermic which means heat is evolved and this heat is used to meet the demand of thermal energy. The capacity of fuels for small scale applications ranges from 1-50 KW and the efficiency is 80%. The fuel required is Hydrogen which can be obtained from different fuels like natural gas, propane, coal and electrolysis of water. The fuel cell system includes different subsystems like fuel cell stack, auxiliary equipment's and inverter. The reforming process is carried out to generate hydrogen; it can be internal reforming or external reforming. There are many different kinds of fuel cells used like Alkaline fuel cells, Polymer Electrolyte fuel cell, Phosphoric Acid fuel cell, Molten Carbonate fuel cell, Solid Oxide fuel cell, Direct methanol fuel cell (Onovwiona and Ugursal 2006). The advantages are as follows.

a. Low noise
b. Low maintenance cost
c. Better load management
d. Lower emissions
e. Overall efficiency is nearly 85-90%.

This technology is basically based on the piston-cylinder arrangement with the discovery of "free piston" arrangement. This technology is getting extremely famous, especially in the automotive industry to develop a dream car without the main shaft but for now this technology is still not developed yet. For this engine a wide range of fuel can be used like oil, gas, renewable like solar or biomass. The emission level is very low as compared to most of the technologies like 80-120 mg/m^3 NO_x, 40-60 mg/m^3 CO and its capacity is 2-25 KW which is suitable for small scale generation. The electrical efficiency is nearly 40% for now, but it is expected to increase to about 50% in the next years . The overall efficiency is about 75-85% (Onovwiona and Ugursal 2006). The advantages of Stirling engine are as follows.

a. High electrical efficiency
b. Flexibility of fuel
c. Low emission
d. Low vibration/noise
e. Exceptional performance at partial loads.
f. Low wear and long maintenance free operation.

2.9. Future Cogeneration Technologies.

The use of biofuels with cogeneration has gained a lot of importance in recent time and several studies have been carried out. Thus, in (Rasul, Ault, and Sajjad 2015) an Australian household micro-generation by using local bio energy sources as a fuel source for turbine generators was presented. Federico and Umberto (Brizi et al. 2014) worked on the energy and economic analysis in Brazil based on a comparison between natural gas and bio gas for compact cogeneration systems for applications in residential sector, universities and hospitals. Livio and Frencesco (de Santoli et al. 2015) presented a study on Environmental and Energy sustainability analysis for Bari Airport using a biofuel based cogeneration system in which the biofuel is collected from the region of about 70 KM area. Apart from that economic analysis, carbon saving potential, incentives is also demonstrated. Laurencas and Zilvinas (Raslavičius and Bazaras 2010) experimentally determined the economic and environmental aspects of diesel engine based cogeneration based on biofuels partially or completely in Lithuania. The biofuel used to be rapeseed oil from the farmers area's nearby while the economic analysis depicted great prospective with thermal energy cost of 0.033 €/KWh. Ricardo and Monica (Chacartegui et al. 2015) carried their study for utilizing urban waste residue in cogeneration system. The case studies were performed based on previous legislations in 2007 and new policy which implemented in 2014 in Spain.

Apart from research on the fuel diversity, renewable energy or thermal energy storage techniques are also being implemented with cogeneration techniques and several researches have been carried out in this field. James with Klaus (Freeman, Hellgardt, and Markides 2015) carried out an assessment of a solar thermal collector, a comparison was made between concentrating and non-concentrating collectors in combination with small scale cogeneration system like household for the United Kingdom. Gianluigi, Livio and Bendetto (Lo Basso et al. 2015) worked on the development of cogeneration technologies based on environmental friendly fuel like hydrogen and natural gas mixture. After carrying out experiments with a single cylinder engine fuelled by natural gas and hydrogen 15% by volume. The energy efficiency was increased by 2.28%. Its application covered small scale like residential, civil sector with the potential decrease in energy consumption and GHG reduction. Osamu and Norihiko (Kurata et al. 2014) evaluated the use of noval heat storage techniques, especially latent heat storage techniques and combined it with micro cogeneration it increases energy saving by storing high density energy and reducing environmental pollutants. Marek and Alexander (Patsch and Čaja 2015) carried out a study on the operating parameters of cogeneration using the fuel cell based on natural gas. These cogeneration systems are applicable for very small application like flat or single family house. Alexandro and Jeferson (Szklo, Soares, and Tolmasquim 2000) worked on two case studies one is based on chemical plant and other is at shopping mall based on cogeneration systems and developing economic potential. Antonio, Nilay and Sergio (Pantaleo, Camporeale, and Shah 2014) worked on dual fuel based cogeneration system, where fuels used were biomass and natural gas. Different operating scenarios were created and the economic analysis was done for each case which showed that duel fuel cogeneration systems are more efficient depending upon the operating condition. Raul and Silvia (Palomino and Nebra 2012) investigated the potential use of natural gas in commercial and industrial sector in Peru, as Peruvian government is increasing their natural gas distribution system, which will allow it to exploit natural gas, nine different cases were considered and cogeneration resulted in a sustainable approach to address the energy demand. Daila and Tomas (Streimikiene and Baležentis 2013) carried out assessment of different CHP/Cogeneration technologies in Lithuania by taking account environmental, social and economic aspects. As Lithuania relies on the old technologies, their intention is to decentralize the energy system which will result in less transmission cost, more efficiency and providing district heating at low prices and CHP technologies offer a sustainable efficient way to overcome this situation. Pino and Iribarren (González-Pino et al. 2015) investigated the effect of regulatory framework in Spain for Stirling engine based micro cogeneration units and compared the results with the policy of European countries like Germany to highlight the flaws of the policy. Alexis and Liakos (Alexis and Liakos 2013) investigate a case of hospital by implementing cogeneration system, two scenarios were developed, one on partial load and other full load. The economic analysis suggests that annual energy cost reduced about 33% and annual energy consumption decreased about 28%. Celador and Erkoreka (Celador et al. 2011) investigated the feasibility of a gas based cogeneration system for a 100-1000 kW system, a simulation model was applied by considering the current framework in Spain for residential an economic analysis followed by sensitivity techniques are also applied to check the variation of prices and its effect.

Other researchers have focused on policies and other aspects highlighting cogeneration and the policies to increase investments. Howard and Saba (Howard et al. 2014) investigated the policies to meet the goal of New York’s 800 MW of distributed energy and policies were analyzed to access either cogeneration will be able to meet the demand or not. The analysis shows that the distributed ownership in micro cogeneration system can help to meet the goals, while some amendments in polices will boost the performance and investments in this sector.

Benjamin analyzed the case of Denmark that how Denmark became the most energy secure and sustainable country in the world from 100 dependent, reliable on foreign sources to net exporter of energy to the world today (Sovacool 2013). It describes the approach and strategy employed for zero energy dependence by giving incentives for combined heat and power generation and wind energy. Now it has become one of the most energy secure country in organization of economic cooperation and development. Sonar and Soni evaluated the micro trigeneration system, these systems which are considered for the small scale less than 15 KW. The analysis has been based on economic, environmental and sustainability impacts.

2.10. Cogeneration in Universities

A large number of universities have implemented cogeneration facilities. Some of them had old plants, mostly in the United States but now after the revival of the cogeneration technologies and thermal storage facilities, those plants have been modified and are working efficiently to meet the institutional needs.

In Clarke University in the U.S founded in 1887, a student first proposed a cogeneration plant in 1982 based on diesel or natural gas as a fuel and was providing 70% of the university's electricity and heating demand. After modifications in the process, now its efficiency has been increased (DeCarolis, Goble, and Hohenemser 2000). Fritz and Kahn investigated the feasibility of cogeneration at a university with distributed cogeneration system (Fritz and Kahn 2009), this study was formed after the universities in South Africa faced a crisis regarding electricity in 2006. A case study by Robert and Wendy (Goble and Goble 1980) investigated the cogeneration options in universities, they evaluated the problems by considering the plants in two universities, then analyzed what solution could be found to make universities capable of self-generating their own energy resources. At Bucknell's University a coal fired power plant was converted to a combined cycle power generation plant based on gas and oil (Bucknell). It was used to supply 90-95% electricity and heat requirement for the university. Some new modifications have enabled the university to meet environmental, sustainability goals and future demands. Princeton University also has its own cogeneration plant, which enables them to produce its own energy in cheaper, efficient and sustainable way and it has an efficiency up to 85% (Princeton). One of the top

American university MIT has its own cogeneration plant for the last 20 years, not only generating energy for the university itself, but also supplying to the neighborhood(MIT). A study carried out by Lee (Lee 2012) pointed out the future prospects of cogeneration in universities, he pointed out the common hurdles for implementation of these technologies, why this technology was important in the institutions and how the problems could be eliminated. Not only in the United States, but all over Europe, cogeneration is being implemented to replace inefficient heating systems for generating efficient heating and electricity production. In 2014, Dalkia Hungary and University of Warwick were given COGEN Europe Recognition Award for their efforts in promoting cogeneration in every sector. The innovation award was given to the University of Warwick because of their contribution in cogeneration and carbon storage.

Minett and Simon (Minett and Simon 2000) presented an article in which the focus was on two areas, one known as Promasco whose objective is to promote cogeneration in rural areas and the other one was Educogen, its objective is to promote cogeneration as an energy efficiency tool in universities and institutes.

Cogeneration is playing an important role of sustainability in many universities. Many have successfully implemented such systems, and are continually improving their systems for improving efficiency. Several universities can be cited which are using Cogeneration Efficiently for Sustainable Campus utilities.

- Massachusetts Institute of Technology, 22 MW plant based on gas turbine is the primary source of utilities. More upgrades are being made to increase capacity and efficiency to meet the energy needs with improving GHG standards (Lund 2015).
- Princeton University, Princeton, New Jersey meets their energy demand from 14 MW Cogeneration/Trigeneration Power Plant.
- Clark University, Worcester, Massachusetts has a Cogeneration Plant of 1.8 *MW* capacity for utility demand.

2.11. CHP in Turkey

Turkey’s Combined Heat and Power market is characterized by small projects and it involves mainly reciprocating engines. In 2011, the installed capacity was 1100 MW which only increased 100 MW in 2012 but last year the increase is quite significant, nearly 200 MW. The sector which has contributed towards this increase is the commercial sector and hospitals. Several companies like are trying to improve the growth of CHP on industrial and commercial Scale.

Siemens has invested in a CHP large scale plant which is expected to be operational at the end of 2017 with a capacity of 375 MW. OUTOTECH has designed a plant for the paper mill which is capable of generating 27 MW from waste. Another major agreement is by Turboden a Mitsubishi Heavy Industries Company destined to set up a biomass based cogeneration plant in bursa, Turkey. This shows that the upcoming years for CHP are very suitable in Turkey, which will lead to significant development of Cogeneration and Trigeneration plants in Turkey to utilize local resources for energy production.

2.12. Contribution

In this study, the main purpose is to propose a cogeneration/tri generation system for Izmir Institute of Technology. This institute takes the electricity from the grid and heating is provided by its own systems as commissioned in each building separately. During shortage they do have diesel generators providing energy when there is any cutoff of the electricity from the grid. The existing systems most of them are based on the electricity from the grid and are conventional systems. These systems have poor efficiencies.

By implementing Combined Heat and Power system, the Institute can get benefit from its highly efficiency utility generation in order to meet the requirement of campus utilities. Apart from this system. The aim is to highlight that heating and cooling sector is being neglected in Turkey, yet they consume the second highest energy resources. The need of hour is to emphasize the small, medium and large scale sector without discrimination in order to achieve energy security and sustainability for Turkey.

In this study, a combined heat and power plant is analyzed for Izmir Institute of Technology, which is a quite new theme for the Institute in order to integrate electricity, heat and cooling into one system and implementing fourth generation system.

CHAPTER 3

METHODOLOGY

A theoretical analysis of the case study carried to analyze the feasibility of a cogeneration for the Izmir Institute of Technology consists of systematic steps. The first step is the analysis the existing system with the electricity, heating and cooling consumption referred as the data collection; most of the data has been collected from the institute administration for basic utilities. After interpretation of data and careful analysis of the demands, the capacity of the plant is estimated. Two general case are considered for the institute, which are gas turbine based CHP and reciprocating engine based CHP. After that the emissions and the cost estimation is carried out. In the end, a comparison is made to show which case provides the most feasible solution for sustainability generation for the institute.

3.1. Data Collection and Interpretation

Most of the data has been collected from the responsible authorities of the institute. Detailed data is available for the years of 2014 and 2015 with consumption of each department and building. Still for year 2015 the last four months data is not available. Apart from that, a graphical representation of data from 2010 to 2014 is also available which can be used to predict demand for next years. For data extrapolation, accurate data is required to analyze the expected demand to anticipate the demand of the cogeneration plant.

The data is divided into two parts. First is electricity while the other heating and cooling demand. Data consist of the values, which represents the total electricity consumed by the institute for all the system including heating and cooling. The institute's heating and cooling systems are mostly electricity based, but some buildings use heating system based on fuel, such as fuel based furnace or boilers and variable refrigerant flow system. For cooling, electric chillers are used during the summer season. All the departments include a combination of all these system but no specific system design is available to better analyze the situation of each department. Therefore, a specific generalized approach is taken that the electricity demand represents both heating and cooling consumptions data.

To analyze and extrapolate the data, accurate data for certain years is required. During 2013 to 2015, there was no further addition of building which leads to the assumption that these three years would provide the basis for extrapolation of data for the last months of 2015 and the annual increase in electricity, which can be used to extrapolate the data for following 10 years.

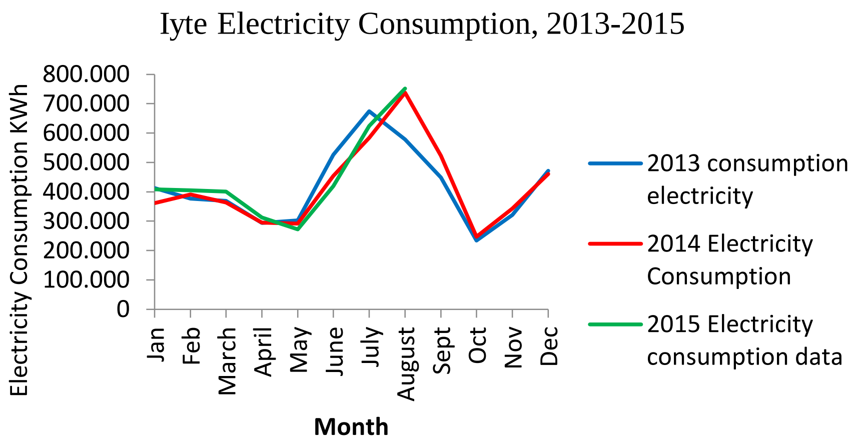

Figure 3.1. Actual Electricity Consumption from Institute Authorities.

Figure 3.1 shows consumption in kWh per month and it can be observed that there is not much change during these three years, only a small difference can be seen which can be due to the variation in heating or cooling demand because of weather conditions or the consumption of electricity in departments. The values of 2015 electricity consumption is given until the month of August and approximate change within 2013-2014 during the last four months from September to October provides the consumption for last four months of 2015.

For analyzing the feasibility of the cogeneration plant, the hourly electricity consumption is the preferred way to analyze the consumption because the heating and cooling demand is influenced by several factors including occupation, weather change, construction of the building and materials used. Consumption on monthly basis does not provide the peak consumption hours and the percentage of electricity consumed during the night time or the consumption during the time when the university is closed. Each department shows a specific trend of electricity consumption and its heating and cooling demand is also different. Considering the consumption of electricity for engineering buildings shows that these buildings follow the same trend during summer and winter with an annual increase, but for the administration buildings it is different, for buildings like Reactorate building, administration building, R&D department, each has a peculiar change and even the increase is different for each department, which shows that in order to do precise extrapolations, each department’s electricity, heating and cooling demand must be evaluated separately and extrapolation should be made for each building.

For heating and cooling demand, the limitation of data has forced to make certain assumption to find out the consumption of each building. As given by the officials, October represents the lowest demand in electricity because it represents the most moderate weather and there is normally no consumption of heating or cooling for each department. Figure 3.2 shows the average weather conditions for Izmir, Turkey (BBC 2011)

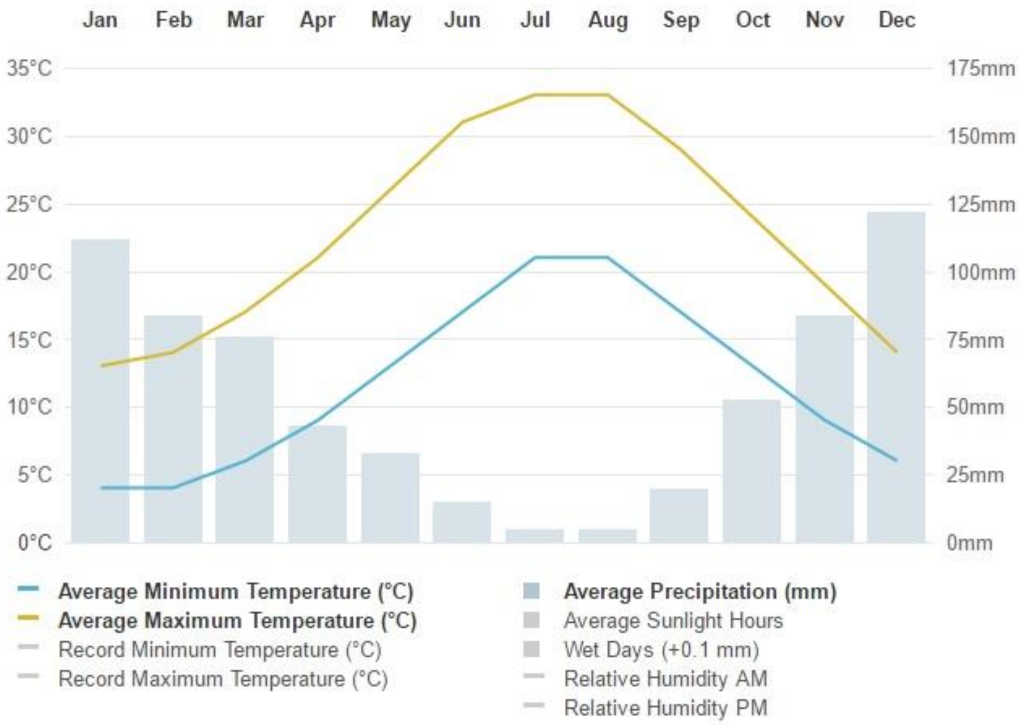

Figure 3.2. Average Weather Condition for Izmir, Turkey.
(Source: BBC Weather Data)

As it can be observed in Figure 3.2 that two months represent the normal temperature range that can be used for a baseline case to generate data for heating and cooling, one is April with the average maximum temperature of 21 °C and minimum temperature of 9 °C and October, which shows 24 °C maximum temperature and minimum temperature of 14 °C. The data in Figure 3.1 suggests that in April there is still little amount of cooling being used during this month. But in October the data in Figure 3.2 reflects the minimum amount of usage of electricity. The assumption is that October utilizes minimum amount of electricity with no consumption for heating and cooling. The heating and cooling consumption can be evaluated from the difference of consumption between each month and the base line consumption taken is October consumption. Year can be divided into two periods, summer from May to September with April being considered in winter or summer depending on the conditions and winter from November to March. Considering the change in the heating and cooling consumption, each department has a specific trend irrespective of the type building. The reason lies in specific consumption of utilities as each department differs from the scale of laboratories being used and amount of heating or cooling consumed, which is different. Detailed description of the data is given in the Chapter 4.

After evaluation of the 2015 missing data, the next target is to predict the increase in consumption with respect to the combined cycle plant life. The extrapolation is based on the addition of new department buildings and the annual percentage increase. To get the electricity increase due to the addition of new department buildings, an average of the existing buildings is evaluated and that average reflects the consumption of each new department. The annual percentage increase is based upon the last year's difference. After 2019 the annual percentage increase is assume to decrease linearly until it reaches a stable value in 2023. After 2023, no further increase is assumed based on the assumption that there is no addition of department and energy efficiency measures leads to a stable or decrease in annual percentage increase of electricity.

The total capacity of the plant in 2023 is evaluated from 2010, with the extrapolation of each year heating, cooling and electricity consumption. It is assumed that during the following 5-7 years the consumption, it most likely remains stagnant after 2023. The total capacity of combined cycle plant is based on electrical and cooling consumption, as heat and cooling does not occur at the same time, for this reason the heat produced can be by passed before the steam turbine to meet the heating requirement.

As the electricity consumption is in kWh, a time based value represents the trend of consumption of electricity on hourly basis, another assumption will be made to calculate the university electricity capacity. Unavailability of the hourly data makes it difficult to analyze the peak electricity hours. As the normal operating hours for the institute are 9 to 5 which suggests 8 working hours per day. As 8 hours per day and 5 days a week gives the consumption of the working days but considering the other 2 remaining days provide value of the fluctuations that can occur during weekends or during the night time, weekdays and weekends for better approximation. After analyzing the total operating hours for the whole year, total capacity can be calculated by dividing total consumption after increment by total operating hours per year and will give the total capacity in megawatt per year required to meet the utility demand of the institute. After this, the heat to power ratio is evaluated which is helpful for defining the best possible system for the institute.

3.2. Calculation and Design

The most interesting aspect of cogeneration is that it is not applicable for every site. Even, if it is, not all the systems are applicable to that specific site. Each specific site is appropriate for a specific system. In cogeneration, the main aspect is the balance between a thermal and electrical consumption to achieve high efficiency of combined heat and power plant, but the final decision for selection of plant depends upon the capacity and desired thermal or electrical output. Waste heat recovery represents the most important point for achieving better efficiency, efficient heat recovery system provides better economical and feasible results which can be implemented, even if in the earlier stage, efficiency is little low, it can be modified in later years with better integration and heat utilization of the system.

Cogeneration plants can operate on various loads, some of the plants operate all year to provide electricity and other utilities for the facility and some operate at partial load. Each system has its own benefits, the first one gives better payback and allows to work in continuous smooth operation with on-site generation minimizing the transmission and distribution losses while the other reduces the capital cost. Selection of system and operating cost is entirely dependent on the mode and the requirement of cogeneration generation capacity. Generally, there are two ways to get high efficiency

- First is to design the system in such a way that it runs to achieve thermal load at all time at full load and standby power is purchased from the grid.
- Second is to design the system to meet electrical demand of the facility at full load operating at maximum operating hours and selling excess electricity to the grid.

As the system of the institute rely on electricity even the new buildings are being installed with combination of electric and fuel based heating system, it could be more feasible to operate the plant to meet the electrical requirement at full load and analyze the condition, which gives better results.

After selection of the capacity, the most important things in designing a cogeneration plant is choosing the prime mover, and choice of a prime mover depends on analyzing the heat to power ratio. The rule of thumb given for the CHP installation provides values which could be used to analyze the systems and these are as follows (Luther 2016)**.**

- If Thermal to Power ratio is 3 to 20, consider boilers and steam turbine.
- If Thermal to Power ratio is 1 to 10, consider gas turbine and HRSG
- If Thermal to Power ratio is 0.5 to 1.5, use reciprocating engines.

Each part of CHP system has an effect on the other and influence the efficiency, as the gas turbine inlet and outlet effect the electrical output while HRSG also effect's the overall efficiency of the system. During designing of the system, choice of prime mover and the parameters to operate the plant are very important for achieving high efficiency. There are generally two basic kinds of cycles, one is topping cycle, in which electricity is produced first and then waste heat is recovered while the other is bottoming cycle in which main purpose is to generate heat then power.

Waste heat can be recovered in two forms, directly or indirectly. Direct use of waste heat means supplying heat into a system like absorption chiller, which eliminates the use of other HRSG equipment, reducing capital cost and complexity of the system.

Indirect use utilizes the waste heat into the heat recovery steam generation equipment or boiler to generate steam and then using this steam for further generation of electricity from steam turbine or just for space or process heating depending on the requirement. Choice of utilizing waste heat is strictly depends on the requirement of the facility. In most of the cases, electricity is produced first, then heat is recovered for more electricity production and some part of the steam is bypassed to meet the heating requirement of the campus using the pressure regulators or pressure relief valves (Murphy 2012).

On a large scale, combined power cycle or combine heat and power generation is generating electricity with more than 70% of the maximum theoretical efficiency, but in small scale plants, innovate techniques and unique integration of system is required with to achieve higher efficiencies.

For combined cycle applications, several operating cycles which can be used for combined cycle applications and to choose which cycle shows the best option. These operating cycles can be graded by the temperature range. Otto Cycle has a maximum temperature range from 400 to 2200 °C, Joule cycle or Gas turbine has a range from 450 °C to 1400 °C, high temperature, fuel cell operates from 600 °C to 1300 °C, while Joule bottoming cycle operates at very low temperature range 250 °C to 550 °C, Striling cycle from 250 °C to 1100 °C, Rankine cycle with combination with Kalina cycle from 50 °C to 650 °C while Organic Rankine and low temperature fuel cells operates at a temperature range of 50 °C to 350 °C.

Table 3.1. Matrix of Combined Cycle Systems.
(Source M.A Korobitsyn (1998))

		Topping Cycle			
		Rankine	Otto/Diesel	Joule	Fuel Cell
Bottoming Cycle	Rankine	•	•	•	•
	Kalina	•	•	•	•
	Joule		•	•	•
	Otto/Diesel			•	•
	Stirling	•	•	•	•
	Fuel Cell				•
	Heat Pump	•	•	•	•

For combined cycle usually high temperature cycles provide more feasible option for the topping operation, medium and low temperature are suitable for bottoming cycle. A matrix of the cycle in Table 3.1 shows the possible combinations used for combined cycle. this matrix is used to identify the best possible system according to desired requirement, system specification, system complexity and the cost associated with the system. Case study carried out for the institute includes two of the cycles and a comparison of these two combined cycles with each other and with the current system of generation based on the grid.

This case study includes consideration of two cycles, one is Joule/Rankin cycle utilizing the gas turbine for power generation as topping cycle, later heat recovery steam generation system used to recover heat and convert it into high quality steam. After that depending on the requirement of heating, electricity and cooling consumption, the amount of steam directed towards steam turbine is analyzed for generation of electricity and some part of steam is redirected for other heating application by using pressure regulator and relief valves to decrease the pressure. Benefits of using Joule/Rankin system is that they are most developed, readily available, widely spread, which means easier maintenance than other system like Fuel cells or Kalina cycle and these are relatively inexpensive than the other systems. The fluid used as air when using as topping cycle and water or steam as bottoming cycle. If these are considered for large applications above 250 MW, efficiency can reach up to 70% with the triple pressure recovery system while for 15-50 MW, efficiency is 40-50% with the double pressure system. When considering heat recovery steam generation system, it is important to evaluate the efficiency, for single pressure HRSG it is about 30%, for double pressure HRSG, it can increase up to 10-15% and triple pressure HRSG can achieve 3-6%, more efficiency than double pressure. Apart from efficiency, other important factor is cost, most of the time double pressure HRSG is preferred because it represents the best solution in terms of heat recovery and cost while triple pressure becomes more costly when compared with its heat recovery. There are several companies claims to achieve more efficiency, like ABB which claim to achieve 58.5% efficiency and General Electric (GE) claims to achieve 60%, but all these represent large capacity scenarios.

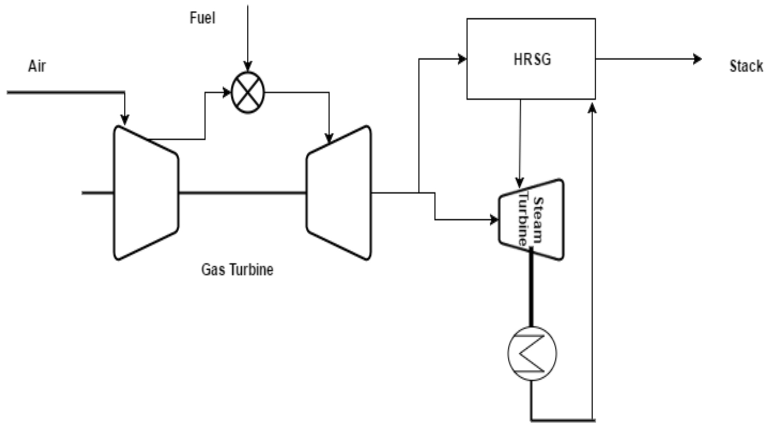

Figure 3.3. Brayton/Rankin Cycle Flow Sheet

Figure 3.3 shows the simplified flow sheet of Brayton-Rankin Cycle. Better integration of the system on a small scale in case of combined heat and power and using the latest technology while integrating and using optimal conditions can lead to the generation of higher efficiencies. Gas turbine has low startup time, but its disadvantage is that one half of the power of the turbine is used to drive the compressor which makes back work ratio to be higher, with a higher back work ratio large turbines are required. Gas turbine's efficiency can be improved in many ways, increasing turbine inlet temperature, increasing efficiency of turbo machinery, equipment, adding some modifications into the existing cycle like intercooling, regeneration and reheating.

