Application of Micro-CHP System for a Student Accommodation Building in North Cyprus

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Submitted to the
Institute of Graduated Studies and research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
June 2016
Gazimağusa, North Cyprus

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ABSTRACT

Increased use of fossil fuels is the primary source of the greenhouse gasses causing the global warming. This paved the way for increased research on renewable energies and energy efficient systems, for producing heat and power. With this regard, combined heat and power systems are used as energy efficient systems leading to a reduction in fossil fuel consumption.

The objective of this study is to investigate the energetic (thermal and electrical) performance and economic feasibility of employing a 5.5kW Micro Combined Heat and Power (Micro-CHP) plant to a 400m^2 student accommodation building in Cyprus. The analysis is carried out for two scenarios;

i. Micro-CHP system following the thermal load of the building

ii. Micro-CHP system following the electrical load of the building.

The building's constructions material's thermophysical properties, building's schedules (occupancy, lighting, electrical appliances, heating requirements and hot water use), are defined for the case study building. These parameters are required for the investigation and analysis. The investigation is done by carrying out dynamic simulations by the thermal simulation software Energy Plus. The simulations are done for the heating season (1st of November-28th of February). The parameters required for the simulations are explained extensively in the work. Monthly, daily and hourly results (energy produced by Micro-CHP plant) are presented for the simulation period and given for the two scenarios; Micro-CHP system following the thermal load and electrical load of the building. The results show that the maximum energy production by the Micro-CHP system for following the thermal load is in January with thermal energy production of 14680.57 MJ and electrical energy production of 6867.43 MJ. When the Micro-CHP follows the electrical load of the building, the maximum energy output is obtained again in January with electrical output of 6458.6 MJ and thermal output of 13976.49 MJ.

Finally, an economic feasibility analysis of the Micro-CHP has been carried out at the end of this study for both cases; Micro-CHP following thermal load and following electrical load of the building. It has been shown that for following the thermal load 6539 kWh electrical energy is saved but 3654 kWh of more thermal energy is used with Micro-CHP compared with a conventional system. The overall energy saving is 2885 kWh. For following the electrical load, 6946.5 kWh of electrical energy saved but 8502 kWh of more thermal energy is used with Micro-CHP. The overall energy saving is - 1555 kWh.

It is seen that when the thermal load is followed energy is saved but when the electrical load is followed there is no energy saving. Although there is energy saving while the Micro-CHP is following the thermal load of the building, the system is not feasible as Savings to Investment Ratio=0.4, Internal Rate of Return=0%, and Simple Payback Period= 23.8 years. This has several reasons such as the high installation cost in Turkish Lira, low oil prices causing lower electricity prices etc. It has been showed that if the Turkish Lira rate is stable such as it was 3 years ago and the electricity prices were at the same value as 3 years ago the project would be feasible with SIR=1.1, IRR=11%, and SPP=8.2 years.

Keywords: electrical load of the building, thermal load of the building, Micro-CHP analysis, economic analysis.

ÖZ

Fosil yakıtların kullanımının artması, küresel ısınmaya neden olan sera gazlarının başlıca kaynağıdır. Bu durum, ısı ve güç üretimi için, yenilenebilir enerji sistemleri ve enerji verimliliği konusunda yapılan araştırmaları artırmıştır. Bu bağlamda, kombine ısı ve güç sistemleri (CHP), fosil yakıt tüketiminde tasaruf sağlayan verimli enerji sistemleri olarak kullanılmaktadır.

Bu çalışmanın amacı, Kıbrıs'ta 400m^2'lik bir öğrenci konaklama binasına 5.5 kW'lık bir Mikro-CHP uygulamasının enerji (ısı ve elektrik) performansını ve ekonomik uygulanabilirliğini incelemektir. Bu çalışmada iki durum ele alınmıştır;

i. Mikro-CHP sisteminin binanın ısıl yükünü takip etmesi
ii. Mikro-CHP sisteminin binanın elektriksel yükünü takip etmesi

Mikro-CHP sisteminin incelenmesi ve analizi için gerekli olan parametreler; bina yapı malzemelerinin ısıl ve fiziksel özellikleri, binanın çalışma koşulları (doluluk, aydınlatma, elektriksel yükler, ısıtma gereksinimleri ve sıcak su kullanımı) tanımlanmıştır. Mikro-CHP sisteminin incelenmesi, bir dinamik ısıl simülasyon yazılımı olan Energy Plus ile yapılan simülasyonlar vasıtası ile gerçekleştirilmiştir. Simülasyonlar Kıbrıs'ta ısıtma sezonu olan Kasım ayının başından Şubat ayının sonuna kadar olan süre için yapılmıştır. Yapılan simülasyonlar için gerekli parametreler bu çalışmada detaylı bir şekilde açıklanmıştır.

Aylık, günlük ve saatlik sonuçlar (Mikro-CHP sistemi tarafından üretilen enerji) simülasyon dönemi için her iki senaryo (bina ısıl yükü takibi ve bina elektriksel yükü takibi) için de verilmiştir. Binanın ısıl yükü takip edilmesi halinde Mikro-CHP sistemi ile maksimum ısı enerjisi üretimi 14680.57 MJ, maksimum elektrik enerjisi üretimi ise 6867.43 MJ ile ocak ayında gerçekleşmiştir. Binanın elektriksel yükü takip edilmesi halinde Mikro-CHP sistemi ile maksimum ısı enerjisi üretimi 13976,49 MJ, maksimum elektrik enerjisi üretimi ise 6458,6 MJ ile yine ocak ayında gerçekleşmiştir.

Bu çalışmanın sonunda her iki senaryo için de ekonomik uygulanabilirlik çalışması yapılmıştır. Binanın ısıl yükünün takip edilmesi halinde 6539 kWh'lık elektrik enerjisi tasarruf edilmiş fakat fazladan 3654 kWh'lık ısıl enerji tüketilmiştir. Toplam enerji tasarrufu ise 2885 kWh olmuştur. Binanın elektriksel yükünün takip edilmesi halinde ise 6946,5 kWh'lık elektrik enerjisi tasarruf edilmiş fakat fazladan 8502 kWh'lık ısıl enerji tüketilmiştir. Toplam enerji tasarrufu ise -1555 kWh olmuştur.

Görülmektedir ki binanın ısıl yükü takip edildiği zaman enerji tasarrufu oluşmakta fakat binanın elektriksel yükü takip edildiği zaman tasarruf oluşmamaktadır. Binanın ısıl yükünün takip edilmesi halinde enerji tasarrufu sağlanmasına karşın yapılan ekonomik uygulanabilirlik çalışması sonucunda Mikro-CHP sisteminin ekonomik olarak uygulanamaz olduğu görülmüştür.(SIR=0,4, IRR=0% ve SP=23,8 yıl). Bu durumun en önemli sebepleri USD/TL kurunun bu çalışma yapıldığı esanada çok yüksek olması ve petrol fiyatlarının düşüklüğüne bağlı olarak elektrik fiyatlarının düşük olmasıdır.Çalışmada USD/TL kurunun ve elektrik fiyatlarının 3 yıl önceki gibi istikrarlı seyretmesi halinde ise projenin ekonomik olarak uygulanabilir olduğu ayrıca gösterilmiştir.

Anahtar Kelimeler: binanın elektrik yükü, binanın ısı yükü, Mikro-CHP analizi, ekonomik analiz.

ACKNOWLEDGMENT

First I would like to thank the EASTERN MEDITERRANEAN University and especially PROF. DR. Uğur ATİKOL for all the understanding and tolerance he has showed through the years of study.

Second I would like to show my gratefulness towards Assist. Prof. Dr. Murat Özdenefe my instructor and supervisor through my master years and showed a lot of care and set me ready to take the next step that is ahead of me now that I hope I will be graduating this year.

I would also like to thank special instructors, Prof. Dr. Fuat Egelioğlu and Prof. Dr. Uğur Atikol who didn’t simply teach me but also helped me to know what the word Engineering was and what will be waiting for me ahead. Last but not least this project is dedicated to my parents, Assist. Prof. Dr. Murat Özdenefe, friends and every person who was present to help me through my entire academic and nonacademic path.

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η_e:	Steady-state part-load, electrical conversion efficiency of The engine
η_q:	Steady-state part load, thermal conversion efficiency of the Engine.
$\dot{m}_{cw}$:	Mass flow rate of plant fluid through the heat recovery [kg/s]
$T_{cw.i}$	Bulk temperature of the plant fluid entering the heat recovery Section [°C].
$T_{cw,0}$:	Bulk temperature of the plant fluid leaving the heat recovery Section [°C].
$P_{net.ss}$:	Steady-state electrical output of the system (W).
q_{gross}:	Gross heat input into the engine (W).
$q_{gen,ss}$:	Steady-state rate of heat generation within the engine (W).
$[MC]_{eng}$:	Thermal capacitance of the engine control volume (W/K).
T_{eng}:	Temperature of the engine control volume (°C).
UA_{HX}:	Effective thermal conductance between the engine control Volume and the cooling water control volume (W/K).

UA_{loss}:	Effective thermal conductance between the engine control volume And the surrounding environment (W/K).
T_{room}:	Temperature of the surrounding environment (°C).
$[MC]_{cw}$:	Thermal capacitance of the encapsulated cooling water and heat Exchanger shell in immediate thermal contact (J/K).
$[\dot{m}c_p]_{cw}$:	Thermal capacity flow rate associated with the cooling water (W/K).
$\dot{N}_{fuel}$:	Molar fuel flow rate [kmol/s].
LHV_{fuel}:	Lower heating value of the fuel used [J/kg or J/kmol].
$P_{Elec,Operating}$:	Actual (operating) electrical power output [W].
$ElecEff_{operating}$:	Electrical efficiency at the current operating conditions.
$\dot{Q}_{Fuel,LHV}$:	Fuel energy consumption rate, LHV basis (W).
C (1-4):	Pump part load ratio.
l_{th} :	Thermal limit
η_{el}:	Electrical efficiency
η_{th}:	Thermal efficiency
η_t:	Overall efficiency

LIST OF ABBREVIATIONS

SPP:	Simple payback period
NPV:	Net present value
SIR:	Saving to investment ratio
IRR:	Internal rate of return
PLR:	Part load ratio.
CHP:	Combined Heat and Power.
PV:	Photovoltaic.
USD:	United States Dollar
N:	North
PTAC:	Packaged Terminal Air Conditioner
HVAC:	Heating Ventilating Air Condition

Chapter 1

INTRODUCTION

1.1 Energy Need

For human societies to continue and to assure that they will have a more equitable and sustainable future, alternative and efficient energy sources are required. For that reason more studies, tests and experiments should be done for finding new alternatives for the fossil based energy sources. Recent studies show that after 2020, the world dependence on gas and oil as a source of energy will lessen. The future view of the world after 2020 also suggests that globally, there will be more demand for different energy sources. Hence, there would be different technology installation techniques and different trade patterns [1].

Today's studies suggest that the fossil fuels were the most reliable energy source. Fossil fuels is used extensively in almost all sectors. However, this does not mean that fossil fuels will maintain this reliability. Therefore, it is crucial that people use energy efficiently and find alternative sources.

1.2 Renewable vs. Nonrenewable Energy

Energy sources that are continuous and that will not deplete in the near future are called, renewable energies, e.g. solar thermal, hydro, geothermal, and wind, whereas nonrenewable energies are those that will vanish in the future and cannot be replaced by nature. Example to nonrenewable energy sources are nuclear energy and fossil fuels.

- Advantages of renewable energy

This kind of energy sources are less harmful to the environment than fossil fuels. Technologies which require this kind of energy sources are advancing and this is resulting in decreased installation and maintenance costs for these systems [2]. Using renewable energies has no greenhouse gas emissions, comparing with nonrenewable energies which are leading to increase the planet's temperature.

- Disadvantages of renewable energy

Although the installation and maintenance costs for renewable energy systems are decreasing due to the recent advancements, they are still costing more than conventional fossil based systems.

Maintenance for particular renewable systems such as hydroelectric power plants is very costly and require lots of experience. Solar and wind energies require vast areas to be able to perform as good as fossil fuel based power plants [3]. Also, weather has significant effect on the performance of renewable energy systems. Uncertainties in the weather reduces the reliability of renewables. For example, solar thermal power plants are not very efficient on cloudy days.

- Advantages of nonrenewable energy sources

The world's most used energy source for power plants is fossil fuels. Almost all industrial facilities, and transportation vehicles rely on fossil fuels. Nonrenewable energy can operate in all weather conditions; it doesn't matter if it is cloudy or rainy, windy or wind free. Plants can still give high performance. There are new inventions for reducing the environmental impact of fossil based fuels such as mixing carbon with the fuel to reduce its harmful effects [4]. This kind of application captivates carbon dioxide (CO2) from industrial and electrical plants and hoards it underground.

- Disadvantages of nonrenewable energy sources

The environment was widely damaged from fossil fuels as a result of strip mining and accidental oil spills. The extensive use of fossil fuels deployed greenhouse gasses especially carbon dioxide (CO2), which is the main contributor to global warming. The use of nuclear stations is extremely dangerous resulting from potential radiation leaks and waste storage problems. Also, it is extremely costly to build new nuclear power plants and to decommission the old ones.

1.3 Motivation

There is extensive research on renewable energy technologies. This broad research is tending to diminish the principal drawback of the renewable energy technologies i.e. high installation and maintenance cost. Although the rapid progress in renewable energy technologies, fossil fuel use is still constituting the substantial portion of the primary energy consumption. Therefore, first measure in energy field should be the efficiency. Engineers should design and use energy efficient systems in order to reduce the use of fossil fuels and thus their harmful effects.

Combined Heat and Power (CHP) which produces heat and power simultaneously is one of those efficient systems. A particular application of CHP is a Micro-CHP which is a small scale CHP system ranging from 3kW to 350 kW. These systems are applied to relatively small buildings and have higher efficiencies than conventional systems (separate production of heat and electricity)

Simultaneous production of heat and power increases the system overall efficiency and reduces the fuel use. Apart from having higher efficiency than the conventional systems, CHP enables the power generation to be distributed, thus decreasing the load on thermal power plants. Having distributed and localized power generation requires no transmission and distribution of power thus no transmission and distribution losses occur. This is an important factor in locations such as North Cyprus which has high transmission and distribution losses [5]. In North Cyprus for the period of 2006-2015 the average transmission and distribution losses was 14.9% [6] whereas, the World's and European Union's average for the same period was 8.4% and 6.4 % respectively.

Awareness for energy efficiency is rising rapidly and will continue to rise in the near future. This will lead to the extensive applications of energy efficient systems such as Micro-CHP. Micro-CHP system is a promising technology, yet to be widespread. To fully benefit from the advantages of Micro-CHP systems and to understand the importance of every element involved in it as well as to use it effectively, thoroughly investigated case studies should be considered. Thus, the motivation of this thesis is to contribute the widespread use of Micro-CHP and demonstrate its applicability by investigating its energetic performance and carrying out its economic feasibility analysis under the conditions of North Cyprus for a case study.

1.4 Objectives

This study aims to investigate the Micro-CHP system application to supply electricity and heat for a particular building type in N. Cyprus and to carry out an economic feasibility for the system. It is aimed to do this investigation for a student accommodation building where there is a continuous demand for electricity and heat. It is intended to model the case study building and the assigned Micro-CHP system with Energy Plus which is a robust dynamic thermal and plant energy simulation program. It is aimed to simulate the energy generated by the Micro-CHP system and energy savings obtained for the heating season in Cyprus which is from 1st November to 28th February.

1.5 Organization of the Thesis

In chapter 2, a brief comparison between combined heat and power with separate heat and power has been done. Then some of the CHP technologies were introduced such as Micro-Turbine, Fuel Cell, and Internal Combustion Engine. At the end of chapter 2, published articles were introduced to describe the Micro-CHP applications.

In chapter 3, the fabric, electrical capacity, schedules, heating system, water use system, plant loops and system diagram of the modelled building were introduced to meet the requirements for installing a Micro-CHP system.

In chapter 4, the used equations for the simulation were introduced. Reaching chapter 5, monthly, daily, and hourly results were given for both when Micro-CHP follows the thermal load of the building, and when Micro-CHP follows the electrical load of the building.

Moreover, an economic analysis was done in chapter 6 for the current currency and the past 3 years currency to study the feasibility of the Micro-CHP system. Discussion and conclusion are presented in chapter 7.

Chapter 2

LITERATURE REVIEW

2.1 Combined Heat and Power vs. Separate Heat and Power generation

Combined Heat and Power is a simultaneous conversion of primary energy (usually fossil fuel) to electricity and useful heat. CHP system can provide heat and power simultaneously from a single fuel source see Figure 2.1. Moreover, CHP system of appropriate size can produce adequate heat energy to satisfy all the building’s heating loads in the heating season. Combined heat and power is a viable source of clean energy generation and a source to fulfill all the loads on energy demands [7].

Figure 2.1 shows the Separate Heat and Power Generation with 2 separate power inputs one for the boiler and the second for the power plant. The boiler’s thermal efficiency is 85% and the power plant’s electrical efficiency is 35%. While for Combined Heat and Power, only one power input with a thermal efficiency equal to 62%, and electrical efficiency equal to 28%. CHP system is more recommended because the resulting heat loss is less than the heat loss from the separate heat and power system.

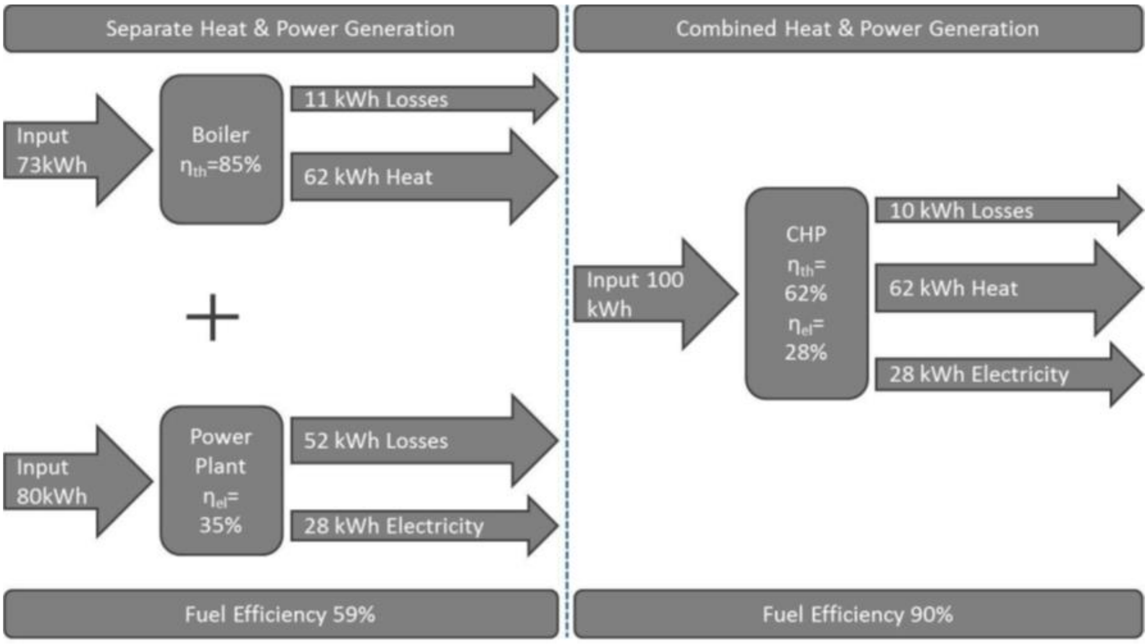


Figure 2.1: Comparison between Separate and Combined heat & power generation [8].

2.2 Micro-CHP Technologies

A particular application of CHP is a Micro-CHP which is a small scaled cogeneration, and it can be applied in almost all facilities i.e. residential house, hotels, universities, hospitals, etc.

Micro-CHP systems operate 18 hours to 24 hours per day. It reduces the nitrogen oxide (NO) emissions approximately by five tons per year (5tons/year) which is equal to removing 258 cars off the roads [9].