Diesel/Rankin Cycle is used for relatively smaller scale than former cycle, Diesel cycle gives better efficiency in terms of electricity generation when compared with Gas turbine cycle, Diesel cycle is easier to maintain, it has high volume mass production, lower capital cost, higher electrical efficiency. There are usually two kinds of reciprocating engine, namely compression ignition and spark ignition, while for this case study natural gas is used for the compression ignition system. These systems are relatively well established, provide long working hours between maintenance, provides flexible power source and high reliability (Korobitsyn 1998).

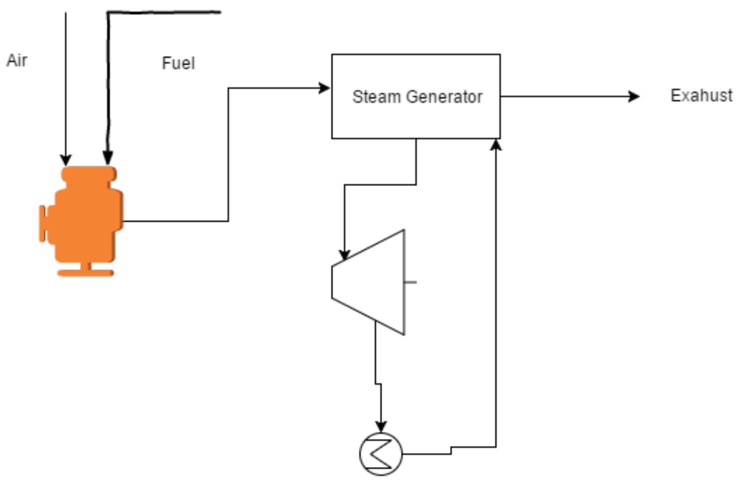

Figure 3.4. Diesel or Natural Gas/ Rankin Cycle Flow Sheet.

Figure 3.4 shows the flow sheet of reciprocating engine based combined cycle. Case study to be carried out for the Institute consist of two cases, one based on the gas turbine based combined cycle and other based on reciprocating engine based combined cycle. For the gas turbine based combined cycle system, the gas turbine selection is based on the demand of the institute needs to be generated. A general gas turbine cycle is used consisting of compressor, combustor, turbine with an open cycle system as the heat released is utilized in the waste heat boiler. There are several manufacturers of gas turbine, but most of them comes under large category manufacturer's. As the institute, does not consume more utilities, the system fall in a small-scale category, usually one of the most famous manufacturer is Solar Turbine for making small scale gas turbine, which generates more efficiency and better control monitoring with dual fired fuel system. It comes in different grades like Centaur, Taurus, Saturn and Mars with different numbers representing the horse power and capacity of the turbine. Each turbine has its own catalogue which represents the maximum, minimum input and output flow rate with heat rate and optimum conditions.

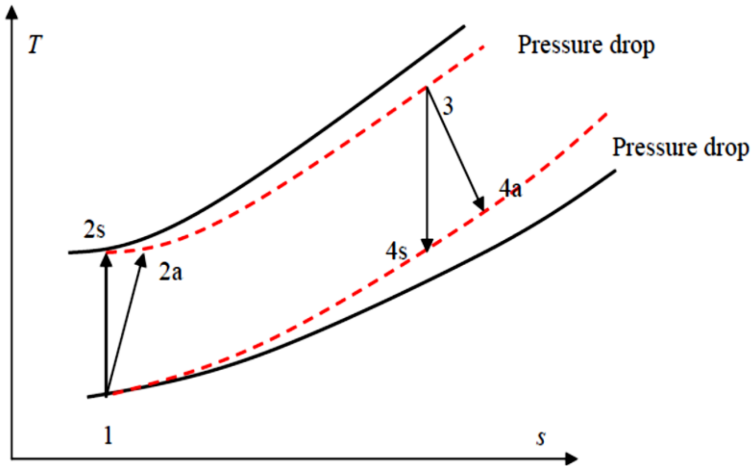

Figure 3.5.Actual vs Ideal Brayton Cycle

The ideal Brayton cycle consist of 4 processes, isentropic compression, constant pressure heat addition, isentropic expansion and constant pressure heat rejection. In all these processes it is thought that there is no pressure change during cycle, which is merely an assumption while as shown in the diagrammatic presentation of the actual Brayton cycle, pressure drop reduces the efficiency of cycle. Another limitation is the temperature that turbine blades can bear, which play important part in the production of power, in the ability of blades to tolerate high temperature limits the pressure ratio of the compressor.

In case of gas turbine, the compressor calculation is based upon ideal gas assumption, which is taken to analyze the output temperature and pressure of the compressor, after that combustion chamber analysis is done. Fuel to be used in this case study is natural gas for both cases as it is the cleanest fuel in terms of fossil fuel and is used widely in combined cycle applications. The combined cycle system can run on different fuel like biofuel or others or a combination of two. After evaluation of the pressure and temperature, power input required by the turbine is evaluated. Usually, first the mass balance is used to analyze the fuel flow rate as the official catalogues of prime movers defines some of the important parameters and are used for precise analysis.

$$m_{in} + m_{fuel} = m_{out} \quad (3.1)$$

The ideal case equations are used for the calculations. The pressure ration gives the pressure at the compressor exit and the equation 3.2 will provide the isentropic temperature in order to calculate isentropic work which later gives actual work based on isentropic efficiency.

$$T_{2s} = T_1 \left(P_2/P_1\right)^{k-1/k} \quad (3.2)$$

$$W_{sc} = h_{2s} - h_1 \quad (3.3)$$

$$n_{is} = W_{sc}/W_{ac} \quad (3.4)$$

The actual work gives the temperature at the exit of compressor, which is used for combustion chamber analysis.

In the combustion chamber, the stoichiometric analysis is made for analyzing the theoretical and excess air required in specific cases, while the flow rates were assumed to be maximum to generate maximum power output from the turbine. The stoichiometric and actual air to fuel ratio is evaluated using equation 3.5 in order to determine the equivalence ratio by equation 3.6 and the excess air from equation 3.7.

$$\left({}^{F}\!/_{A}\right) = {}^{m_f}\!/_{m_{air}} \quad (3.5)$$

$$\varphi \text{ (equivalence ration)} = {}^{F_a}\!/_{F_s} = {}^{\left({}^{F}\!/_{A}\right)_{actual}}\!\Big/_{\left({}^{F}\!/_{A}\right)_{stoichiometric}} \quad (3.6)$$

$$\% \text{ Excess Air} = \frac{(A/F)_{actual}}{(A/F)_{stoichimetric}} \quad (3.7)$$

The specific heat of air assumed to be temperature dependent. The gas specific heat is calculated based on the composition of gas and finally heat balance around combustion chamber gives the temperature at the exit of combustion chamber from where actual work output of gas turbine can be calculated. All these calculation are based on Cengel's Thermodynamics (Cengel and Boles 2006) and some combustion analysis books specifically used for combustion chamber calculations. The Natural gas composition is taken from the case study done by (Duzen 2014). The

The lower heating value of natural gas is taken as 35 MJ/Nm^3 and from composition the exact molecular weight for this natural gas is used for calculation. For Combustion analysis, first stoichiometric calculation is done to find the theoretical amount of air to fuel ration theoretical and actual calculation is based on the mass flow rates given in turbine catalogue after that excess air will calculated using given formula.

Table 3.2. Natural Gas Composition. Turkey.
(Source: Duzen 2014.)

Component	**Mole Percent,%**
Methane	81.74
Ethane	7.56
Propane	5.50
n-Butane	1.49
iso-Butane	1.42
n-Pentane	0.28
iso-Pentane	0.40
n-Hexane	0.36
CO_2	0.96
N_2	0.24

After evaluation of the gas turbine for determining the inlet temperature of gas turbine is done using equation 3.8 and heat input to calculate efficiency.

$$W_{gt} = m_g\, CP_{gas}(T_3\text{-}T_{4a}) \tag{3.8}$$

$$n_{th} = {}^{W_{net}}/_{Q_{in}} = 3{,}500\ /12{,}357.37 \tag{3.9}$$

Next is to evaluate the heat recovery steam generation system to produce high quality steam for the steam turbine, generally the steam quality depends upon the selected steam turbine inlet pressure and temperature.

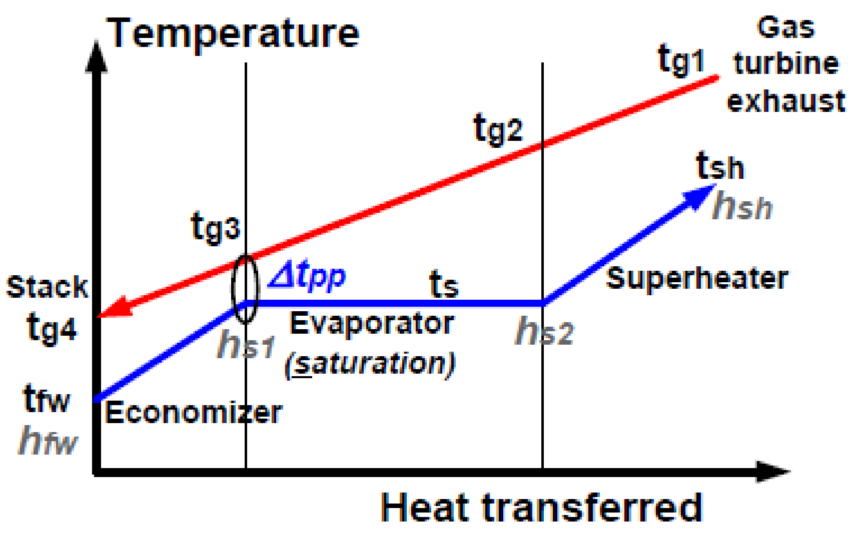

Figure 3.6. Heat-Temperature Diagram of HRSG.

A heat recovery steam generation system consists of three section, these are known as economizer, evaporator and superheater. Each pressure section has separate sections. For single, only one of each is required, for a dual pressure couple of each equipment is required and for third in the same way. The function of economizer is to heat the incoming water near saturation point while the evaporator is used to produce saturated steam at constant temperature and the superheater is used to produce superheated steam used in steam generation turbine. The most important thing is the pinch and approach point in designing the HRSG.

The Approach Point is the difference between saturation temperature and economizer outlet temperature. The purpose of lower economizer temperature than saturation temperature is to avoid evaporation as evaporation can cause tube corrosion and other problem, the general range of approach temperature is from 5 -12 °C.

Pinch Point is the difference between the temperature at the exit of the evaporator and the saturation temperature. Water evaporation usually takes place at constant temperature and pressure that exist at the drum while if there is no significant loss of pressure than drum pressure equals to feed water pump pressure but in actual case pressure drop exists. The range of pinch point is normally taken to be 5 to 15 °C. The upper line in red shows the part of exhaust gas entering from gas turbine exhaust and released in air after exchanging heat while the blue line shows the process of steam generation where water is converted to superheated steam. As the temperature difference between two media is impossible to be zero but if the temperature difference is large enough, which will depict less heat recovery, more losses and high temperature of the exit fluid. Also, a lower pinch point gives efficient heat recovery but it is restricted with cost limitation, very low pinch point will cost a large amount of cost for which will make the system not feasible.

While doing calculations certain assumption are made, once the inlet temperature of feed water, blow down to be negligible, pinch point and approach point assumption steam turbine inlet pressure same as the superheater pressure, considering no pressure drop and minimal temperature drop, steady state conditions, unfired HRSG considered. While in case of evaporator to superheater, pressure drop is considered because of the change in temperature and pipe losses. Calculations are based on single pressure heat recovery steam generator. For calculation of the exit stack temperature and the exit mass flow rate of steam required for steam turbine to work at designated temperature and pressure are evaluated using balance on the evaporator, superheat and then economizer to evaluated the missing parameters.

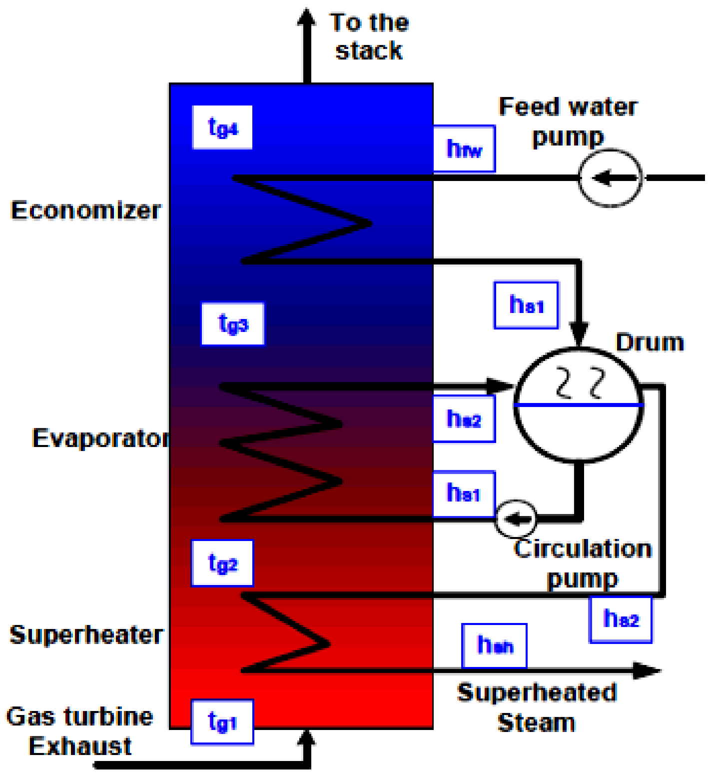

Figure 3.7. Single Pressure HRSG Schematic Source: (Ganapathy 1997)

The heat balance must be carried out along the three sections as shown in Figure 3.7 of heat exchanger in order to calculate the missing parameter's like exhaust steam flow rate, stack temperature. Consideration of reasonable pinch point is very important without it calculations can lead to inaccurate results, far from the actual system.

$$\text{For Economizer: } m_{gt}\, Cp_g\,(tg_3 - tg_4) = m_{st}\,(h_{app} - h_{fw}) \tag{3.10}$$

$$\text{For Evaporator: } m_{gt}\, Cp_g\,(tg_2 - tg_3) = m_{st}\,(h_{S2} - h_{app}) \tag{3.11}$$

$$\text{For Superheater: } m_{gt}\, Cp_g \cdot (tg_1 - tg_2) = m_{st} \cdot (h_{sh} - h_{S2}) \tag{3.12}$$

Here, h_{app} = Approach point Enthalpy, h_{fw}= Feed Water Enthalpy, h_{S2}= Exit Enthalpy of Evaporator and the tg represents the temperature as shown in Figure 3.4 and 3.3.

The saturation temperature is based on the interpolation formula in between the designated conditions using equation 3.13

$$T_s = T_1 + \frac{(P-P_1)\,(T_2-T_1)}{(P_1-P_2)} \tag{3.13}$$

Usually, there is no need for tg_2 to be considered because the overall heat balance on super heater and evaporator, gives the heat transferred from the super heater and evaporator using equation 3.14.

$$Q_1 + Q_2 = m_{gt\text{-}exahust}\ C_{pg}\ (T_{g1}-T_{g3})\ (1\%\ \text{heat loss}) \tag{3.14}$$

The saturation temperature and other conditions are known with consideration of 1% heat losses in the system. Calculation of steam rate requires the ratio of energy transferred and energy absorbed by the evaporator and superheater, which provide the steam rate generated from HRSG. The steam generation rate is evaluated using equation 3.15 and 3.16.

$$E = (h_{sh} - h_{s1})\ \text{kJ/kg} \tag{3.15}$$

$$Ws = \frac{(Q_1+Q_2)}{E} \tag{3.16}$$

After this, a separate analysis is made to determine the individual amount of energy absorbed on the basis of the steam generation rate and from there, the calculation of stack temperature, calculation of HRSG with the selection of the prime mover is done, which is an iterative process and it requires several iterations to achieve optimal conditions. It should be noted that the stack temperature should be greater than the feed water temperature because it represent an accurate calculation as it is impossible to achieve a lower temperature than the cooling medium.

$$Q_1 = Ws\ (h_{sh} - h_{s2}) \qquad (3.17)$$

$$Q_3 = Ws\ (h_{s1} - h_{fw}) \qquad (3.18)$$

Q_1, Q_2 and Q_3 show the energy absorbed by each equipment and after that it is used to evaluate stack temperature.

$$T_{g4} = T_{g3} - Q_3\ \ (1\text{- heat losses})\ Cp_g \qquad (3.19)$$

After analyzing the HRSG and the steam flow rate, the calculation is made to determine the HRSG efficiency with the given mass flow rate.

$$\eta_{HRSG} = {Q_1+Q_2+Q_3}\Big/{m_{gt\text{-}exhaust}\ \ H_{inlet}} \qquad (3.20)$$

Steam turbine is selected before HRSG calculations as the steam turbine inlet pressure is used as a basis for super heater pressure and temperature assumptions. The basis of steam turbine selection is the energy required, steam turbine efficiency, whether steam turbine can operate in condensing or back pressure mode for increased efficiency and energy requirement. Assumptions made for steam turbine are: steady state process, no heat losses and kinetic and potential energies to be negligible. The general steam turbine calculation procedure is used in which enthalpies are calculated to evaluate actual work based on isentropic efficiency for determining the efficiency of turbine using Equation 3.21.

$$\eta a = 1 - Tc/Th \quad (3.21)$$

After that, pump work is calculated based on the assumption that the steam turbine also drives the pump used for feed water pumping. The pump mass flow rate, work input and overall efficiency is determined using Equation 3.22, 3.33 and 3.34

$$m_{fw} = m_{gt\text{-}exhaust} Cp_{exahust} (T_{g4} - T_{g1}) / (h_{sh} - h_{fw}) \quad (3.22)$$

$$W_p = m_{fw} v_1 (P_2 - P_1) \quad (3.23)$$

$$\eta_{C.C} = W_{GT} + W_{ST} / Q_{fuel} \quad (3.24)$$

The same methodology is used for reciprocating engine, the operating conditions differ based on steam turbine for HRSG and reciprocating engines are used as prime mover, which changes the calculation procedure for the prime mover.

Reciprocating Engine technology has improved a lot in the past decades and the factors which are responsible for significant improvement are increased fuel efficiency, pollution reduction and increased power density resulting in better economic and environmental parameters. Reciprocating engines have several benefits like thermal output with low pressure steam, very fast start up time, part load efficiencies, improved reliability and emissions. Usually, diesel engine generates more NO_x and particulate matter, while in case of natural gas, emissions are reduced. Reciprocating engines are widely used in every sector i.e commercial, public and domestic for residential purpose. They do have higher electrical efficiencies when compared with the gas turbine of the same size with low fuel cost. The upfront cost that at start of the project is lower than that of gas turbine while maintenance cost is higher, but reciprocating engine is a widely used technology, local maintenance activities can reduce the maintenance cost of these systems.

The prime mover selection from the manufacturer is based on the efficiency and the capacity of the plant. Usually, reciprocating engine is used in small scale generation from kW to 5 MW. In this case, utilization of two small engines with combined heat recovery unit and utilization of steam turbine can provide more effective results. Some major manufactures that provide gas and diesel engines are Wartsila, JCB, Caterpillar and General Electric. Some of them are specialized in diesel while some in gas or both. The reciprocating engine selected for Institute is from General Electric (LGElectronics) because it is renowned for its high efficiency in combination with combined heat and power systems. GE Provides these efficient systems with multiple fuel utilization mechanism with better system integration and proper testing.

The Diesel Engine is a four stroke engine, , a fuel injector is used to inject fuel directly in the cylinder while only air is compressed during the compression cycle. Fuel injection starts when the piston approaches the clearance volume. The general operating cycle for gas and diesel based compression ignition engine is the same which includes isentropic compression or compression of air, then constant pressure heat addition known as power stroke which allows combustion of fuel and air mixture, then isentropic expansion and constant volume heat rejection.

As compression stroke only takes air, the air will be assumed to be ideal, but the specific heat will be temperature dependent at the exhaust of the compression stroke, after combustion the mixture of gas with its composition is taken based on stoichiometric analysis. In compression stroke only air is assumed to be part of it as fuel injector will inject fuel at clearance volume.

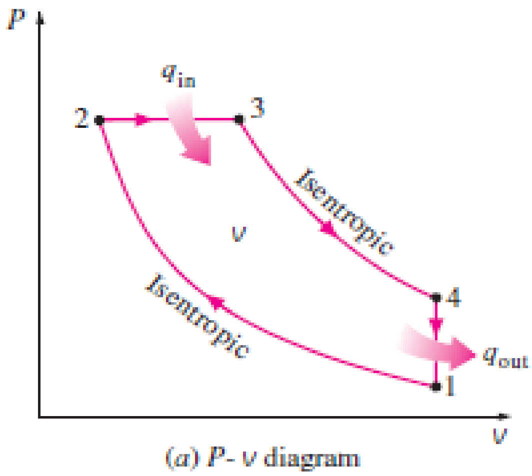

Figure 3.8. Operating Cycle Compression Ignition Engine.

$$T_2 = T_1 \left({}^{V_1}\!/_{V_2} \right)^{k-1} \qquad (3.25)$$

$$P_2 = P_1 \left({}^{V_1}\!/_{V_2} \right)^{k} \qquad (3.26)$$

$$Q_{in} = m_{out}\, Cp_{gas}\, (T_{3-}\, T_2) \qquad (3.27)$$

Isentropic equations are used to evaluate T_2 and P_2, after that heat input is given in the official catalogue which is used to evaluate the T_3. Then equation 3.28 and 3.29 gives the efficiency and heat output into the HRSG.

$$\eta = Q_{in}/W_{out} \qquad (3.28)$$

$$Q_{out} = m_{out}\, C_v\, (T_4 - T_1) \qquad (3.29)$$

As most of the system are based on electricity, all heat recovered is used in the steam turbine and if required only the desired amount of steam can be bypassed using pressure relief valves for the heating requirement (Al-Rahman.H.AL-Hobo and Abid)
Reciprocating engine calculations are also based on the same methodology, the difference is in the diesel cycle calculations. Usually, reciprocating engines are used for medium or small scale while according to requirements; number of reciprocating engines can be increased in order to meet the demand. The selection of a reciprocating engine is based on the electricity to be generated, natural gas of same composition and lower heating is the same as in the case of the gas turbine. The calculation of the diesel cycle for the first process takes air as ideal gas assumption and fuel is injected at the end of compression cycle. Specific heat is temperature and composition dependent. After calculation of the reciprocating exhaust conditions, the same approach is used for the HRSG calculations, only the difference is the selection of the steam turbine, a small capacity steam turbine to be used, which affects the pressure and temperature assumptions of the HRSG. These calculations are based on Handbook of Mechanical Engineering. Descriptive calculation can be reviewed in Chapter 5.

3.3. Emission Estimation

Global Emissions are a serious threat to the climate change. These emissions are being generated from the pollution caused mainly by human activities. Each sector is responsible for the generation of specific pollutants. Power generation and industrial sector based on fossil fuel is responsible for sulfur oxide production, transportation sector generates nitrogen oxides while the energy related emission represents the major source of carbon dioxide production. These gases are commonly referred as greenhouse gases and are responsible for climate change. The concentration of pollutants is often termed as pollution generated from cities but this concept is totally false, rural communities have also their share like cooking from solid biomass and generation of light from kerosene while the pollutants being generated from industrial activities can also travel at very long distance depending upon the wind speed and stack discharge height, but all these factors represents that it is not a related to specific area, it represents a general problem for all geographical regions. As the energy sector depicts the largest emissions percentage contributing to pollution, drastic measures must be taken such as improve efficiency, post combustion treatment and fuel quality to improve the air quality.

Several protocols and agreements signed by a large number of countries show their intention to solve this problem, but much effort is required to improve these standards. The Kyoto Protocol is an international agreement under the United Nation Framework Convention on the climate change, hold’s developed countries accountable for the current environmental problems due to their industrial activities leading from past 150 years to contribute in environmental emissions. Under this agreement, several steps were highlighted, which can contribute in reducing global emissions, international emission trading, clean development mechanism and joint implementation, these mechanism help to provide green investments to meet the environmental target set by the organization (unfccc 2016a).

The Paris agreement in 2015 brought all countries to contribute towards the existing crisis of climate change. The purpose is to strengthen the global response towards the increasing temperature; the focus is to keep it to 2 °C or more nearly 1.5 °C. This agreement help’s all countries to achieve their goal, helping financial flows and improving technologies, which can help to reduce the global emissions (unfccc 2016b).

Despite of the intensive actions being taken, which has enabled some industrialized countries to reduce emissions by shifting its energy infrastructure for conventional fossil fuel to low carbon intensity fuel’s, China will be able to reduce 40% emissions by 2040. However in India and some African countries the percentage will increase and premature death rate will increase from 3 million to 4.5 million in 2040 (OECD 2016).

There are several sources used like coal and gas, mostly used in the generation of electricity or utilities while gas is also a major constituent of industries like fertilizer for the production of syngas. Oil varies in its use ranging from transportation, small scale stationary, for example buildings and agriculture.

It can be classified into various sources namely, stationary source arise from power generation industry, which is the biggest contributors towards SO_2, NO_x and PM emissions. While power generation globally contributing towards CO_2 emissions.

Some gases get trapped in the atmosphere and have the ability to store heat or energy. These are commonly known as Green House Gases (GHG’s), CO_2 represents the highest percentage 81%, which is being generated mostly due to energy related sources. Common sources responsible for emissions are fossil fuel, trees, wood and waste products burning (Brander and Davis 2012).

It is also essential part of photosynthesis as it is absorbed by plants, but excessive amount is responsible for global warming leading to major water and food crisis. Methane has the second largest share of 11% produced due to the transportation of coal, oil and natural gas. It is also released from other agricultural sources. Others are Nitrous oxide and Fluorinated gases constituting 6% and 3%. This group is known to have then highest global warming potential. Figure 3.9 illustrates the pollution standards for new power plants for different countries.

Region	Policy	SO_2		NO_X		PM	
		Existing	New	Existing	New	Existing	New
China	Emission standard of air pollutants for thermal power plants	200-400	100	200	100	30	30
European Union	Industrial Emissions Directive	200-400	150-400	200-450	150-400	20-30	10-20
United States*	New Source Performance Standards	160-640	160	117-640	117	23	23
India	Environment (Protection) Amendment Rules, 2015	200-600	100	300-600	100	50-100	30
Indonesia	MOE decree no. 21 2008	750	750	850	750	150	100
Japan**	Air Pollution Control Law	-	-	123-513	123-513	30-100	30-100
Mexico***	Mexican Official Standard NOM-085-ECOL-1994 (in PPMV for SO_2 and NO_X)	550 -2 200	30 -2 200	110 -375	25 -375	60 -450	60 -450
Philippines	National Emission Standards for Particulate Matter for Stationary Sources	1 000 -1 500	200 -700	1 000 -1 500	500 -1 000	150 -200	150 -200
South Africa	The Minimum Emissions Standards are published by the government	3 500	500	1 100	750	100	50
Korea	Special Measures for Metropolitan Air Quality Improvement	286	229	308	164	40	20-30
Thailand	Royal Thai Government Gazette	700 -1 300	180 -360	400	200	80-320	80
Vietnam	Industrial emission standards for dust and inorganic substances	1 500	500	1 000	650 -1 000	400	200

Figure 3.9. Emission Limit for existing and new power plants for countries (mg/m3). (Source: Nalbandian-Sudgen (2006).)

These gases are termed as Kyoto Gases, named after the international treaty called the Kyoto Protocol, which proposed to control the release of these gases from human activities. Global warming potential is a term used to represent, how much a gas has potential to warm the earth and how much it can stay inside the Earth's Environment. These gases absorb energy and each gas has its specific capacity of storing energy and acts like a blanket insulating the Earth. Total CO_2 equivalent emissions estimated for 2014 were 6,870 Million Metric tons CO_2 equivalent.

Global Warming Potential is a comparison made between gases, how much it can store energy for 1 ton emissions as compared to 1 ton emission of CO_2 over a specific period of time. Usually, the time is 100 years and the larger the GWP, the larger the warming potential. CO_2 has been given the Global Warming Potential (GWP) of 1 as it has the ability to stay for thousands of years. CH_4 has GWP of 28-36 over 100 years, it has more potential to absorb energy than CO_2 but stays for small time in the atmosphere. Likewise, N_2O has GWP of 265-298 time as compared to CO_2 for over 100 years' time period (EPA 2016).