It is more than clear that human race should radically decrease vitality related CO2 discharges so as to minimize the effect of environmental change. One area that merits specific consideration in this appreciation is the residential sector, which has a huge potential in reducing the CO2 emissions. The use of a cogeneration system opens a vast opportunity to solve these problems.

Many problems in delivering energy demands were recognized by the U.S. Combined heat & power Association such as; global climate change, energy prices, and power quality. Micro-CHP has many advantages and disadvantages, Figures 2.1, and 2.2 summarize the major advantages and disadvantages, that are communicated in the market between suppliers and customers.

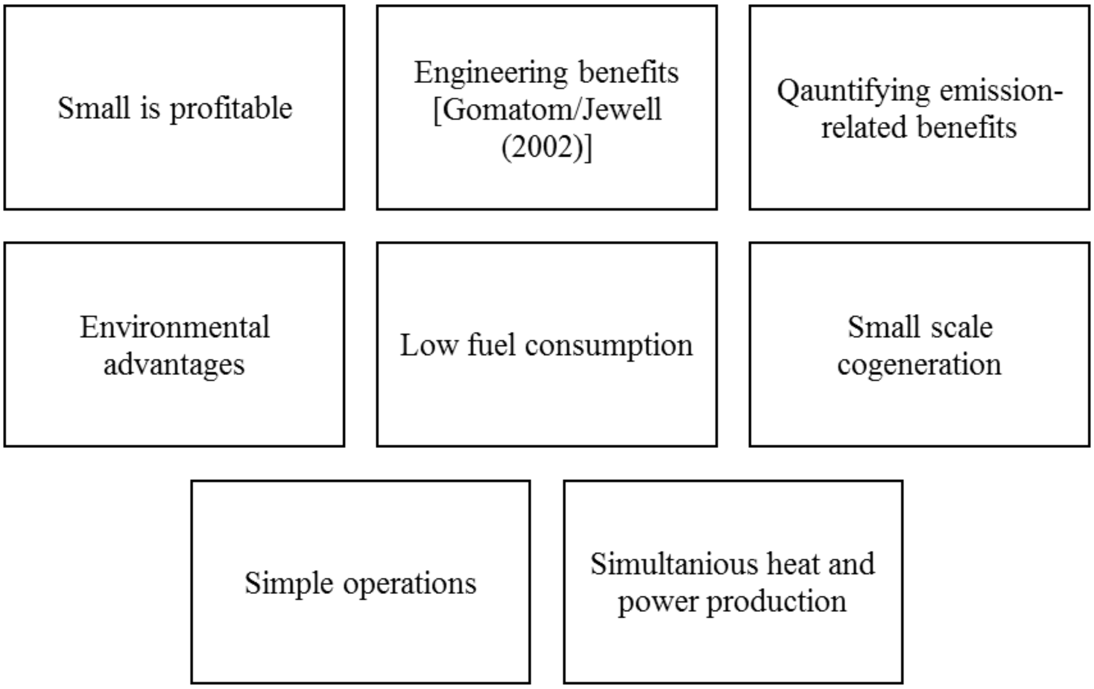


Figure 2.2: Micro-CHP technologies advantages [10], [11].

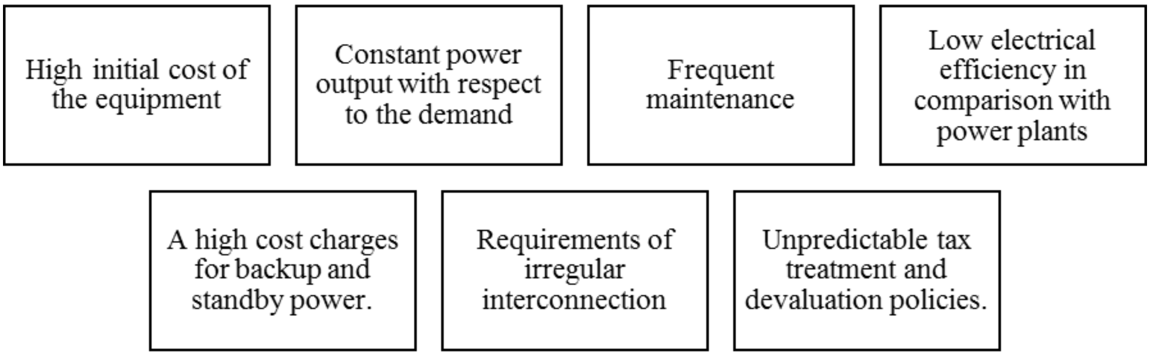


Figure 2.3: Micro-CHP technologies disadvantages [12].

In the energy market, there is a huge competition between different technologies related to CHP systems, specifically in residential sector. These technologies basically include Micro-Turbine, Fuel cells, and Internal Combustion Engine; the main characteristic of these technologies will be listed below.

However, the above listed technologies are operated using fuel that will be introduced in details in the following part of the project.

2.2.1 Micro-CHP Fuels

Combined Heat and Power system consists of a prime mover such as gas turbine, a heat recovery system etc. The components employed in the CHP system can vary depending on the type of fuel used.

The selection of fuel plays a significant role in CHP systems. Fuel can influence the price of the system by wavering the energy price. Also, the fuel used can lead to side effects on the environment [13]. The high heating value (HHV) and low heating value (LHV) of the fuel have a primary influence on the efficiency of the CHP systems. Heating values of standard fuels can be seen in Table 2.1.

Table 2.1: Heating Values of common fuels [14], [15].

Fuel	**HHV [MJ/kg]**	**LHV [MJ/kg]**
Hydrogen	141.8	121
Methane	55.5	50
Ethane	51.9	47.8
Propane	50.35	46.35
Butane	49.5	45.75
Pentane	-	45.35
Gasoline	47.3	44.4
Paraffin	46	41.5
Kerosene	46.2	43
Diesel	44.8	43.4
Coal (anthracite)	27	-
Coal (lignite)	15	-
Wood (MAF)	21.7	-
Peat (damp)	6	-
Peat (dry)	15	-
Methanol	22.7	-
Ethanol	29.7	-
Propanol	33.6	-

The heating value refers to the energy released per unit mass when any fuel is completely burned. Propane and/or butane possess a higher heating value than natural gas as seen in Table 2.1 which makes them better to use, but it is not cheap as natural gas.

2.2.2 Micro Turbine

Micro turbines are small turbines that include a compressor, generator, alternator, combustor, and recuperator. Micro turbines were developed from small jet engines, automotive and auxiliary power units for airplanes. Micro turbines are a small version of gas turbines. Its outputs vary from 30 kW to 250 kW with a life cycle up to 80,000 operating hours. Like every device, it needs maintenance, the maintenance takes place between 4000-8000 working hours; thus, Micro-Turbine technology is better than the CHP technologies with an internal combustion engines [16].

Micro-Turbines offer many advantages such as light-weight, low emissions, greater efficiency and lower electricity costs. This technology recovers waste heat to assure efficiencies greater than 80% [17].

The single shaft or two shafts, inter-cooled and reheat, simple cycle or recuperated are the physical classification of the turbines. The single shafted turbine design is frequently used because it is less expensive and very simple to build and install.

First of all, this kind of micro turbine technology is based on the ideal Brayton cycle. Ambient air enters into the compressor and then handled to the combustion chamber to be mixed with the fuel in use. Once the air fuel mixture is burned, it expands in the turbine to produce work see Figure 2.4.

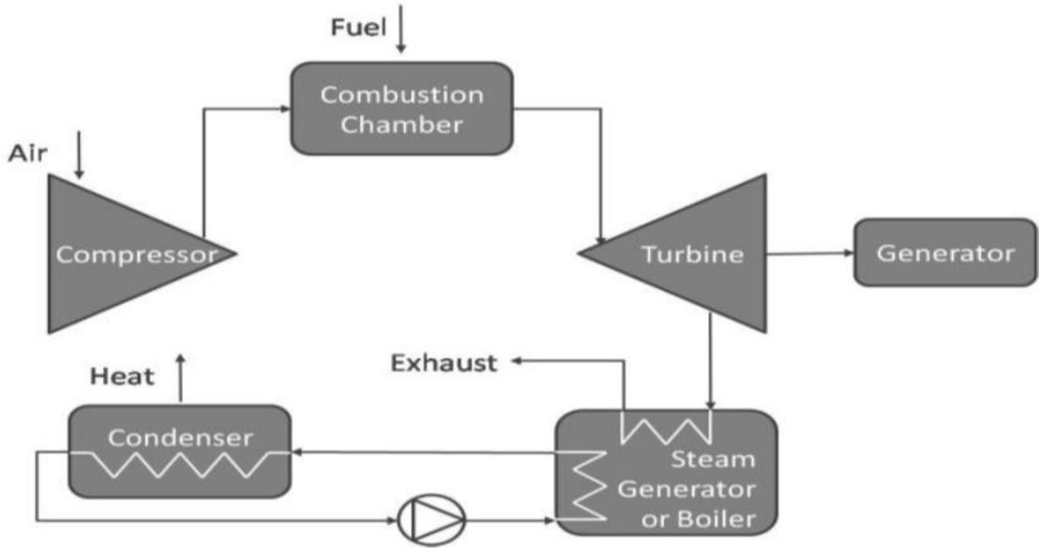


Figure 2.4: Micro-Turbine with ideal Brayton Cycle as displayed in [18].

Micro gas turbines vary from 3kW to 250 kW electric power with a compression ratio of 1:16. No cooling equipment required because excessive heat is drained to the environment. The main disadvantage of the micro gas turbine is that it is affected by the ambient air conditions. High-pressure gas compressors operate on a compression ratio 1:30 resulting in increasing the thermal efficiency of the system.

In this system recuperators play the role of heat exchangers, its primary objective is to preheat the compressed inlet air by using the hot turbine exhaust. Figure 2.5 shows the process of a simple Micro gas turbine power plant.

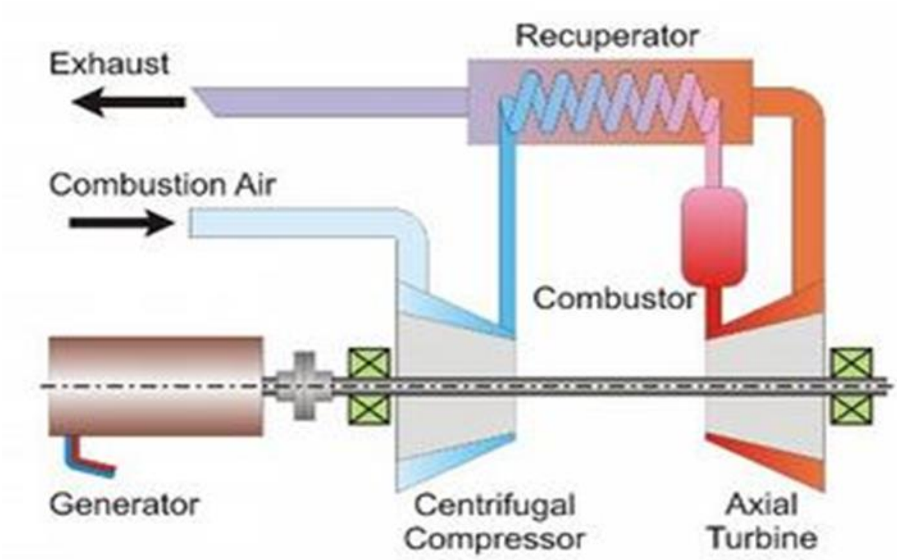


Figure 2.5: Micro gas turbine power plant as displayed in [19].

Also, we have two types of micro turbines: simple and recuperated cycles [20]. In simple turbine cycle, the compressed air is mixed with fuel and scorched in constant pressure. Recuperated cycle rely on the heat from an exhaust stream and transmits it to the input air stream. A typical micro turbine can be seen in Figure 2.6.

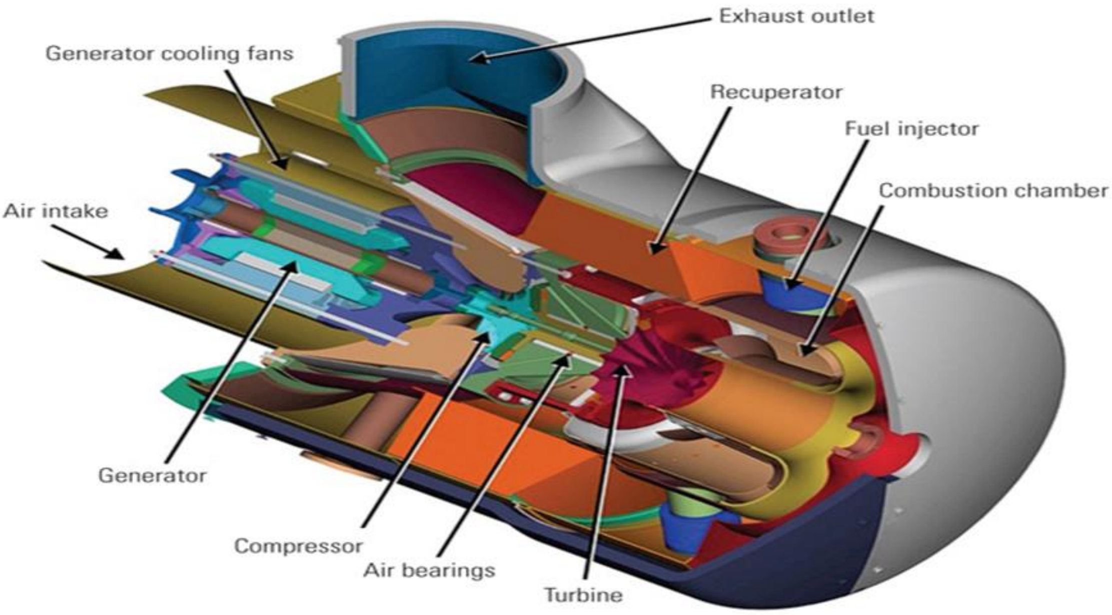


Figure 2.6: Micro Turbine inside components as displayed in [21].

2.2.3 Fuel Cells

This kind of technology has been used as an energy source for space applications. It is still under study technologies and still not applicable yet. Despite all technologies, fuel cells energy generation doesn't rely on combustion process, it is an electrochemical reaction technology. Five different types of fuel cell technology occur Solid oxide fuel cells, phosphoric acid fuel cells, proton exchange membrane fuel cell, molten carbonate fuel cell and alkaline fuel cells. Table 2.2 below shows the difference between the five types of fuel cell technologies.

Table 2.2: Comparison of Fuel Cell Technologies by NREL [22].

Fuel cell type	**SOFC**	**PAFC**	**PEMFC**	**MCFC**	**AFC**
Electrolyte	Ceramic	Acid	Membrane	Liquid	Liquid
Temperature	Highest	Medium	Low	High	Medium
Precious Metal	No	Yes	Yes	No	No
Fuel Flexible	Yes	No	No	No	No
CO2 Emissions [lbs/MWh]	750	1200	1200	1000	1200
Electrical Efficiency [%]	58	37	32	44	35
Availability	99	95	95	95	95

The inside boundaries of the fuel cell are divided into anode, cathode, and electrode [23].

2.2.4 Internal Combustion Engine (ICE)

Internal combustion engines can be found everywhere, in automobiles, trucks, buses and even airplanes, etc... The fundamental about IC engines is to generate work using the products of combustion as the working fluid rather than as a heat transfer medium. To produce work, the combustion is performed in a way that provides high-pressure combustion products that can be expanded through a turbine or piston [24]. There are three major types of IC engines in use nowadays:

- The spark ignition engine which is used mainly in automobiles
- The diesel engine which is used in large vehicles (buses, trucks)
- The gas turbine which is used in aircraft

The spark ignition engines take a mixture of air and fuel then compress it with a piston that goes up, later ignites it through the utilization of a spark plug, and finally, the piston goes back up again to push the exhaust through the exhaust valve.

In a diesel engine, the explosion process is different. The intake valve opens and air is led through, then the piston goes up compressing the air, then fuel is injected at a well calculated time with ignition and the piston goes down, finally the piston goes up to push the exhaust through the exhaust valve [25].

In light of the above introduction to the different technologies related to Micro-CHP, a summary table below is reflecting the major contrast between the systems (Table 2.3 below) say by – Operation Philosophy, Fuel type allowed and Characteristics of three different Micro-CHP technologies.

Table 2.3: Comparison between different Micro-CHP Technologies [26].

	Combustion makes turbine rotate	• Diesel • Natural gas	• Good for CHP • Reliable • Low maintenance • High CO_2 emissions • Good for Residential Buildings • Possible for residential buildings
	Chemical Process That Causes Electrons to Flow through semiconductors	• Oxygen/air plus • Direct or reformed hydrogen • Natural gas and other gases • methanol	• Good for CHP • High efficiency • High set-up cost • Reliable • Low Maintenance • Less Noise • Good for residential buildings
	Reciprocating engine with diesel	• Diesel • Natural gas	• Good for CHP • Reliable • Low maintenance • High CO_2 emissions • Good for Residential Buildings

2.3 Micro-CHP Application

Energy consumption is the need of energy input available in many aspects such as space heating, electricity, air conditioning and hot water. Any facility that has need of hot water is called a potential user for cogeneration. Combined heat and power system requires lower essential energy utilization contrasted with the separate heat and power generation, decreasing wide-reaching energy expenses and fatal liberations to the environment. In addition, the utilization of the electricity delivered can give financial advantage to the client of the facility.

Jose Pascual Martí [27] published a work characterizing an Organic Rankine Cycle module for small-scale CHP applications by fixing a low grade heat source, about 165°C, and simulate it with the presence of a boiler working with natural gas and a heat transfer loop based on thermal oil as operating fluid. The outcomes demonstrate that the thermal power set aside is expanded for higher weight proportions. This additionally infers higher electrical preparations and thermal power profits.

Another work was published by David Mertens [28], studying and comparing 5 different CHP technologies; two gas engines running with natural gas, two external combustion engines (Stirling engines), and one fuel cell with hydrogen gas as working fuel. The results reached were a 90% electricity production from CHP units but only 10% is used. Moreover, these 5 types led to a reduction in heat demand, CO2 reduction, and energy savings especially in CHP system with Stirling engines.

Referring to Yingjun Ruan [29], the main aim of the research was to lessen the annual cost of energy system by employing a residential CHP system involving a storage tank and a back-up boiler. The results reached show that the capital cost, and energy prices affect CHP systems capacity, and the storage tank can extent the operating period of the CHP plant if and only if the tank doesn’t exceed the recommended size, or else it will lead to less economic values.

Finally Enrico Saverio Barbieri, Pier Ruggero Spina, Mauro Venturini [30] evaluated the feasibility and the energy performance of 5 different Micro-CHP systems (internal combustion engines, micro gas turbines, micro Rankine cycles, Stirling engines and thermophotovoltaic generators) to meet the household demands. A prime mover, a thermal energy storage unit, and an auxiliary boiler were existing in each CHP technology. The results reached showed that CHP units satisfied 80% of the thermal energy demand, while the ratio between the produced and required electric energy remains below 85%. However the economic study showed that CHP systems are feasible projects.

Chapter 3

METHODOLOGY AND MODEL PARAMETERS

3.1 Introduction

In this chapter, the methodology followed in this study is explained. First, the modelled building is defined. Then the electrical capacity and the heating requirements of the building is introduced. Subsequently, the building schedules such as occupancy, lightings, etc. are defined.

It is thought to carry out simulations for two different scenarios; Micro-CHP following the building thermal load and Micro-CHP following the building electrical load. However, it should be noted that the unit will be selected to meet the building's electrical capacity.

Figure 3.1 shows the schematic block diagram of the followed methodology. As mentioned earlier Energy Plus is used for modelling and simulation of the Micro-CHP system. In order to do that, first geometrical 3D modelling should be generated. As the geometrical modelling features of Energy Plus is poor Google Sketchup program is used to generate the 3D model of the building. Subsequently 3D model is imported to Energy Plus input data file (IDF) where all the other parameters such as electrical capacity of the building, internal loads, water use rate etc. are inputted to the same IDF. The simulations are carried out for two scenarios with the Energy Plus; Micro-CHP system following the thermal load of the building and Micro-CHP system following the electrical load of the building. The outputs of the Energy Plus simulations are obtained from the Energy Plus output files and are analyzed. The results are presented in Chapter 5. These results then are used to evaluate the economic feasibility of the two scenarios by using excel spreadsheet program. Economic feasibility analysis of the Micro-CHP system for the two scenarios are presented in Chapter 6.