Consequences of global warming will increase Earth's temperature, only small changes in global surface temperature can affect many variables to influence global climate change. Among them will be the frequency of extreme temperatures, circulation patterns of the atmosphere, precipitation, soil moisture, ocean currents, humidity and latitude temperature difference. These climatic conditions can be considered as one big package in which it contains sub packages of environment, habitats, animals and human beings. In short, all things on Earth will be affected by the slight or humungous change in climate.

The existing most important threat to Earth is the meltdown of glaciers all around the globe. There are no exact models predicting climatic change, but some findings have been gathered by scientist that shows that the carbon dioxide contents before pre-industrialization have been doubled, which could lead to significant weather changes in Europe and it will result in more colder winter's in Europe (Broecker 1997). Climate will induce a series of harmful effects on productivity of farms, forests, human disease, fisheries, abundance and geography of plant and animals, biodiversity of microorganisms, availability of water and floods. It's been estimated that the average temperature increase rate would be greater in the 21st Century than the previous 10,000 years (Holdren et al. 2000).

Accounting of Green House Gases involves evaluation of emissions associated with specific organization or the emissions from the grid. There are several emission factors being used to estimate the emissions for different countries. There are several agencies responsible for generating emission factors, one of them is IEA, which serves as baseline for most of the grid base emission calculations. There are many tools for calculating emissions, one of them is the tool designed by World Research Institute (WRI, 2011), which is used to estimate emissions from purchased electricity. Department of Environment, Food and Rural affairs (DEFRA) is also responsible for continuous monitoring and estimation of emission factors for United Kingdom but it has also published some emission factors for non-UK countries for emission calculations. As these factors accounts for both emissions from heat and electricity which means that while in some cases these factors cannot predict accurate results. The work done by Brander, Sood, Wylie, Haughton and Lovell represents a new methodology and emissions factor's which are modified after incorporating two limitations, one was that those reports does not account for gases other than CO_2 mentioned in the Kyoto Protocol while another was that it does not account for distribution and transmission losses.

In all countries emission factors are not available. Most common factors to be used are the composite factor for Electricity/ Heat in CO_2 emissions by the IEA. Even using these factors will create an uncertainty in the calculation as each country has a specific ration of carbon electricity generation to carbon heat generation. The brander's work contains electricity specific emission factor are evaluated from total emissions produced from the generation of electricity to the total amount of electricity generated within country and for calculating CHP emissions, efficiency method was used for heat and electricity to analyze total emissions. The result shows that there is great difference among the electricity specific emission factors and factors given by IEA on basis of Electricity/Heat ratio (Brander et al. 2011).

Grid related calculations uses the emission factors of Electricity based emission factors for Turkey while for CHP there are no specific emission factors available for Turkey. Defra's guidelines which are based on fuel intake or lower heating value of natural gas are used to calculate emission factors from CHP but it is specifically for England and can cause huge variation.

As in the Institute, most of the system is based on electricity being purchased from the grid, even most of the heating and cooling systems. The calculations are based on Electricity specific emission factors. For Combined heat and power generation, all heat to electricity assumption will be employed. No heat based emission factors will be required during calculations.

There are generally two ways for calculating emissions, one is by continuous monitoring of the emission source while the other is controlling emission factors. The evaluation of emission factors is strictly dependent on the country specific emission factor. As emission factor varies based on production, consumption and generation of electricity with its specific emission rate.

For calculations, the emission factors for CHP calculation are taken from Environmental protection Agency, which has specific emission factors for stationary combustion applications based on fuel on net calorific value.

Most detailed emission factors are being given by Defra's but the use is strictly for UK specific companies, because those emission factors are being calculated based on UK emission and electricity consumption and generation. Those emission factors will create some deviation in the calculation of the specific consumption based emissions. Using same emission factors for both reciprocating engine and gas turbine as both falls under stationary combustion power generation application will be more accurate. The emission factors are shown in Table 3.3 (USEPA 2014).

Table 3.3. Emission factors from EPA Stationary Combustion.

Natural Gas (per scf)	Heating value of gas mmbtu/scf	kg CO_2 per mmbtu	g CH_4 per mmbtu	g N_2O per mmbtu
	0.001026	53.06	1.0	0.10

$$LHV = 0.001026\ \text{mmbtu/scf} \times 1\text{btu}/0.000001\ \text{mmbtu}\ \text{ft}^3/1\text{btu} \times 0.0372\text{MJ/m}^3 \quad (3.30)$$

$$LHV = 38\ \text{MJ/m}^3. \quad (3.31)$$

The natural gas heating value is taken from literature, which is 35 MJ/m^3 for our calculation (Duzen 2014). It is appropriate to use these factors in the calculation after adjusting them according to Turkey natural gas calorific value by using error method.

$$\text{Error} = \text{Desired value- Given value} \Big/ \text{Given value} \qquad (3.32)$$

$$\text{Error} = -\ 7.89\ \% \qquad (3.33)$$

This shows that our emission factor values will also decrease by 7.89% of its original value in order to account for 35 MJ/m^3. Multiplying of the emission factors, by 0.9211 gives the emission factor for natural gas having the heating value of 35 MJ/m^3.

$$\text{Emission factor } CO_2 = 48.87 \text{ kg } CO_2 \text{ per mmbtu} \qquad (3.34)$$

$$\text{Emission factor } CH_4 = 0.9211 \text{ kg } CH_4 \text{ per mmbtu} \qquad (3.35)$$

$$\text{Emission factor } N_2O = 0.09211 \text{ kg } N_2O \text{ per mmbtu} \qquad (3.36)$$

Conversion factor used to convert emission factors into desired units of kg of gas/ kWh, as 1 mmbtu = 293.071 kWh

$$\text{Emission factor } CO_2 = 0.16675 \text{ kg } CO_2/\text{kWh}. \qquad (3.37)$$

$$\text{Emission factor } CH_4 = 3.14 \times 10^{-6} \text{ kg } CH_4/\text{kWh} \tag{3.38}$$

$$\text{Emission factor } N_2O = 3.14 \times 10^{-7} \text{ kg } N_2O/\text{kWh.} \tag{3.39}$$

Table 3.4 shows the values of emission factors after converting into desired units.

Table 3.4. Emission Factor after Conversion to kg of gas/kWh.

Natural Gas (per m^3)	**Heating value of gas MJ/m^3**	**kg CO_2 per kWh**	**kg CH_4 per kWh**	**kg N_2O per kWh**
	35	0.16675	3.14×10^{-6}	3.14×10^{-7}

3.3.1. Gas Turbine and Reciprocating Engine Emission Calculation:

For calculation of the gas turbine based emissions, the emission factors are multiplied with the energy input and the energy input is obtained from the volumetric flow rate that comes from the mass flow rate of and density of the natural gas.by multiplying with the operating hours.

$$\text{Energy input} = \text{NCV} \times \text{Volumetric flow rate} \times \text{Operating hours/year} \tag{3.40}$$

$$\text{Emissions} = \text{Energy Input} \times \text{Emission factor (kg of gas/year)} \tag{3.41}$$

The emission factors are in gas specific units. Usually, the pollution is represented as CO_2 equivalent. It is based on the global warming potential index of each gas known as a GWP. The GWP represents the amount of energy that a gas can store over 100 years when compared with CO_2. For conversion into CO_2 equivalent the Global Warming Potential number or index will be used. If gas is N_2O and its global warming potential is 298 than 1 kg of N_2O*298 = 298 kg CO_2 equivalent.(Brander and Davis 2012). As 1 ton equals to 907 kg, this conversion is used to convert kg into ton emissions

$$\text{Emissions kg } CO_2 \text{ equivalent} = \text{GWP} \times \text{Emission factor (kg of gas/year)} \qquad (3.42)$$

The same methodology is used for evaluation of the emission from the reciprocating engine. The only difference lies in the mass flow rate of fuel as it is dependent on the engine output generation. The same emission factors will be used as taken for the gas turbine calculations based on US-EPA, Stationary combustion emission factor (USEPA 2014).In this case fuel input is in terms of kWh, conversion of kJ/Nm^3 to kWh is done by multiplying with the volumetric flow rate of gas, which can be obtained by multiplying the mass flow rate with density and then multiplying with operating hours which are taken 2880 hours per year. Density and the reciprocating engine fuel flow rate is taken from the given data of reciprocating engine.

3.3.2. Grid Based Emission Calculation

The best possible emission factors are given by the International Energy Agency, IEA, which incorporates the composite emission factor for both heat and electricity. These are also used in some of the tools designed to calculate emissions like World Research Institute WRI tool for evaluation of the estimate emissions. Other factors are given by Defra, which are represented in 2012 guidelines for calculation of emissions for non-UK countries. The problem with IEA is that only factors for CO_2 are available and no information about other gases is mentioned.

An alternative way to do calculation is by using Electricity specific emission factors for grid emissions (Brander et al. 2011), using composite electricity/heat emission factors will lead to inaccurate results. If a country has low carbon electricity generation, but high carbon heat generation, then the composite electricity/heat factor will overestimate the emissions from electricity consumption. Similarly, if a country has relatively high carbon electricity generation and low carbon heat generation, then using the composite factors will result in an underestimation of the grid electricity emissions.

Comparison is made between electricity and the composite emission factor and an error of 75% has been evaluated for Turkey. Using electricity specific emission factors will provide better results. Using Appendix 1 of Brander (Brander et al. 2011) for emission per kWh of Electricity Consumption for Turkey.

In this case, as the total energy consumption is already known in kWh per year is used as for emission calculation. The procedure for estimation of grid based emission remains same, only the emission factors are being replaced in order to determine precise emission rate per year. The emissions from grid also include the emission associated with transmission and distribution losses as the transmission and distribution losses incorporates specific amount of fuel and cost. Thus emissions based on grid and T&D losses are added together for accurate analysis.

$$\text{Total emissions} = \text{Emissions from consumed electricity} \tag{3.43}$$

$$+ \text{Emission from transmission and distribution losses.}$$

Then in the end a comparison between emissions will provide a better picture of the best optimal solution with respect to environmental reduction. The detailed analysis is done in chapter 6.

3.4. Cost Estimation

Cost Estimation in case of CHP is the most important step for deciding whether the system is feasible for a specific site as described earlier as each system has peculiar characteristics and each site is fit for only one system, which provides the optimized and most efficient results. Each system is analyzed specifically and a comparison is made between the two cases of gas turbine and reciprocating engine with the cost associated with electricity, generators and fuel oil for heating.

3.4.1. Cost Analysis of Grid.

As the existing electricity generation system of Izmir Institute of Technology is mostly based on the grid and is used to operate the electrical and cooling system throughout year. Fuel oil 4 also known as diesel fuel is used to operate the diesel engines and some heating systems are used for heating utilities based on furnace or boilers. The old buildings are based on these systems, while some modifications are being made by implementing a VRF system known as variable refrigerant flow, this system is famous for minimizing losses and to save cost which includes cost associated with large fans, water pumping and piping costs. These system has lower life cycle cost when compared with any other system. The new VRF MULTI V system has improved seasonal efficiency, upgraded fault detection and diagnosis system, smart monitoring and control, synchronized heating and cooling, high efficiency heat recovery unit but these systems are based on electricity itself (LGElectronics).

The new buildings will use combination of old and new systems which will operate on electricity from the grid, VRF system will be for some departments and special faculty rooms, other than that fuel based heating system and chilling system for cooling will be used based on electricity. All these systems show that, most of the system will run on electricity from the grid in future.

In order to calculate the cost, it is divided into 4 subsections.

a. Grid Electricity purchase cost
b. Maintenance cost
c. Transmission and distribution loss cost
d. Fuel for generator and heating system.

All data has been collected from the administration responsible for record keeping and maintaining all the necessary activities regarding these systems. Not, all data is available like no specific information regarding old heating system and cooling system. The calculations are based on the electricity data which is available while some extrapolations are made to make estimations more accurate and to predict future consumption.

The cost of electricity is 0.199 TL/kWh as taken from the responsible authorities. The Turkish statistical institute maintains and release reports on quarter or biannual basis shows that during the period of July to December the average industrial consumer below 20 MWh has paid an average price of 31.1 kurus/ kWh and largest consumption band 150 MWh and above has paid an average of 21.2 kurus/kWh. This value includes all the taxes which are imposed by Turkish government. While in 2016, during period of January to June, consumer who falls in the category of 20 MWh and below consumption band has paid an average of 30.3 kurus /kWh and consumer in the category of 150 MWh and above consumption band has paid 22.8 kurus/kWh (TUIK 2016).The price of electricity has been given for 2016.

Dollar Price, 1 USD = 3.15 TL (ZiraatBank 2016). The price of dollar is considered for 6 November 2016. Now University pays 0.199 TL for per unit kWh of electricity consumption. The electricity consumption price based on our electricity data can be evaluated by multiplying the total electricity consumption with price per kWh.

For calculation until 2023, a report by the Finance Department of Garanti Bank has done analysis to extrapolations increase in the base load price of electricity on hourly basis. As in 2016, the price according to this report is 5.38 USD cent/KWh (0.169 TL/kWh) but due to recent economic and political situation of Turkey, the dollar has jumped a little bit more than expected, which increased the price of electricity to 6.30 USD cents/ kWh (0.199 TL/kWh). By analyzing the difference of each year and adding the same differences for the next years provide the annual increase in electricity price. Assumptions will be the same as described in that report regarding dollar volatility and other variables that can affect the electricity price (GarantiBank 2015).

As the value of 2023 is not given in the report, taking an average of the values of 2015-2022 gives an expected reasonable average increase and this average increase provides value for 2023 value. No updates are made for the values of 2017-2022 based on dollar price because current year reflects special political uncertainty. Assuming that the economic and political stability in later years will provide the expected outcome for base load electricity price as predicted in Garanti Bank report.

Average increase in base load price (2015-2022) is of the sum of change from 2015 to 2022 by the total number of values.

$$\text{Average Increase (2015-2022)} = {\text{sum of change (2015-2022)}}\Big/{\text{Total values}} \qquad (3.44)$$

$$\text{Average Increase (2015-2022)} = \frac{-0.17+1.14+0.72+0.56-0.16-0.05+0.09}{7} = 0.304 \quad (3.45)$$

$$\text{Average Increase 2015-2022} = 0.304 \text{ USD cent/kWh} \quad (3.46)$$

Negative sign indicates the decrease in price of electricity per kWh. Table 3.5 shows the Electricity price extrapolated for 2023 based on the Garanti Bank Report.

Table 3.5. Base Load Price Extrapolation.
(Source: Garanti Bank, 2015)

Price Rate Analysis	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Based load price Electricity, U.S cents/KWh	5.55	5.38	6.52	7.24	7.80	7.64	7.59	7.68	**7.98**

It is difficult under current circumstances to estimate the exact dollar volatility. Based on trading economics, economic forecast from 2016-2020 for Turkey. Considering the average change during given years provides an expected dollar price for 2023 (TradingEconomics 2016). Data suggests that during last 5 years, the price increased linearly from 1.70 in 2011 to 3.15 in 2016 and will increase steadily in future depending upon the economic and political stability be the main factors.

If 2016 ends at $3.05 and the average price in 2017 remains at 3.11 while from 2017-2020 the average increase 0.17 $, as assumed steady increase based on last 5 years, predicted value for 2023 based on the same average increase rate per year is $4.13 . Table 3.6 shows the predicted dollar price until 2023.

Table 3.6. Dollar Price Extrapolation
(Source Trading Economics, 2016.)

Market	**Actual**	**4th Quarter 2016**	**1st Quarter 2017**	**2nd Quarter 2017**	**3rd Quarter 2017**	**2020**	**2021**	**2022**	**2023**
Dollar $	3.15	3.05	3.08	3.11	3.14	3.62	3.79	3.96	4.13

Price of base load electricity and dollar price of 2023 gives the price of annual electricity consumption for 2023.

For 2023; 1 USD = 4.13 TRY

Electricity base load price = 0.251 USD/kWh (0.0798 USD/kWh)

Multiplying with the extrapolated electricity price per kWh gives the annual price of electricity consumption for 2023.

$$\text{Annual Price, 2023 (TL)} = \text{Total Consumption Electricity} \times \text{Electricity price} \qquad (3.47)$$

Cost associated with transmission and distribution losses:

The electricity transmission and distribution losses account for the fuel loss due to transmission between the source of supply and point of distribution. The World Bank maintains the record of how much each country is losing in term of transmission and distribution. The total percentage of transmission and distribution losses in the World has decreased. The most important reason especially, in Germany and European Countries is the implementation of decentralized combined heat and power units. For Turkey, case is opposite; it is increasing steadily. The World Bank suggests that the losses have been increased in 3 years from 14.11 to 15.46% with an average of 0.675% per year (WorldBank 2014) **.** If no measures are taken in this matter, then the same increase each year for transmission and distribution loss is expected. Same average increase is used for extrapolation of the transmission and distribution loss percentage until 2023. Table 3.7 shows the transmission and distribution loss extrapolation based on last years.

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Table 3.7. Transmission and Distribution losses
(Source: World Bank, 2016.)

Year	Percentage of T&D losses
2011	14.11
2012	14.88
2013	15.46
2014	16.13
2015	16.81
2016	17.48
2017	18.16
2018	18.83
2019	19.51
2020	20.18
2021	20.86
2022	21.53
2023	22.22

The Transmission and distribution loss can be calculated from the equation below.

Transmission and Distribution losses price =Percentage of loss * Total Price (3.48)

The maintenance cost includes the cost of the generator, transformers, electrical appliances, heating and cooling systems. The fuel cost associated with generators and heating or cooling system is also taken from the authorities. The total cost involves all these cost and can be represented by following formulae.

$$\text{Total Cost, 2016} = \text{Electricity price 2016} + \text{Fuel Cost} + \text{Maintenance Cost} \quad (3.49)$$
$$+ \text{Transmission and Distribution cost.}$$

3.4.2. Gas Turbine and Reciprocating Engine Cost Analysis.

The cost analysis is based on the fuel input that is being utilized by each prime mover. The price of Natural gas in Turkey is taken from the Turkish statistical Institute, press release in January-June 2016, which depicts that industrial consumption band below 26 thousand 94 m^3. The consumer paid an average of 118.6 kurus/m^3, for consumption band of 26 million 94 thousand and 104 million 376 thousand m^3 paid an average of 93.5 kurus/m^3 but for this case the values exist between lowest and highest consumption band, the average amount paid by both which is 96.9 kurus/year or 0.969 TL/ m^3 is considered (TUIK 2016). The dollar conversion is as follows, 1 USD equals to 3.15 TL as taken for November 2016.

Two operating cases are being analyzed, one based on 2880 hours per year and the other 8000 hours per year for each prime mover. The cost analysis methodology remains same for each case. First the natural gas price is used to evaluate per unit cost.

$$\text{Natural gas consumption} = \text{Fuel Flow Rate} \times \text{Consumption per year} \quad (3.50)$$

$$\text{Natural gas price per year} = \text{Gas Consumption} \times \text{Price of Natural Gas} \quad (3.51)$$

$$\text{Electricity cost per kWh} = \text{Total Cost of Natural} / \text{Total Electricity Generated} \quad (3.52)$$

After this analysis, the aim is to determine the excess electricity based on the 2016 year. This electricity is then sold on the rate fixed by EMRA. To evaluate the excess electricity generated based on operating hours the total electricity consumed during that year is subtracted from the total electricity produced. The excess electricity is evaluated using total consumption and total generation of capacity of plant.

Excess Electricity, 2016 = Total Electricity Generation-Total Consumption (3.53)

For excess electricity in kWh for 2016, multiplying with operating hours gives the final value in kWh in order to determine profit obtained from selling electricity to the grid. There are two authorities responsible for the electricity market and regulations in Turkey. One is known is MENR, Ministry of Energy and Natural Resources, its role is to determine Turkey’s short term and long term needs for energy and other natural resources, policy making for these resources and to co-ordinate with other electric transmission and distribution authorities.

Another is EMRA, Energy Market Regulatory Authority, its role is to monitor and carry out all energy market activities like issuing licenses, prepare and implement market legislation for electricity, establish and supervise tariff price from consumer, impose sanctions and resolving disputes. In 2015, total power generation share owned by private companies was 75%. The statistic of Electric Generation Transmission Company shows that in the year 2015, natural gas has a share of 40% in meeting energy demand while 70% of total electricity generation was based on fossil fuel.

Several laws have been introduced to change the dynamics of energy in Turkey and shifting it towards renewable and sustainable energy like The Renewable Energy Law No: 5346 and Energy Efficiency Law No:5627. In the energy efficiency law; cogeneration has been introduced as a key participant in the energy sector but its specific role has not been described in detail for residential, commercial and public sector on small and medium scale. Turkey is determined to increase the share of renewable energy to 35% from hydroelectricity, solar, wind and geothermal until 2023 from 27% (Arseven, Ersin, and ARSEVEN 2015).

Under the Renewable Energy Resource Support Mechanism RER, the selling price or tariff scheme is set by EMRA under its own regulation. While a company responsible for selling electricity can sell electricity for 10 years and the minimum price per kWh are as follows:(Arseven, Ersin, and ARSEVEN 2015).

1. Hydro Electric Plant, USD cents /kWh 7.3

2. Solar Power, USD cents /kWh 13.3
3. Biomass or landfill based Power Plant, USD cents /kWh 13.3
4. Geothermal Power Plant, USD cents /kWh 10.5
5. Wind Power, USD cents /kWh 7.3

These incentives are for the facilities which started operation in 2015 and are applicable until 2020.

As the combined cycle plant comes under energy efficiency law and there is no special price tariff scheme for combined cycle plant operating on natural gas. The price of biomass power plant is used as it is identical with this case study as combined cycle can work on the multiple fuels and later it can operate on biofuel or combination of any fuels. Excess electricity is sold at this rate to the grid.

Conversion of the price = 0.133 USD/kWh = 0.418 TL/kWh.

$$\text{Profit from excess electricity} = \text{Excess electricity} \times \text{Selling price} \tag{3.54}$$

Than the natural gas price paid per year is subtracted from the profit gained shows that whether there will be spending’s or saving after selling electricity to the grid. Price paid shows the amount of money required for the fuel after the profit gained.

$$\text{Price paid} = \text{Natural gas price per year} - \text{Profit from selling electricity per year} \tag{3.55}$$

Report by John and Cliff(Cuttica and Haefke 2009) shows an assessment of combined heat and power generation whether it is feasible or not. The report is made by the Midwest CHP application Center and the University of Illinois Chicago in participation with United States Department of Energy. In this report, the step 4 provides details about cost estimation and gives an approximate value for installation cost, operation and maintenance cost for standard installations. Cost is given for 3 kinds of system, which is reciprocating engine, gas turbine and micro turbine based CHP applications. Operation and maintenance cost is based on analysis of several plants which depicts that it ranges from \$ 0.005-\$0.008 per kWh (Luther 2016) for the gas turbine and for reciprocating engines, the operation and maintenance (O&M) cost is in the range $0.010 per kWh to $0.015 per kWh (0.0315-0.04725 TL/kWh) (Luther 2016).

Assuming maximum value for operation and maintenance, converting into Turkish Liras O& M fixed cost per KWh= 0.008 USD/KWh =0.0252 TL/KWh

$$\text{O\&M cost, 2016} = \text{Total electricity generated} \times \text{O\&M fixed cost} \tag{3.56}$$

$$\text{Total Cost} = \text{Price Paid} + \text{O\&M} \tag{3.57}$$

For the most feasible solution the payback period and net profit will be analyzed based on the following formulas.

$$\text{Payback period} = \text{Installation cost / Net profit} \tag{3.58}$$

$$\text{Net Profit} = \text{Total Profit} - \text{Total Cost} \tag{3.59}$$

The same procedure is implemented for all the cases in order to analyze the cost scenario to estimate the best optimal solution for the Institute and detailed analysis can be found in chapter 7.

CHAPTER 4

DATA COLLECTION

The capacity of the plant depends upon the procedure of data collection and interpretation to make certain extrapolations as accurate as possible in order to estimate the demand. For analyzing the feasibility of combined heat and power plant, it is very important to make these estimations based on the parameters that can affect the consumption pattern for anticipating future projections. Institutes, Organization and Hospitals need a continuous energy supply of utilities, which makes them suitable candidate for implementing Combined Cycle System.

An analysis of the existing systems is very important for the selection of the prime mover for the facility, for this reason heat, electricity and cooling demand must be analyzed separately to estimate the heat to power ratio. The general sizing and the selection of the combined cycle plant is based on the collection of the electrical and thermal data. Electrical data must include details of all equipment being run on electricity, heating and cooling based on electricity or separate fuel based systems. The electricity data must be in hourly basis, an hourly basis data provide an appropriate explanation of peak demand and daily thermal load data. Monthly and yearly data are useful for anticipating the future demand from previous year's trend and fluctuation. To analyze the heating data, gas and fuel consumption with gas meters provides an accurate estimate of heat flow, in case if thermal data or electrical data is not available, data logging is applied which can be termed as an energy audit. Without sufficient resources of funds extrapolations can be made instead of an energy audit.

For this case study, data collection relies on the data available from responsible authorities of the institute. Complete electricity data for 2013 and 2014 is available in tabulated form while for 2015, as the last four months data was not available, extrapolations will be made based on the last two year trend for the same months. The Institute consists of several buildings (administrative, technical departments and several laboratories), each building having its own specific trend of consumption and the heating, cooling and electricity scale differs.

Equipment data for the existing system is not available, only some catalogues are useful, which provides a limited insight of the equipment's being used for heating, cooling and electricity. Most of the system is based on electricity purchased from the grid. Chilling system operates on electricity, as one of the latest additions made is the electrical chilling system in newly operational civil engineering building. This system contains liquid which is supplied to the facility at a specific temperature depending upon the condition and the liquid leaves the facility at a higher temperature by removing heat from the facility. There are several advantages of using electric chillers instead of absorption chillers, most important the coefficient of performance (COP), electric chillers have higher COP, they produce less noise, cover less area, requires less maintenance and the shipment cost is lower. Some of the departments use multiple chilling systems, while in some departments single unit is sufficient.

For heating, several methods are being implemented; one of them is VRF systems, which is used in some departments or separate rooms in each department. The VRF systems known as Variable Refrigerant Flow, it is an air conditioning system used for mostly heating purpose, the cost associated with this technology is little bit higher than others but more efficient. As, the name Variable Refrigerant flow suggests, the flow can be controlled, flowing to multiple departments or rooms. VRF includes only one outdoor unit and multiple indoor units and flow can be controlled depending upon each room or building consumption. VRF usually come in many packages and has many manufacturers. Like VRF heat pump which only provides heating or cooling, but not simultaneously, also heat recovery systems (VFR-HR) availability makes it easier to operate in simultaneous heating and cooling operation. VFR- HR has more cost even higher than VFR heat pump systems, but efficiency is significantly greater 11-18% as compared to other systems (LGElectronics 2016). Several VRF systems are being implemented in several departments like a VRF heat pump, heat recovery, water heat pump and water heat recovery, but unavailability of exact layout or quantity of systems with consumption of electricity puts a limitation while analyzing heating and cooling demand. Apart from these systems, conventional heating systems are also being used based on fuel oil-4 which is known as diesel fuel.

Backup generators used during the cut down time also participates in meeting the electricity requirement during the time when electricity cutoff occurs due to some problem or maintenance, but the share of these generators is quite low, while estimating the total capacity, an assumption can be taken that a certain amount of increase in capacity apart from calculated will be added to account for the heating system while generators power generation can be neglected as it happens only a few times a year.

Figure 4.1 illustrates the increase in consumption for the Reactorate Building, which was approximately 4,800 kWh until August during 2013-2014 year. While the increase during 2014-2015 until August was 500 kWh, which shows a large difference. When considering more precisely half of the increase occurred during the period of September to October. The last four month values represent the extrapolated values. Considering same pattern of behavior, a slightly higher increase was considered while extrapolating those values. The total increase during 3 years was 9,402 kWh.

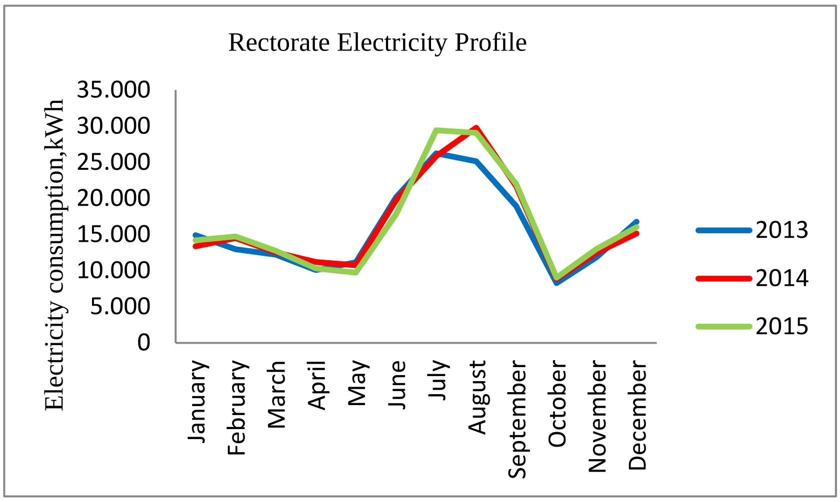

Figure 4.1. Reactorate Electricity Consumption Pattern 2013-2015.

Figure 4.1 shows a smooth increase each year, increase is slightly more during the cooling period, which means that more electricity is consumed during June to October but an overall percentage increase of 3.7% (2013-2014) and 1.2% (2014-2015). The same methodology was applied for each building to extrapolate values from these 3 years in order to estimate the projections for next 15 years. For each department separate calculation being made to depict the individual trend of the department.

Several buildings like the Administration building depicts the same behavior in terms of electricity consumption. For example, percentage increase in the Administration building is 1.9% (2013-2014) and 2.2% (2014-2015), the only difference lies in the pattern of consumption. As, cooling demand depicts less consumption than the Reactorate building, but maximum demand occurs during June to September period for both buildings.

Figure 4.2 exhibits that the annual consumption for the Administration building increased from 401,828 kWh (2013) to 409,558 kWh (2014) but during the following year a slight sharper increase occurred to about 418,867 kWh (2015). As both these departments utilize different amount of the electricity, but the increase is quite same for both the buildings.

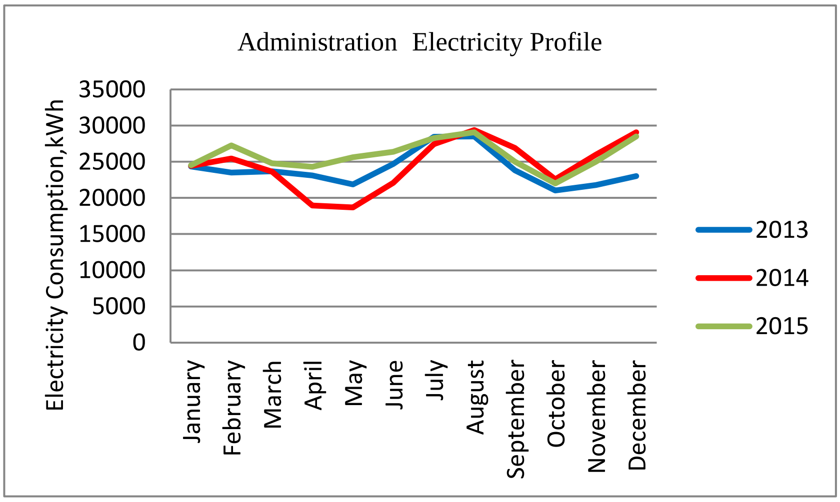

Figure 4.2. Administration Electricity Consumption Pattern 2013-2015.

Figure 4.3 reveals the behavior of the R&D building. For R&D building the consumption pattern was entirely different, the fluctuation in consumption is quite regular and consistent, even the consumption during 3 years decreased. For the 2013-2014, an increase of 6 % occurred. While during 2014-2015, 18 % decrease occurred.

It can be observed easily, there is no continuous trend in this building, but each year the consumption rate is in the range of 8,000 to 12,000 kWh for 3 years. But decrease in 2015 of nearly 22,482 kWh is abnormal and the reason is unknown, while extrapolating the values, this fall is appears from January to August consumption, but this unique trend poses challenge to determine the future change in demand.

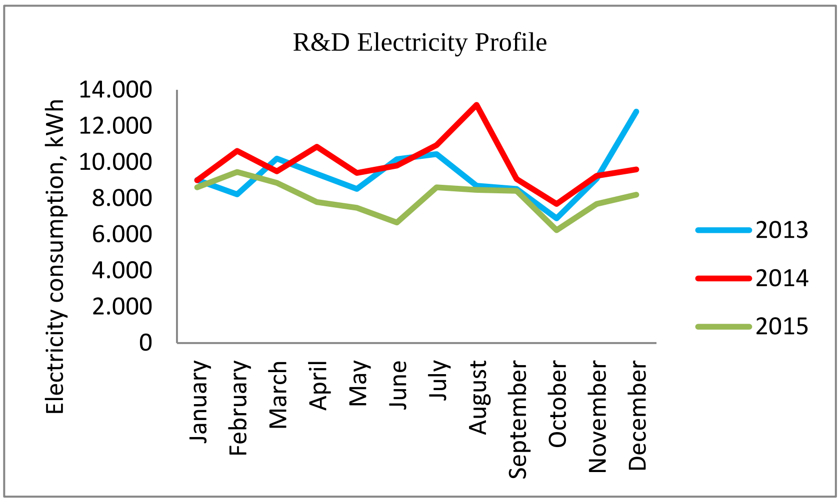

Figure 4.3. R&D Electricity Consumption Pattern (2013-2015).

The science faculty consists of many buildings, apart from buildings it includes departments and several lecture buildings. Departments of Physics, Mathematics, Biology come under this building with two blocks A&B and some lecture buildings. Each building consumes depending upon the requirement. Each building was nearly same trend of consumption of electricity, cooling represents the highest consumption period.

Figure 4.4 shows that the total consumption of the science department, which is significantly greater as it includes 6 buildings consumption. It represents an overall increase in consumption through each year from 2013-2014 but the percentage of increase is different. From 2013 to 2014, increase was only 36,446 kWh but from 2014 to 2015 an abrupt change happened with an increase of 121,541 kWh. For evaluating the values of the last four months of 2015, the same percentage of 5.8% increase was maintained in order to determine the total consumption in 2015.

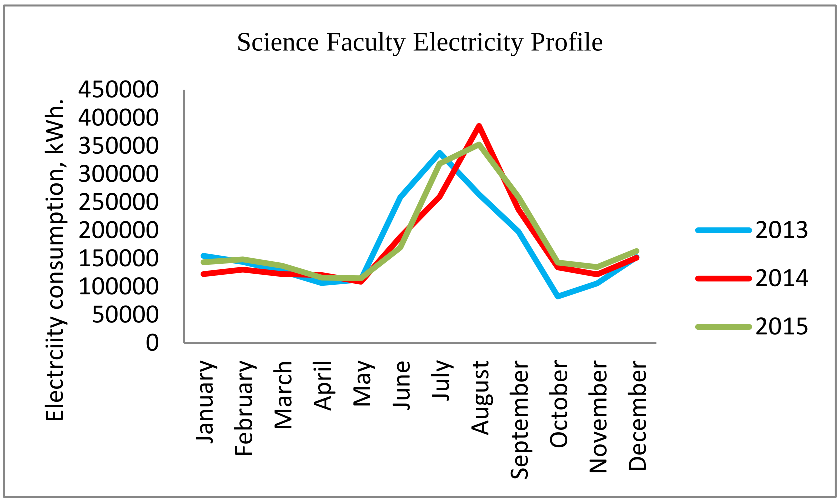

Figure 4.4. Science Faculty Electricity Consumption Pattern (2013-2015).

The Engineering Faculty comprises of 6 buildings, it includes preparatory school building, offices of academic staff, foreign language school and some other departments. Some building has smooth utilization of electricity while some lecture building depicts less usage in summer time.

Figure 4.5 demonstrates the behavior of the engineering faculty electrical consumption. The engineering faculty depicts a different pattern from other departments, for others the trend was generally increasing through year for this case its vice versa, consumption decreased from 622,096 kWh to 515,582 kWh (2013-2014) with a percentage of 17% while during 2015 it decreased further to 474,950 kWh with percentage of 7.9 %. Although the percentage is half of that in 2014 but still the trend depicts a continuous decrease.

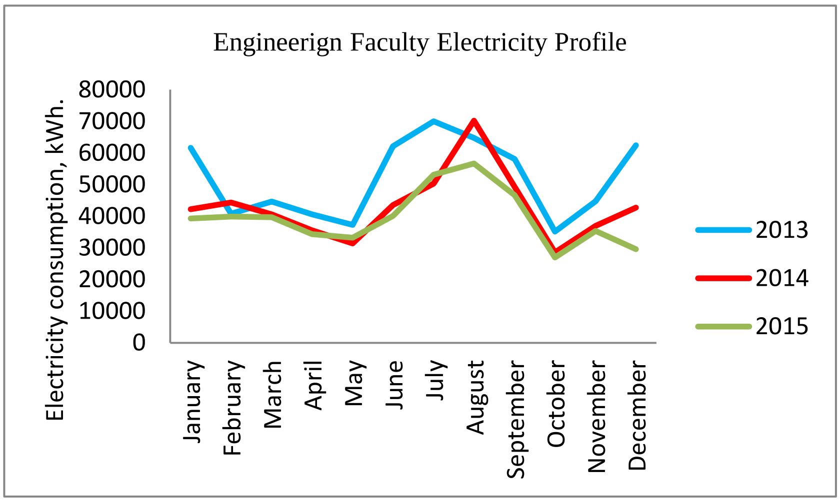

Figure 4.5. R&D Electricity Consumption Pattern (2013-2015).

The Mechanical Engineering department consumes nearly the same amount of energy as the entire Engineering Faculty, which shows that the size of its building in terms of electricity consumption; reason is laboratories related to mechanical, energy, materials and robotics which include machines that require a large portion of electricity.

Figure 4.5 illustrates that for the technical department, the consumption value shows peculiar behavior. The overall heating and cooling trend remain same when compared with other departments, but the consumption starts decreasing in 2015. The reason can be of excessive use of electricity in 2014, but this rapid change during 3 years is quite unpredictable to predict the change for next years. Until 2014, the percentage of electricity consumption increased to about 16%, while next year it decreased 12 % during 2015. The peak demand occurred during July to August where cooling represents the major share of consumption, as this duration represents summer period.

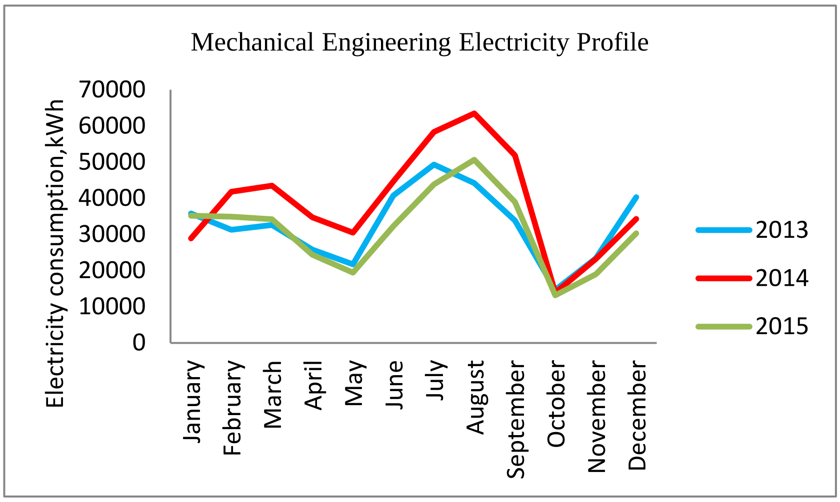

Figure 4.6. Mechanical Engineering Electricity Consumption Pattern (2013-2015)

The architecture department building is also considered one big building due to a combination of several buildings or blocks in terms of electricity consumption. These blocks are named as A, B, C, D and K. Cumulative consumption of this building is nearly same as the mechanical department or the engineering faculty, but the pattern of consumption varies.

Figure 4.7 represents the general trend for architecture building, which resembles the mechanical engineering building, increase until 2014 and then decrease in 2015 but change in 2014 for mechanical was 75,369 kWh and for architecture 36,126 kWh which represents only 9.48% half of that of mechanical engineering. While, in 2015 a decrease in mechanical engineering was 92,701 kWh and for architecture 40,631 kWh, which is nearly 9.7 % which is much less than mechanical engineering.

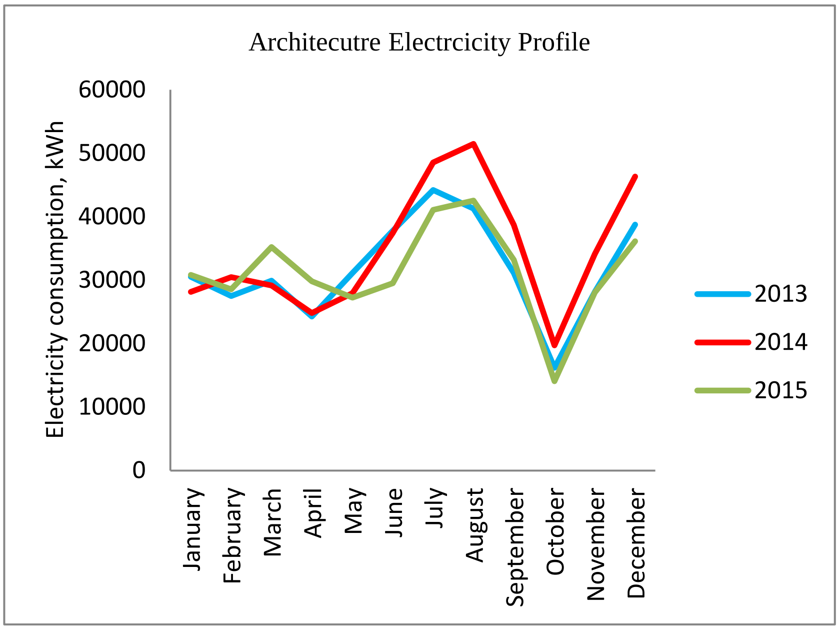

Figure 4.7. Architecture Electricity Consumption Pattern (2013-2015).

For this building, the consumption rise is sharp for heating during winter nearly same as compared to heating, but after December if starts decreasing, still heating consumption during summer in July to September gives the peak value for maximum consumption.

Figure 4.8 shows the consumption pattern for the chemical engineering building. This building is the biggest consumer of electricity as an individual department, the average consumption of the building for 3 years can be considered as 700,000 kWh which is nearly twice than mechanical engineering and other departments. The trend is same for the changes during 2014 and 2015 with mechanical, architecture department, only quantity differs. During 2013-2014, decrease in consumption was 56,347 kWh (7.7%) while in 2015, an increase of 12.1%, about 82,229 kWh.

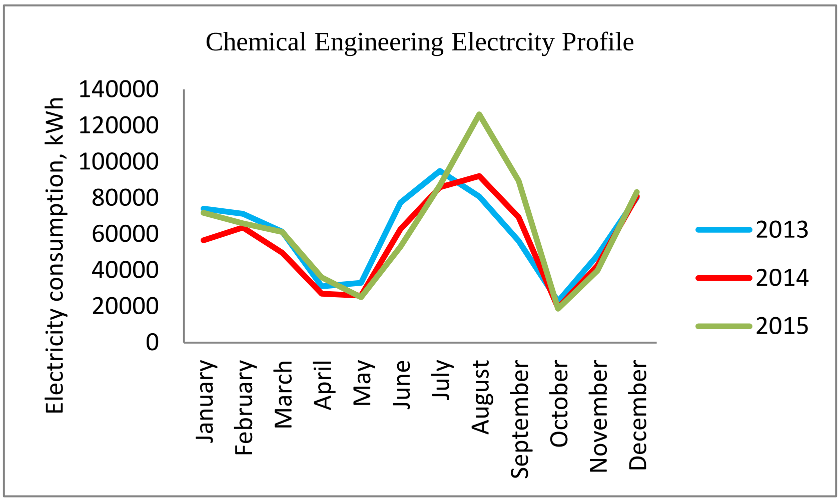

Figure 4.8. Chemical Engineering Electricity Consumption (2013-2015).

Chemical engineering department, peak demand lies also during the summer season where cooling consumption occurs, but the heating consumption is also important as it shows higher cooling consumption required with respect to other departments, even in January cooling consumption was huge, which started decreasing in March or April. In 2015, overall consumption increased, but consumption in May is lower than the last two years.

The medical facility is inside the computer engineering department, no data were available for computer engineering. The electricity consumption and the data for medical facility consume energy of one department. It was assumed during estimation and extrapolation that the data given for medical facility consume electricity equivalent to one department. So, it also includes consumption of electricity of both medical and computer engineering.

Figure 4.9 exhibits trend in the medical and computer engineering building. For this department, the consumption pattern differs from other department like mechanical and chemical engineering, not only in consumption, but also the change is different during 3 years. Small change occurred during 2014 approximately 0.74% decrease, but 2015 depicts huge increase of 37% from 244,992 kWh to 335,768 kWh. Peak demand lies in the same period of July to August or September, while the cooling demand varies as it represents major cooling consumption occurring from January to March or April.

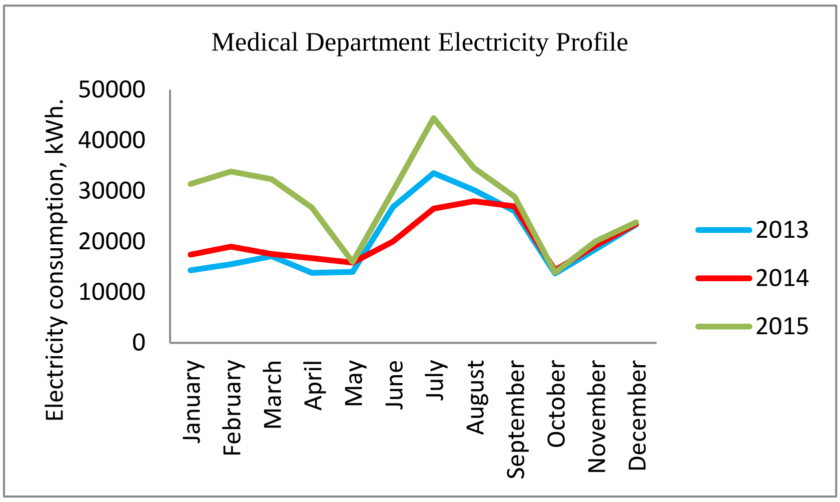

Figure 4.9. Medical and Computer Engineering Electricity Consumption Pattern (2013-2015).

The library utilizes electricity even in the night time because of the working hours. Usually, the library consumption of electricity is mostly because of the offices and study rooms for students. The library usually open 11-12 hours per day and on weekends it opens late, which reduces its operating hours to 6-8 hours. The library also includes a seminar or conference hall, which utilizes electricity on designated days for function or seminars.

Figure 4.10 illustrates the consumption of the library. Library consumption can be compared with mechanical engineering or other similar departments. It has the same trend of change during 3 years, until 2014 a decrease of about 2.5 % and then in 2015, a sharp increase of 12.8%.

Library electricity consumption figure shows no stability through years, yet it gives peak demand in the same period as for other departments. Electricity values of months for each year vary significantly and each month depicts irregular and varying behavior with respect to other years. The lowest and highest consumption remains same for 2013 and 2014 while in 2013 it changes.

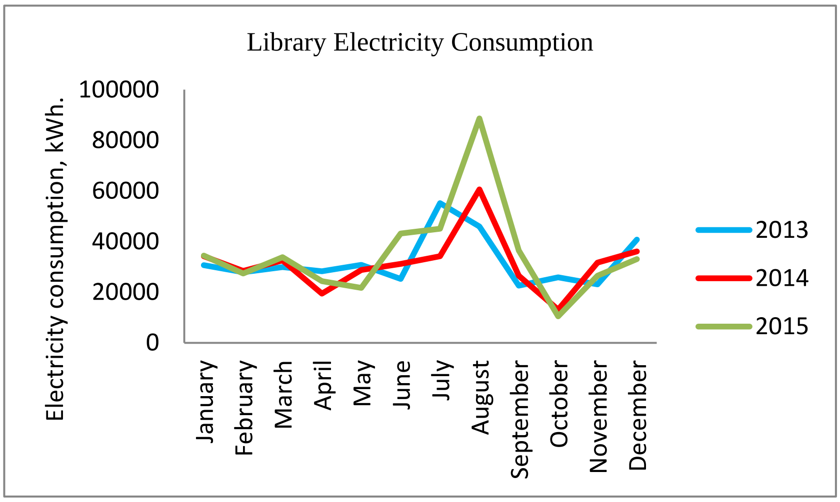

Figure 4.10. Library Electricity Consumption Pattern (2013-2015).

The electricity consumption of the sports saloon includes two kinds of sports center indoor sports and outdoor sports utilities, major consumption share occurs due to indoor sports activities which also includes gymnastic center and swimming pool. As, for the library, the sports center and cafeteria have no specific consumption pattern for a year as their consumption is dependent on usage of facilities which depends on the number of students utilizing these resources, each day it changes and which shows the improper pattern to analyze consumption. During 2014, it shows an increase in consumption 27.2 %, while in 2015 there is a decrease of nearly similar parentage of 15.9%.

Figure 4.11 depicts that the peak demand in case of a sports saloon shows a completely different scenario when compared with other departments. As in other departments, peak demand or consumption occurs in summer while for sports saloon, it occurs in winter. The reason lies in vacation period, as during summer vocation there is no usage of electricity and heating, it does not require much electricity. As the semester starts in October, the consumption also starts increasing with a rapid increase in November and December because of heating requirement.

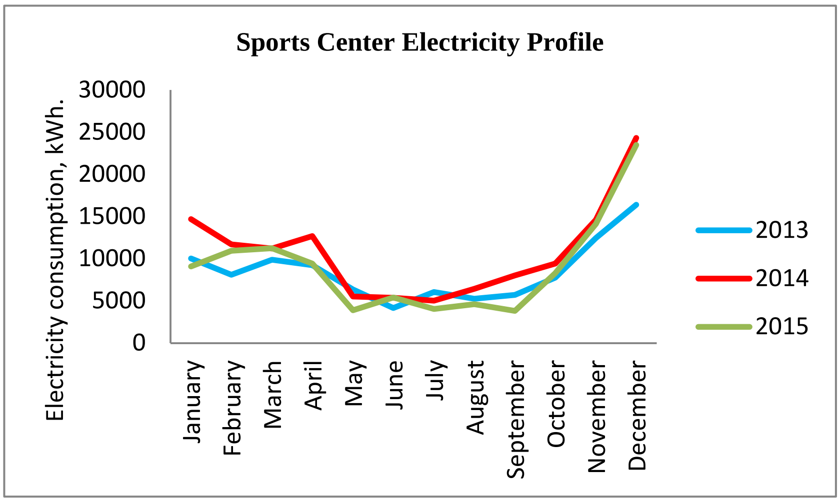

Figure 4.11. Sports Center Electricity Consumption Pattern (2013-2015).

The cafeteria also consumes a great amount of electricity. Usually, the cafeteria uses electricity at its peak during lunch hour in the day.

Figure 4.12 illustrates that the overall consumption for the cafeteria increased from 2013-2015, until 2014 it increased to about 5.25%, while in 2015 the increase was lower, 0.12%. An increase during 3 years does not provide a complete description of the situation; it can be observed that in 2013, consumption during winter was more than 2014 and 2015, while at the start of winter in November it is same. Peak demand lies in the same period as for other departments.

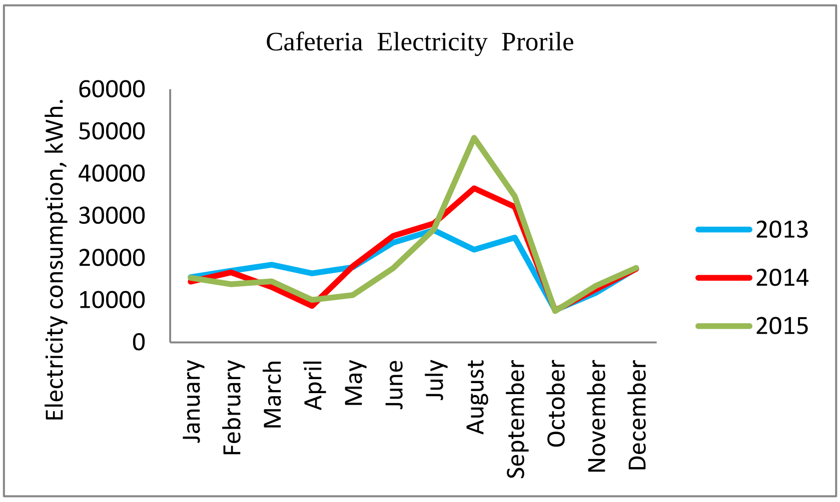

Figure 4.12. Cafeteria Electricity Consumption Pattern (2013-2015).

After evaluation of each department missing data for 2015 based on the change in consumption of each department, now the overall consumption can be found in these years. This can be used to further extrapolated data for some years.

Before calculating the total electricity consumption, the heating and cooling demand must be analyzed. As no specific information or record was available, an assumption was made to consider one month, which consumes the lowest amount of electricity under normal atmospheric conditions which suggests no usage of heating and cooling. When analysis made based on figures and tabulated values, October can be taken as the reference month for calculation of heating and cooling demand as it consumed less electricity with respect to other months. Summer considered from May-September while October considered as month with normal living environment with moderate conditions and winter starts from November to March or April. The BBC weather report also verifies the October reference condition for Izmir as it represents most moderate living condition with minimum and maximum temperature of 14 and 24 °C (BBC 2011).

As October is taken as the reference month for evaluating the heating and cooling consumption, this value will be subtracted from all other months. Months included in winter will give heating consumption while summer months will provide cooling consumption. As shown in the figures representing electricity consumption that the peak consumption occurs during summer period in the months from July to

September depending upon condition each year. A general trend for heating and cooling remains the same as in the case of electricity. Separate heating and cooling consumption values will allow evaluating heat to power ratio for estimating prime mover. For the institute most of the equipment's are electricity based but a separate analysis for heating and cooling annual consumption which can be used for better extrapolation.

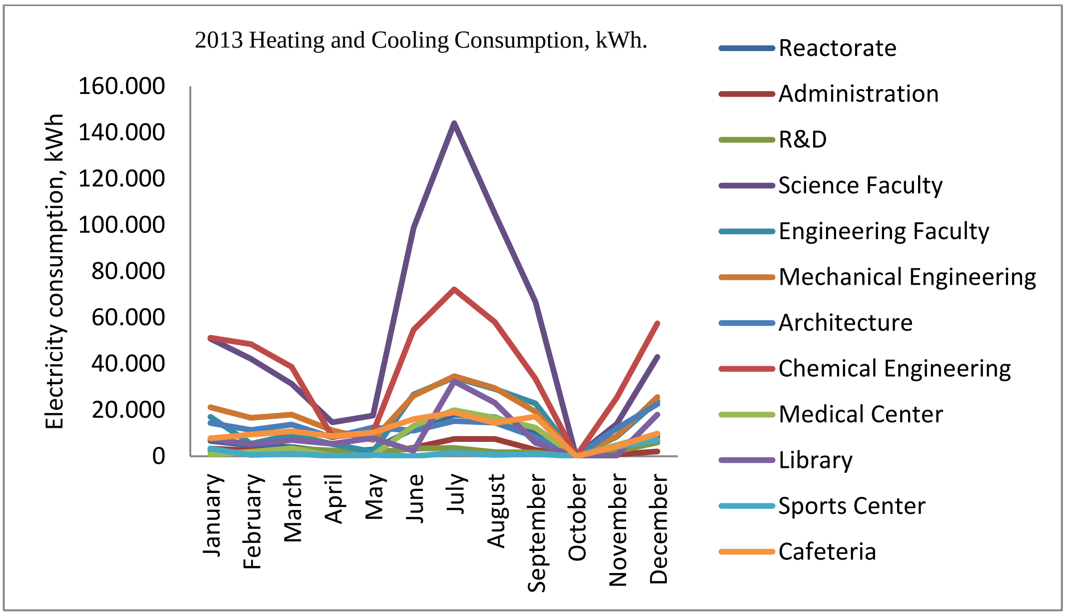

Figure 4.13. 2013 Heating and Cooling Consumption.