3.2 Modelled Building

The building that is going to be modelled is a residential building which is a student accommodation building. The building is 400 meters square, composed of one story with 12 occupants. The building's specifications are explained in detail in the following sections. As the project is considered for Cyprus, the building properties are selected as typical values used in Cyprus buildings. The architectural plan of the student hall given in Appendix A consists of a big kitchen, living room, 9 bedrooms (3 big bedrooms with the presence of 2 beds in each). The 3D model of the building generated by Google Sketchup is provided in Figure 3.2.

The walls of the building are made up from perforated clay bricks; the floor is composed of hardcore, concrete, sand, screed and marble respectively from bottom to top. Finally, for the roof, a reinforced concrete slab covered with plaster from both sides is employed. All the thermophysical properties of the building materials are taken from "ASHRAE Handbook" [31].

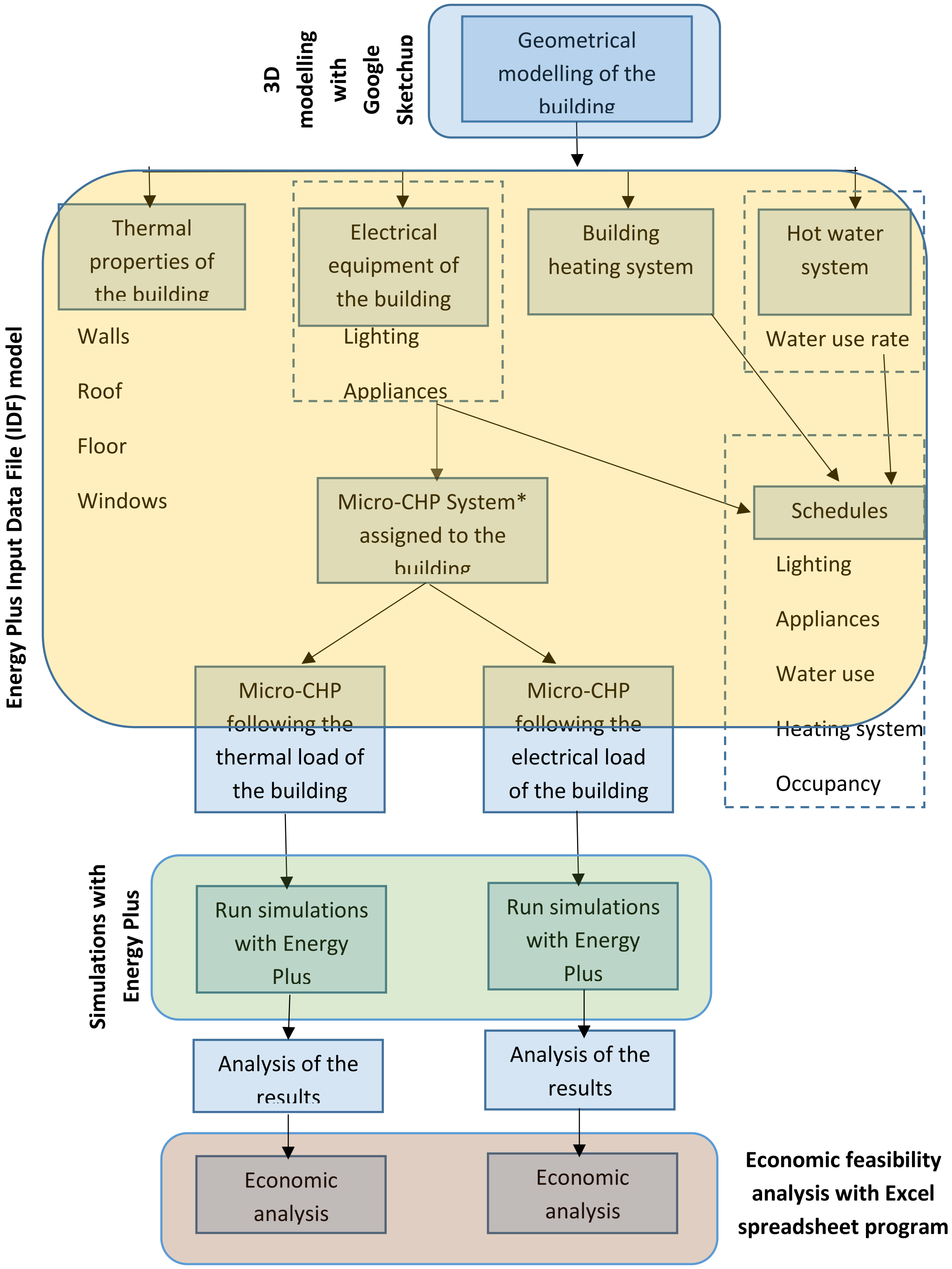


Figure 3.1: Methodology for modelling and analyzing Micro-CHP system. (*: Electrical capacity of the building is used to select the Micro-CHP system)

3.2.1 Building Fabric

Different types of building fabric are used in the constructions of Cyprus. In the modelled building the most widely used ones are considered.

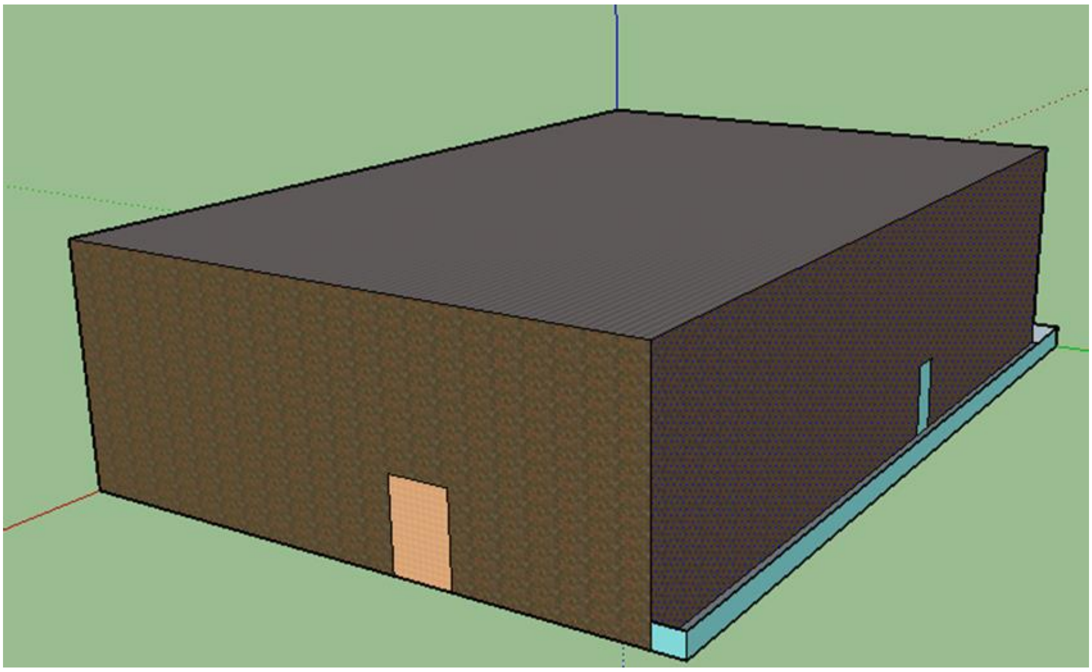


Figure 3.2: 3D Google Sketchup model of the building.

The most commonly used fabric in the walls of Cyprus buildings is clay bricks and cement. The wall configuration is composed of cement plaster on the outer surface, brick wall and another cement plaster on the inner surface. The wall thermophysical specifications are given in Table 3.1.

In Energy Plus, five different properties should be entered for each building model. These properties are the specific heat, thermal conductivity, thickness, density, and roughness. Roughness values are affecting the heat transfer coefficient. Therefore, they are having an effect on the heat loss and gain from and to the surfaces.

Table 3.1: Thermal specifications of the exterior wall of the building.

Layers (outer to inner)	**Plaster**	**Perforated clay Brick**	**Plaster**
Roughness	M. smooth	M. rough	M. smooth
Thickness(mm)	30	200	30
K (W/m.K)	1.35	0.4	1.35
Cp (J/Kg.K)	700	850	700
Density (kg/m^3)	2000	700	2000

Roofs of the buildings in Cyprus are flat. The roof configuration is composed of screed on the outer surface, concrete followed by cement plaster in the inner surface. The roof thermophysical properties used are given in Table 3.2.

Table 3.2: Thermal specifications of the roof for the building.

Layers (outer to inner)	**Screed**	**Concrete**	**Cement Plaster**
Roughness	M. rough	M. rough	M. smooth
Thickness(mm)	50	100	30
k (W/m.K)	1.7	1.7	1.35
Cp (J/Kg.K)	700	700	700
Density (kg/m^3)	2000	2000	2000

Floors of the buildings in Cyprus have 3 layers which are: floor tiles on the inner surface, screed followed by concrete on the outer surface. The construction configurations for the floor materials thermophysical properties used are given in Table 3.3.

Table 3.3: Thermal specifications of the floor for the building.

Layers (outer to inner)	**Concrete**	**Screed**	**Floor tiles**
Roughness	M. rough	M. Rough	smooth
Thickness(mm)	50	100	10
k (W/m.K)	1.7	1.7	1.35
Cp (J/Kg.K)	840	700	700
Density (kg/m^3)	2500	2000	2000

In Cyprus double glazed windows are widely used. Double glazed windows are composed of two separate glass layers of 6 mm thick separated by a 3.2 mm air gap. In the modelled building all the windows employed are double glazed with 6 mm glass separated by 3.2 mm airgap.

3.2.2 Electrical Capacity of the Building and Selected Micro-CHP System

The modelled building has 12 occupants. It is thought that each resident will require 100 W for illumination. It is thought that every student will have a computer (80 W each), for the other appliances 1000 W is assumed. Then the electrical capacity of the building becomes 3160 W. It is seen that the capacity does not include any electrical load for cooling. This value would be much greater if the electrical capacity of the cooling equipment is included. The electrical capacity of the cooling equipment is not included because it is thought that Micro-CHP is going to be used only in heating season.

The Micro-CHP unit will be selected by considering this electrical load. Therefore, it should be greater than this.

A commercial Micro-CHP unit having an electrical capacity of 5.5 kW is selected. The Micro-CHP system selected is a four stroke internal combustion engine (ICE) that can be fueled by either LPG or natural gas. This technology is suitable for new and old constructions e.g. residential buildings, commercial buildings etc. The Micro-CHP unit under study delivers 5.5 kW electrical power and 14.7 kW thermal energy. Thus it does have heat to power ratio of 2.6. Its electrical efficiency is 27 %. This technology needs a little space (length= 1.07m, width=0.9m and height= 1m). The system is light in weight (530kg). As mentioned above the engine is a 4 stroke single cylinder. Its lifetime operating hours before maintenance is up to 3500 operating hours. The features of the selected Micro-CHP unit is given in Appendix B. Thermal specifications of the selected system is given in Table 3.4.

Table 3.4: Thermal specifications of Micro-CHP (5.5kW) system.

Thermal specifications	
Heating output	14.7 kW
Maximum thermal efficiency	65%
Flow temperature	80°C
Maximum return temperature	70°C
Minimum return temperature	10°C
Maximum flow rate	0.35 l/s
Maximum working pressure	3 bar

3.2.3 Schedules for the Building

In this section, the schedules for the modelled building is explained in detail. Building schedules are the features that describe the use of building and building equipment, such as occupancy of the building the time schedules for the on and offs for the equipment. All of these have an effect on the electrical use and thermal load of the building. Because the modelled building is a student hall, the schedules are prepared based on this particular type of building.

- Building occupancy: The building is a student hall occupied by 12 students. Students attend classes in weekdays and on weekends they go out. For all days between 24:00 and 08:00 the building is fully occupied, from 08:00 until 09:00 half of the students are out, so the building is half occupied. From 10:00 till 16:00 the building is unoccupied. From 16:00 until 17:00 half of the occupants go back home, so the building is half occupied, some finishes classes at 18:00 so during this period the building is half occupied. At 19:00, 75% of the students are back. Finally, from 20:00 till 08:00 the building is fully occupied. Figure 3.3 shows the occupation of the building. During weekends, the occupancy is very irregular for student halls. Therefore, same occupancy schedule is used for the weekends for the sake of simplicity.

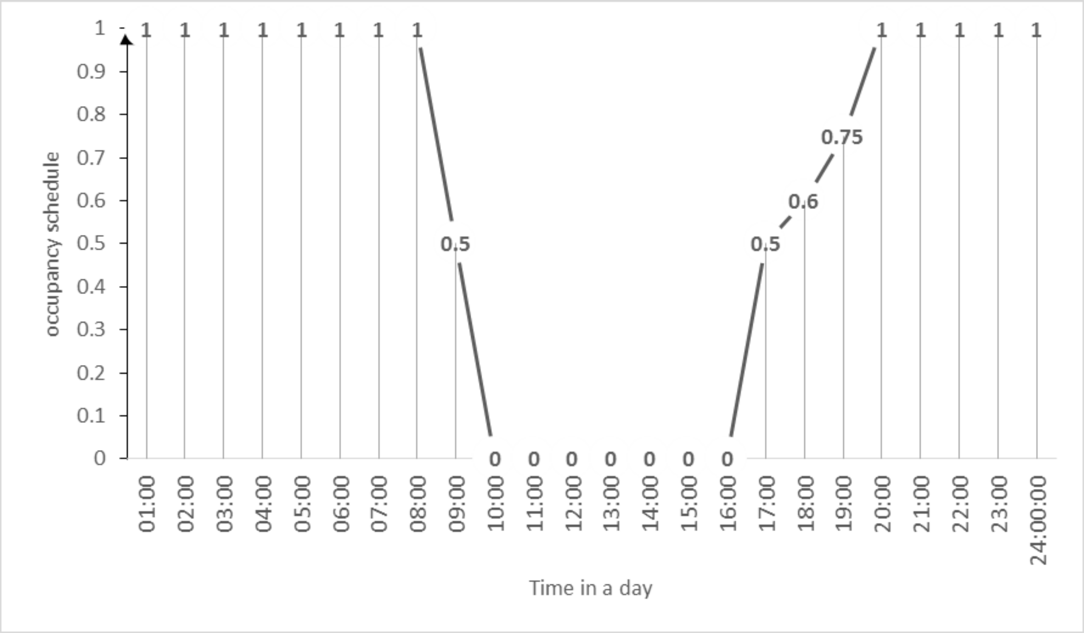


Figure 3.3: Occupancy schedule in weekends and weekdays.

- Lighting: It is thought that the building will use natural light until 16:00, therefore, they are off until 16:00. Then the lights are on until 24:00. The lighting schedule can be seen in Figure 3.4.

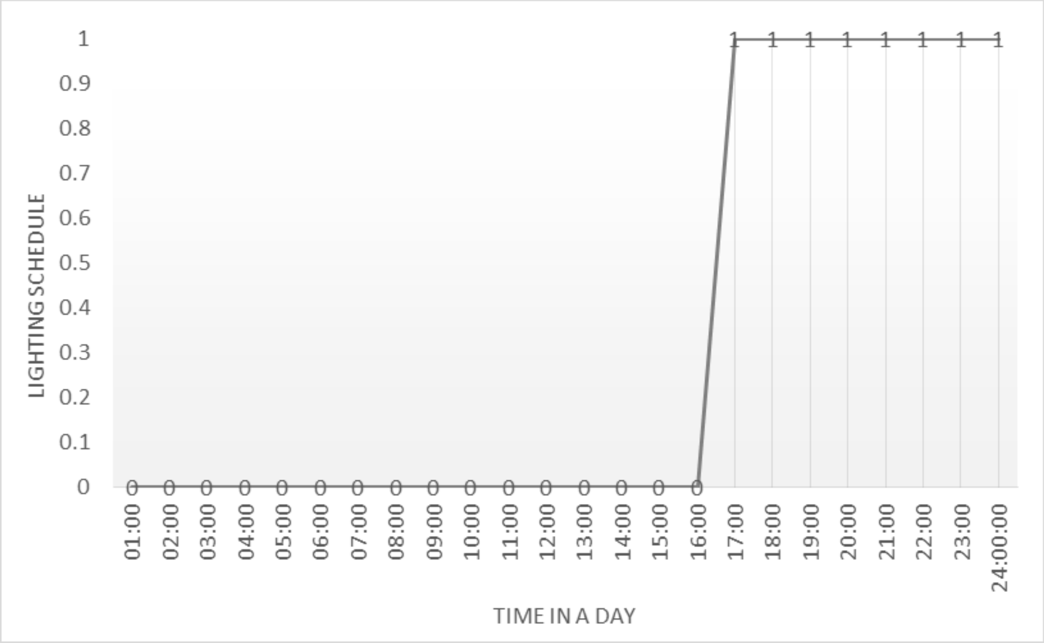


Figure 3.4: Lighting schedule in weekends and weekdays in a day.

- Electrical Appliances: The electrical appliances are on when the building is occupied therefore the schedules for the electrical appliances are same as the building occupancy schedule.
- Schedule for Heating Equipment: the schedule for the heating equipment is always on, always available when needed. A thermostat has been assigned to the zone which turns on the heating equipment when the zone air temperature goes below 18 C. The heating equipment used in the modelled building is Packaged Terminal Air Conditioner (PTAC). Details of PTAC is explained in section 3.2.4.
- Schedule for the water use: It is thought that the hot water will always be available at 55 oC. The cold water mains temperature is evaluated based on the weather data file of Larnaca used in energy plus software. Referring to the weather data file the average temperature of the water in the pipes is 19.3°C. The schedule of hot water use is defined in the Figure 3.5.

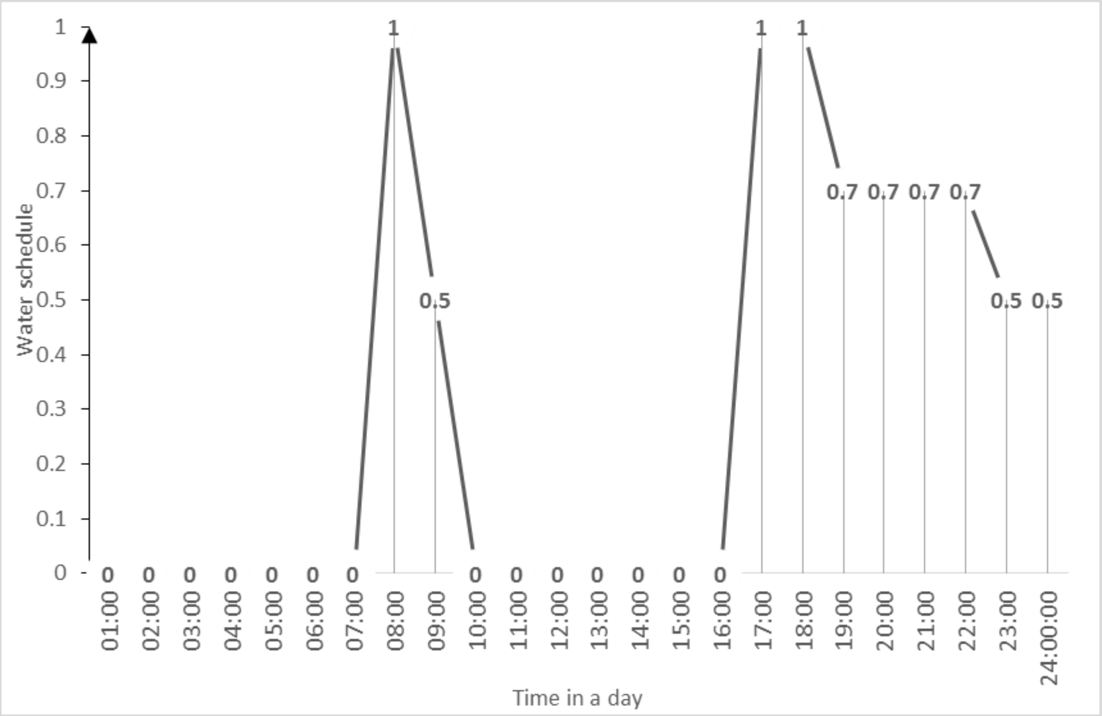


Figure 3.5: Hot water schedule on weekends and weekdays in a day.