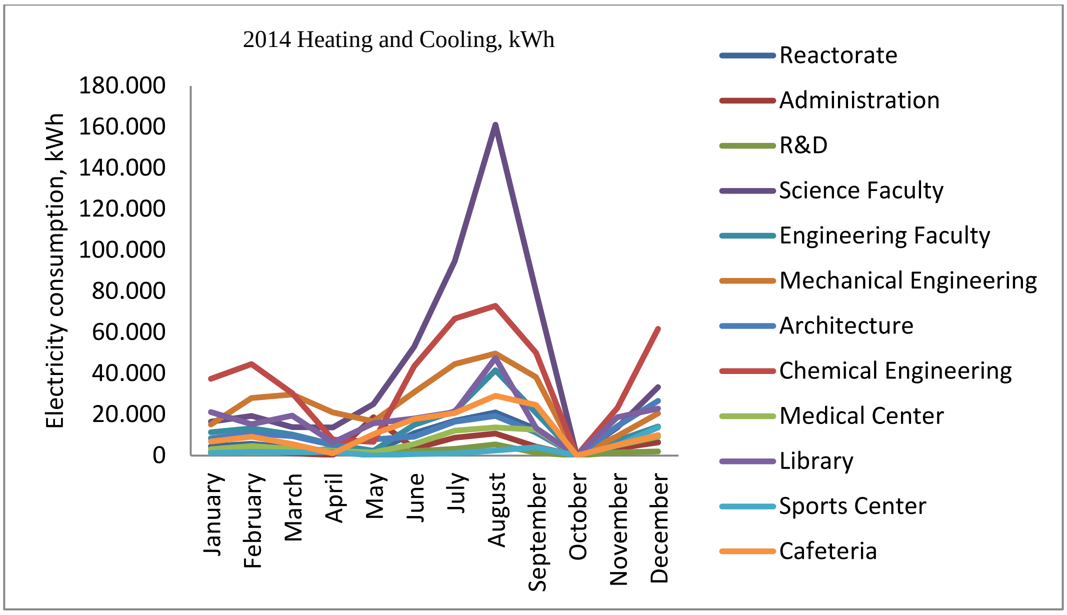

Figure 4.14. 2014 Heating and Cooling Consumption.

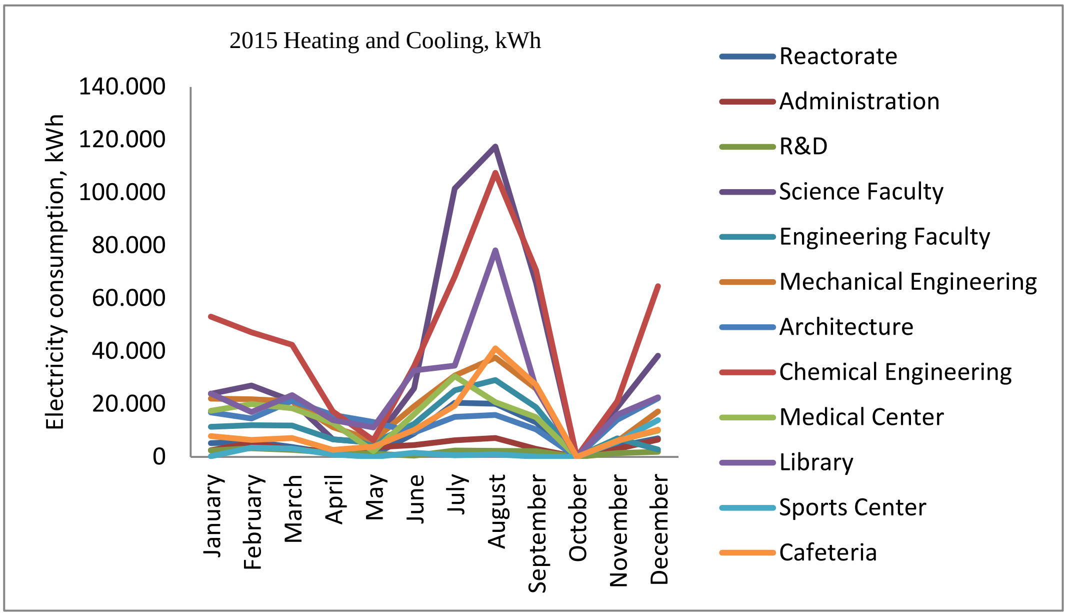

Figure 4.15. 2014 Heating and Cooling Consumption

The Heating and Cooling consumption is evaluated from the electricity data after extrapolation. The pattern of change in consumption remains the same as for electricity. Increased heating and cooling consumption for science, engineering and architecture department is the result of the combined analysis of their sub blocks. The Chemical Engineering department consumes greater energy if compared individually for each department and block. Identical pattern was observed for heating and cooling demand for the change over 3 years.

Total consumption analyzed, provides the percentage share of each utility in electricity. That share of percentage used to define the quantity of heating and cooling for the extrapolated years. Total cooling consumption in 2013 was 1,260,968 kWh with a percentage share of 59.2% and for heating it was 925,144 kWh with percentage of 43.46%. In 2014, share of heating and cooling was increased from 2,128,844 kWh to 2,216,900 kWh, which represents an increase of 4.14% in one year, but the share of cooling increased to 62.85% (1,393,336 kWh) with respect to heating which was 37.15% (823,564 kWh). During 2015, percentage share came to the same level as it was in 2013 to about 58.46% (1,344,509 kWh) and for heating 42.10% (968,296 kWh). Even if the change decreased for cooling and increased for heating, but the consumption is still greater than 2014 and 2013 which depicts that the overall increase share was increased more for cooling.

Table 4.1. Heating and Cooling Consumption (2013-2015)

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<table>
<tr><th rowspan="2">Year</th><th>Heating Consumption (kWh)</th><th>Percentage of Heating</th><th rowspan="2">Total Consumption</th></tr>
<tr><th>Cooling Consumption (kWh)</th><th>Percentage of Cooling</th></tr>
<tr><td rowspan="2">2013</td><td>1,260,968</td><td>59.2%</td><td rowspan="2">2,128,844</td></tr>
<tr><td>925,144</td><td>43.4%</td></tr>
<tr><td rowspan="2">2014</td><td>1,393,336</td><td>62.8%</td><td rowspan="2">2,216,900</td></tr>
<tr><td>923,564</td><td>41.6%</td></tr>
<tr><td rowspan="2">2015</td><td>1,344,509</td><td>58.4%</td><td rowspan="2">2,300,026</td></tr>
<tr><td>968,296</td><td>42.1%</td></tr>
</table>

Table 4.1 illustrates the heating and cooling consumption from 2013 to 2015. Percentage change during 3 years provides the average percentage consumption. Average Consumption for Cooling 60.1% and heating 40.0% will be used to evaluate consumption on an annual basis, considering these percentages will remain constant as neglecting small changes.

After the evaluation of the heating and electricity data, the aim is to determine the increase in consumption, which will provide the capacity for the Cogeneration case. As, a simple Cogeneration power plant has a life time of 20 years. Data extrapolated for 20 years will be based on the existing plan of modifications and expansion of the university with the annual percentage increase during each year. For the next five years, 6 buildings considered to be added for extension of university after which there will be no increase due to additions in the buildings. The annual percentage increase will be based on the comparison of last year with a current year increase and will be taken until 2023. After 2023, no annual increase will be made based on the assumption that the electricity consumption will become stable or reduce due to the energy efficiency measures for next years.

Evaluation of the share of each building addition is based on the consumption of large departments which includes science, engineering faculty, mechanical and chemical engineering, architecture and administration building. As, science, engineering and architecture faculty contain several buildings, to calculate the average consumption of these departments, each department consumption divided by actual consumption provides average consumption of the departments as the buildings included as these departments makes them one big department.

Table 4.2. Average Building Consumption, kWh.

Average of 2015 kWh	**Building**
551,170	Science faculty includes 4 departments
474,950	Engineering faculty 5 blocks
376,426	Mechanical Engineering
376,402	Architecture 4 Blocks
757,632	Chemical Engineering
418,867	Administration Building
492,574	**Average of all buildings**

Table 4.2 shows the average consumption of buildings. The Science faculty total consumption 22,004,683 kWh divided by the number of total buildings included in this department gives the average value, the same method is applied in the Architecture and Engineering faculty building. The overall average consumption evaluated using the total consumption of all buildings divided by the number of buildings which comes out to be 492,574 kWh. This value will be added for each building addition.

The Civil Engineering building considered to be added or operational with central laboratory built in 2016, the average consumption multiplied by 2 provides the increase due to the addition of 2 buildings in 2016, in 2017 Teknopark building, Electrical Engineering, 2018 Food Engineering and 2019 Central Cafeteria for Engineering departments. The value of the total electricity consumption from 2010 – 2015 on a yearly basis is available, the annual increase will be evaluated based on the difference between two successive years.

Table 4.3. Building addition Consumption, kWh.

Building additions		Number of Buildings added
2016	985,149	2
2017	985,149	2
2018	492,574	1
2019	492,574	1
2021	0	0
2022	0	0
2023	0	0

Table 4.3 shows the increase in electricity consumption due to addition of buildings, each year. Annual percentage increase depends on each year's increase. While estimating the increase for 2016, the difference between 2014 and 2015 was evaluated based on annual increase was about 3.23% when multiplied with consumption of 2015 5,126,449 kWh, gives the value of percentage increase for 2016 which is 165,682 in kWh.

Table 4.4. Extrapolated Data from 2016-2023, kWh.

Year	Building addition (kWh)	Departments added	Annual percentage Increase	Annual Increase (kWh)	Total Consumption kWh per year
2010	0	0	-----	-----------	3,716,780
2011	0	0	22.38	831,918	4,548,698
2012	0	0	5.19	236,192	4,784,890
2013	0	0	3.56	170,725	4,955,615
2014	0	0	0.20	10,339	4,965,954
2015	0	0	3.23	160,495	5,126,449
2016	985,149	2	3.25	165,682	6,277,280
2017	985,149	2	3.50	204,011	7,466,441
2018	492,574	1	3.05	261,325	8,220,341
2019	492,574	1	3.12	250,720	8,963,636
2020	0	0	3.01	279,665	9,243,301
2021	0	0	2.50	269,805	9,733,335
2022	0	0	1.6	243,333	9,976,668
2023	0	0	0	159,626	10,136,295

Table 4.4 shows the total increase and the consumption extrapolation until 2023. After 2016, the annual percentage increase is independent of the increase per year. 2010 shows an annual increase of 22.38, % which can be possible because of the building addition, after 2010 the annual increase varies from 5.19 to 0.20%. An average increase taken for the later years about 3.5% to 3.12 % until 2019, but the annual increase is assumed to decrease slowly each year to about 1.6 in 2022. After 2022, no change will be considered for electricity consumption, which will remain stagnant in later years after 2023.

The annual increase in kWh until 2015 is based on the difference between two successive years while from 2016 to onwards, the difference is based on the annual percentage increase assumed to vary from 3.5 to 1.6% until 2022 and after that it remains stable.

Table 4.5. Heating and Cooling Extrapolated Data from 2016-2023, kWh.

Year	Electricity (kWh)	Heating (kWh)	Cooling (kWh)
2010	2,057,874.5	671,260.0	987,645.3
2011	2,518,483.7	821,506.5	1,208,707.6
2012	2,649,256.4	864,163.4	1,271,470.0
2013	2,743,782.0	894,996.8	1,316,836.1
2014	2,749,506.4	896,864.0	1,319,583.4
2015	2,838,367.9	925,849.8	1,362,231.1
2016	3,475,550.2	1,133,692.9	1,668,037.0
2017	4,133,954.5	1,348,458.4	1,984,028.1
2018	4,551,367.3	1,484,614.7	2,184,359.0
2019	4,962,908.5	1,618,855.7	2,381,871.9
2020	5,117,751.3	1,669,364.0	2,456,186.3
2021	5,389,068.7	1,757,865.3	2,586,401.0
2022	5,523,795.5	1,801,812.0	2,651,061.0
2023	5,612,176.2	1,830,640.9	2,693,478.0

Table 4.5 provides the heating and cooling extrapolations. Heating and cooling data extrapolation based on average percentage consumption, which 60.1% for cooling and 40.9% heating from 2013-2015. The capacity of the plant can be analyzed by evaluating the maximum consumption, provided for 2023 where electricity has a major share of 5.6 GWh per year, heating has 1.8 GWh per year and cooling 2.7 GWh per year. For conversion of GWh to GW or KW, operating hours assumed to be 8 hours per day, 7 days per week. Reason lies in the fact that the university does not operate on a 24-hour basis, all departments are closed, utilization of utilities is very low. As hostels are not considered in the electrical consumption data, as no data is available for their utility consumption. Normal working hours for university are 9 from the morning to 5 until evening. As, these operating hours only depicts working hours, in order to consider other electricity consumption, assumption of 7 days a week instead of 5 is made to determine capacity more effectively and to incorporate the changes which is are

cannot be predicted from the utility consumption data. Cooling and Electricity consumption will be added to make capacity analysis as heating and cooling consumption does not appear at the same time and duration. After diving with 8 working hours for 7 days in a year it gives 2.88 MW capacity, which is assumed to be around 3 MW exactly in order to account other important load changes or modifications.

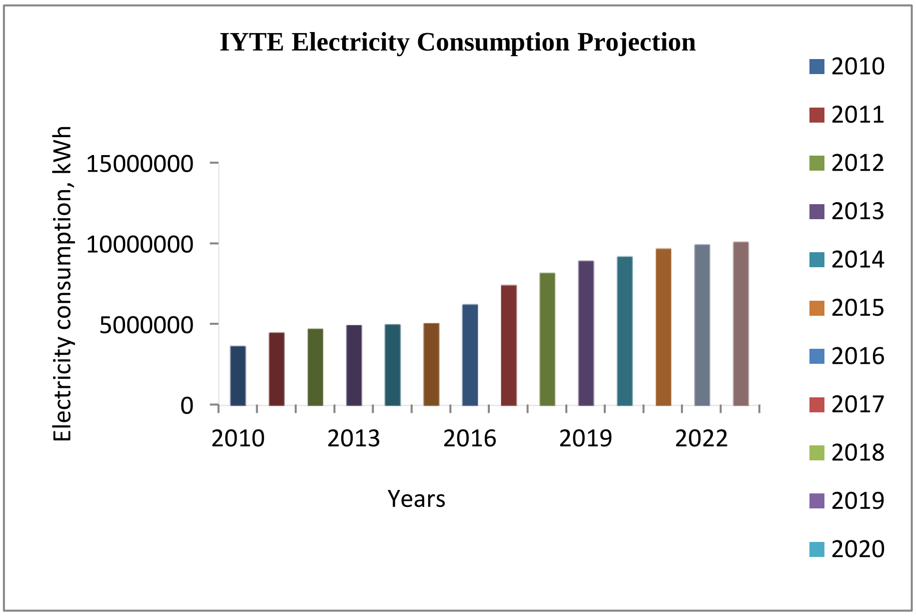

Figure 4.16. IYTE Electricity Consumption Extrapolation , 2010-2023

Figure 4.16 demonstrates the predicted electricity consumption of the institute until 2023. The electricity consumption data from 2010 to 2013, depicts the increase until 2013 and then a slight decrease occurs during next 2 years. After extrapolation because of the increase in departments, rapid increase occurs during the next 4 years, after that slight increase represents an annual increase of electricity. After 2023, the electricity demand will remain same or will decrease slightly as assumption of no department addition leads to stability in electricity consumption.

Heat to power ratio when evaluated gives us a result of 0.33 which depicts that a small prime mover will be enough to meet the demand of electricity as heat to power ratio is not big. The reason for small heat to power ratio is the utilization of electrical equipment and assumption considered in the study. Now the capacity has been analyzed, the next important step comes to be the selection of the prime mover and integration of heat recovery system.

CHAPTER 5

ENERGY AND MASS ANALYSIS

5.1. Brayton-Rankine Cycle Calculations.

Basic Operating Cycles to be used for calculations are Brayton or Gas turbine cycle while steam turbine will be operating on Rankine Cycle. As described in the methodology, natural gas will be used as a fuel in both cases with the same composition and a Lower Heating Value. The gas turbine is considered as the heart of the system as heat and electricity generation depends on it. Its efficiency determines the waste heat and power generation. Gas turbines utilize a mixture of air and fuel which burns at high temperature in the combustion chamber to get a gaseous mixture at high temperature and pressure to spin the blades of a turbine-generator system. Generally, the blades are of two types known as stator and rotor, the function of stator is to increase the pressure energy converted from kinetic energy through principle of diffusion and to direct the steam towards rotor blades resulting in rotation of shaft. A shaft is connected to a generator which in return produces electricity. In an Open Cycle, the heat is allowed to move out of the system, which can be utilized in any other system. A heat recovery steam generator is utilized for this purpose.

The calculations for gas turbine are based on actual cycle while isentropic efficiency is used to evaluate the actual parameters and expected power outcome. The gas turbine selection is based on the institute energy requirement. As, the capacity to be generated is taken nearly 3 MW, a gas turbine of small capacity is required. Most of the manufacturers are producing high capacity gas turbine. Manufacturers like Solar Turbine are quite famous for the efficient turbine system for small and high scale. There are several other manufactures like Siemens and General electric but they manufacture turbines for power capacity of 5 MW or more, which is undesirable for our system. The selection of Gas–Steam turbine combined cycle is based on its traits like high reliability, availability, lower emissions, ability to utilize clean fuel from multiple sources and high quality exhaust production. It can be utilized for a variety of purposes like process, space or domestic heating, improved reliability and worldwide service. There are several packages according to design and specifications; each package has specific output generation. Two small gas turbine packages can be used to meet the institute requirements, Saturn 20 and Centaurs 40 having generation of capacities of 1.2 MW and 3.5 MW respectively. Generation capacity of Saturn 20 is not enough to meet the energy requirements of institute. Centaurs 40 has generation capacity of 3.5 WM, which is little bit higher than our requirement but with the option of selling electricity to grid or other consumers seems to be a beneficial option (SolarTurbine).

The Manufacturer provides a catalogue for flow rate and temperature limitations. Usually, calculations are being made at full load operating conditions with maximum power output generation while the catalogue suggest power output of 3.5 MW is apart from that of compressor. Turbine back power term is used for turbine coupling with compressor to provide power to compressor for its operation. Turbine is based on single shaft operation, axial flow compressor with 11 stages having a pressure ratio of 10.3:1, which is used for actual pressure output of compressor. The inlet and outlet mass flow rates are used for evaluating the fuel mass flow rate. Combustion chamber is conventional lean mixture combustion, which can also be verified by the combustion calculations with the mixture to be lean, lean mixture reduces significant amount of emissions. The turbine has net generation capacity of 3.5 MW which does not count compressor power. It is three stage reaction turbine with 14,950 rpm shaft speed (SolarTurbine).

During calculations, the density is composition dependent while the specific heat is taken as function of temperature. The procedure is followed from Cengel's Thermodynamics (Cengel and Boles 2006) for actual cycles, isentropic efficiency is taken highest from the literature. First, the compression cycle with given pressure ratio will be used to evaluate the inlet temperature and pressure for combustion process, after that fuel flow rate with given heating value used for stoichiometric combustion analysis is done to obtain the actual and theoretical air to fuel ratio, which provides the excess air required for the lean combustion phenomena. The outlet of compressor is considered the gaseous mixture used for turbine calculations.

5.1.1. Gas Turbine based Cogeneration Calculations.

Brayton Cycle Analysis:

Data is taken from the official Catalogue of Centaurs 40 generator set. Only required data is taken for calculations.

- m_{in} = 18.4 kg/s (5.1)
- T_1 = 15 °C and P_1 = 100 kPa (5.2)
- m_{out} = 18.9 kg/s (5.3)
- W_{net} = 3.5 MW (5.4)
- Pressure ratio $(\frac{P_2}{P_1})$ = 10.3:1 (5.5)
- T_4 = 445 °C (5.6)

Assumptions:

The assumptions considered for the case study are as follows:

- Air assumed to be ideal for compression cycle only.
- Steady state operation.
- Kinetic and potential energies to be negligible.
- Values represent full load operation condition.

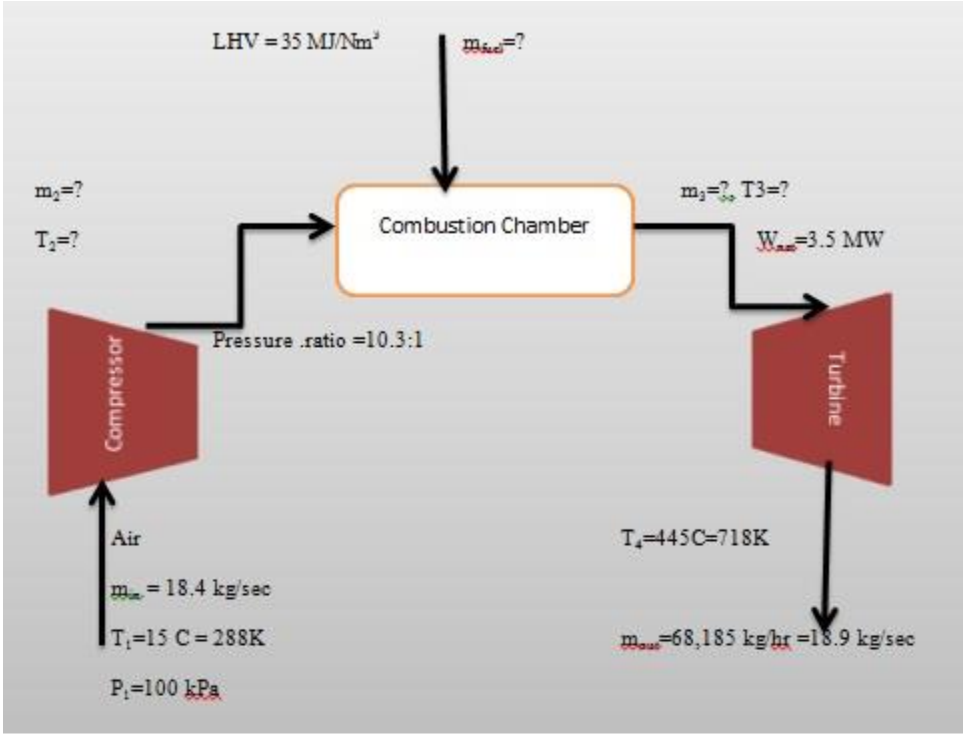

Figure 5.1: Operating Cycle with Parameters

The mass balance Equation 3.1 is used to get the fuel flow rate.

$$m_{fuel} = 18.9\text{-}18.4 = 0.54 \text{ kg/s} \tag{5.7}$$

As Compressor is Control Volume and converting fuel flow rate into kg per second. So, m_{in}=m_2

$$m_{fuel} = 18.4 \text{ kg/s} \tag{5.8}$$

$$m_{out} = 18.9 \text{ kg/s} \tag{5.9}$$

The first step involves the calculation over the compression cycle. As the compression ratio given gives the pressure at the exit of compression.

$$P_2/P_1 = 10.3:1 \quad (5.10)$$

$$P_2 = 1,030 \text{ kPa} \quad (5.11)$$

Assuming Air to be an ideal gas and using Equation 3.2.

$$T_{2s} = 561.13 \text{ K} \quad (5.12)$$

Now we find h_{2s} from T_{2s}. By using table, A-17 from Cengel's Thermodynamics(Cengel and Boles 2006).

$$h_{2s} = 566.30 \text{ kJ/kg} \quad (5.13)$$

At, T_1 = 288 K, h_1 = 288.18 kJ/kg. Using Equation 3.3 for isentropic work.

$$W_{sc} = 278.12 \text{ kJ/kg} \quad (5.14)$$

Assumed, isentropic efficiency to be considered n_{is}=0.89 and using equation Equation 3.4.

$$W_{ac} = 312.49 \text{ kJ/kg} \quad (5.15)$$

Multiplying equation 5.23 with mass flow rat to get the power in MW.

$$W_{ac} = 5749.8 \text{ kJ/s} = 5.749 \text{ MW} \quad (5.16)$$

As, $W_{net} = 3.5$ MW

Calculating T_2 at exhaust of compressor.

$$h_{2a} = 600.67 \text{ kJ/kg} \quad (5.17)$$

To find T_{2a} Using Table-A17 Cengel's Thermodynamics (Cengel and Boles 2006).

$$T_{2a} = 593.9 \text{ K} \quad (5.18)$$

After the compression cycle analysis, next is the combustion analysis. In the combustion chamber, fuel is injected with high pressure air, combustion occurs at high temperature. Usually, the stoichiometric calculations are done in order to know the amount of air required for combustion of reactants and to evaluate the gaseous products. Balancing atomic abundance on both sides provides an overall reaction situation. Usually, the amount of air evaluated from stoichiometric calculation is called theoretical air required for combustion but in actual case it is different. If less air is required than stoichiometric value than mixture is termed as fuel rich and if more air is required than mixture is called lean mixture. Lean mixture is preferred as it represents a complete combustion while for rich mixture the composition of the gaseous mixture can differ and unburned fuel with carbon monoxide can become a problem resulting in loss of fuel with more environmental emissions. Methodology used for stoichiometric calculation is based on Fundamental of Air pollution (Flagan and Seinfeld 1988) and Fundamental of Combustion Process (McAllister, Chen, and Fernandez-Pello 2011).

Composition of natural gas in mole % (Duzen 2014).

CH_4 = 81.74, C_2H_6 = 7.56, C_3H_8 = 5.50, C_4H_{10}-iso = 1.42, C_4H_{10}-n=1.49, C_5H_{12}-iso=0.40, C_5H_{12}-n= 0.28, C_6H_{14} = 0.36, CO_2 = 0.96, N_2= 0.24.

Evaluating chemical reactions:

1. **CH_4:**

$$0.8174\{CH_4 + 2(O_2+3.76\ N_2) \rightarrow CO_2 + 2\ H_2O + 2(3.76)\ N_2]\} \quad (5.19)$$

2. **C_2H_6**

$$0.0756\{C_2H_6 + 3.5(O_2+3.76\ N_2) \rightarrow 2CO_2 + 3\ H_2O + 3.5(3.76)\ N_2]\} \quad (5.20)$$

3. **C_3H_8**

$$0.0550\{C_3H_8 + 5(O_2+3.76\ N_2) \rightarrow 3CO_2 + 4H_2O + 5(3.76)\ N_2]\} \quad (5.21)$$

4. **C_4H_{10}**

$$0.0292\{C_4H_{10} + 6.5(O_2+3.76\ N_2) \rightarrow 4CO_2 + 5H_2O + 6.5(3.76)\ N_2]\} \quad (5.22)$$

5. **C_5H_{12}**

$$0.0068\{C_5H_{12} + 8(O_2+3.76\ N_2) \rightarrow 5CO_2 + 6H_2O + 8(3.76)\ N_2]\} \quad (5.23)$$

6. C_6H_{14}

$$0.0036\{C_6H_{14} + 9.5(O_2+3.76\ N_2) \rightarrow 6CO_2 + 7H_2O + 9.5(3.76)\ N_2]\} \quad (5.24)$$

<u>Overall Reaction:</u>

$$0.8174\ CH_4 + 0.0756\ C_2H_6 + 0.0550C_3H_8 + 0.0282\ C_4H_{10} + \\ + 0.0068\ C_5H_{12} + 0.0031\ C_6H_{14} + 2.77\ (O_2+3.76\ N_2) \\ \rightarrow 2.79\ CO_2 + 2.29\ H_2O + 2.45\ (3.76)\ N_2]\} \quad (5.25)$$

$$m_{f,s} = 0.8174\ (16\ g/mol) + 0.0756180\ (30.07\ g/mol) + 0.0550491(44.1\ g/mol) \\ +0.0282187\ (58.12\ g/mol) + 0.006885\ (72.15\ g/mol) \\ + 0.0031933\ (86.18\ g/mol) + 0.0096299\ (44\ g/mol) + 0.0024562\ (28\ g/mol) \quad (5.26)$$

$$m_{f,s} = 20.73\ g/mol \quad (5.27)$$

$$m_{air,s} = 2.77\ (4.76)\ 29\ g/mol \quad (5.28)$$

$$m_{air,s} = 382.4\ g/mol\ or\ kg/kmol \quad (5.29)$$

The stoichiometric air to fuel and fuel to air ratios are calculated using Equation 3.5.

$$\left(\frac{F}{A}\right)_{stoichiometric} = 20.7386/382.4 = 0.054225\ kg\ of\ fuel/kg\ of\ air \quad (5.30)$$

$$\left(A/F\right)_{stoichiometric} = 382.4/20.7386 = 18.43\ kg\ of\ air/kg\ of\ fuel \quad (5.31)$$

Calculating real case air to fuel ratio is done using actual air and fuel flow rates,

$$(F/A)_{actual} = 0.50/18.4 = 0.027 \quad (5.32)$$

$$(A/F)_{actual} = 18.4/0.50 = 34 \quad (5.33)$$

$$\varphi \text{ (equivalence ration)} = 0.027/0.05423 = 0.493 \quad (5.34)$$

φ known as the equivalence ratio. As φ <1, Which represents a lean mixture and combustion products contains CO_2, H_2O, N_2, O_2 and the excess air is evaluated using Equation 3.7

$$\% \text{ Excess Air} = (34/18.43)100 = 185.38\% \quad (5.35)$$

Cp of natural gas at ambient temperature.

$$Cp_{N.G} = 2.0567 \text{ kJ/kg.K} \quad (5.36)$$

Converting Products into mole fraction
H_20 = 2.79 , CO_2 = 2.29, N_2 = 9.22,Total = 14.28.

$$\text{Faction of } H_20 = 2.79/14.28 = 0.19 = 19\% \quad (5.37)$$

$$\text{Fraction of } CO_2 = 2.29/14.28 = 0.16 = 16\% \tag{5.38}$$

$$\text{Fraction of } N_2 = 9.22/14.28 = 0.65 = 65\% \tag{5.39}$$

$$Cp_{gas} = 0.19 \times H_2O + 0.16 \times CO_2 + 0.65 \times N_2 \tag{5.40}$$

$$Cp_{gas} = 0.369 + 0.19744 + 0.7585 \tag{5.41}$$

$$Cp_{gas} = 1.32499 \text{ kJ/kg.K} \tag{5.42}$$

The combustion analysis provides the insight of the combustion, but in order to analyze the exhaust mass flow rate and the temperature, gas turbine analysis is made to determine the efficiency in order to evaluate the parameters for HRSG. First the inlet temperature of the gas turbine is evaluated using Equation 3.8, which is later used to evaluate heat input to determine the actual efficiency.

$$W_{gt} = m_g \, CP_{gas} (T_3 - T_{4a}) \tag{5.43}$$

$$T_3 = 1{,}087.36 \text{ K} = 814.36 \text{ °C} \tag{5.44}$$

Calculating heat from the combustion chamber for evaluation of the efficiency by using Equation 3.9.

$$Q_{in} = Cp_{gas} (T_3 - T_2) \tag{5.45}$$

$$Q_{in} = 653.82 \text{ kJ/kg} \quad (5.46)$$

$$Q_{in} = Qin \times mfuel \quad (5.47)$$

$$Q_{in} = 653.82 \times 18.9 \quad (5.48)$$

$$Q_{in} = 12{,}357.37 \text{ kJ/s} \quad (5.49)$$

$$n_{th} = 28.32\% \quad (5.50)$$

$$\text{Heat rate} = \text{Heat input turbine} / \text{Net work output} \quad (5.51)$$

$$\text{Heat Rate} = 12{,}710.437 \text{ kJ/kWe.hr} \quad (5.52)$$

The density of natural gas is based on the composition at normal temperature and pressure (20°C and 1 atm)(EngineeringToolBox). The density of natural gas is evaluated by multiplying the composition with given density at normal temperature and pressure while for pentane and hexane, densities are not available even the percentage of these components are very low which will make its affect negligible for overall density.

$$CH_4 = (0.668 \text{ kg/m}^3)0.8174 = 0.546 \text{ kg/m}^3 \quad (5.53)$$

$$C_2H_6 = (1.264 \text{ kg/m}^3)0.0756 = 0.0955 \text{ kg/m}^3 \quad (5.54)$$

$$C_3H_8 = (1.881\ kg/m^3)\ 0.0567 = 0.1066\ kg/m^3 \tag{5.55}$$

$$C_4H_{10} = (2.489\ kg/m^3) 0.0291 = 0.0723\ kg/m^3 \tag{5.56}$$

$$N_2 = (1.665\ kg/m^3) 0.0024 = 0.00399\ kg/m^3 \tag{5.57}$$

$$CO_2 = (1.842\ kg/m^3)\ 0.00962 = 0.0177\ kg/m^3 \tag{5.58}$$

$$\text{Density of natural gas} = 0.8421\ kg/m^3 \tag{5.59}$$

$$Q_{fuel} = {W_{net}}/{\eta} = 3.5 / 0.28 = 12.36\ MW \tag{5.60}$$

5.1.2. HRSG Calculations

The Heat Recovery Steam Generation system is the most important system after the gas turbine, increased efficiency of HRSG defines increased heat recovery with minimum loss to the environment and maximum utilization of resources. The selection of HRSG is not dependent on the manufacturer as it was for gas turbine, but HRSG cycle plays an important role in determining efficiency. For making good comparison, each case has an identical HRSG system; only the conditions change depending upon the size of prime mover and the steam turbine. As, the prime mover decides the waste heat generation, steam turbine finalizes the HRSG exit pressure and temperature for getting the desired quality steam, which can be used to generate electricity from a steam turbine.

In both cases, single pressure HRSG is selected because the aim is to compare the performance of both systems. Double pressure HRSG will increase the efficiency up to 10% for each case, triple pressure is usually not recommended due to its increased cost. Each single pressure HRSG has a superheater, economizer and evaporator. The superheater pressure and temperature is dependent on steam turbine inlet conditions. Several industrial calculations have been performed which depict the optimal operating conditions for single pressure HRSG.

The inlet mass flow rate of HRSG is same as the exit gas flow rate of gas turbine as no pressure drop is considered. HRSG is a counter flow system, water first comes in contact with exhaust gas of turbine in which water is heated below saturation temperature, the approach point plays an important role because it reduces the chance of evaporation in economizer saving it from corrosion of tubes while evaporator is responsible for heating of water to saturated temperature, usually the economizer pre-heat the water in order the reduce the temperature difference between hot gas and water to minimize tube damage. In the evaporator, steam is still saturated, which means the composition is nearly 0.90-0.98, this steam then goes to the superheater to produce dry steam from saturated steam via incoming hot gaseous mixture from the steam turbine. The give inlet conditions are as follows:

$$m_{gt\text{-}exhaust} = 68{,}185 \text{ kg/hr} \tag{5.61}$$

Assumptions and Conditions:

The assumptions considered also provide some of the parameters required for calculations, which are as follows:

- After pump, the feed water enters at 110 °C (Hicks 1998).
- As, selecting the steam turbine with 700 KW-3 MW capacity from manufacturer PBS Energo which is condensing turbine. It has higher efficiency than a conventional multi-stage turbine and can work on both fully condensing/fully back pressure mode. This turbine gives multiple operating options as it can provide extraction stages to recover heat and utilize for other purpose with its increased efficiency advantage (PBSENERGO).

  Max Operating Conditions are:

  - Temp. Max. = 500 °C
  - Max Pressure = 4,200 kPa.

- Nominal operating conditions are taken from various industrial articles by V. Ganapathy, to analyze different combined cycle and HRSG systems with single or dual pressure recovery mechanism (Ganapathy 1997).
    - Nominal Operating Pressure of 3100 kPa.
    - Nominal Operating Temperature of 350 °C.
- Blow down negligible.
- Approach Point ($\Delta t_{App} = T_s - T_{eco,out}$), Δt_{App} = 5 K for this case.
- Pinch Point ($\Delta t_{pp} = T_{g3} - T_s$), Δt_{pp} =10 K. (It is the most important parameter in HRSG, lower the pinch point, higher is the cost, but lower pinch point also means high heat recovery. So, an optimized pinch point must be used. Avoiding pinch point can lead to thermal cross situation which is impossible in terms of thermodynamics (Ganapathy, 2001).
- As assumed that there is no pressure drop which means, the superheater has the same pressure as a steam turbine inlet.
- Another assumption that the minimum temperature drop from the superheater to the steam turbine is 20 K.
- Assuming, in superheater there is a pressure drop of 70 kPa which makes Drum pressure 3,100+70 = 3,170 kPa.

Interpolation Equation (3.13) is used to calculate saturation temperature. Using Table A-5 Cengel's thermodynamics(Cengel and Boles 2006).

$$T_s = 237\text{ C } (510\text{ K}) \qquad (5.62)$$

From the pinch and approach point, the economizer outlet temperature and superheater inlet temperature can be found as in the equations below.

- $$T_{g3} = 520\text{ K}. \qquad (5.63)$$

$$T_{eco,out} = 505\text{K}. \qquad (5.64)$$

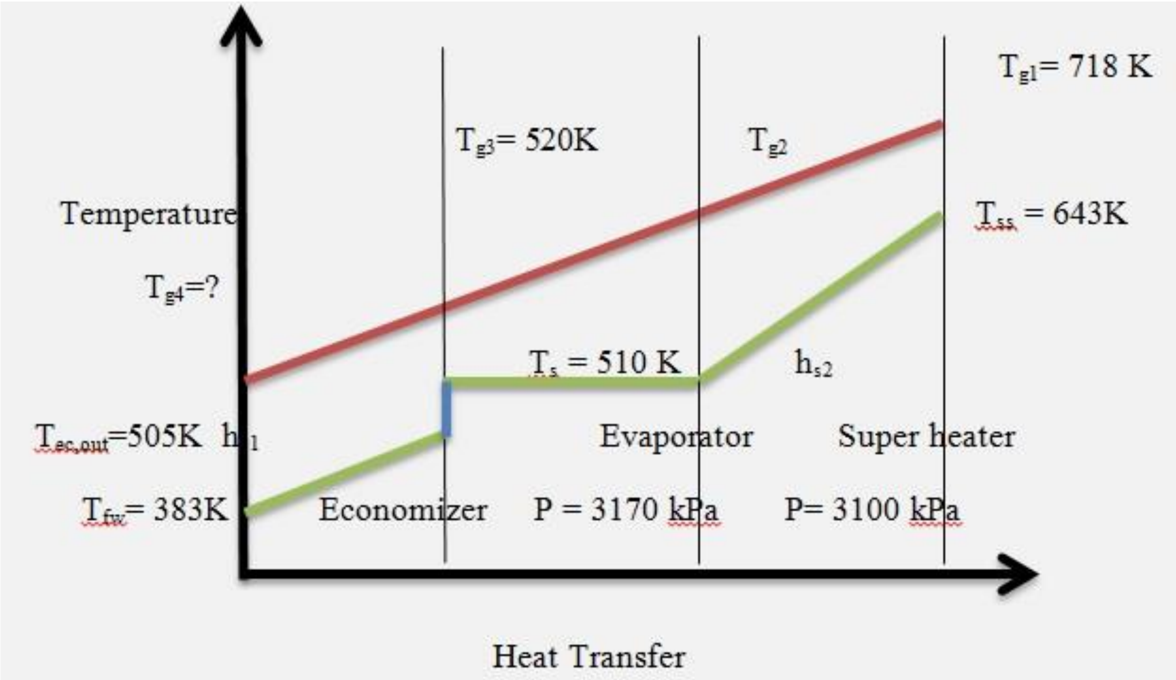

Figure 5.2 : Temperature -Enthalpy Diagram of HRSG

General calculation methodology used for HRSG is based on Waste heat boiler desk book (Ganapathy 1991).

Energy Balance on Superheater and Evaporator:

Assume 1 % heat loss in this section and using Equation 3.14 to evaluate heat absorbed.

$$Q_1 + Q_2 = m_{Gt\text{-}exahust}\ C_{pg}\ (T_{g1}\text{-}T_{g3})\ (1\%\ \text{heat loss}) \quad (5.65)$$

Q_1, Q_2 represent the energy balance on superheater and evaporator. Using Table A-2, Cengel's thermodynamics and Equation (3.13), At 718 K

$$Cp_{N2} \text{ at } 718\text{ K} = 1.1023\text{ kJ/kg.K} \quad (5.66)$$

$$Cp_{CO2} \text{ at } 718K = 1.133 \text{ kJ/kg.K} \tag{5.67}$$

$$Cp_{H2O} = a+bT+cT^2+dT^3 \tag{5.68}$$

A= 32.24, B= 0.1923*10^-2, C= 1.055*10^-5, D= 7.469*10^-9 from Table A-2.Putting constant values in Equation (5. 70).

$$Cp_{H2O} = 32.24+1.38+5.438+2.7646 \tag{5.69}$$

$$Cp_{H2O} = {}^{41.8}/_{18} = 2.32 \text{ kJ/kg} \tag{5.70}$$

Now, using Equation (5.40) to find Cp of exhaust gas.

$$Cp_{gas} = 0.19(2.32) +0.16(1.133) +0.65(1.1023) \tag{5.71}$$

$$Cp_{gas} = 1.337 \text{ kJ/kg.K} \tag{5.72}$$

$$Q_1+Q_2 = 17{,}869{,}830.1 \text{ kJ/hr} \tag{5.73}$$

Enthalpy absorbed by steam:

The Energy absorbed by steam is given by Equation 3.15.

$$E = (h_{sh} - h_{s1}) \text{ kJ/kg} \tag{5.74}$$

h_{s1} enthalpy at economizer exit and hsh enthalpy at superheater

T_{sh} = 643 K, P = 3,100 kPa.

1. h_{sha} at 370 for 3.0 MPa using Equation (3.13).

$$h_{sha} = 3{,}162.3 \text{ kJ/kg} \tag{5.75}$$

2. For h_{shb} at 370 for 3.5 MPa using Equation (3.13)

$$h_{shb} = 3{,}152.2 \text{ kJ/kg} \tag{5.76}$$

Now calculating for 3.1 MPa desired pressure by using Equation 3.77 and 3.78 result.

3. h_{sh} at 3.1 MPa using Equation (3.13).

$$h_{sh} \text{ at } 3.1 \text{ MPa} = 3{,}160.3 \text{ kJ/kg} \tag{5.77}$$

h_{s1} at T (505 K) & P (3170 kPa), using steam table A-4 for water(Cengel and Boles 2006) by using Equation (3.13).

$$h_{s1} = 999.564 \text{ kJ/kg} \tag{5.78}$$

Now using Equation 3.15 to calculate the total energy absorbed by steam.

$$E = (3,160.3 - 999.564) = 2,160 \text{ kJ/kg} \quad (5.79)$$

Energy absorbed by steam/ enthalpy absorbed in evaporator and superheater is 2,160 kJ/kg

As, steam generation rate is given by Equation 3.16.

$$Ws = 8,273.06 \text{ kg/hr} \quad (5.80)$$

$$Ws = 9.01 \text{ ton/hr.} \quad (5.81)$$

Energy absorbed by the superheater and exit temperature of Superheater.

Energy absorbed by superheater is evaluated using Equation 3.17.As, hsh= 3,160.3 kJ/kg at Tsh= 643K can be used in Equation (3.13) to find hs_{2}.

$$h_{s2} = 2,803.12 \text{ kJ/kg} \quad (5.82)$$

$$Q_1 = 2,954,971.57 \text{ kJ/hr} = 2,954.9 \text{ MJ/hr} \quad (5.83)$$

Temperature exit as taken by assumption after 20K temperature drop to be 623 K. The energy absorbed by economizer is determined by Equation 3.18.

$$Q_2 = = 14,914.58 \text{ MJ/hr.} \quad (5.84)$$

Economizer duty and exit gas temperature:

The exit temperature from the economizer is determined by first evaluating the heat absorbed by using Equation 3.18, then using these values in Equation 3.19.

$$Q_3 = Ws\,(h_{s1} - h_{fw}) \tag{5.85}$$

$$h_{fw} = 461.42 \text{ kJ/kg at } (110\ °C) \tag{5.86}$$

Using interpolation, Equation (3.13)for h_{f1} at 232C or 505 K, sat liquid.

$$h_{s1} = 999.564 \text{ kJ/kg} \tag{5.87}$$

$$Q_3 = 4{,}423.93 \text{ MJ /hr} \tag{5.88}$$

Formula for calculating the exhaust temperature of HRSG, Equation 3.19 is used. Cp_g at 520K is calculated using Equation (3.13)

$$Cp_{N2} \text{ at } 520 \text{ K} = 1.0596 \text{ kJ/kg.K} \tag{5.89}$$

$$Cp_{CO2} \text{ at } 520\text{K} = 0.9924 \text{ kJ/kg.K} \tag{5.90}$$

For calculation of water specific heat, Equation (5.94), and the parameter are as follows:

A=32.24, B=0.1923*10^$^{-2}$, C=1.055*10^$^{-5}$, D=7.469*10^$^{-9}$

$$Cp_{H2O} = 32.24+0.996+2.85272+1.050 \quad (5.91)$$

$$Cp_{H2O} = {}^{37.13}/_{18} = 2.063\ kJ/kg \quad (5.92)$$

Now, using Equation (5. 40) to evaluate specific heat of gas at the evaporator outlet.

$$Cp_{gas} = 1.238\ kJ/kg.K \quad (5.93)$$

Now using Equation 3.19 for the stack temperature evaluation.

$$T_{g4}\ (\text{stack temperature}) = 467.3\ K\ (194.6\ °C) \quad (5.94)$$

As, T_{fw} is 110 °C and $\mathbf{T_{g4} > T_{fw}}$, which shows that our assumption for approach and pinch point is correct.

ASME Efficiency of HRSG:

The efficiency for HRSG is by Equation 3.20 but first inlet enthalpy calculations are done by first analyzing the composition of entering gas. Entering gas HRSG, composition calculated by Equation (3.13).to evaluate @ 718 K and table A-18, 19 from Cengel's thermodynamics(Cengel and Boles 2006).

<u>N_2;</u>

$$h= 755.65\ kJ/kg \quad (5.95)$$

$\underline{CO_2 :}$

$$h= 636.8 \text{ kJ/kg} \tag{5.96}$$

$\underline{H_2O:}$

$$h = 1,375. \text{ kJ/kg} \tag{5.97}$$

Now, using Equation (5. 40) to evaluate enthalpy based on composition.

$$H_{inlet} = 854.3 \text{ kJ/kg} \tag{5.98}$$

Using Equation (3.20) to evaluate the HRSG efficiency.

$$Q_1+Q_2+Q_3 = 22,293,766.2 \text{ kJ/hr} \tag{5.99}$$

$$\eta_{HRSG} = 38.27\% \tag{5.100}$$

5.1.3. Steam Turbine Calculations

The working principle of the steam turbine is the same as the gas turbine, but the difference lies in the working fluid as the gas turbine utilizes a mixture of gases while steam turbine utilizes high pressure steam, steam should be dry or superheated because saturated steam at higher kinetic energy acts as bullets for turbine blades with moisture content which can cause huge damage in form of erosion and corrosion causing blade imbalance, vibration and early depreciation. Inlet and outlet conditions are provided by the catalogue of PBS Energo, while isentropic efficiency will be used to determine the actual conditions, as pressure drop and other reversibility's cause deviation from ideal conditions.

The power output of the steam turbine is calculated using the input flow rate estimated from the HRSG exit of super heater. It is also assumed that the work output of steam turbine also has share in driving the pump for feed water pumping which is subtracted at the end to get the overall power from combined generation. All the conditions given in the figure below are taken from the official catalogue of the turbine manufacturer.

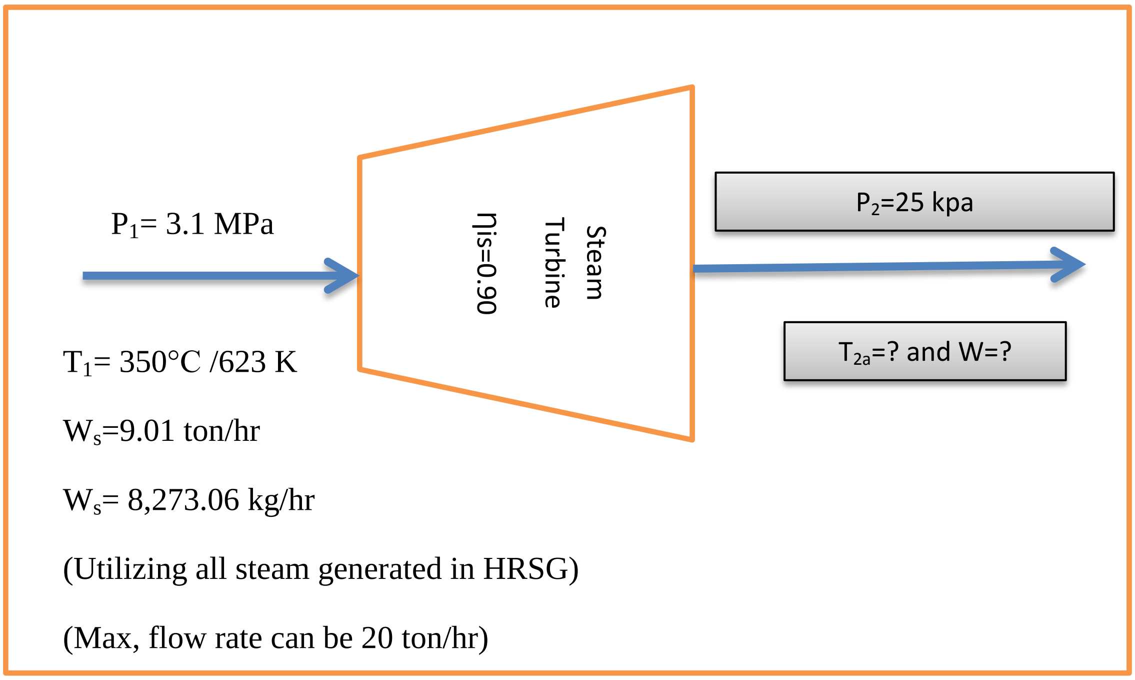

Figure 5.3: Steam turbine Flow with Operating Condition

<u>Assumptions:</u>

The assumptions taken are given as:

1. Steady state system
2. The turbine is adiabatic, which means no heat losses to be considered
3. Kinetic and potential energies are negligible
4. The system is assumed to be controlled volume

5. P_1= 3.1 MPa and T_1= 350°C /623 K

Table A-6, from Cengel's thermodynamics give entropy and enthalpy values (Cengel and Boles 2006). At 350 °C, h_1@ 3.0 MPa = 3,116.1 kJ/kg and s_1 @ 3.0 MPa = 6.7450 kJ/kg.K, h_2 @ 3.5 MPa = 3,104.9 kJ/kg and s_2 @ 3.5 MPa = 6.6601 kJ/kg.K. Using interpolation Equation (3.13) for h_1 @ 3.1 MPa.

$$h_1 \text{ @ } 3.1 \text{ MPa} = 3{,}113.7 \text{ kJ/kg.} \quad (5.101)$$

Using interpolation Equation (3.13) for s_1

$$s_1 \text{ @ } 3.1 \text{ MPa} = 6.6432 \text{ kJ/kg.K} \quad (5.102)$$

As the process is considered istentropic. P_{2s} = 25 kPa , $s_{2s} = s_1$

$$x_{2s} = s_{2s} - s_f/s_{fg} = 0.82 \quad (5.103)$$

$$h_{2s}= h_f +x_{2s}h_{fg} =2{,}216.09 \text{ kJ/kg} \quad (5.104)$$

$$\eta_{is} = 0.90 = h_1\text{-}h_{2a}/h_1\text{-}h_{2s} \quad (5.105)$$

$$h_{2a} = h_1\text{-}0.90(h_1\text{-}h_{2s}) \quad (5.106)$$

$$h_{2a} = 2{,}305.8 \text{ kJ/kg} \quad (5.107)$$

At P_{2a} = 25 kPa the temperature is $T_{2a} = T_{@sat25kPa}$ = 64.49 °C (337.9 K)
The power output of the steam turbine is as follows:

$$W_a = W_s(h_1 - h_{2a}) \tag{5.108}$$

$$W_a = 1.836 \text{ MW} \tag{5.109}$$

The actual efficiency of the steam turbine is calculated using Equation 3.21

$$\eta a = 46\% \tag{5.110}$$

Feed water pump is being driven by the steam turbine. The feed water pump inlet pressure will be same as after condensation, but make up water addition will increase the pressure to a certain limit because condensation pressure is usually lower than normal pumping water pressure. Equation 3.22 is used to find the mass flow rate of water.

$$m_{fw} = 10{,}163.7 \text{ kg/hr} \tag{5.111}$$

As v_1 represents the specific volume of saturated liquid at P_1, v_1= 0.001017 m^3/kg at 20 KPa from Table A-5 Cengel's Thermodynamics(Cengel and Boles 2006). The condenser pressure is assumed to be 6.8kPa and after makeup water addition, the water pressure is assumed to be 20kPa, kinetic and potential energies are assumed to be negligible. Now, using Equation (3.23) to evaluate work input required for the water pump.

$$W_p = 9.04 \text{ kW.} \qquad (5.112)$$

Net power generated by a steam turbine is given as:

$$W_{net,st} = W_{st} - W_p \qquad (5.113)$$

$$W_{net,st} = 1{,}846.9 \text{ kW} = 1.84 \text{ MW} \qquad (5.114)$$

The total electricity generation is sum of gas turbine and steam turbine net power output.

$$\text{Total Electricity Output} = 1.84 + 3.5 = 5.34 \text{ MW} \qquad (5.115)$$

Combined Cycle Overall efficiency (C.C.E) is given by Equation 3.24:

$$Q_{fuel} = W_{Gt} / \eta_{gt} = 12.3 \text{ MW} \qquad (5.116)$$

$$\eta_{C.C} = 43.5\ \% \qquad (5.117)$$

General Electric Efficiency of Cogeneration Plant.

Total Efficiency = 29% (gas turbine)+ 46% (Steam Turbine)= 75% (Electricity)

5.2. Reciprocating Engine Based Cogeneration

Reciprocating Engine technology has improved a lot in the past decades and the factors which are responsible for significant improvement are increased fuel efficiency, pollution reduction and increased power density resulting in better economic and environmental parameters. Reciprocating engines have several benefits like thermal output with low pressure steam, very fast start up time, part load efficiencies, improved reliability and emissions. Usually, diesel engine generates more NO_x and particulate matter, while in case of natural gas, emissions are reduced. Reciprocating engines are widely used in every sector i.e commercial, public and domestic for residential purpose. They do have higher electrical efficiencies when compared with the gas turbine of the same size with low fuel cost. The upfront cost that at start of the project is lower than that of gas turbine while maintenance cost is higher, but reciprocating engine is a widely used technology, local maintenance activities can reduce the maintenance cost of these systems.

The type of the system selected is Jenbacher type 4 which has high performance with applicable heat source for engine cooling, oil, mixture gas and exhaust gas and it can operate on multiple fuels like natural gas, petroleum gas, sewage gas, propane, landfill, biogas, coal gas and other gases. The type 4 has the same design as other type of engines, they do have turbocharger, which allows the air intake at higher temperature and level. Type 4 includes three engines with different power output with 820 kW, 1,137 kW and 1,415 kW. For this case study selected system is 1,415 kW known as JSM 420 GS- NL, this code defines the power output with operating fuel which is natural gas(GeneralElectric). As, the aim is to implement two engines with same power output, two engines of 1.415 MW will give total power output of 2.9 MW, which after heat recovery and utilization of steam in steam turbine will generate approximately 3 MW of total power output, matching desired demand for Institute.

Diesel cycle represents the idea cycle for power generating reciprocating engines. The air is compressed to a temperature that is above the auto ignition temperature of fuel, and fuel injection takes place when piston approaches Top Dead Centre (TDC) “Clearance Volume”.

5.2.1. Reciprocating Engine Calculation

Data has been acquired from the official catalogue of type 4 JSM 420 Engine, provided by General Electric website (GE 2009)The data available from the manufacturer is as follows:

- Compression ratio, r_c = 13.5
- T_1=298K, P_1=100 KPa
- T_4= 370 °C
- Electrical output , Wnet = 1,415kW
- Energy Input, Qin = 3295 kW
- Lower heating value, LHV = = 35 MJ/Nm^3
- Air flow rate, m_{air} = 7,417 kg/hr
- No. of cylinders = 20
- Piston displacement = 61.10 liter
- Bore = 145 mm, Stroke = 185mm
- Exhaust gas flow, m_{out} = 7,654 kg/hr
- Density of natural gas = 0.8421 kg/m^3

The Diesel Engine is a four stroke engine, a fuel injector is used to inject fuel directly in the cylinder while only air is compressed during the compression cycle. Fuel injection starts when the piston approaches the clearance volume. The general operating cycle for gas and diesel based compression ignition engine is the same which includes isentropic compression or compression of air, then constant pressure heat addition known as power stroke which allows combustion of fuel and air mixture, then isentropic expansion and constant volume heat rejection.

As compression stroke only takes air, the air will be assumed to be ideal, but the specific heat will be temperature dependent at the exhaust of the compression stroke, after combustion the mixture of gas with its composition is taken based on stoichiometric analysis. In compression stroke only air is assumed to be part of it as fuel injector will inject fuel at clearance volume. Mass balance Equation 3.1 is used to evaluate the fuel flow rate.

$$m_{fuel} = 237 \text{ kg/hr} \quad (5.118)$$

As, volume is not given in the catalogue, displacement volume and number of cylinders data is used to evaluate the difference between the volumes, after that compression ratio is used to determine the volume before and after compression.