3.2.4 Building Heating System

The building heating system assigned to the building is a Packaged Terminal Air Conditioner (PTAC). PTAC units are assembled to the walls of the building and involves heating and cooling assemblies such as fan, heating coils (by hot water, steam or electric resistance), cooling coils and separable outdoor louvers [32]. Schematic of the PTAC is shown in Figure 3.6.

In this work cooling coil is assigned to the PTAC but is unused as this study is carried out only for the heating season. The system is using the hot water in the heating coils that is stored in the water heater. The water heater is a tank which the hot water produced in the Micro-CHP system is circulated through it to heat the stored water in it.

The topology of the Micro-CHP system, heating system and the hot water use system is explained in the latter sections. However it should be mentioned here that the hot water circulates in 2 loops (Micro-CHP plant loop and Use hot water plant loop) with loop exit temperatures of 60°C and 70°C for use hot water and Micro-CHP plant loops respectively (see Appendix C). The third loop, Packaged Terminal Air Conditioner (PTAC) loop is having air as the working fluid and is set to be always on.

The PTAC fan's motor efficiency is 85% with a pressure rise by 297.23 Pascal. The temperatures of water and air entering and leaving the PTAC heating coil are 82.2°C and 71.1°C for water and 16.6°C and 32.2° for air respectively. The PTAC system is always turned on even if it is not needed for space heating. The need for space heating is arranged by the thermostat that is assigned to the zone. Thermostat runs the PTAC system whenever the zone's temperature goes below 18°C.

3.2.5 Building Water Use System

As the considered building is a student hall, there is continuous demand for domestic hot water. It is thought that the hot water will be supplied at 55°C with a 0.000013 m^3/s peak flow rate [33]. The schedule for hot water use in the input file is entered as same as the occupancy schedule. This means that when the building is fully occupied (occupation=1) 1x0.000013 m^3/s of hot water is required whereas when the building is half occupied (occupation=0.5) 0.5x0.000013 m^3/s of hot water is required. Whenever the building is unoccupied, there is no need for hot water. Figure 3.6 illustrates the "Source hot water" part in the system diagram that is explained in section 3.3.

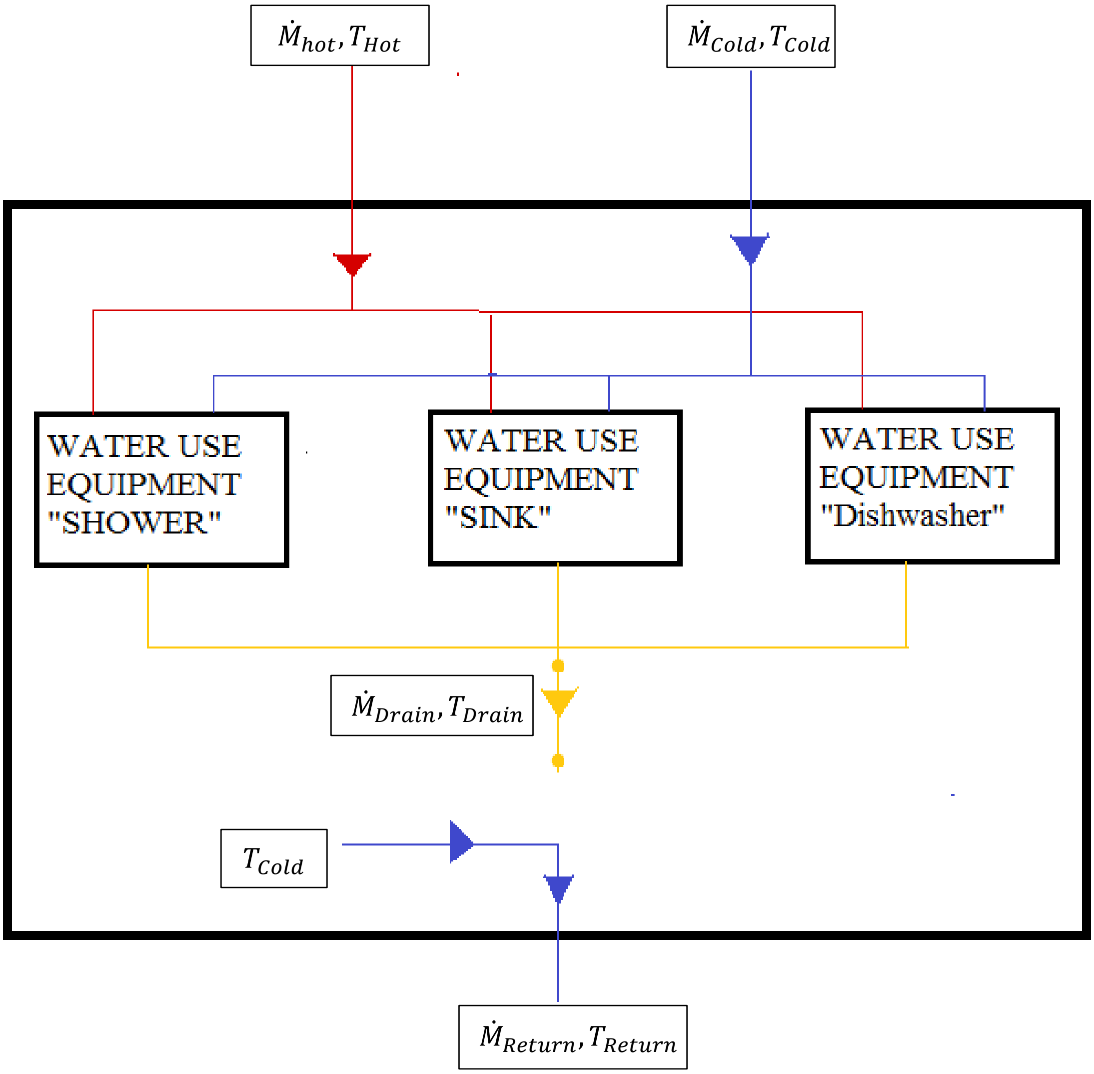


Figure 3.6: Water Use Connections Subsystem [34].

In this figure M_{hot} is the flow rate of the hot water that is used in hot water use equipment (showers, sinks etc.). The used hot water goes to the drain whereas simultaneously cold water is introduced into the loop and returns to the hot water tank to be heated.

3.3 Building Plant Loops and System Diagram

In Energy Plus the building plants (heating and cooling systems or power and heat generating systems such as CHP) are modelled as loops. Loops in Energy Plus are defined as paths where working fluid circulates in order to meet heating or cooling demand. Loops are paths for the working fluid to content a cooling or heating load.

The loops are divided into two half loops (supply side and demand side half loops) [35]. In the supply side half loop, the components existing in this loop (i.e. Micro-CHP in this study) deliver energy to the working fluid to supply the demand of the demand side components. The demand side half loop once receive the working fluid, uses the energy in the the working fluid to deliver the load.

Each half loop and loops are made up from components, nodes, branches and connectors.

- Components are physical objects such as pumps or fans that exists in the loops.
- Nodes define the starting and ending points of components.
- Branches are objects that are made up from nodes and components. (e.g. inlet node for the pump-pump-outlet node for the pump)
- Connectors bond the branches in a loop. It is divided into two types; the splitters and mixers. If there are several inputs and one output then the connector is mixers. If there is one input and several outputs the connector is splitter.

In this project, the plant under study is divided into 3 loops; “Micro-CHP Plant Loop”, “Use Hot Water Plant Loop” and “Air Plant Loop’’.

In the first loop, Micro-CHP Plant Loop, there are 12 components namely; Micro-CHP, 4 connectors (2 splitters and 2 mixers), 3 pipes, 2 bypass branches, a water heater and a pump. The Micro-CHP Plant Loop can be seen in Figure 3.8.

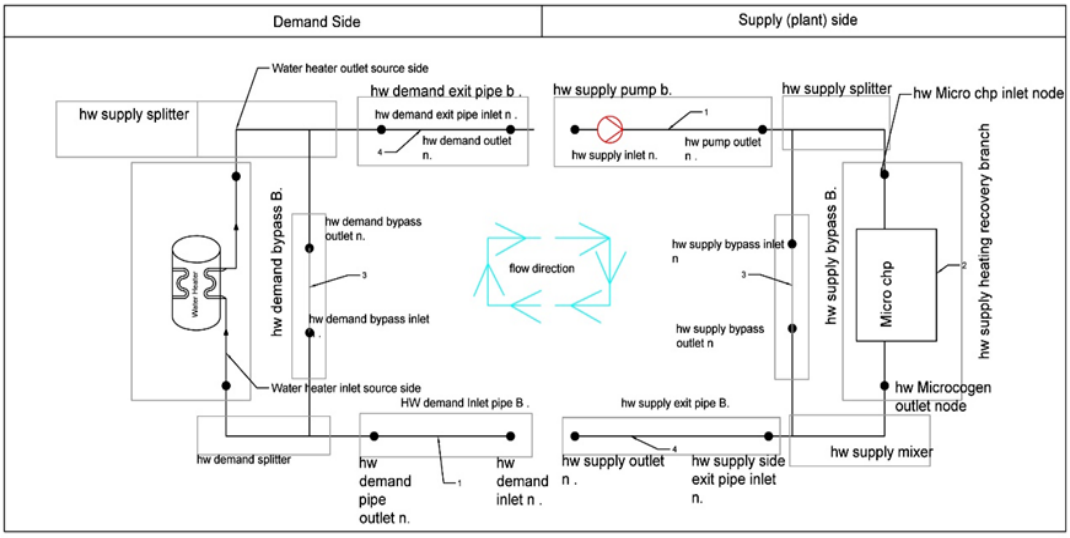


Figure 3.7: Micro-CHP Plant Loop.

In the second loop, Use Hot Water Plant Loop, there are 13 components namely PTAC Heating Coil, 4 connectors (2 splitters and 2 mixers), 3 pipes, 2 bypass branches, Source Hot Water, a water heater and a pump. The Use Hot Water Plant Loop can be seen in Figure 3.9.

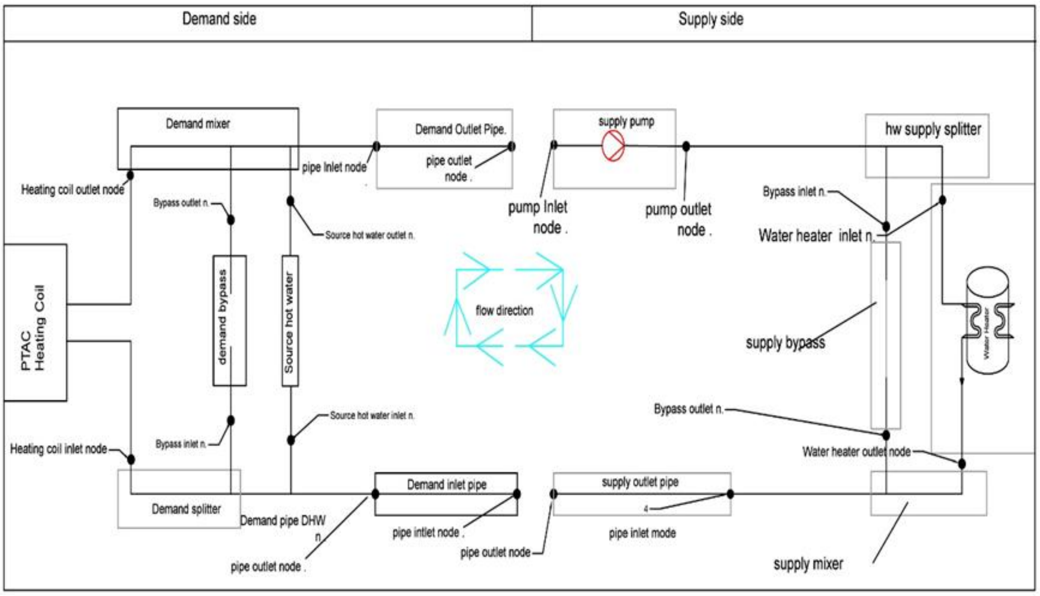


Figure 3.8: Use Hot Water Plant Loop.

In the third loop, Packaged Terminal Air Conditioner Plant Loop, there are 5 components namely PTAC Heating Coil, PTAC Cooling Coil, Air Mixer, Zone and PTAC Fan. Packaged Terminal Air Conditioner Plant Loop can be seen in Figure 3.10.

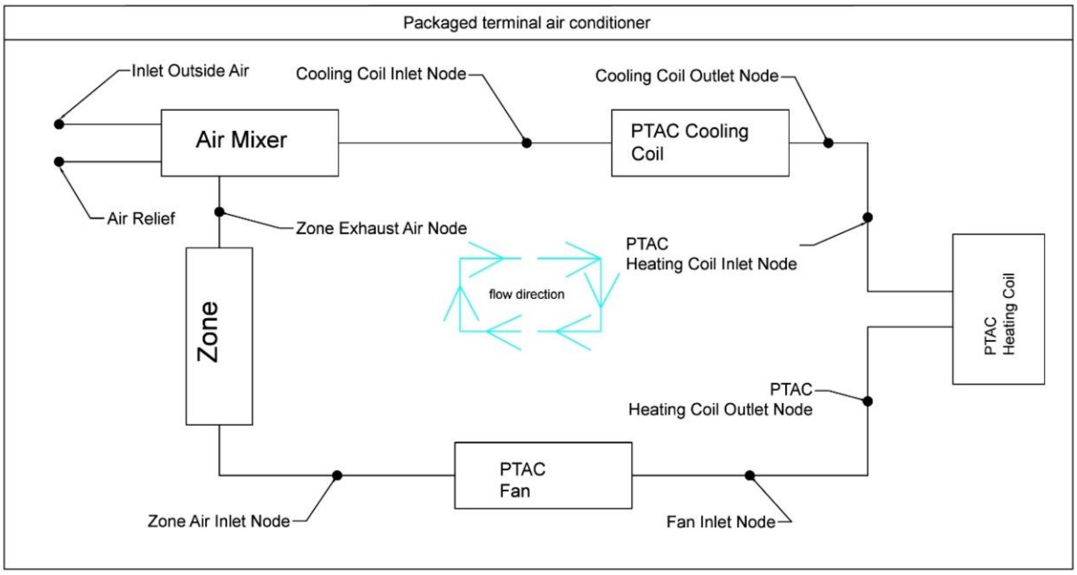


Figure 3.9: Packaged Terminal Air Conditioner Plant Loop.

The whole system diagram is given in Appendix C.

3.4 Simulation Methodology

Two sets of simulations are carried out. The first set is following the thermal load, followed by the electrical load as the second set.

3.5 Weather Data

A weather date file is assigned to the model to carry out dynamic energy simulation for the considered building and the assigned Micro-CHP system. As the building is located in Cyprus, the assigned weather data for the model is for Cyprus. The only available weather data for Cyprus to be used in Energy Plus is for Larnaca, so Larnaca’s weather data is used. The weather file that is used involves all the parameters necessary for load calculations and energy evaluations. These parameters are dry bulb temperature, wet bulb temperature, solar radiation, relative humidity, wind speed, etc...

These parameters are stored in the weather file for every hour, a summary of the weather data file is given in Appendix D. As the simulations are carried out for the heating season (1st November – 28th February) only that Energy Plus uses a portion of the weather data in the simulation. The location Cyprus is situated at 33° 22' (longitude, East) and 35° 10' (latitude, North) can be seen in Figure 3.10, and the yearly maximum temperatures for Larnaca can be seen in Figure 3.11.

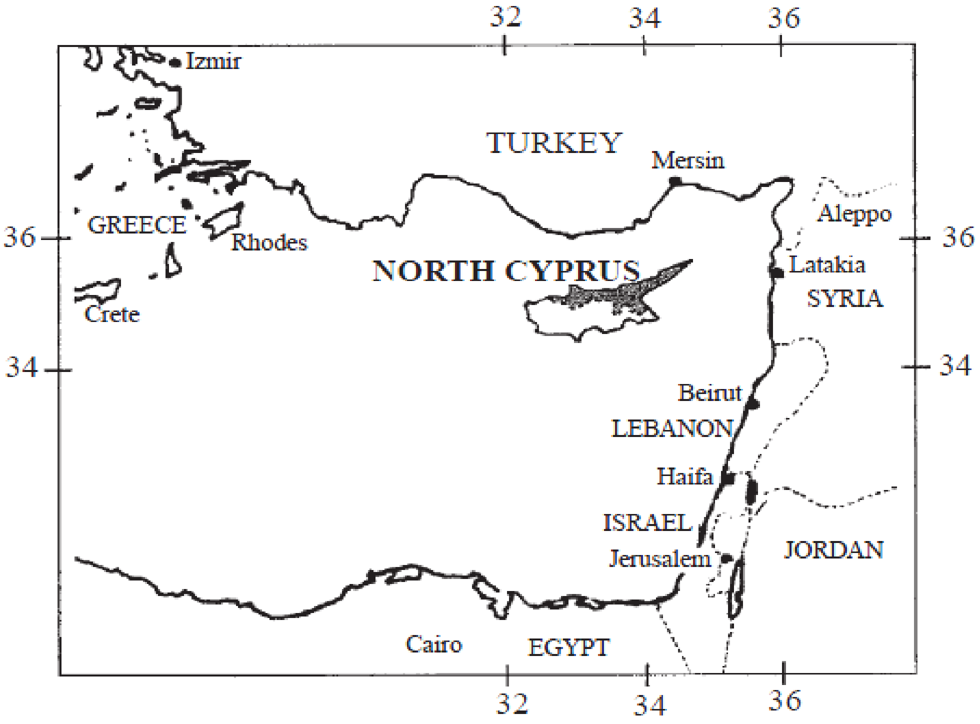
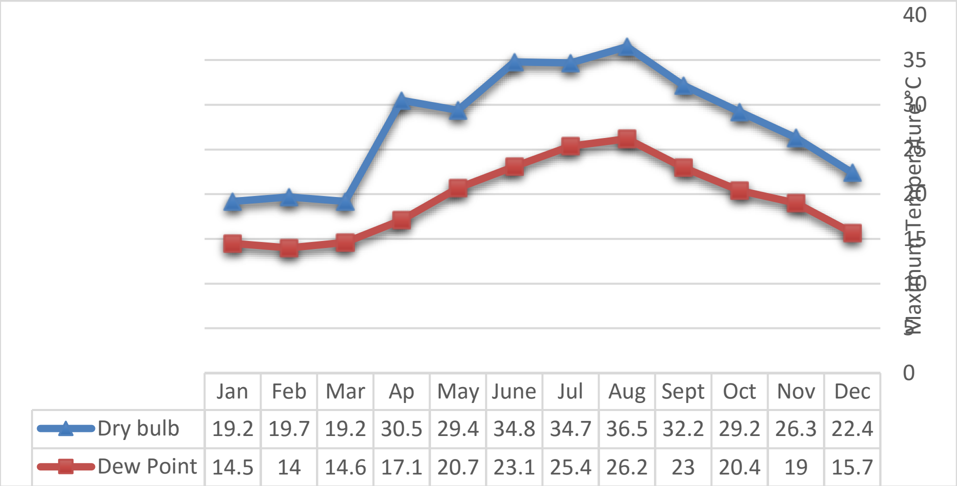


Figure 3.10: Map of Cyprus as displayed in [36].



	Jan	Feb	Mar	Ap	May	June	Jul	Aug	Sept	Oct	Nov	Dec
▲ Dry bulb	19.2	19.7	19.2	30.5	29.4	34.8	34.7	36.5	32.2	29.2	26.3	22.4
■ Dew Point	14.5	14	14.6	17.1	20.7	23.1	25.4	26.2	23	20.4	19	15.7

Figure 3.11: Yearly Maximum Temperature in Larnaca.