Displacement volume= 61.10 liter.

$$V_1\text{-}V_2 = 0.00306 \text{ m}^3 \quad (5.119)$$

$$r_c = V_1/V_2 = 13.5 \quad (5.120)$$

$$V_1 = 13.5\ V_2 \quad (5.121)$$

Putting compression ratio value in the Equation (5.134).

$$V_2 = 0.0002448 \text{ m}^3 \quad (5.122)$$

$$V_1 = 0.00306 + 0.0002448 = 0.0033 \text{ m}^3 \quad (5.123)$$

Calculation of reciprocating engine will be based on Cengel's Thermodynamics guidelines for the compression ignition system and tables to evaluate the values (Cengel and Boles 2006). Now the first process of the gas cycle is evaluated where air is assumed to be an ideal gas and isentropic, following the isentropic Equation 3.25 is used to evaluate each parameter of the compression ignition cycle. Air is at 298 K , k=1.4

$$T_2=844\ K \tag{5.124}$$

The air inlet temperature is taken as the normal ambient temperature. P_1 = 100 kPa to evaluate P_2 by using Equation 3.26.

$$P_2=3{,}823.5\ kPa. \tag{5.125}$$

The next step is to evaluate the constant pressure heat addition process, where Equation 3.27 is used to determine T_3.

$$3{,}295\ kW\ \ (kJ/sec)/kW = 7{,}654\ kg/hr\ Cp_{gas}\,(T_{3-}\ 844K) \tag{5.126}$$

$$Cp_{air\ @\ 822\ K} = 1.103\ kJ/kg.K \tag{5.127}$$

Table 5.1. Cp Calculation, $Cp = a+bT+cT^{\wedge 2}+dT^{\wedge 3}$.

Component	**A**	**B**	**C**	**D**	**T (K)**	**Cp (kJ/kmol.K)**
CH_4	19.89	0.0502	$1.2*10^{-5}$	$-1.1*10^{-8}$	822	63.650
C_2H_6	6.9	0.172	$-6.4*10^{-5}$	$7.2*10^{-8}$	822	109.62
C_3H_8	-4.04	0.304	$-15.7*10^{-5}$	$3.1*10^{-8}$	822	157.92
C_4H_{10-n}	3.96	0.3715	$-18.3*10^{-5}$	$3.5*10^{-8}$	822	204.85
C_4H_{10-n}	7.91	0.416	$-23.0*10^{-5}$	$4.9*10^{-8}$	822	206.28
C_5H_{12}	6.77	0.454	$-22.4*10^{-5}$	$4.2*10^{-8}$	822	251.94
C_6H_{14}	6.938	0.552	$-28.6*10^{-5}$	$5.7*10^{-8}$	822	299.30
CO_2	22.2	0.059	$-3.5*10^{-5}$	$7.4*10^{-9}$	822	51.920
N_2	28.9	0.0015	$8.0*10^{-6}$	$-2.8*10^{-9}$	822	31.520

Cp of natural gas is evaluated using Equation (5.94). The values of specific heat in mole is evaluated by using Cengel's thermodynamics Table A-2 (Cengel and Boles 2006). Ideal gas specific heat is a function of temperature. After the evaluation of this specific heat, desired values comes in mass basis, than molecular weight of each component is divided by specific heat values on mass basis and then multiplied with composition to determine the specific heat based on mole basis as shown in table (5.2). Table 5.1 and 5.2 depict the calculations for estimating the specific heat of natural gas.

Table 5.2. Cp calculation based on Composition at 822 K

Actual Cp based on Composition			
Molecular Weight kJ/kg	**CP kJ/kg.K**	**Composition**	**Actual Cp**
16	3.997	0.8170	3.250
30.07	3.640	0.0756	0.275
44.1	3.580	0.0550	0.197
58.12	3.520	0.0149	0.0527
58.12	3.540	0.0142	0.0505
72.15	3.490	0.00707	0.0246
86.18	3.470	0.00369	0.0128
44	1.1799	0.0096	0.01132
28	1.120	0.0024	0.00275
Total CP at 822 K			**3.94**

$$Cp_{N.G\ @822\ K} = 3.94\ kJ/kg.K \tag{5.128}$$

$$\text{Fraction of air} = 7.417/7.654 = 0.969 \tag{5.129}$$

$$\text{Fraction of fuel} = 0.237/7.654 = 0.03096 \tag{5.130}$$

$$Cp_{Total} = 1.190\ kJ/kg.K \tag{5.131}$$

Using Equation (5.140) to evaluate the temperature T_3.

$$T_3 = 2{,}124 \text{ K} \quad (5.132)$$

$$\text{Cut off ratio} = B = T_3/T_2 = V_3/V_2 = 2.51 \quad (5.133)$$

Cut off ratio depends upon the inlet and outlet temperature of the constant heat addition process. Using Equation (5.214) to evaluate V_3 and this process occurs at constant pressure, which means pressure $P_3 = P_2$.

$$V_3 = 2.51V_2 = 0.000621 \text{ m}^3 \quad (5.134)$$

$$P_3 = P_2 = 3{,}823.5 \text{ kPa.} \quad (5.135)$$

Stoichiometric analysis remains same as the gas turbine. Only, the mass flow rate of the actual gas will change as a reciprocating engine consumes less fuel and we are considering only one engine for calculation (Flagan and Seinfeld 1988);(McAllister, Chen, and Fernandez-Pello 2011). The stoichiometric analysis is same for both cases because the natural gas composition remains same.

For real case:

$$(F/A)_{actual} = 0.0319 \quad (5.136)$$

$$(A/F)_{actual} = 31 \quad (5.137)$$

$$\acute{\phi} = 0.0319/0.05423 = 0.583 \quad (5.138)$$

As φ <1, so, lean combustion and combustion products contain CO_2, H_2O, N_2, O_2, diesel engines usually operates at a higher compression ratio, which gives them a better advantage of complete combustion and production less waste heat with lower emissions. Equation (3.7) is used to evaluate percent excess air.

$$\% \text{ Excess Air} = = (31/18.43)100 = 168.20\% \qquad (5.139)$$

Cp of natural gas at ambient condition is from Equation (5.40). The exhaust gases mole fraction also remains same. The temperature is taken from the manufacturer catalogue.

$$T_4 = 643 \text{ K} \qquad (5.140)$$

As, the volume remains constant during heat rejection.

$$V_4 = V_1 = 0.0033 \text{ m}^{3,} \qquad (5.141)$$

As, we know that the actual power output and heat input from engine catalogue Using Equation (3.9) to find the efficiency of the engine.

$$\eta = 1{,}415 \text{ kW}/3{,}295 \text{ kW} = 44\% \qquad (5.142)$$

Heat rejected is found using Equation 3.27 and Cv is calculated using table A-2, Cengel’s thermodynamics (Cengel and Boles 2006) and Equation (3.13).

$$C_{v\ CO2\ @\ 643\ K} = 0.9092\ kJ/kg.K \quad (5.143)$$

$$C_{v\ N2\ @\ 643\ K} = 0.7874\ kJ/kg.K \quad (5.144)$$

$$C_{v\ H2O\ @\ 643\ K} = 1.58\ kJ/kg.K \quad (5.145)$$

Using Equation (5.40) for estimating overall specific heat.

$$C_{v\ total} = 0.9574\ kJ/kg.K \quad (5.146)$$

Using Equation (3.27) to determine the heat output of the engine.

$$Q_{out} = = 702.26\ kJ/s \quad (5.147)$$

5.2.2. HRSG Calculations

The process of evaluation is same as done in gas turbine, only parameters change due to steam turbine, which is compact turbine used for small scale operation with power generation capacity from 750-300 KW, it has a high degree of operational reliability, with short start p and extremely compact design with favorable price. It is specifically designed to use for waste heat recovery system, small scale CHP and decentralized solar facilities. Heat recovery steam generation system has the same components as gas turbine HRSG. The values below are shown in given data section of reciprocating engine.

m_{out} =7,654 kg/hr and T_{g1} = 350 °C

Assumptions:

- After pump, the feed water enters at 110 °C(Hicks 1998).

- As, selecting the steam turbine with 75 kW-300 kW capacity from the manufacturer Siemens (Siemens 2016).

  Max Operating Conditions are:

  a. Temp. Max. = 400 C (Dry saturated steam)

  b. Max Pressure = 4,200 kPa.

- Nominal operating pressure of 3,000 kPa and temperature of 310 °C (Ganapathy 2001).
- Blow down negligible (Ganapathy 1997).
- The approach and pinch point remains same as in the first case, $\mathbf{\Delta t_{App}}$ = 5 and $\mathbf{\Delta t_{pp}}$ =10 K
- As assumption is that from super heater to the steam turbine there is no pressure drop which means, super heater has same pressure as steam turbine inlet.
- Assuming that the temperature drop is minimum from super heater to steam turbine is 20 K.
- Assuming, super heater has pressure drop of 70 kPa which makes Drum pressure 3,000+70 = 3,070 kPa (Ganapathy 1991).

To get saturation pressure using table A-5 Cengel's thermodynamics (Cengel and Boles 2006) and Equation (3.13) .

$$T_s = 235\ °C \tag{5.148}$$

$$T_{g3} = 518\ K \tag{5.149}$$

$$T_{eco,out} = 503K \tag{5.150}$$

$$T_{sh} = 583+20 = 608\ K \quad (5.150)$$

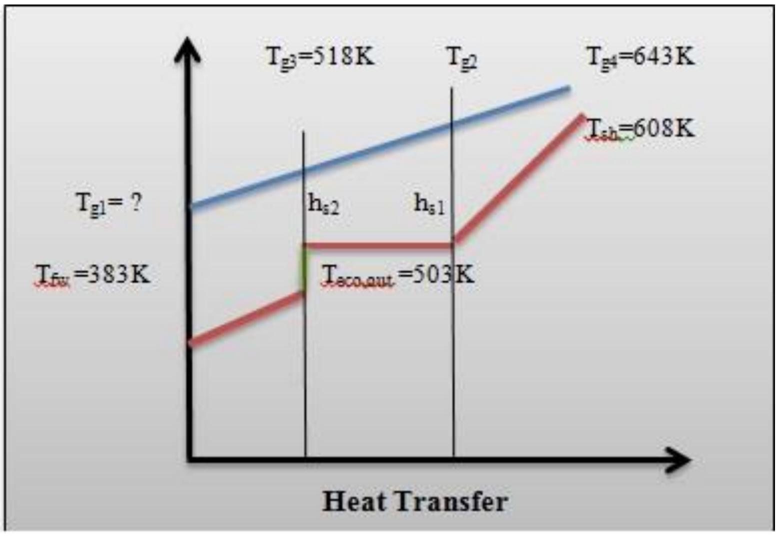

Figure 5.4: Operating Parameters of HRSG

The heat transferred by the superheater and evaporator is evaluated and specific heat is determined by using Cengel's thermodynamics, Table A-2 (Cengel and Boles 2006) and Equation (3.13).

$$Cp_{N2@643K} = 1.0844 \text{ kJ/kg.K} \tag{5.151}$$

$$Cp_{CO2@643K} = 1.1025 \text{ kJ/kg.K} \tag{5.152}$$

Specific heat for water vapor is evaluated and constant values from Cengel Thermodynamics (Cengel and Boles 2006).

A=32.32, B=0.1923*10^$^{-2}$, C= 1.055*10^$^{-5}$, D= -3.545*10^$^{-9}$

Putting above values in Equation (5. 94).

$$Cp_{H2O@643K} = 36.287 \text{ kJ/kmol.K (kmol/18kg)} \tag{5.153}$$

$$Cp_{H2O@643K} = 2.0492 \text{ kJ/kg.K} \quad (5.154)$$

Specific based on composition of overall gas is obtained by Equation (5.40).

$$Cp_{gas} = 0.389 + 0.1764 + 0.7048 = 1.27 \text{ kJ/kg.K} \quad (5.155)$$

Now putting values in Equation (3.14).

$$Q_1+Q_2=337.5 \text{ kJ/s} \quad (5.156)$$

Enthalpy absorbed by steam in evaporator and super heater:

Energy absorbed by steam is given by Equation (3.15) and Equation (3.13) for $h_{sh.}$

$$h_{sh} = 3{,}079.5 \text{ kJ/kg} \quad (5.157)$$

h_{s1} is obtained using the steam table at T=503 K and P = 3,070 kPa, as at this pressure the the saturation temperature is higher than the given temperature. So, taking values for saturated liquid.

$$h_{s1}= 990.14 \text{ kJ/kg} \quad (5.158)$$

Putting values in Equation (3.15).

$$E = 2{,}089.36 \text{ kJ/kg} \quad (5.159)$$

Steam generation rate is evaluated using Equation (3.16).

$$W_s = 0.639 \text{ ton/hr} \quad (5.160)$$

<u>Energy absorbed by super heater and exit temperature:</u>

Energy absorbed by superheater is given by Equation (3.17). As the steam generation rate is known.

$$Q_1 = 581.55 \text{ kg/hr} \, (h_{sh} - h_{s2}) \quad (5.161)$$

h_{s2} is evaluated at saturation temperature, Ts = 508 K.

$$h_{s2} = 2{,}803.2 \text{ kJ/kg} \quad (5.162)$$

$$Q_1 = 44.63 \text{ kg/s} \quad (5.163)$$

Temperature at exit is based on the steam turbine assumption which is 583+20 = 608 K

<u>Energy absorbed by Evaporator:</u>

As the total energy absorbed by superheater and evaporator is known. Subtracting the energy absorbed superheater from total value provides the energy absorbed by the evaporator.

$$Q_1 + Q_2 = 1{,}215{,}072.5 \text{ kJ/hr} \quad (5.164)$$

$$Q_2 = 292.88 \text{ kJ/s} \quad (5.165)$$

Economizer duty and exit gas temperature

Equation (3.18) provides the economizer duty and Equation (3.19) gives the exhaust temperature. h_{f1} is found at 503 K Temperature and h_{fw} at T_{fw} = 383K.

$$h_{fw} = 461.42 \text{ kJ/kg} \quad (5.166)$$

$$h_{f1} = 990.14 \text{ kJ/kg} \quad (5.167)$$

Putting values of h_{fw} and h_{f1} in Equation (3.18).

$$Q_3 = 85.41 \text{ kJ/sec} \quad (5.168)$$

Temperature dependent specific heat of the gas is used to evaluated the exhaust temperature.

$$Cp_{CO2@518K} = 1.0255 \text{ kJ/kg} \quad (5.169)$$

$$Cp_{N2@518K} = 1.059 \text{ kJ/kg} \quad (5.170)$$

Specific heat of water is calculated as follows:

A=32.32, B=0.1923*10^-2, C= 1.055*10^-5 , D= -3.545*10^-9

$$Cp_{H2O@643K} = 1.977 \text{ kJ/kg.K} \quad (5.171)$$

$$Cp_{gas} = 0.375 + 0.164 + 0.688 = 1.227 \text{ kJ/kg.K} \quad (5.172)$$

Putting value of the specific heat of gas in Equation (3.19).

$$T_{g4} = 485 \text{ K } (212\ °C) \quad (5.173)$$

The exhaust temperature from HRSG is higher than the feed water temperature, which means that assumptions are valid for pinch and approach point.

ASME HRSG Efficiency:

HRSG efficiency evaluation is done using the Equation (3.20) and enthalpies are calculated using interpolation.

$$H_{exhaust\ gas} = 0.19\ h_{N2} + 0.16\ h_{CO2} + 0.65\ h_{H2O} \quad (5.174)$$

$$h_{N2} = 673.67 \text{ kJ/kg} \quad (5.175)$$

$$h_{CO2} = 553.07 \text{ kJ/kg} \quad (5.176)$$

$$h_{H2O} = 1{,}030.07 \text{ kJ/kg} \quad (5.177)$$

$$H_{exhaust\ gas} = 720.8\ kJ/kg \quad (5.178)$$

Using Equation 3.20 to calculate HRSG efficiency.

$$\eta_{HRSG} = 28\% \quad (5.179)$$

5.2.3. Steam Turbine Calculation

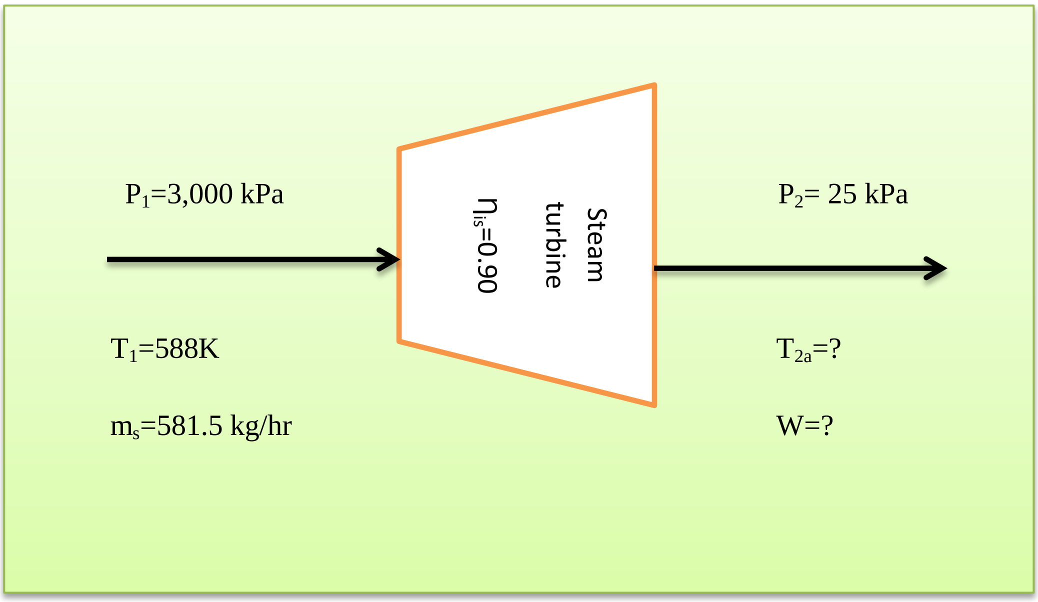

Figure 5.5: Steam Turbine Operating Parameters

Assumptions:

1. Steady State System
2. Turbine is adiabatic which means no heat losses to be considered
3. Kinetic and potential energies are negligible.
4. P_1= 3 MPa and T_1= 588 K

AT 315 °C using Equation (3.13) to determine value of h_1 @ 3.0 MPa.

$$h_1 = 3{,}030.84 \text{ kJ/kg} \tag{5.180}$$

s_1 @ 3.1 MPa is based on interpolation Equation (3.13).

$$s_1 \text{ @ 3.1 MPa} = 6.6023 \text{ kJ/kg.K} \tag{5.181}$$

The process is isentropic at P_{2s} = 25 kPa, which shows that $s_{2s} = s_1$.

$$x_{2s} = s_{2s} - {}^{s_f}\!/_{s_{fg}} = 0.82 \tag{5.182}$$

$$h_{2s} = h_f + x_{2s}\, h_{fg} = 2{,}195.27 \text{ kJ/kg} \tag{5.183}$$

$$n_{is} = 0.90 = {}^{h_1 - h_{2a}}\!/_{h_1 - h_{2s}} \tag{5.184}$$

$$h_{2a} = 2{,}279.25 \text{ kJ/kg} \tag{5.185}$$

At P_{2a} = 25 kPa, the temperature is saturation temperature, $T_{2a} = T_{@sat25kPa}$= 64.49 °C (337.9 K).The power output of turbine is evaluated as follows:

$$W_a = 0.135 \text{ MW} \tag{5.186}$$

Actual efficiency of steam turbine is based on the Equation (3. 21).

$$\eta_a = 42.5\% \quad (5.187)$$

Calculating work for feed water pump as we assume pump power is being supplied by electricity generated, because steam turbine also provides work input of the feed water pump. The mass flow rate required for the feed water pump is evaluated using the Equation (5.22).

$$m_{fw} = 586.6 \text{ kg/hr} \quad (5.188)$$

V_1 represents specific volume of saturated liquid at $P_{1,}$.v_1= 0.001017 m^3/kg at 20 kPa from Table A-5 (Cengel and Boles 2006).As, the condenser pressure is 6.8kPa and after makeup water addition, the water pressure assumed to be increased to 20 kPa, kinetic and potential energies assumed to be negligible. Also, assuming there is no pressure drop between pump and drum. So, taking P_2 as drum pressure. Equation (3.23) used for evaluation of the pump work.

$$W_p = 0.5054 \text{ kW} \quad (5.189)$$

Total power generated by the steam turbine is given as.

$$W_{net,st} = 134.49 \text{ kW} = 0.1349 \text{ MW.} \quad (5.190)$$

$$\text{Total Electricity Ouput} = 0.1349 + 1.415 = 1.5499 \text{ MW.} \quad (5.191)$$

Combined Cycle Overall efficiency (C.C.E) is given by Equation (3.24).

$$\eta_{C.C} = 1.415\ MW + 0.1349\ MW / 3.295\ MW = 47\ \% \qquad (5.192)$$

General Electric Efficiency of Cogeneration Plant is sum of gas and steam turbine efficiency.

Total Efficiency = 44% (gas turbine) + 42% (Steam Turbine)= 86% (Electricity)

As the desired capacity of the institute is considered to be 3.0 MW for the university generation.

Taking two same reciprocating engines = 2*1.415 MW = 2.83 MW.

Total electricity generation = 2.83+0.2698 = 3.0998 MW.

CHAPTER 6

EMISSIONS CALCULATIONS

The emission calculation is an important aspect for deciding, which prime mover gives the best optimal solution in terms of pollution reduction. As the study aims to present a solution for providing sustainable approach towards energy security for the Institute and to reduce the carbon footprints in order to achieve the environmental targets on global and national scale set by Turkey. In order to achieve those targets several steps are required at every scale.

The cases are divided into 3 sections, first the gas turbine, second is the reciprocating engine and third is the emission from based on the grid. After analyzing each case, a comparison of emissions between existing and proposed system will highlight the optimal solution in term of environmental reduction. The methodology to be employed for assessment of emissions is discussed in the methodology section.

6.1. Case1: Calculation of Emissions for Gas Turbine Based CHP

The mass flow rate and density values are taken from Equation (5.81) and (5.8) and are utilized for evaluation of volumetric flow rate in order to determine the energy input.

Fuel input rate = m_{fuel} = 0.54 kg/sec and Density of natural gas = 0.841 kg/m^3

$$\text{Volumetric flow rate} = 0.642\ m^3/sec \tag{6.1}$$

The value from Equation (6.1) is multiplied with net calorific value, to obtain energy input in kW.

$$\text{Energy Input} = 64{,}713{,}600 \text{ kWh/year} \tag{6.2}$$

The emission factors are in gas specific units. Usually, the pollution is represented as CO_2 equivalent. For conversion into CO_2 equivalent the Global Warming Potential number or index will be used. If gas is N_2O and its global warming potential is 298 than 1 kg of N_2O*298 = 298 kg CO_2 equivalent.(Brander and Davis 2012). As 1 ton equals to 907 kg, this conversion is used to convert kg into ton emissions. Table 6.1 shows the emission generation for gas turbine.

Table 6.1.: Emissions for Gas Turbine Based CHP

Total Energy consumed kWh/year	**Pollutant**	**Emission factor**	**Emissions of kg Gas /year**
64,713,600	**CO_2**	0.16675	10,790,992.8
	CH_4	$3.14*10^{-6}$	203.2
	N_2O	$3.14*10^{-7}$	20.32
	Pollutant	**GWP**	**Emission kg CO_2/year**
	CO_2	1	10,790,992.8
	CH_4	25	5080
	N_2O	298	6055.3
TOTAL	**-**	-	10,802,128.2
			Emissions ton CO_{2eq}/year
			10,802.3

6.2. Case2: Emissions Calculation for Reciprocating Engine Based CHP.

The same procedure is being followed as in the gas turbine, only the mass flow rate changes as the reciprocating engine used, generates less power output and two reciprocating engines are being operated in order to meet the required utility demand.
Fuel input rate = 0.06583kg/sec

$$\text{Volumetric flow rate} = 0.07827\ m^3/\text{sec} \tag{6.3}$$

Using equation (3.40) to evaluate the energy input and multiplying with 2 for two reciprocating engines to meet desired requirement.

$$\text{Energy Input} = 15{,}779{,}232/\ \text{kWh/year} \tag{6.4}$$

Table6.1.Emission for Reciprocating Engine based CHP with Conversion into CO2 equivalent

Total Energy consumed kWh/year	**Pollutant**	**Emission factor**	**Emissions of kg Gas /year**
15,779,232	**CO_2**	0.16675	2,631,186.9
	CH_4	$3.14*10^{-6}$	49.5
	N_2O	$3.14*10^{-7}$	4.95
	Pollutant	**GWP**	**Emission kg CO_2/year**
	CO_2	1	2,631,186.9
	CH_4	25	1,237.5
	N_2O	298	1,475.1
TOTAL	**-**	-	2,633,899.5
			Emissions ton CO_{2eq}/year
			2,633..9

6.3. Case 3: Emission Calculation for Grid Electricity.

As there is no specific technology that can be taken as a base case in order to utilize the emission factors for stationary emissions. Rather a more appropriate approach is being utilized by using emission factors based on electricity as most the system of the Institute are based on electricity provides more better results. The methodology remains in which the energy input is multiplied with the emission factors and then emission with global warming potential for obtaining carbon dioxide equivalent emissions. Then the emissions associated with T&D losses are evaluated using T&D specific emission factors and later added with grid based emission to analyze the total emission being generated when electricity is purchased from the grid.

Table 6.2. Grid based Emissions Calculation

Total Energy consumed kWh/year	Pollutant	Emission factor	Emissions of kg Gas /year
10,136,295.24	**CO_2**	1.0098	10,235,631.1
	CH_4	0.000013	131.77
	N_2O	0.000012	121.6
	Pollutant	**GWP**	**Emission kg CO_2/year**
	CO_2	1	10,235,631.1
	CH_4	25	3294.2
	N_2O	298	36254.6
TOTAL	**-**	-	10,275,180
			Emissions ton CO_{2eq}/year
			10,275.18

The above mentioned emissions are only due to the consumption of electricity, yet there are 20-25% losses of electricity during transmission and distribution of electricity, the emissions due to transmission and distribution are also incorporated using specific transmission and distribution loss emission factor. Appendix 1 is used for electricity specific transmission and distribution loss emission factor for Turkey (Brander et al. 2011). Combining both emissions gives more accurate value that can be used for comparison. Table 6.4 shows the emissions associated with the transmission and distribution losses.

Table 6.3. Emissions from Transmission and Distribution losses.

Total Energy consumed kWh/year	**Pollutant**	**Emission factor**	**Emissions of kg Gas /year**
10,136,295.24	**CO_2**	0.145	1,469,762.8
	CH_4	0.00000185	18.7
	N_2O	0.00000165	16.7
	Pollutant	**GWP**	**Emission kg CO_2/year**
	CO_2	1	1,469,762.8
	CH_4	25	467.5
	N_2O	298	4976.6
TOTAL	**-**	-	1,475,207.5
			Emissions ton CO_{2eq}/year
			1,475.2

$$\text{Total Emissions} = 11,750.4 \text{ ton } CO_2e/\text{year} \quad (6.5)$$

It is assumed that the total electricity emissions also include the emissions from other sources. Emissions for all cases are shown in the following Table 6.5 for comparison.

Table 6.4. Emission Comparison for all 3 cases.

	Gas Turbine Net CV Based	Reciprocating Engine Net CV Based	Grid Emission Electricity specific article based
Emissions	10,802,128.2	2,631,186.9	11,750,387.2
Units	kg CO_2e/year	kg CO_2e/year	kgCO_2e/year
Emissions	10,802.3	2,633..9	11,750.4
Units	ton CO_2e/year	ton CO_2e/year	ton CO_2e/year

These emission factors are used after complete survey of different agencies like IPCC, EPA, Defra/DECC. IPCC is a body which involved in establishing a database and monitoring emission from different countries. For Turkey, there is no specific emission factors available related to energy emissions or combined heat and power at any scale (IPCC 2006). EPA gives guidelines on composite heat and electricity emission basis, which does not provide accurate results for this case study, while Defra only monitors emission factors for UK- based activities and it has been recommended by Defra not to use those factors outside UK (DEFRA 2012),(IPCC).

6.4. Emission Analysis:

A simple comparison of the result of the grid based emissions and two cases of this study are summarized as follows.

- The CO_2 reduction for the Gas turbine based CHP was 948.08 ton CO_2e/year which represents 82 % of the grid. The CO_2 reduction for the natural gas reciprocating engine based CHP was 9,116.5 ton CO_2e/year which represents 23% of the grid.

These results show that reciprocating engine is better in terms of CO_2e savings per year, when compared to gas turbine based CHP. The reason lies in the efficiency of the system. Reciprocating engine gives an efficiency of 44% as compared to the gas turbine, which is around 28%. Also the overall efficiency of a reciprocating engine is higher than gas turbine.

- Environmental analysis suggests both gas turbine and reciprocating engine shows carbon dioxide equivalent saving. For gas turbine case, the total savings in emission is 8.1 %, when compared with grid based emissions and reciprocating engine indicates a saving of 76%.

CHAPTER 7

COST ESTIMATION

Cost estimation is the process of calculating the cost of the program or project. It is difficult to analyze that cost estimation can be viewed as art or science, but it has its influence on both sides because it involves using a systematic approach and calculations to determine the cost of the project but also involves visualization of project that how a project will be formed.