Chapter 4

MODELLING WITH EPLUS

4.1 Background

Energy Plus has its roots in both the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 programs which were released in the late 1970s and early 1980s. These two programs are used for simulating HVAC equipment, energy performance, heating loads and cooling loads of the buildings.

Energy plus is an energy analysis and thermal load simulation program. It calculates the building loads (heating and cooling) required to maintain the specified thermal conditions, the energy consumption or production by the plant equipment of the building and all the other thermal parameters related with the building energy performance.

Energy Plus is composed of various modules or elements which are all designed to solve and deliver the required parameters (e.g. heating load, PV electricity generation, indoor air temperature etc.) for the particular items using specific mathematical models. It does have dynamic feature which means that it accounts for the building and plant responses, it can model systems having variable properties (e.g. phase change materials) and it is using hourly weather data of a complete year for the simulations. The diagram below illustrates some of the modules involved in the Energy Plus program.

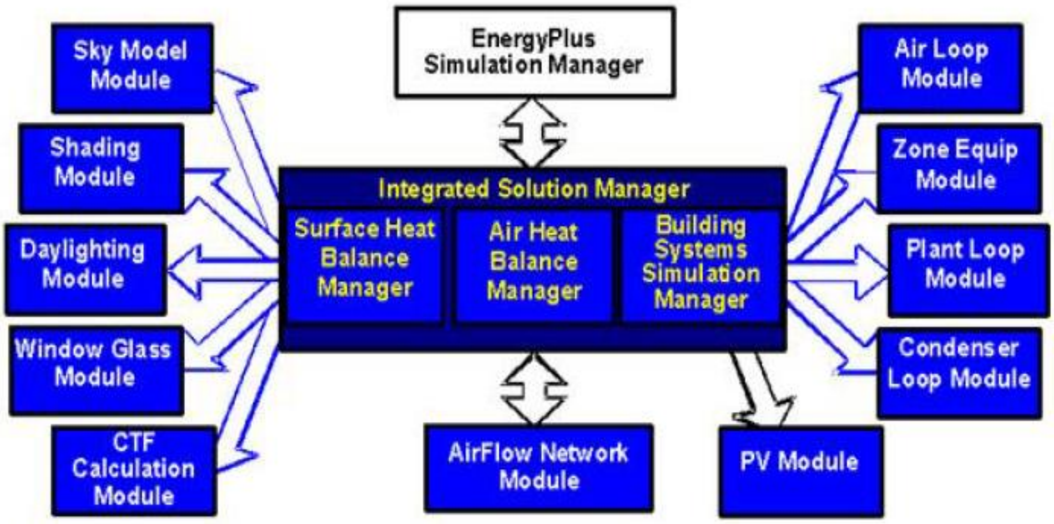
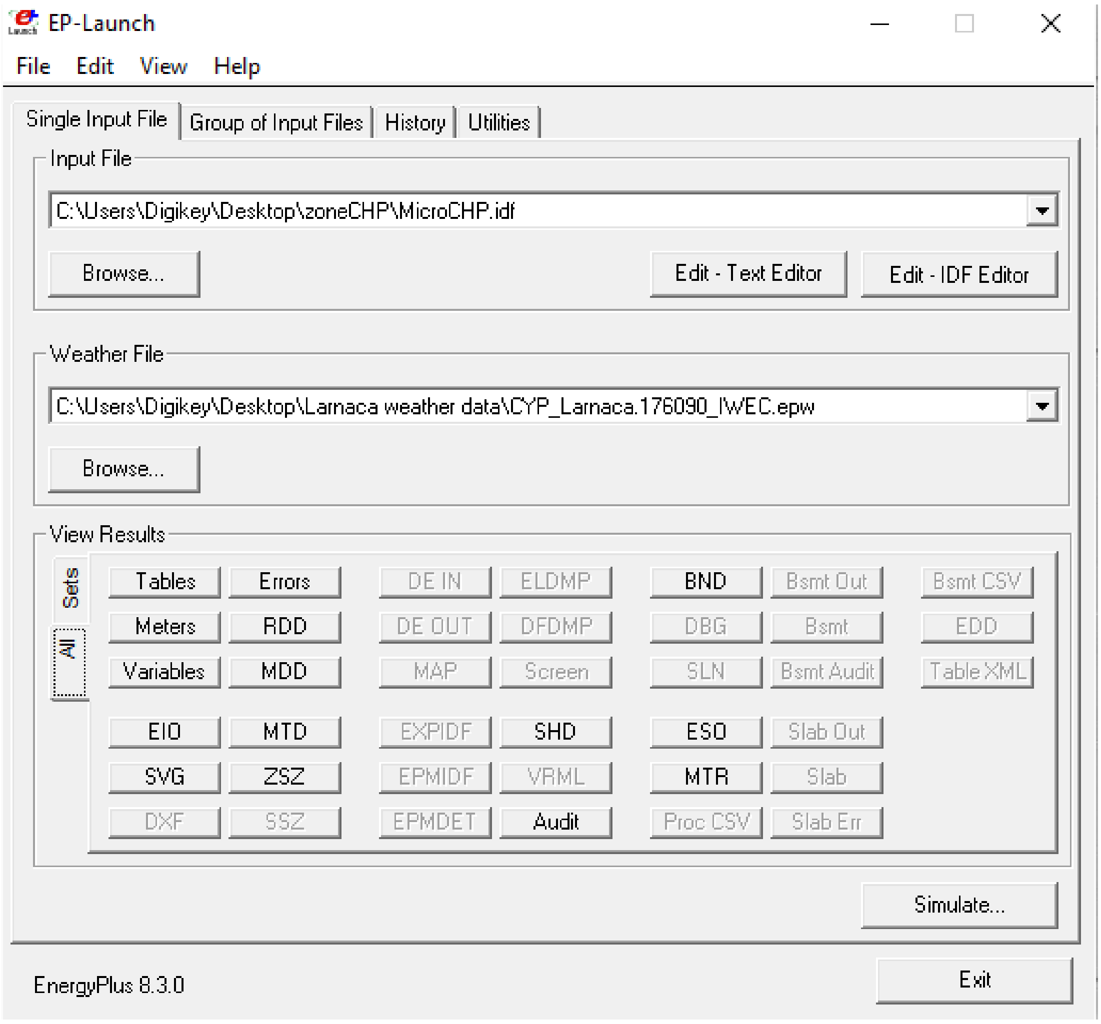


Figure 4.1: Energy Plus internal elements or modules as displayed in [37].

4.2 EP-Launch and IDF Editor

Energy Plus is a simulation engine, not a user interface. Therefore, it involves only simple components for entering the input parameters, for selecting the input files and for running the simulations. EP-Launch and IDF Editor are the components of Energy Plus that are used for these operations. Third parties can design user interfaces which can use the Energy Plus as their engine.

EP-Launch is a component of Energy Plus which is used for selecting the input files (defined by user) and weather data files as well as for opening outputs of simulations and drawing files. EP-launch is also used for running the simulations. Simulation run is carried out by selecting the predefined input data file (IDF) as well as appropriate weather data file and pressing the button “Simulate”. A snapshot of the EP-Launch window is given in Figure 4.2.



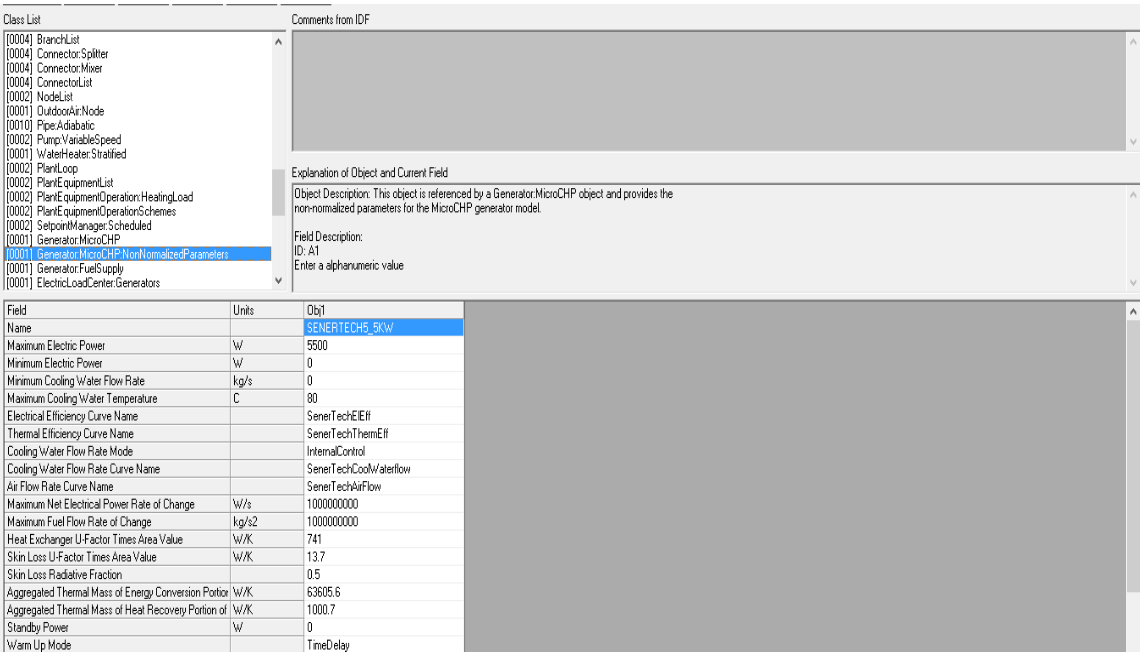
Input File: C:\Users\Digikey\Desktop\zoneCHP\MicroCHP.idf

Weather File: C:\Users\Digikey\Desktop\Larnaca weather data\CYP_Larnaca.176090_IWEC.epw

EnergyPlus 8.3.0

Figure 4.2: A snapshot of EP-Launch.

The parameters for the building or plant that is going to be simulated entered to the program via IDF editor. IDF editor involves all the parameters required for any model simulation. For instance if a user wants to simulate the heating load of a building, thermophysical properties of the building materials should be entered via IDF editor. In the case of this study all the features of the Micro-CHP system; electrical capacity, thermal efficiency etc. as well as the other parameters for complete building and plant simulation has been entered via IDF editor. Figure 4.3 shows a snapshot from IDF editor.



[0004] BranchList
[0004] Connector:Splitter
[0004] Connector:Mixer
[0004] ConnectorList
[0002] NodeList
[0001] OutdoorAir:Node
[0010] Pipe:Adiabatic
[0002] Pump:VariableSpeed
[0001] WaterHeater:Stratified
[0002] PlantLoop
[0002] PlantEquipmentList
[0002] PlantEquipmentOperation:HeatingLoad
[0002] PlantEquipmentOperationSchemes
[0002] SetpointManager:Scheduled
[0001] Generator:MicroCHP
[0001] Generator:MicroCHP:NonNormalizedParameters
[0001] Generator:FuelSupply
[0001] ElectricLoadCenter:Generators

Object Description: This object is referenced by a Generator:MicroCHP object and provides the non-normalized parameters for the MicroCHP generator model.

Field Description:
ID: A1
Enter a alphanumeric value

Field	Units	Obj1
Name		SENERTECH5_5KW
Maximum Electric Power	W	5500
Minimum Electric Power	W	0
Minimum Cooling Water Flow Rate	kg/s	0
Maximum Cooling Water Temperature	C	80
Electrical Efficiency Curve Name		SenerTechElEff
Thermal Efficiency Curve Name		SenerTechThermEff
Cooling Water Flow Rate Mode		InternalControl
Cooling Water Flow Rate Curve Name		SenerTechCoolWaterflow
Air Flow Rate Curve Name		SenerTechAirFlow
Maximum Net Electrical Power Rate of Change	W/s	1000000000
Maximum Fuel Flow Rate of Change	kg/s2	1000000000
Heat Exchanger U-Factor Times Area Value	W/K	741
Skin Loss U-Factor Times Area Value	W/K	13.7
Skin Loss Radiative Fraction		0.5
Aggregated Thermal Mass of Energy Conversion Portior	W/K	63605.6
Aggregated Thermal Mass of Heat Recovery Portion of	W/K	1000.7
Standby Power	W	0
Warm Up Mode		TimeDelay

Figure 4.3: A snapshot from Energy Plus IDF editor.

4.3 Energy Plus Micro-CHP Module Equations

Before giving the equations used in the Micro-CHP module of the Energy Plus it is worth to mention about the general expressions that are used for any combined heat and power calculations. These expressions are for evaluating the electrical efficiency, thermal efficiency and overall efficiency of the system.

The ratio of useful energy output to the energy input is called the energetic efficiency. Thus, electrical efficiency of a CHP system is the ratio of the electrical output of the system to the fuel energy input whereas, thermal efficiency of CHP system is the ratio of the thermal output of the system to the fuel energy input. As CHP system produces thermal and electrical energy simultaneously there is an overall efficiency term for CHP systems which is the ratio of summation of electrical and thermal output of the system to the fuel energy input. The following equations are the electrical, thermal and overall efficiencies of a CHP system:

Electrical efficiency: $$\eta_{el} = \frac{P_{el,out}}{P_{fuel.in}} \quad (4.1)$$

Thermal efficiency: $$\eta_{th} = \frac{P_{th,out}}{P_{fuel.in}} \quad (4.2)$$

Overall efficiency: $$\eta_{t} = \frac{P_{el,out}+P_{th,out}}{P_{fuel,in}} \quad (4.3)$$

The Micro-CHP model in Energy Plus is dynamic with respect to thermal heat recovery where the recovery performance is a function of the engine temperature. Also, the Micro-CHP energy output is dynamic (or variable) with respect to possible warm up and cool down periods of the Micro-CHP engine. These periods can modify the capacity of the generator to deliver the needed power.

The part load electrical and thermal efficiencies of the Micro-CHP system are determined through linking the conversion efficiencies to the flow rate and temperature of cooling water, and the systems electrical loading [38]:

$$\eta_e = f(\dot{m}_{cw}, T_{cw.i}, P_{net.ss}) \quad (4.4)$$

$$\eta_q = f(\dot{m}_{cw}, T_{cw,i}, P_{net,ss}) \quad (4.5)$$

These correlations form a “performance map”, which describes the steady-state cogeneration behavior beneath a diversity of loading conditions.

Where:

η_e:	Steady-state, part-load, electrical conversion efficiency of the engine
η_q:	Steady-state, part load, thermal conversion efficiency of the engine.
$\dot{m}_{cw}$:	Mass flow rate of cooling water [kg/s].
T_{cw}	Bulk temperature of the plant fluid (^{o}C)
$P_{net.ss}$:	Steady-state electrical output of the system (W).

The control volumes are used to model the Micro-CHP unit's thermal characteristics. These control volumes and the energy flow between them are shown in Figure 4.4. The energy conversion control volume shown in the figure is the engine working fluid, combustion gasses and the engine alternator. This control volume delivers the data from engine performance map to the thermal model. The engine control volume on the other hand represents the engine block and heat recovery system elements. The cooling water control volume is the cooling water flowing through the Micro-CHP system.

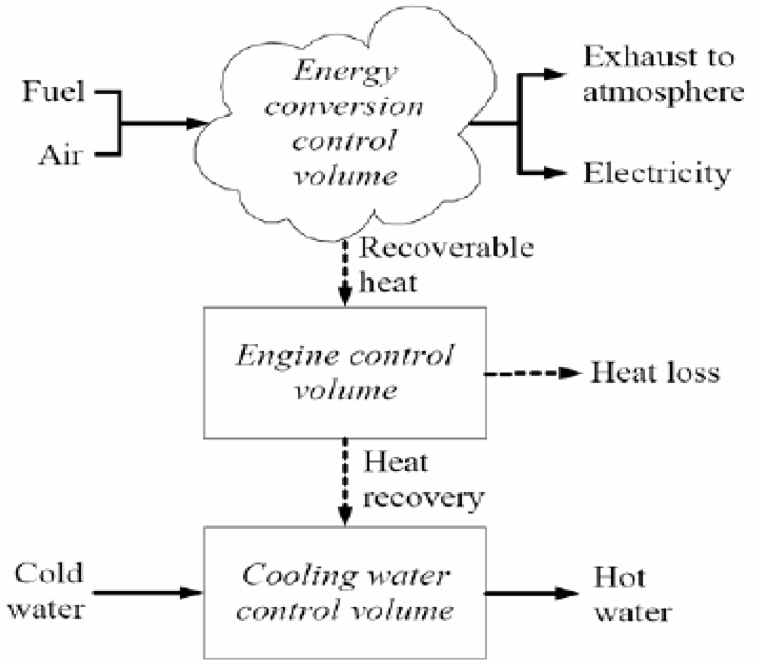


Figure 4.4: Control volume for combustion cogeneration model.

The steady-state energy balance for the energy conversion control volume is given as:

$$\dot{H}_{fuel} + \dot{H}_{air} = P_{net,ss} + q_{gen,ss} + \dot{H}_{exh} \qquad (4.6)$$

$\dot{H}_{fuel}$:	Total enthalpy of the fuel.
$\dot{H}_{air}$:	Total enthalpy of the combustion air.
$q_{gen,ss}$:	Steady-state rate of heat generation within the engine.
$\dot{H}_{exh}$:	Total enthalpy of the exhaust gases.

The model in the Micro-CHP module does not describes the every element in the previous equation however it, correlates the engine’s steady state (part load) performance to the total energy input to the system which is q_{gross} and are given in the form of below equations:

$$q_{gross} = \frac{p_{net,ss}}{\eta_e} \tag{4.7}$$

$$q_{gen,ss} = \eta_q * q_{gross} \tag{4.8}$$

$$q_{gross} = \dot{m}_{fuel} * LHV_{fuel} \tag{4.9}$$

Where:

q_{gross}: Gross heat input into the engine (W).

$q_{gen,ss}$: Steady-state rate of heat generation within the engine (W).

$\dot{m}_{fuel}$: Fuel flow rate [kg/s].

LHV_{fuel}: Lower heating value of the fuel used by the system [k/kg].

The energy balance of the engine control volume is given as:

$$[MC]_{eng} \frac{dT_{eng}}{dt} = q_{gen,ss} - q_{HX} - q_{skin\ loss} \tag{4.10}$$

Where:

$[MC]_{eng}$: Thermal capacitance of the control volume (W/K).

q_{HX}: Rate of heat transfer to the cooling water (W).

$q_{skin\ loss}$: Rate of heat loss from the unit (W).

T_{eng}: Bulk temperature of the thermal mass control volume (^{o}C).

The energy balance of the cooling water control volume is given as:

$$[MC]_{cw} \frac{T_{cw,o}}{dt} = [\dot{m}c_p]_{cw}\left(T_{cw,i} - T_{cw,o}\right) + q_{HX} \tag{4.11}$$

Where:

$[MC]_{cw}$: Thermal capacitance of the cooling water (J/K).

$T_{cw,o}$: Bulk exit temperature of the cooling water (^{o}C).

$T_{cw,i}$: Temperature of the cooling water entering the unit (^{o}C).

$[\dot{m}c_p]_{cw}$: Thermal capacity of the cooling water flow (W/K).

The associated heat transfer between the engine and the cooling water control volume and the heat loss from the engine are:

$$q_{HX} = UA_{HX}(T_{eng} - T_{cw,o}) \tag{4.12}$$

$$q_{skin\ loss} = UA_{loss}(T_{eng} - T_{room}) \tag{4.13}$$

Where:

UA_{HX}: Overall thermal conductance between the engine and cooling water control volumes (W/K).

T_{eng}: Average temperature of the engine control volume (^{o}C).

UA_{loss}: Overall thermal conductance between the engine control volume and the surroundings (W/K).

T_{room}: Temperature of the surrounding environment (°C).

The engine control volume equation, cooling water control volume equation and associated heat transfer equations that are given above are used to rewrite the engine and cooling water control volume energy equations as below. These equations are then solved within the Energy Plus for T_{eng} and $T_{cw,o}$.

$$[MC]_{eng}\frac{dT_{eng}}{dt} = UA_{HX}\left(T_{cw,o} - T_{eng}\right) + UA_{loss}\left(T_{room} - T_{eng}\right) + q_{gen,ss} \tag{4.14}$$

$$[MC]_{cw}\frac{dT_{cw,o}}{dt} = [\dot{m}c_p]_{cw}\left(T_{cw,i} - T_{cw,o}\right) + UA_{HX}(T_{eng} - T_{cw,o}) \tag{4.15}$$

Chapter 5

RESULTS AND OPTIMIZATION

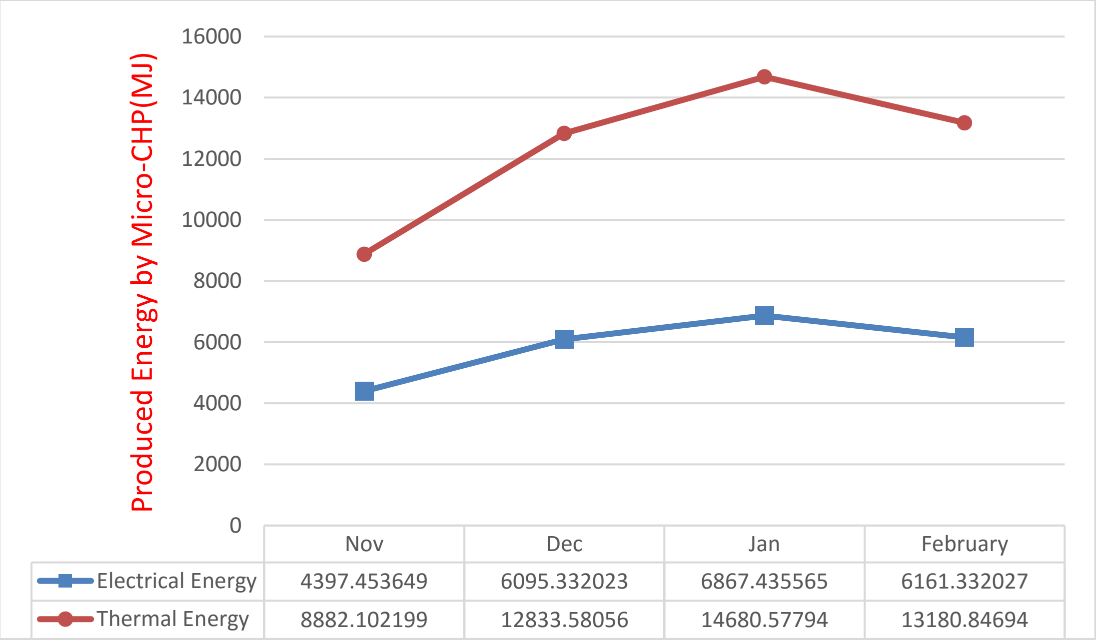
5.1 Introduction

The Micro-CHP system is intended to be used during the heating season; therefore, the simulations are carried out for the period 1st November- 28th February. The results presented in this chapter is for this period. Monthly, daily and hourly (for a typical day) results i.e. electrical and thermal energy outputs for heating season (November to February) is explained in detail. As described in the subsequent sections two modes were considered; Micro-CHP following the thermal load and Micro-CHP system following the electrical load.

5.2 Following Thermal

5.2.1 Monthly Results

The produced thermal and electrical energies of the Micro-CHP system in monthly designs hits its maximum production with 14680.577 MJ for thermal and 6867.433 MJ for electrical in January. It is typical because January is known as the coldest month of the year in Cyprus.



	Nov	Dec	Jan	February
Electrical Energy	4397.453649	6095.332023	6867.435565	6161.332027
Thermal Energy	8882.102199	12833.58056	14680.57794	13180.84694

Figure 5.1: Electrical and Thermal energy monthly production.

5.2.2 Daily Results

5.2.2.1 November

The thermal and electrical energy on 30th and 21st of November reach its peak by 403.952 MJ and 404.133 MJ respectively for thermal and 193.163 MJ and 192.643 MJ respectively for electrical. On 6th of November, the energy production is at its minimum by 270.717 MJ and 135.105 MJ for thermal and electrical energy respectively. Finally, the HVAC equipment (1 fan and 2 pumps) consumption remains constant by 61.448 MJ for all November days, and that refers to the occupancy schedule as mentioned before in Chap3.

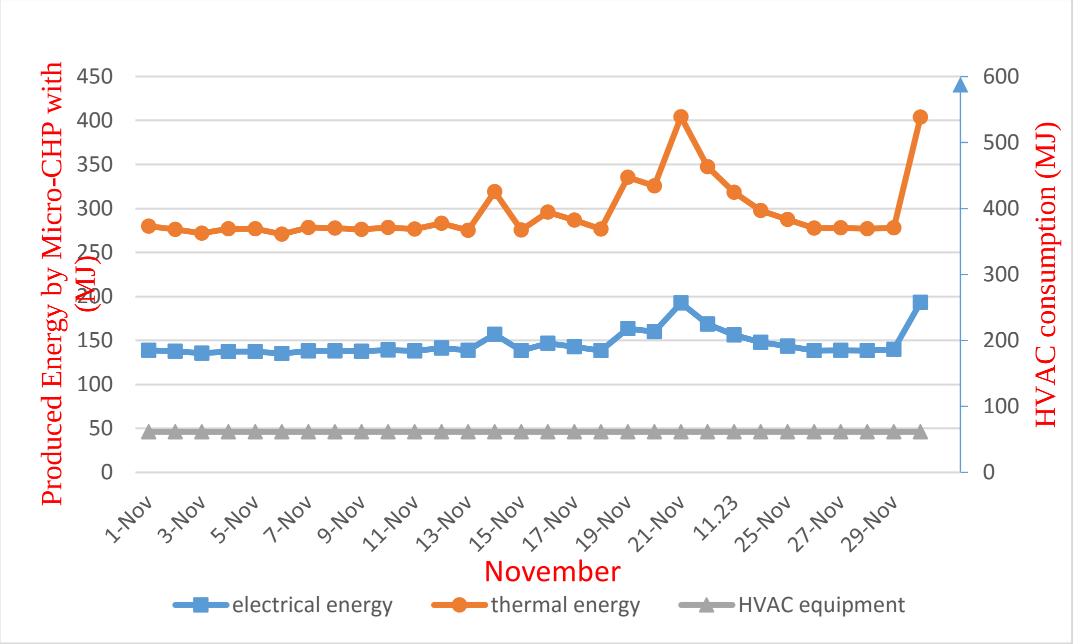


Figure 5.2: November outputs.

5.2.2.2 December

As shown in Figure 5.3, the thermal and electrical energy reach its peak on 20th of December by 696.501 MJ and 313.343 MJ respectively. Whereas, the minimum value is on 13th of December by 274.448 MJ and 138.26 MJ for thermal and electrical energies respectively.

Finally, the HVAC equipment consumption remains constant by 61.448 MJ for all December days.

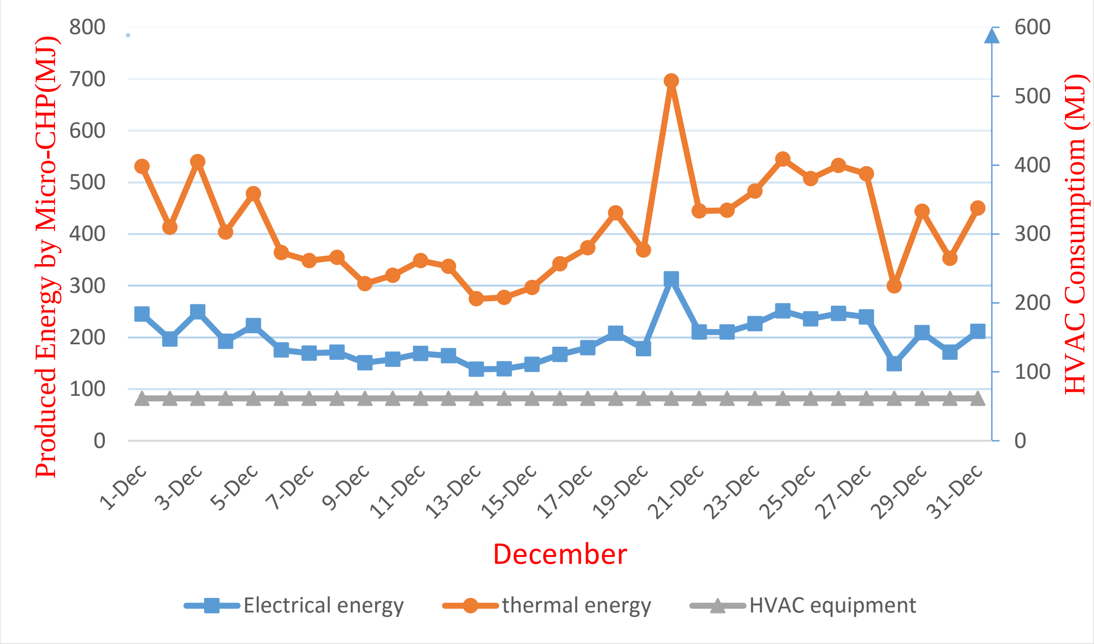


Figure 5.3: December outputs.

5.2.2.3 January

As shown in Figure 5.4, the thermal and electrical outputs reach its peak output on 16th of January by 741.459 MJ and 332.871 MJ respectively. On 31st of Jan. the energetic outputs reach its slightest values by 274.995 MJ for thermal energy and 138.103 MJ for electrical energy. It is known that January is the coldest month in the winter season**.** Finally, the HVAC equipment consumption remains constant by 61.448 MJ for all December days.

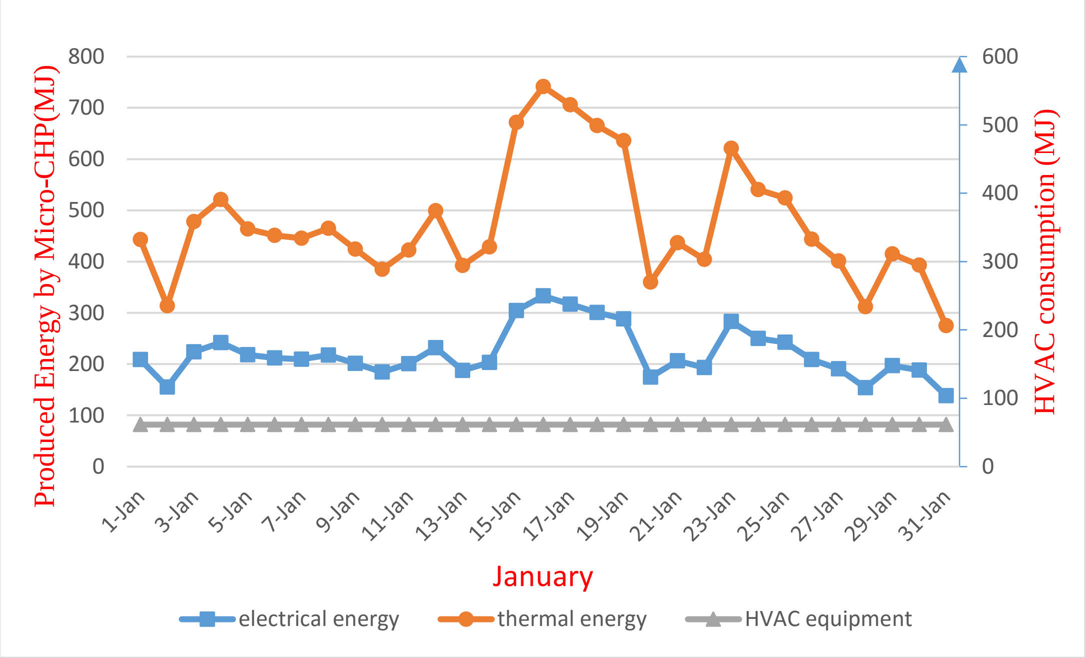


Figure 5.4: January outputs.

5.2.2.4 February

As shown in Figure 5.5, thermal and electrical energies outputs of the micro-CHP reach the peak value by 911.848 MJ and 402.632 MJ for thermal and electrical energies respectively on 2nd of February. Furthermore, the energy production of both thermal and electrical curves increase and decrease slightly during the month to reach its minimum value by 283.08 MJ for thermal and 141.483 MJ for electrical on 23rd of February. Finally, the two curves (electrical and thermal) continue to increase and decrease marginally, while the HVAC equipment curve always remains constant by 61.448 MJ for all days.

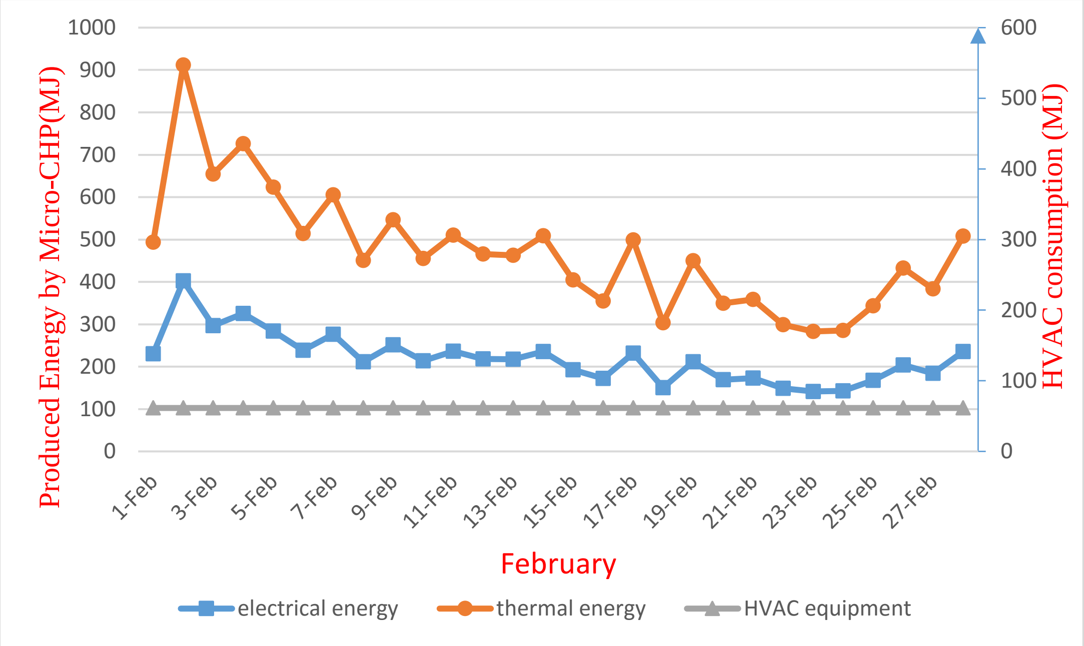


Figure 5.5: February outputs.

5.2.3 Hourly Results

In this section, a peak day was chosen for every month of the winter season. The case study here relies on the maximum energy production by micro-CHP on each peak day of the month.

5.2.3.1 November 30th

The hourly production of the thermal and electrical energy is shown in Figure 5.6. The energy production reaches the highest values at 9:00 with 28.36 MJ for thermal energy and 12.854 MJ for electrical energy. While students are sleeping late in the night, the system remains working but slightly for that reason the curves reach its extreme bottom. The curves hit its minimum by Thermal: 0.17 MJ and Electrical: 0.961 MJ values between 2 and 3am where the need for heating isn't required.

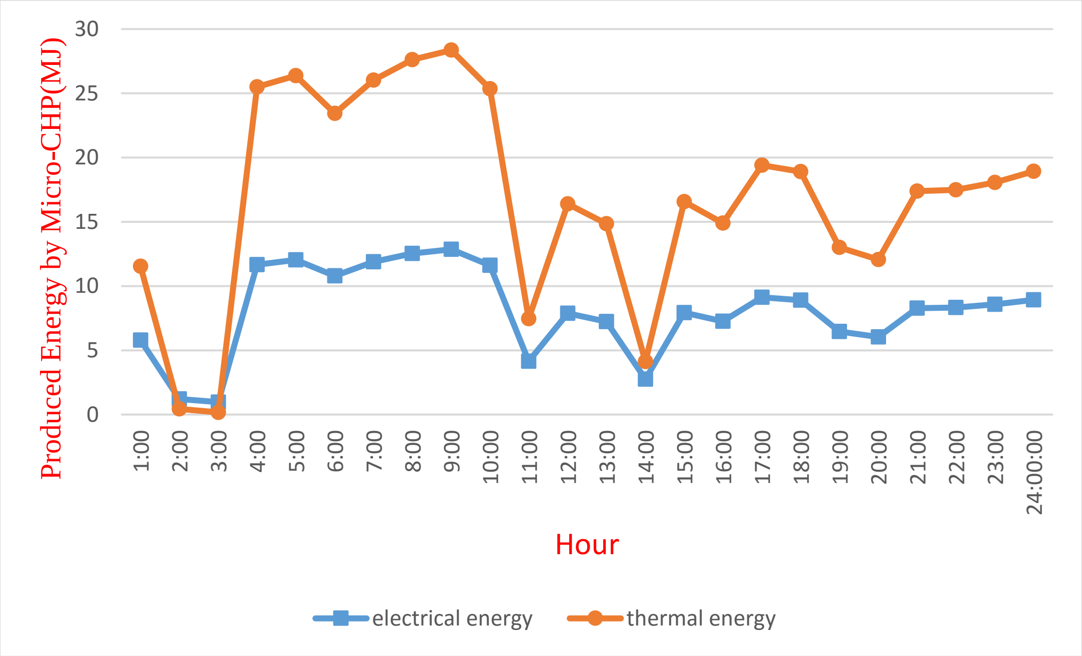


Figure 5.6: Hourly outputs for November 30th.

5.2.3.2 December 20th

As shown in Figure 5.7, the thermal and electrical energy remain constant at the highest value by thermal: 41.588 MJ and electrical: 18.127 MJ from 4 am to 1 pm. Then the curves go down sharply and after that, it increases slightly and decreases to reach its minimum values by thermal: 0.934 MJ and electrical: 1.416 MJ at pm.

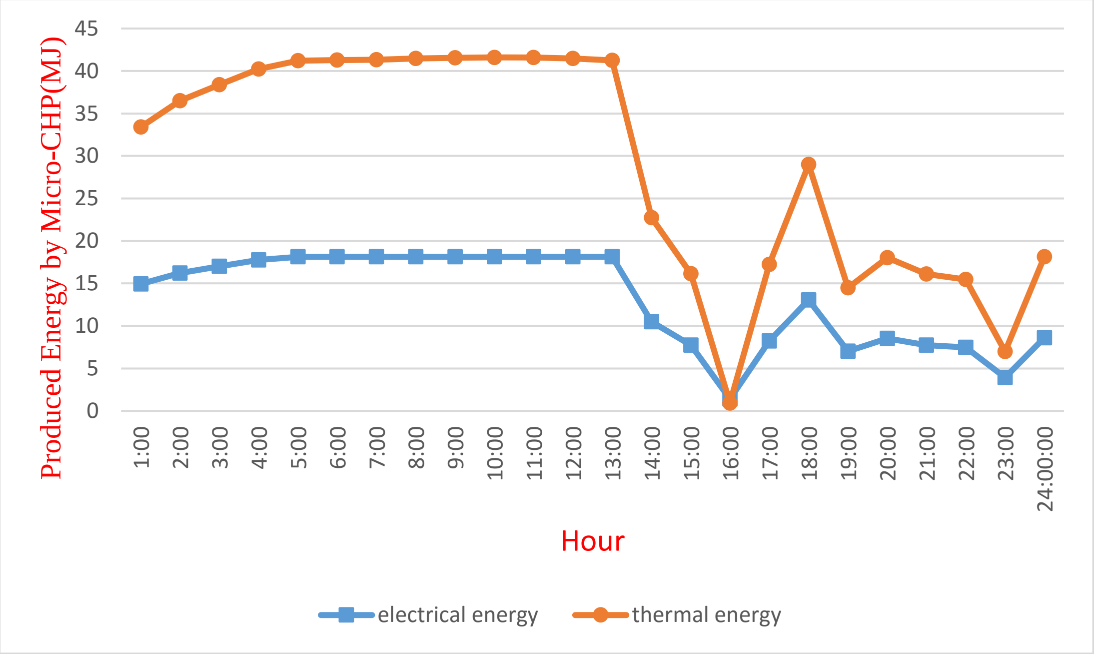


Figure 5.7: Hourly outputs for December 20th.