The comparison is made between three cases. First is CHP based on Gas Turbine and second is CHP based on reciprocating engine and third is the cost analysis of the existing facility in order to make a comparison to analyze which system is more effective for the institute. Cost calculations are done in 3 sections. The first one will be for existing system cost analysis.

7.1. Cost Analysis of Existing Facilities.

As described in the methodology section, the per unit cost is taken from the responsible authorities than multiplied with the consumption of 2016 to evaluate the annual cost.

$$\text{Annual Price of Electricity, 2016} = 1.02 \text{ million TL.} \qquad (7.1)$$

As from the trading economic and Garanti bank report give the dollar price and base load price for 2023 as shown in Table 3.5 and Table 3.6. The electricity base load price comes out to be 0.251 USD/kWh based on the extrapolated dollar price for 2023.

Total consumption of electricity for 2023 is 10,136,295.2 kWh from the data collection and interpretation, which includes heating, cooling and electricity consumption. Multiplying with the extrapolated electricity price per kWh provides the annual price of electricity consumption for 2023.

Annual Price, 2023 (TL) =3.34 million TL. (7.2)

Transmission and Distribution Loss Cost:

To evaluate the price associated with transmission and distribution loss for 2016, the percentage of loss for 2016, which is 17.58 % as shown in Table 3.7 is multiplied with the total price for the purchase of electricity in 2016 by using Equation (3.48).

Transmission and Distribution losses price, 2016 = 0.1748* 1.02 million TL. (7.3)

Transmission and Distribution losses price, 2016 = 0.178 million TL. (7.4)

Same procedure is used to estimate cost for the transmission and distribution loss in 2023 by using Equation (3.48)

Transmission and Distribution losses price, 2023 = 3.34 million TL *0.2222 (7.5)

Transmission and Distribution losses price, 2023 =0.742 million TL. (7.6)

Maintenance Cost:

The data is collected from the officials responsible for the maintenance activities of heating, cooling and electrical systems of the University. The cost of maintenance of all the buildings in 2016 is given by the authorities and it includes following:

1. Generator's cost =55, 900 TL
2. Transformers and other electrical facilities = 20,694 + 51,648 TL = 72,342 TL
3. Heating and Cooling System = 79,051 + 37,760 TL = 1,168,11 TL

The total cost represent sum of the all cost and gives the total spending's per year, which the Institute pays in order to meet its utility requirement. This cost will be used to make a comparison with other cases in order to evaluate the best outcome in order to replace the existing system.

$$\text{Total Cost} = \text{sum of all cost} = 55{,}900 + 72{,}342 + 1{,}168{,}11 = 0.246 \text{ million TL} \qquad (7.7)$$

Generators and Heating Fuel Cost:

Fuel oil 4 commonly known as diesel fuel is used for multiple applications. This fuel has special characteristics of low sulfur content. It is usually used as commercial heating fuel for burner installations in which preheater is not required. Some of the old systems in the University are based on the furnace or boiler based heating, which uses the central heating system to distribute the heat throughout the department. Annual consumption of fuel is also provided by the authorities. Apart from that each department has a specific number of VRF systems for heating. The total price for heating is because of the fuel oil 4 used for heating system directly and generator fuel used for stand by electricity. Fuel oil 4 annual price was 890,727.8 TL and 21,443 liter of generator fuel is used, which is multiplied with diesel fuel price for 2015 4.1 TL/ liter for evaluation of total cost associated with heating and generator fuel.

$$\text{Total Price} = 890{,}727.83 + 879{,}16.30 \text{ TL} = 0.97 \text{ million TL.} \qquad (7.8)$$

The total costs includes sum of all the cost without considering transmission and distribution as well as operation and maintenance cost.

$$\text{Total Cost (without loss and O\&M), 2016} = 1.99 \text{ million TL} \qquad (7.9)$$

The total cost will increase after including transmission and distribution loss.

$$\text{Total Cost, 2016} = 2.414 \text{ million TL} \qquad (7.10)$$

7.2. Cost Analysis of Gas turbine based CHP

Two cases are being analyzed based on the operating hours. The general procedure remains same as described in the methodology, only the operating hours will change in order to evaluate the most profitable option by selling excess electricity at a fixed prices mentioned in EMRA regulation .

7.1.1. Scenario 1: Operating hours 2880 hours/Year

For the gas turbine operating at full load the fuel consumption is 0.54 kg/sec, to get the whole year consumption. The procedure is as follows. Mass of fuel and density is taken from equation (5.81) and (5.8), which is 0.54 kg/m^3 and 0.842 kg/m^3. The natural gas consumption per year is evaluated by finding the volumetric flow rate from mass flow rate and density than multiplying with the operating hours per year.

$$\text{Natural gas consumption} = 6.649 \text{ million m}^3\text{/year} \qquad (7.11)$$

The natural gas price is obtained by multiplying the natural gas consumption with the price of natural gas per cubic meter that is 0.969 TL/m^3.

$$\text{Natural gas price per year} = 6.44 \text{ million TL/year} \qquad (7.12)$$

The capacity of gas turbine based CHP plant is 5.34 MW and taking normal operating hours for the institute of 2880 hours per year to convert into kWh per year.

$$\text{Electricity Generation} = 15{,}379{,}200 \text{ kWh/year} \qquad (7.13)$$

For per kWh cost of electricity for this system Equation (3.52) is used.

$$\text{Electricity Cost} = 0.41 \text{ TL/kWh} \tag{7.14}$$

To evaluate the excess electricity generated based on operating hours the total electricity consumed during that year is subtracted from the total electricity produced. The excess electricity is evaluated using total consumption and total generation of capacity of plant.

$$\text{Total electricity consumption,2016} = 5{,}143{,}587.3 \text{kWh/year} \tag{7.15}$$

$$\text{Total Electricity Consumption, 2016} = 1.785 \text{ MW.} \tag{7.16}$$

$$\text{Excess Electricity, 2016} = 5.34\text{-}1.785 \text{ MW} = 3.55 \text{ MW} \tag{7.17}$$

For excess electricity in kWh for 2016, multiplying with operating hours gives the final value in kWh in order to determine profit obtained from selling electricity to the grid.

$$\text{Excess Electricity kWh, 2016} = 10{,}224{,}000 \text{ kWh/year.} \tag{7.18}$$

Based upon the EMRA’s electricity price specific for plant’s being operated on biofuel or natural gas is 0.133 USD/kWh, which after conversion becomes 0.418 TL/kWh.

$$\text{Excess electricity selling price} = 0.418 \text{ TL/kWh} \tag{7.19}$$

$$\text{Profit from Excess Electricity} = 4.284 \text{ million TL/year} \tag{7.20}$$

The price paid shows the amount of money required for the fuel after the profit gained and is obtained by using Equation 3.55.

$$\text{Price paid} = 2.142 \text{ million TL/ year.} \quad (7.21)$$

Assuming maximum value for operation and maintenance, converting into Turkish Liras O& M fixed cost per KWh= 0.008 USD/KWh =0.0252 TL/KWh For the gas turbine, operation and maintenance (O&M) cost is obtained by multiplying O&M fixed cost with total electricity generated by the system by using Equation 3.56 And total cost by using Equation 3.57.

$$\text{O\&M cost, 2016} = 0.388 \text{ million TL/year} \quad (7.22)$$

$$\text{Total Cost} = 2.53 \text{ million TL/year.} \quad (7.23)$$

The operation and maintenance cost includes maintenance with overhauls, labor and material cost plus the operating while overhaul is usually done after 25,000-50,000 continuous working hours that means 8,760 hours per year which means after every 3 years (Kalam et al. 2012). For case the CHP operates for 2,880 hours/year and it will require overhauling after 8.5 years.

7.1.2. Scenario 2: Operating hours 8000 hours/Year

Selection of 8,000 hours is based on the fact that during summer the consumption reduces to half and the inter-semester break with maintenance per year consumes 67 days of the year.

The same procedure is used as in case of scenario 1, only the operating hours taken as 8,000 hours per year, more than the desired capacity and the excess electricity sold to the grid as per EMRA regulation. Mass flow rate and density given remains same. The natural gas consumption per year is evaluated by finding the volumetric flow rate from mass flow rate and density than multiplying with the operating hours per year.

$$\text{Natural gas consumption per year} = 18.47 \text{ million } m^3/\text{year.} \qquad (7.24)$$

$$\text{Natural gas price} == 17.89 \text{ million TL/year} \qquad (7.25)$$

For electricity cost per kWh is used, but first estimating total generation.

$$\text{Total Generation} = 42{,}720{,}000 \text{ kWh/year} \qquad (7.26)$$

Electricity cost is evaluated using Equation (3.52).

$$\text{Electricity Cost} = 0.418 \text{ TL/kWh} \qquad (7.27)$$

First, estimation the excess hours (8000 – 2880 = 5120 hours/year) is required to evaluate the profit generated by sold electricity. As plan operates 8000 hours per year, but electricity consumption is only for 2880 hour per year and rest is 5120 hours represents the excess electricity generation.

$$\text{Excess Electricity in KWh} = 18{,}176{,}000 \text{ kWh/year} \qquad (7.28)$$

Using, the same price for selling electricity as given by EMRA, which is 13.3 USD cent/kWh (0.418 TL/kWh) (Arseven, Ersin, and ARSEVEN 2015). Equation (3.54) is used to evaluate profit by sold electricity.

Sold electricity Profit =7.6 million TL/year. (7. 29)

Price paid evaluated by Equation (3.55) using values from Equation (7.29) and (7.25).

Price Paid =10.29 million TL/Year. (7. 30)

With the increase in operating hours, the electricity price per kWh remains same for both scenarios, but when compared to the grid electricity price which is 0.199 TL/kWh the electricity price for the gas turbine is quite high. Even the purchase price of fuel is almost 4 times to that of the total cost paid by the institute, including maintenance and the transmission and distribution loss cost.

For the gas turbine scenario 2, multiplying with 0.0252 TL /kWh to obtain operation and maintenance cost of electricity generated by using Equation (3.56).

O&M = 1.073 million TL/Year (7.31)

Total cost is obtained from Equation (3.57).

Total cost = 7.083 million TL/year (7.32)

7.2. Cost Analysis of Reciprocating Engine based CHP

For a cost estimation of reciprocating engines, same methodology is followed as in case of gas turbines. Reciprocating engine operates at full load the fuel consumption is 237 kg/hr. One reciprocating engine with heat recovery unit gives total power output of 1.5499, but desired capacity for the institute is 2.88 MW, which is assumed to be 3

MW. For this reason, two reciprocating engines are employed and the combined power output is 3.0998 MW.

7.2.1. Scenario 1: Operating hours 2880 hours/Year

Multiplying mass flow rate with 2 gives the fuel input for two reciprocating engines. The mass flow rate and density is 0.474 kg/hr and 0.842 kg/m^3

$$\text{Natural gas consumption per year} = 1.622 \text{ million } m^3/\text{year.} \quad (7.33)$$

For highest consumption band using the average amount paid 96.9 kurus/year or 0.969 TL/ m^3 (TUIK 2016) to evaluate natural gas price.

$$\text{Natural gas price} = 1.5710 \text{ million TL/year} \quad (7.34)$$

Electricity cost per kWh is based on total generation and evaluated using Equation (3.52) and total electricity cost is evaluated by the ratio of natural gas price per year and total electricity generation in 2016.

$$\text{Total Electricity Generation, 2016} = 8{,}927{,}424.0 \text{ kWh/year.} \quad (7.35)$$

$$\text{Electricity Cost} = 0.175 \text{ TL/kWh.} \quad (7.36)$$

Total Electricity Consumption in 2016 remains same 1.785 MW.

$$\text{Excess Electricity} = 3.0998 - 1.785 \text{ MW} = 1.314 \text{ MW} \quad (7.37)$$

Excess Electricity== 3,786,624 kWh/year (7.38)

Using same biomass based selling value for excess electricity based on EMRA guidelines for estimating profit.

Profit from sold electricity =1.586 million TL/Year. (7.39)

Price paid evaluated using Equation (3.55).

Price Paid= - 0.016 million TL/Year. (7.40)

The negative sign shows the profit generated after selling electricity to the grid. For reciprocating engines, the operation and maintenance (O&M) cost is in the range $0.010 per kWh to $0.015 per kWh (0.0315-0.04725 TL/kWh) (Luther 2016).

O&M cost, 2016=0.42 million TL /year (7.41)

To analyze the total profit, the expenses in terms of O&M and fuel will be excluded from the profit; profit estimation also includes the cost of electricity paid by institute, which is 0.175 TL/kWh instead of grid which is 0.199 TL/kWh in order to estimate payback period. Net profit obtained using Equation 3.59 and the Institute also pays at the per unit cost price for this case.

Institute Electricity Cost = 0.900 million TL/kWh. (7.42)

$$\text{Net Profit} = 0.495 \text{ million TL.} \quad (7.43)$$

Capital Cost calculated by the generation capacity with the fixed price using the rule of thumb for CHP understanding (Luther 2016) and then payback period by using Equation 3.58.

$$\text{Installation Cost} = \$2{,}000/\text{KW} * 3{,}099.8 \text{ KW} = 6.19 \text{ million TL} \quad (7.44)$$

$$\text{Payback period} = 12.50 \text{ years} \quad (7.45)$$

When operation and maintenance cost of gas turbine is compared with reciprocating engine for same scenario, it shows that O&M of a reciprocating engine is greater than gas turbine by an amount of 0.034 million a TL/year, but the cost of electricity per kWh and other benefits are more in reciprocating engine than gas turbine case.

7.2.2. Scenario 2: Operating hours 8000 hours/Year

The mass flow rate and density remains same and these are used for evaluation of natural gas annual composition as in gas turbine case

$$\text{Natural gas consumption} = 4.5 \text{ million } m^3/\text{year.} \quad (7.46)$$

For the highest consumption band, the average amount paid is same as 0.969 TL/ m^3 (TUIK 2016). Operating hours are 8,000 hours per year.

$$\text{Natural gas price} = 4.36 \text{ million TL/year} \quad (7.47)$$

$$\text{Electricity Generation} = 24{,}798{,}400.0 \text{ kWh/year.} \quad (7.48)$$

Electricity cost per kWh obtained by using Equation (3.52).

$$\text{Electricity Cost} = 0.175 \text{ TL/kWh.} \quad (7.49)$$

Electricity consumption remains same and excess electricity also remains same. During the whole year, 1.314 MW excess electricity is produced which is sold to the grid.

$$\text{Excess Electricity in kWh} = 6{,}727{,}680 \text{ kWh/year.} \quad (7.50)$$

Profit from the sold electricity evaluated by Equation (3.54).

$$\text{Profit from sold Electricity} = 2.82 \text{ million TL/Year.} \quad (7.51)$$

For reciprocating engine, operation and maintenance (O&M) cost is in the range $0.010 per kWh to $0.015 per kWh (Luther 2016).

$$\text{O\&M cost} = 1.01 \text{ million TL/year.} \quad (7.52)$$

Comparison of the operation and maintenance cost of the gas turbine with reciprocating engine for same scenario shows that the O&M of a reciprocating engine is greater by an amount of 0.095 million TL /year, but the cost of electricity per kWh and other cost benefits are more than a gas turbine case. Even this case seem as not a good option due to maintenance and fuel cost as the operation and maintenance cost is in dollars, which means that it is higher but the local manufacturer can provide the same maintenance in lesser cost.

For estimating the capital cost, the cost is in the range of $800-$2000/ KW of electricity generation per year. This installation also includes the HRSG package. The highest value is considered. The Net profit from Equation (3.59).

$$\text{Installation Cost} = 6.19 \text{ million TL} \tag{7.53}$$

$$\text{Institute Electricity Cost} = 0.900 \text{ million TL/year.} \tag{7.54}$$

$$\text{Net Profit} = -\ 1.79 \text{ million TL.} \tag{7.55}$$

The negative sign indicates that cash flow is outward, instead of profit more money has to be paid because of the long hour of operation, which is 8,000 hours per year. The reason for the deficit is the increased maintenance cost, which is almost 3 times as that of the first case of reciprocating engine, the fuel purchase cost which is also 3 times. As there are no positive cash flows for this case, therefore no payback period can be calculated.

The reason for not calculating installation cost and payback period is because of higher per unit cost of electricity than the grid, which makes gas turbines more costly, even in terms of purchase of electricity per kWh but also in operation and maintenance cost.

7.3. Economic Analysis

Analysis of the result is very important and is based on the cases presented in the case study to understand the results better. The economic analysis is made to compare the grid cost with reciprocating engine and gas turbine

First, gas turbine is considered for comparison case with grid electricity. The per unit purchase cost of electricity is far greater than that of the grid. The grid purchase cost is 0.199 TL/kWh, while for gas turbine it is 0.41 TL/kWh, which is twice as more as that of the grid, this cost per kWh makes gas turbine case not feasible for the institute. Other reasons are associated with the operation and maintenance cost and fuel purchase cost. The operation and maintenance cost for grid is 0.246 million TL per year while for the gas turbine's case one it is 0.388 million TL per year and for case two it is 1.073 million TL per year. For case one, it is nearly 0.14 million TL more, while in the second case it is 4.5 times more than that of the grid. Apart from that, the cost spent after selling excess electricity to purchase fuel, operation and maintenance combined is more than that of the price paid by institute with all cost of operation and maintenance, fuel for heating cost, grid electricity and transmission and distribution loss cost. The cost of the existing system is 2.414 million TL, for gas turbine first case the total cost is 2.53 million TL and for second case of the gas turbine the total cost is 7.083 million TL. Cost comparison for each case shows the negative cash flow when compared with existing systems. This reason makes gas turbine based Combined Cycle infeasible for the institute.

The case which includes reciprocating engine as the prime mover shows different results for each scenario. The analysis of per unit price for both cases gives the same result, which is 0.175 TL/kWh. If per unit cost is the deciding factor, then both cases are feasible from the grid as institute pays 0.199 TL/kWh. The total price paid for electricity for 2016 based on 0.175 TL/KWH is 0.90 million TL while for grid it comes out to be 1.023 million TL, which shows a difference of 12 %, which means Institute can save 0.123 million TL each year.

Deeper analysis of reciprocating engine gives a different picture. Reciprocating engine for first scenario generates a saving of 0.016 million TL after selling excess electricity to the grid while when net profit is evaluated by subtracting all cost incurred from the profit, it shows positive cash flow of 0.495 million TL when institute also pays electricity based on 0.175 TL/kWh. The payback period calculated in this case is 12.5 years, which is good enough for a plant whose lifetime is considered as a minimum 20 years.

While for second scenario of reciprocating engine, the per unit cost remains same, while the net profit does not show a positive cash flow, the reason is the operation and maintenance cost which is 1.01 million TL, 4 times more than that of the existing system ,which is 0.246 million TL per year and the fuel purchase cost that is 4.5 million TL, 3 time more than the first case of reciprocating engine and 2.086 million TL more than all the combined cost of existing system which includes maintenance, losses, fuel for heating and generators cost and cost for purchasing electricity from the grid. This represents that, long term operation even per unit price is same is not feasible for the institute.

As both of the system operate at higher efficiency than existing but reciprocating engine is more efficient as compared to gas turbine because aim is to generate maximum electricity from waste heat for electricity based heating and cooling system. The higher operating hours for both cases are not well suited for the institute because of negative cash flows more than that of grid based electricity. The only possible option which provides the best optimal solution for changing conventional old existing system is reciprocating engine first case.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

8.1. CONCLUSION

The aim of this study was to carry out a detailed feasibility analysis of combined cycle system for the Izmir Institute of Technology. Turkish energy policies are quite focused on renewable energy, especially wind and solar energy. Many countries through the integration of the combined cycle system with renewable energy have achieved their goal of reducing energy imports to zero level. Not even this, but implementation of combined cycle application on every scale has enabled countries to reduce the rate of growing energy demand and also used these systems to achieve heating efficiencies at a greater level than conventional systems.

European countries have achieved a significant level of reduction in emissions as well as in energy demands after implementing decentralized combined cycle generation systems. The main purpose of this system is to integrate heat, power and cooling together to ensure continuous and smooth supply reducing the cost associated with transmission and distribution losses.

Turkey’s energy market is large but still the role of combined cycle is not sufficient. Only industrial scale activities make most percentage of combined cycle. Turkey has greater potential to save energy from heating and other sectors, especially in residential and commercial applications. This study highlights the weak points in Turkish Energy Policy in order to improve the energy market. Turkey can achieve a huge growth in local combined cycle market, which can allow cheap facilities in future for installation and maintenance of engines and turbines.

This case study evaluates two kinds of cogeneration/trigeneration facilities for the Izmir Institute of Technology. Firstly, a case is based on a gas turbine as prime mover for combined cycle and secondly is a reciprocating engine as the prime mover. The purpose is to compare the outcomes with the existing utility systems to estimate, what option best fits the Institute’s requirements. After analysis of the capacity by using actual data, heat and mass balance provides the output generation of each combined cycle case. While the economic and environmental analysis provides insight of socio economic aspects. The result deduced from the case study suggests that the long term operation is not feasible for both cases, the reason lies in high natural gas prices due to higher taxes and the high devaluation of the Turkish lira during recent months because of political in-stability, but reciprocating engine with normal operating hours gives a better outcome as compared with the grid based electricity system. The result suggests that implementation of combined cycle system provides a more green approach for achieving the utility requirement for the institute.

This study also evaluates for cooling demand which puts it into the Trigeneration section. Through combined cycles Turkey can achieve sustainability, market growth, energy efficiency and reduction in energy demand. The implementation of this study for the Institute provides an independent source of decentralized generation with less losses, more efficient production of electricity, heat and cooling with efficient utilization of fuel. Combined cycle can act as a bridge to the future, for achieving sustainability targets for Turkey and the Institute.

8.2. RECOMMENDATION

The reciprocating engine provides a better solution, but the total capacity of the institute is small as compared to other universities or campuses. For small scale combined cycle systems, integration of equipment is the key for improving combined cycle efficiency. More heat utilization between equipment's can lead to better recovery of waste heat. The case study was done with a single pressure HRSG, , but double pressure can lead to better efficiency, approximately 10 % more than single pressure in a more cost effective way. Reciprocating engine temperature control and steam turbine heat recovery from extraction stages can lead to better results, which can increase the efficiency 10-15% and can lead to the significant reduction in emissions.

Later the study can be evaluated for the biomass, as a combination of biomass, landfill gas and natural gas will provide a more better outcome both interms of economic and pollution control.

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APPENDIX A

ELECTRICITY CONSUMTPION 2013

	Month	Iyte Total	R&D	Reactorate Building	Administration Building	Science Faculty	Engineering Faculty	Architecture Faculty	Chemical Engineering	Mechanical Engineering
2013	Jan	472,862	9,022	14,918	24,575	108,353	43,215	30,521	74,060	35,776
	Feb	431,368	8,217	12,979	23,722	99,679	32,663	27,517	71,226	31,316
	March	425,858	10,198	12,198	23,847	88,833	34,863	29,914	61,374	32,605
	April	342,752	9,354	10,084	23,102	72,133	30,526	24,288	31,154	25,803
	May	349,659	8,514	11,131	25,433	75,135	29,123	31,147	33,078	21,736
	June	615,702	10,173	20,177	49,248	155,773	53,969	37,793	77,425	40,789
	July	786,096	10,443	26,228	62,670	201,573	63,078	44,228	94,992	49,309
	August	677,598	8,695	25,128	55,043	162,362	57,375	41,291	80,860	44,197
	Sept	525,923	8,519	18,938	43,989	124,295	52,100	31,114	56,279	33,839
	Oct	270,115	6,896	8,279	21,055	57,535	31,281	16,206	22,806	14,675
	Nov	367,841	9,094	11,865	22,939	71,510	39,660	28,152	48,174	23,404
	Dec	538,095	12,802	16,785	26,205	100,499	55,060	38,736	80,322	40,309

	Month	Medical and Computer Engineering	Library	Sports Saloon	Cafeteria
2013	Jan	14,341	30,651	11,655	15,424
	Feb	15,507	27,940	8,574	16,990
	March	17,126	29,919	10,161	18,368
	April	13,794	28,302	8,988	16,319
	May	14,005	30,756	4,636	17,796
	June	26,841	25,254	4,587	23,636
	July	33,511	55,233	6,230	26,622
	August	30,187	46,004	5,269	21,947
	Sept	25,995	22,608	5,616	24,803
	Oct	13,668	25,885	8,462	7,637
	Nov	18,509	23,063	13,379	11,749
	Dec	23,351	40,816	19,224	17,472

Appendix A (Cont.)

APPENDIX B

ELECTRICITY CONSUMTPION 2014

	Month	Iyte Total	R&D	Reactorate Building	Administration Building	Science Faculty	Engineering Faculty	Architecture Faculty	Chemical Engineering	Mechanical Engineering
2014	Jan	685,967	8,991	13,362	26,940	84,313	37,042	28,180	56,576	28,866
	Feb	740,103	10,634	14,516	28,244	87,086	38,918	30,505	63,706	41,810
	March	691,670	9,486	12,516	26,048	81,604	35,983	29,150	49,595	43,477
	April	559,575	10,860	11,201	19,145	79,168	31,098	24,822	26,921	34,768
	May	546,131	9,414	10,728	20,015	72,335	28,031	27,954	25,926	30,458
	June	853,589	9,811	19,785	41,362	116,867	40,588	37,461	62,741	44,671
	July	1,102,307	10,951	25,828	54,146	158,562	47,329	48,565	85,849	58,364
	August	1,394,359	13,167	29,769	63,012	224,935	67,276	51,477	92,179	63,514
	Sept	981,918	9,077	21,669	47,818	143,572	46,393	38,714	69,202	51,899
	Oct	469,051	7,693	8,845	22,596	84,362	25,679	19,749	19,242	13,812
	Nov	651,891	9,250	12,476	28,006	81,449	32,960	34,118	42,480	23,205
	Dec	877,882	9,603	15,142	32,226	101,110	39,758	46,338	80,986	34,283

	Month	Medical and Computer Engineering	Library	Sports Saloon	Cafeteria
2013	**Jan**	17,393	34,233	11,073	14,382
	Feb	18,979	28,393	11,532	16,607
	March	17,556	32,575	12,312	13,068
	April	16,707	19,457	12,352	8,638
	May	15,838	28,768	4,678	17,983
	June	19,984	31,110	4,594	25,237
	July	26,520	34,237	5,089	28,206
	August	27,961	60,587	6,496	36,549
	Sept	26,955	26,522	8,466	32,090
	Oct	14,346	13,112	9,601	7,515
	Nov	19,275	31,695	15,625	12,539
	Dec	23,478	36,051	23,617	17,443

Appendix B (Cont.)

APPENDIX C

ELECTRICITY CONSUMTPION 2015

	Month	Iyte Total	R&D	Reactorate Building	Administration Building	Science Faculty	Engineering Faculty	Architecture Faculty	Chemical Engineering	Mechanical Engineering
2015	Jan	777,523	8,602	14,205	27,584	94,693	36,134	30,856	71,823	35,206
	Feb	772,238	9,464	14,746	30,187	97,951	36,715	28,566	65,936	34,916
	March	765,428	8,851	12,763	27,660	92,095	36,535	35,249	61,209	34,205
	April	597,482	7,789	10,314	25,570	77,491	31,386	29,824	35,992	24,363
	May	515,338	7,470	9,729	25,634	75,478	29,064	27,228	25,059	19,467
	June	796,867	6,660	17,856	40,383	107,705	36,208	29,541	53,088	32,286
	July	1,184,189	8,603	29,419	54,765	189,387	49,875	41,099	87,017	43,853
	August	1,416,400	8,474	29,080	58,754	205,325	53,813	42,546	126,220	50,646
	Sept	1,014,676	8,410	22,000	47,020	153,698	43,458	33,198	89,372	38,987
	Oct	450,719	6,245	9,000	22,010	88,679	24,731	14,078	18,766	13,143
	Nov	627,014	7,689	13,000	27,500	89,686	31,673	28,075	39,821	19,013
	Dec	837,101	8,198	16,000	31,800	109,200	26,521	36,142	83,329	30,341

	Month	Medical and Computer Engineering	Library	Sports Saloon	Cafeteria
2015	Jan	31,379	34,457	7,591	15,270
	Feb	33,819	27,417	11,625	13,764
	March	32,302	33,843	11,576	14,466
	April	26,689	24,362	8,989	10,047
	May	15,991	21,636	3,919	11,187
	June	29,966	43,210	5,014	17,549
	July	44,429	45,037	4,245	26,753
	August	34,566	88,621	4,689	48,486
	Sept	28,854	36,410	3,832	34,608
	Oct	13,897	10,466	8,280	7,374
	Nov	20,087	26,476	14,138	13,387
	Dec	23,789	33,020	23,477	17,665

Appendix C (Cont.)