5.2.3.3 January 16th

The thermal and electrical energy production for January 16th is shown in Figure 5.8. The two curve remain constant at the highest values by thermal: 41.3 MJ and electrical: 18.127 MJ from 2 am to 12 pm. Then the curves go down sharply to reach its minimum value by thermal: 12.816 MJ and electrical: 6.35 MJ at 6 pm.

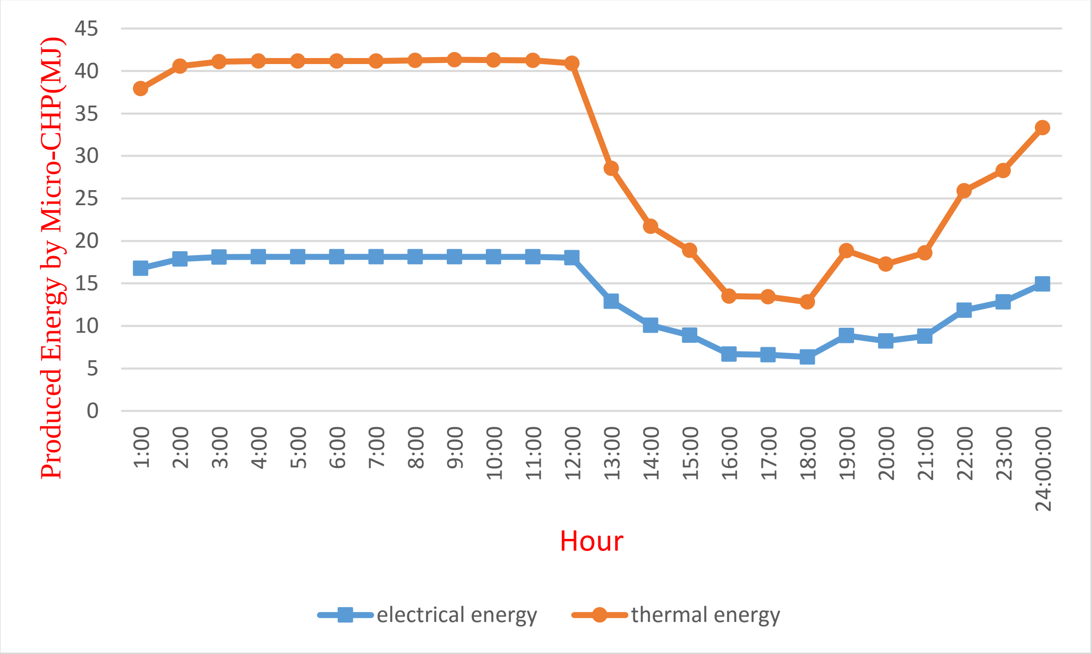


Figure 5.8: Hourly outputs for January 16th

5.2.3.4 February 2nd

As shown in Figure 5.9, the thermal and electrical energy production curves remain constant at the highest values by thermal: 41.517 MJ and electrical: 18.127 MJ from 5 am to 5 pm. Then the curves go down slightly to reach its minimum values by thermal: 25.38 MJ and electrical: 11.608 MJ at 10 pm and 12 am.

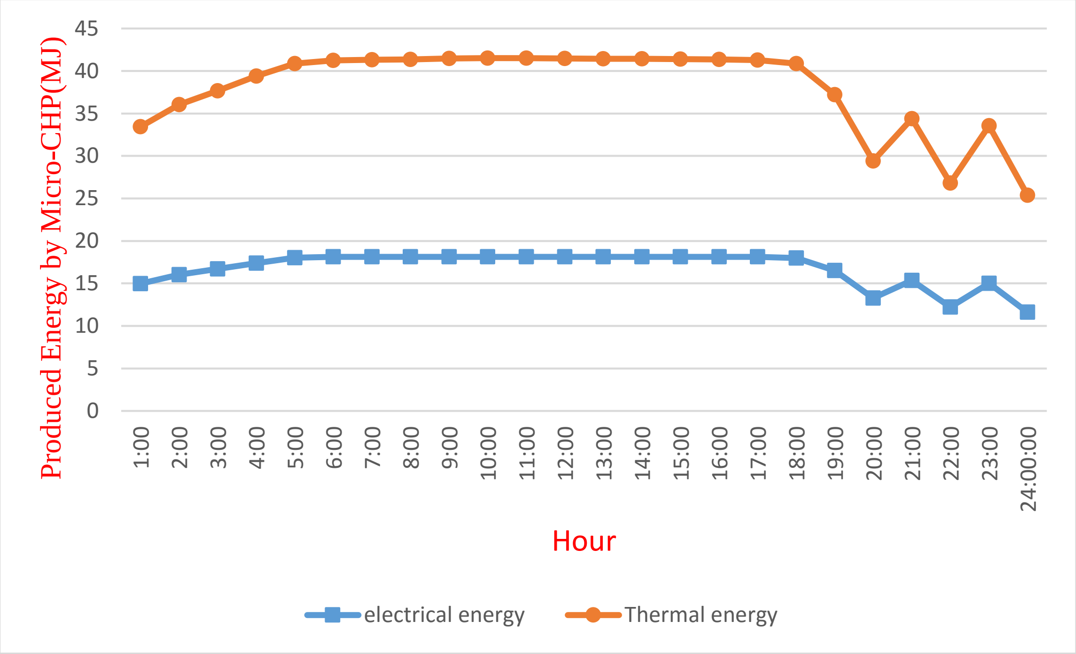


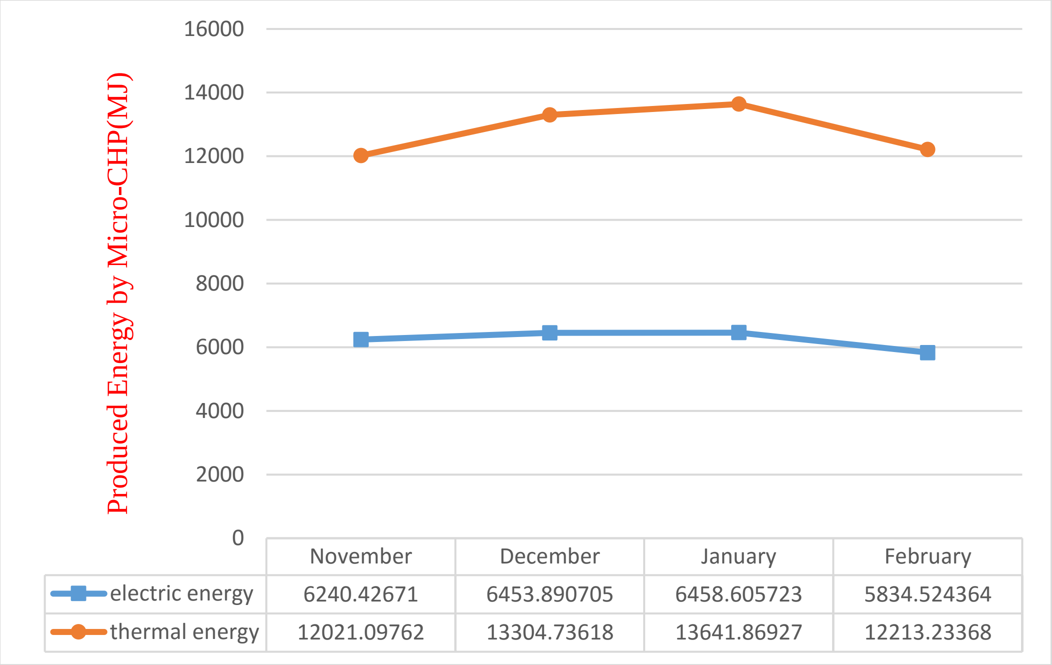
Figure 5.9: Hourly outputs for February 2nd.

5.3 Follow Electrical

As discussed earlier simulation of the system is carried out based on the electrical demand of the building. The Micro-CHP system is tracking the electrical load. The electrical equipment is divided onto 2 pumps, one in the source side and the other in the use side, and a Packaged Terminal Air conditioning (PTAC) fan. As in section 5.3, the results are presented for winter season. The study is carried out for monthly, daily and hourly outputs.

5.3.1 Monthly Results

The produced thermal and electrical energies of the micro-CHP generator in monthly designs is shown in Figure 5.10. The thermal curve hits its maximum production by 13976.50 MJ and the electrical curve by 6458.606 MJ for January. It is typical because January is known as the coldest month of the year in Cyprus.



	November	December	January	February
electric energy	6240.42671	6453.890705	6458.605723	5834.524364
thermal energy	12021.09762	13304.73618	13641.86927	12213.23368

Figure 5.10: Electrical and Thermal energy monthly production.

5.3.2 Daily Results

5.3.2.1 November

As shown in Figure 5.11, the thermal and electrical energy curves are following electrical. The electrical energy curve remains almost constant with a value of 208.013 MJ. As for the thermal energy curve slightly persist the same values between 393.279 and 421.361 MJ.

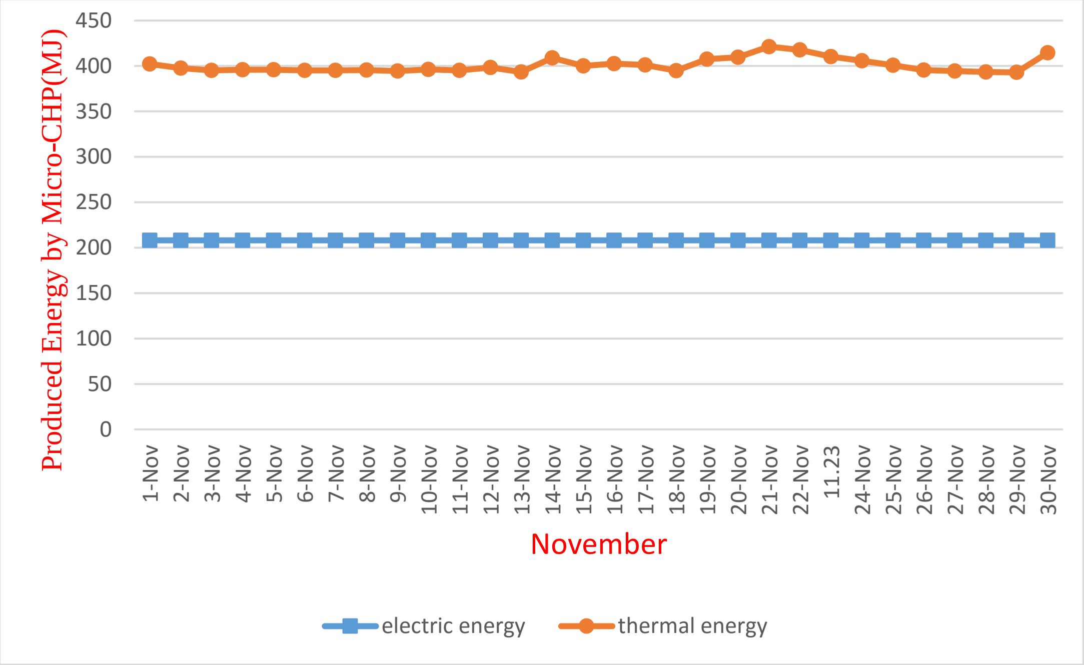


Figure 5.11: Electrical and Thermal energy production for November.

5.3.2.2 December

As shown in Figure 5.12, the electrical curve persists almost constant with a value of 209.025 MJ. Referring to the thermal curve, it slightly increases and decreases with values between 397.369 MJ and 453.638 MJ.

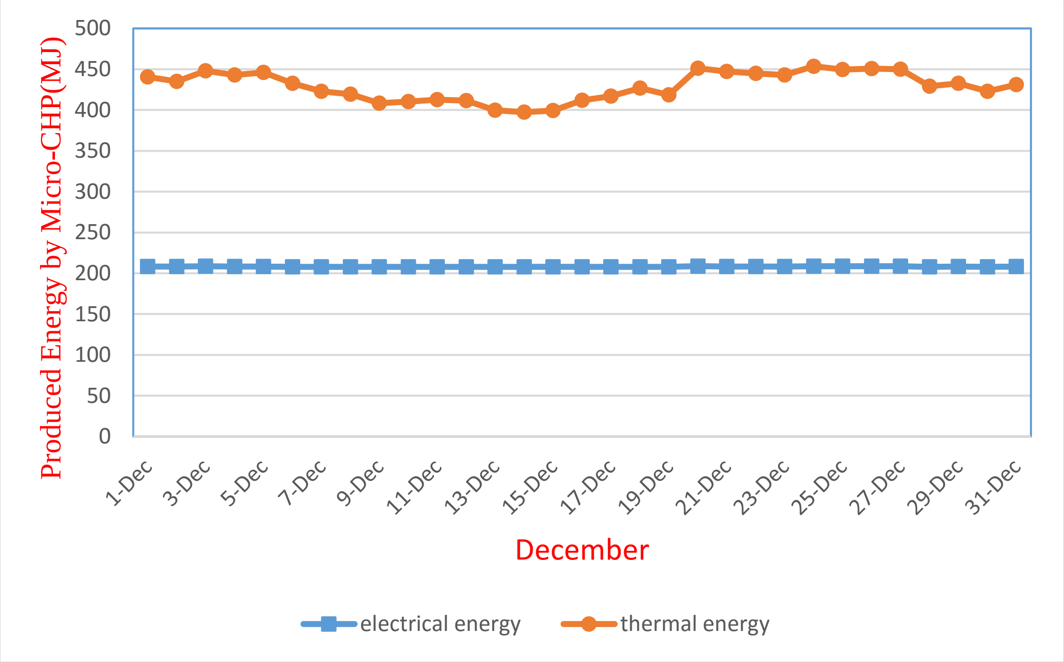


Figure 5.12: Electrical and Thermal energy production for December.

5.3.2.3 January

As shown in Figure 5.13, the electrical curve keeps going on an almost constant line with a value of 209.36 MJ. Referring to the thermal curve, it slightly increases and decreases with values between 405.325 MJ as the minimum value and 461.18 MJ as the maximum value.

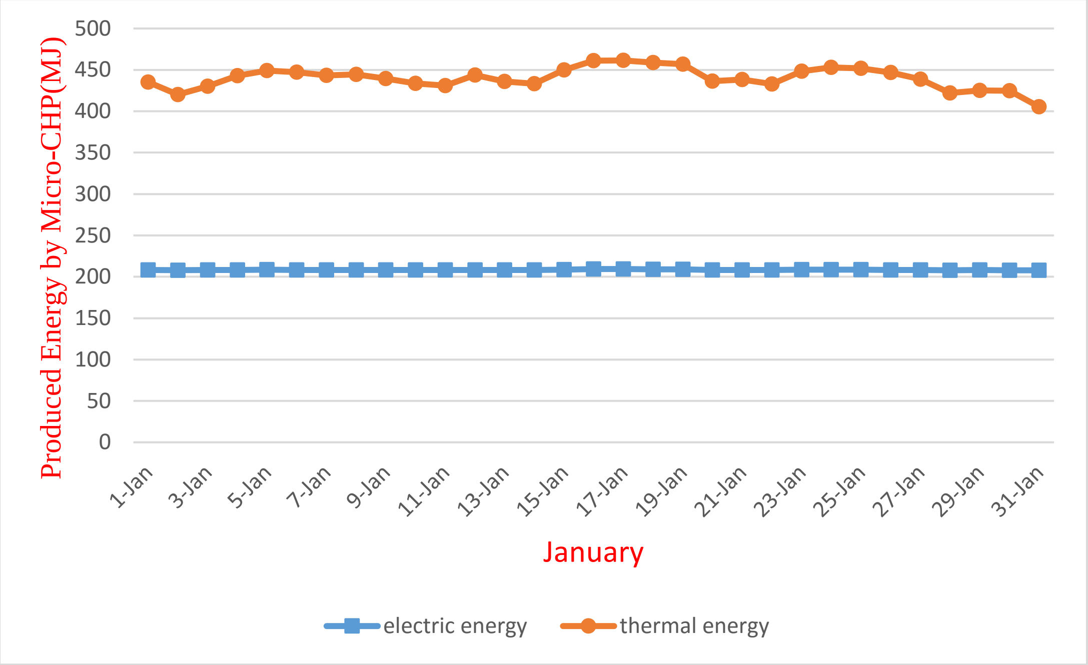


Figure 5.13: Electrical and Thermal energy production for January.

5.3.2.4 February

As shown in Figure 5.14, the electrical curve persists an almost constant line with a value of 208.71 MJ. Referring to the thermal curve, it slightly increases and decreases with values between 395.836 MJ as the minimum value and 462.03 MJ as the maximum value.

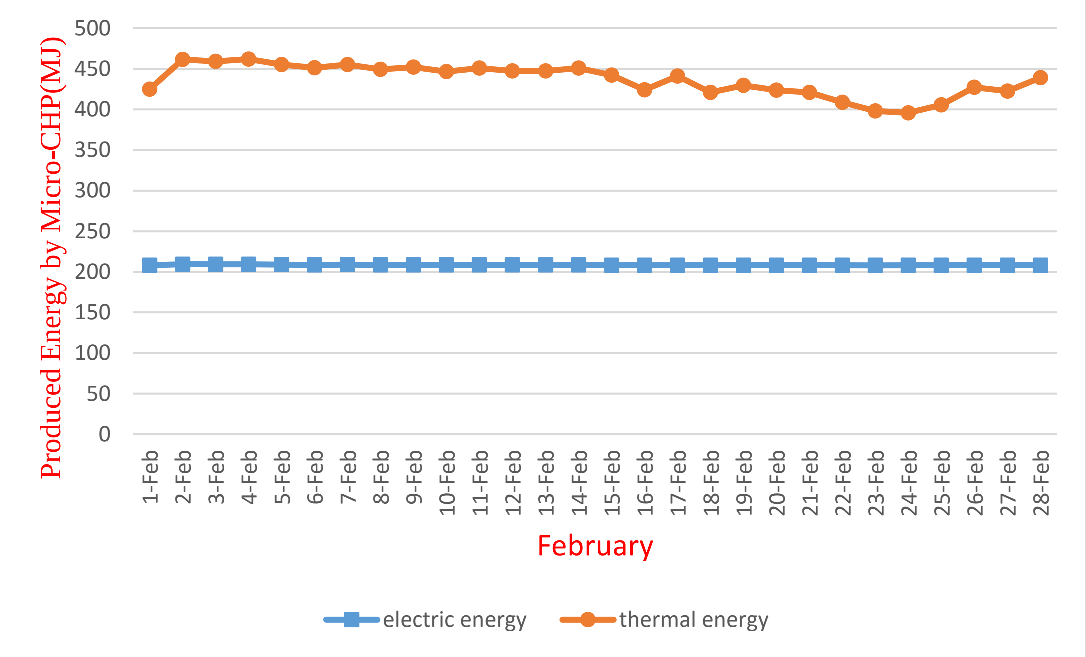


Figure 5.14: Electrical and Thermal energy production for February.

5.3.3 Hourly Results

The peak days chosen in this section are 22nd of November, 20th of December, 17th of January and 2nd of February where the energy production scores the highest values. The electric equipment is divided onto 2 pumps and 1 PTAC (Packaged terminal air conditioner) fan. The values of these days are shown in the following sections.

5.3.3.1 November 22nd

As shown in Figure 5.15, the electric equipment consumption is constant during the whole day by 2.84 MJ. Furthermore, the electrical and thermal curves are dependent on each other and it remains almost constant until 9 am. Once the students go out, the 2 curves hit a minimum peak production by 3.668 MJ for thermal, and 2.828 MJ for electrical between 10 am and 4 pm. Finally, at 5 pm the students start to come back to their dormitory, the thermal and electrical mark a sharp increase in energy production and continue rising to hit a maximum peak at 9 pm by 31.53 MJ for thermal, and by 15.509 MJ for electrical.

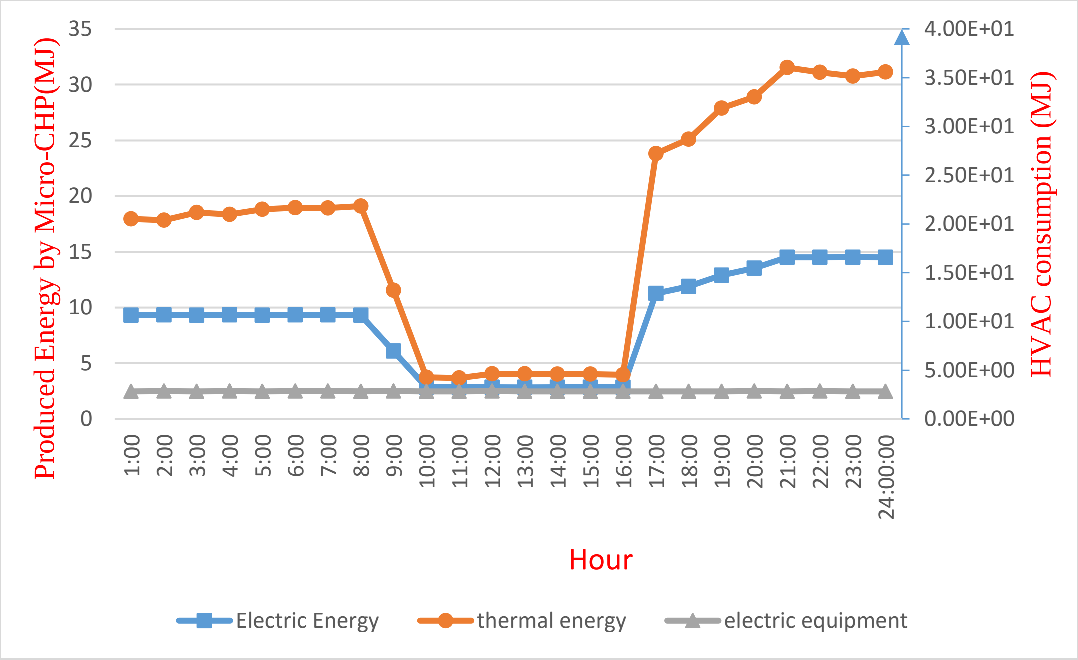


Figure 5.15: Hourly outputs for November 22nd.

5.3.3.2 December 20th

As shown in Figure 5.16, the electric equipment consumption is almost constant during the whole day. Furthermore, the electrical and thermal curves are dependent on each other, and it remains nearly constant until 9 am. Once the students go out the 2 curves hit a minimum peak production by 5.239 MJ for thermal, and 2.855 MJ for electrical between 10 am and 4 pm. Finally, at 5 pm the students start to come back to their dormitory. The thermal and electrical mark a sharp increase in energy production and continue growing to hit a maximum peak at 9 pm by 32.367 MJ for thermal, and a maximum peak energy production at 9 pm and 12 am by 14.507 MJ for electrical.

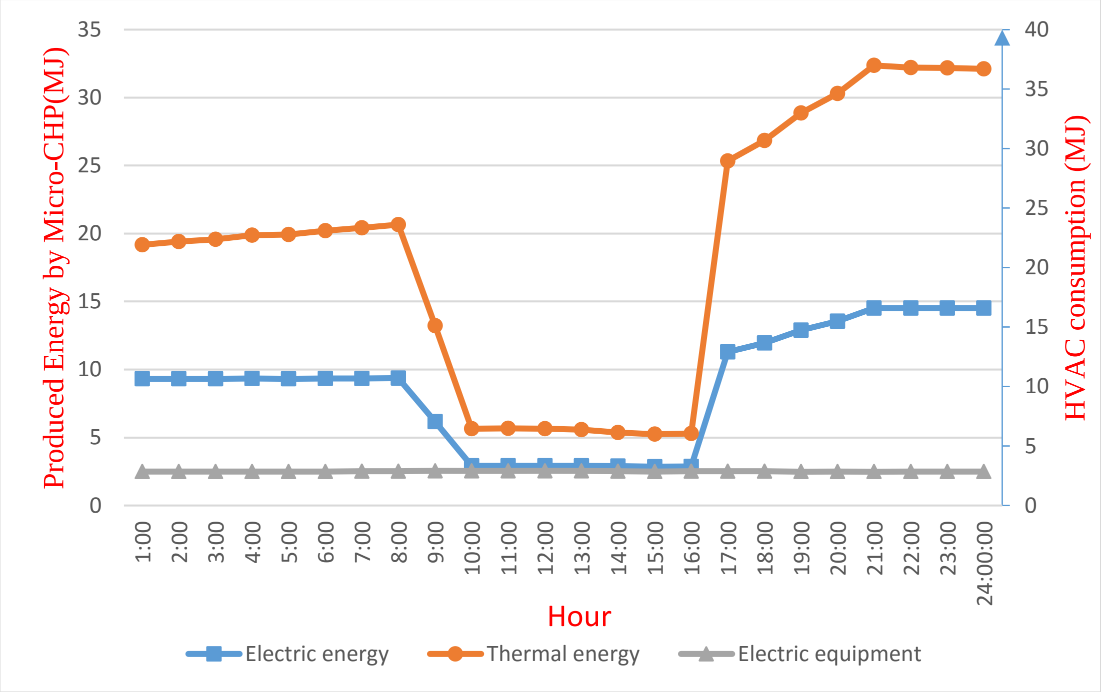


Figure 5.16: Hourly outputs for December 20th.

5.3.3.3 January 17th

As shown in Figure 5.17, the electric equipment consumption is almost constant during the whole day. As the graphs shown above, the electrical and thermal curves follow the same rhythm but with different peak (minimum and maximum) values. Maximum values are from 9 pm to 12 am by 14.521 MJ for electrical and 32.592 MJ for thermal.

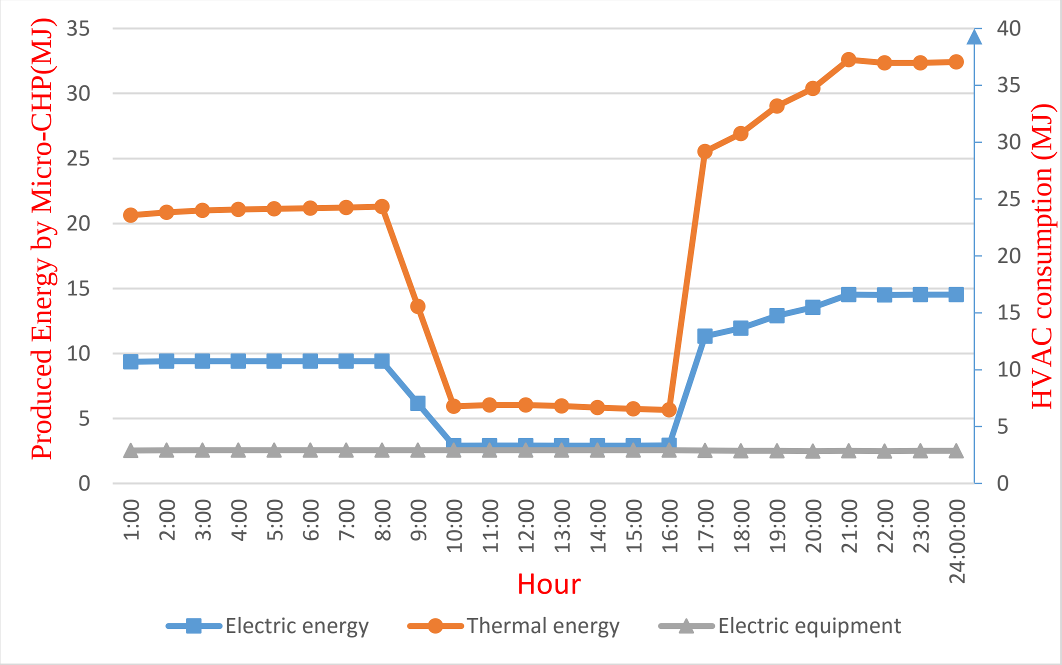


Figure 5.17: Hourly outputs for January 17th.

5.3.3.4 February 2nd

As shown in Figure 5.18, the electric equipment consumption is almost constant during the whole day. As the graphs shown above, the electrical and thermal curves follow the same rhythm but with different peak (minimum and maximum) values. Maximum values are from 9 pm to 12 am by 14.579 MJ for electrical and 33.478 MJ for thermal.

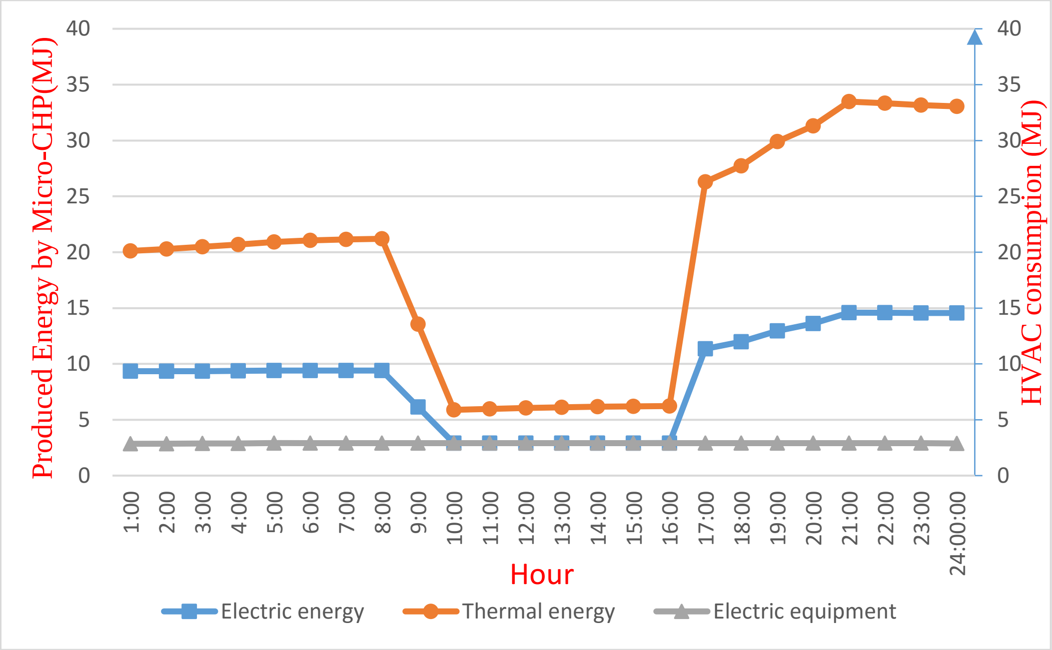


Figure 5.18: Hourly outputs for February 2nd.

Chapter 6

ECONOMICAL ANALYSIS

6.1 Introduction

Perhaps one of the most crucial part of a project that is planned to be applied is its economic feasibility. If an investment or a project is delivering economic benefit it is applicable, however if it is not delivering any economic benefit it is not applicable. The purpose of the economic feasibility analysis is to measure the economic value of the proposed project or its economic applicability and calculate its economic indicators compared with an alternative system. There are several economic indicators that are calculated in order to study the feasibility of an investment or a project. These indicators are given in Table 6.1 and explained in the subsequent section.

Table 6.1: Economic Indicators [44].

Savings to Investment Ratio (SIR)
Internal Rate of Return (IRR)
Simple Payback Period (SPP)
Net Present Value (NPV)

The project under study is a Micro-CHP project so the comparison between this system and an alternative one should be carried out. Micro-CHP is a system which produces heat and electricity simultaneously. Alternative system for a Micro-CHP can be separate production of heat and electricity for supplying the energy need. Therefore, it is thought that for the alternative system 80% efficient boiler can be used for supplying the heating demand and the electricity is purchased from the grid.

6.2 Economic Assessment of Micro-CHP System

In order to determine the feasibility of the Micro-CHP system, first, initial investment cost and annual maintenance costs during its lifetime should be evaluated and compared with the initial investment cost, and annual maintenance costs of the alternative system.

Subsequently annual benefits obtained by the application of the Micro-CHP system must be calculated in order to determine the economic indicators such as, Simple payback (SP), Net Present Value (NPV), Savings to Investment ratio (SIR) and Internal Rate of Return (IIR). The expressions for these economic indicators are given below:

$$SPP = \frac{\$\,cost}{\$\,savings/year} \tag{6.17}$$

$$NPV = \sum PV\ Annual\ Savings - \sum PV\ Life\ Cycle\ investments \tag{6.18}$$

$$SIR = \frac{\sum PV\ Annual\ Savings}{\sum PV\ Life\ Cycle\ Investments} \tag{6.19}$$

IRR= Discount Rate, whenever SIR= 1 or NPV= 0 (6.20)

In brief, if SIR is greater than 1 the project is feasible. If it is equal to 1 the project isn’t profitable; it costs as much as it returns and if it is less than 1 the project costs more than it makes. Also if NPV is a positive value the project is profitable. The SP also should be as small as possible to have a profitable project.

6.3 Parameters for Economic Analysis

The initial cost of the selected Micro-CHP system and the alternative system as well as their maintenance costs are in $, thus the $/TL rate during the time of this study is used to convert the costs to TL. During the time of this study $/TL was 2.80.

The initial cost of the selected Micro-CHP system is $ 30000 which becomes 84000 TL whereas the initial cost of the conventional boiler for the alternative system is $ 8000 that corresponds to 22400 TL. The selected Micro-CHP system requires maintenance cost of $ 75➔210 TL for every year and $ 200➔560 TL for every 5 years. The alternative system on the other hand requires maintenance cost of $ 75➔210 TL for every year.

The building that the Micro-CHP system is thought to be applied is a student hall which is a residential building. From the electricity tariffs of North Cyprus, the electricity price for a residential building for monthly consumption above 750 kWh is 0.54 TL/kWh. The Micro-CHP system is running with LPG and the LPG price in North Cyprus is 3.6 TL/kg. Considering that the heating value of the LPG is 50 MJ/kg and 1 MJ= 0.278 kWh, price for heating energy is found as 0.259 TL/kWh.

The discount rate used for evaluating the economic indicators is taken as 10 % for the TL from the Kooperatif Merkez Bankasi which is a bank in North Cyprus.

The analysis period for the project is chosen as 20 years and the residual value for the Micro-CHP system is taken as 10000 TL.

6.4 Economic Appraisal of the Micro-CHP System When It Follows Thermal Load of the Building

The case study is done for heating season from November 1st to February 28th. When the Micro-CHP is used for covering the thermal load of the building it produces 49577.1 MJ➔13782 kWh amount of thermal energy during the considered period. Thus this value is the total thermal energy demand of the building. Considering that the thermal efficiency of the selected Micro-CHP is 0.66 the total fuel energy consumed becomes 13782 kWh/0.66➔20882.4 kWh. The produced electrical energy during the same mode of operation (following the thermal load of the building) for the same period is 23521.5 MJ➔6539.0 kWh.

When the Micro-CHP is used for covering the electrical load of the building it produces 24987.4 MJ➔6947 kWh during the considered period. Thus this value is the total electrical energy demand of the building. It is seen that when the Micro-CHP is following the thermal load of the building, it cannot cover the total electrical energy demand of the building. Some electrical energy should be purchased from the grid.

When the alternative system which is separate production of heat and electrical energy is used the heating demand of the building is supplied by 80 % efficient boiler and the electrical energy is purchased from the grid. Considering that the heating demand for the period is 13782 kWh, 80% efficient boiler requires 13782kWh/0.66➔17228 kWh of fuel energy. The total electrical energy demand of the building on the other hand which is 6947 kWh is purchased from the grid.

In below table amount of thermal and electrical energy purchases and corresponding costs and savings are given for the Micro-CHP system and the alternative system for the heating period.

Table 6.2: Energy purchases and savings.

	Micro-CHP (0.66 thermal efficiency)	**Alternative system**	**Savings (Alternative-MicroCHP)**
Electricity (kwh)	407.5	6946.5	6539
Thermal energy (kwh)	20882.4	17228	-3654
Electricity cost (TL)	220	3751	3531
Thermal energy cost (TL)	5409	4462	-946
Total energy (kwh)	21290	24175	2885
Total energy cost (TL)	5629	8213	2585

It is seen in above table that when the Micro-CHP system is following the thermal load of the building, 2885 kWh of energy and 2585 TL money can be saved annually. The annual saved money by the application of Micro-CHP and the parameters above are used for evaluating the economic indicators. These calculations are carried out and the results are given in Table 6.3. The spreadsheets that are used for calculations are given in Appendix E

Table 6.3: Economic Indicators of Micro-CHP when it follows the thermal load.

Net Present Value (NPV)	TL -37920
Savings to Investment Ratio	0.4
Internal Rate of Return	0%
Simple Payback (years)	23.8

It can be deduced from these conditions that the project isn't profitable or feasible, since SIR < 1, the project's payback period is 23.8 years (greater than the analysis period which is 20 years), and with net present value equal to -37920 TL.

The main reason that the project becomes not profitable although it gives considerable amount of energy saving is the high $/TL rate as the initial cost and the annual maintenance costs are based on $. In addition, the oil prices are having extreme low values thus, the electricity prices are relatively low in North Cyprus. Thus, for these conditions it might be more economical to purchase electricity from the grid.

6.5 Economic Appraisal of the Micro-CHP System When It Follows Electrical Load of the Building

When the Micro-CHP is used for covering the electrical load of the building it produces 24987.4 MJ➔6947 kWh amount of electrical energy during the considered period. This value is the total electrical energy demand of the building. Considering that the electrical efficiency of the selected Micro-CHP is 0.27 the total fuel energy consumed becomes 6947 kWh/0.27➔25729.6 kWh. The produced thermal energy during the same mode of operation (following the electrical load of the building) for the same period is 51180 MJ➔14228 kWh.

It has been showed in the preceding section that when the Micro-CHP is used for covering the thermal load of the building, it produces 49577.1 MJ➔13782 kWh amount of thermal energy which becomes the total thermal energy demand of the building. It is seen that when the mode of operation is for covering the electrical load of the building, produced thermal energy is more than the demand thus there is no need for purchasing extra energy for the heating purposes.

It is already showed in the preceding section that when the alternative system is used 17228 kWh of fuel energy is required for the 80 % efficient boiler and 6947 kWh of electrical energy should be purchased from the grid.

In below table amount of thermal and electrical energy purchases and corresponding costs and savings are given for the Micro-CHP (following the electrical load of the building) system and the alternative system for the heating period.

Table 6.4: Energy purchases and savings.

	Micro-CHP (0.27 electrical efficiency)	**Alternative system**	**Savings (Alternative-Micro-CHP)**
Electricity (kwh)	0	6946.5	6946.5
Thermal energy (kwh)	25729.6	17228	-8502
Electricity cost (TL)	0	3751	3751
Thermal energy cost (TL)	6664	4462	-2202
Total energy (kwh)	25730	24175	-1555
Total energy cost (TL)	6664	8213	1549

It is seen in above table that when the Micro-CHP system is following the electrical load of the building, additional 1555 kWh of energy should be purchased compared with the conventional system however 1549 TL money can be saved annually. The annual saved money by the application of Micro-CHP and the other parameters are used for evaluating the economic indicators. The results are given in Table… The spreadsheets that are used for calculations are given in Appendix E

Table 6.5: Economic Indicators of the Micro-CHP when it follows the electrical load.

Net Present Value (NPV)	TL -46955
Savings to Investment Ratio	0.2
Internal Rate of Return	-3%
Simple Payback (years)	39.8

When the above table is investigated it is seen that if the Micro-CHP system is working based on the electrical load of the building the system is not giving economic benefit during the considered 20 years period. Therefore with this mode of operation Micro-CHP system is not feasible.

As explained in the preceding section the main reason for the Micro-CHP system being not feasible for both following the thermal and electrical load of the building is that the high $/TL rate as the initial cost and the annual maintenance costs are based on $. In addition, the oil prices' extreme low values makes Micro-CHP no beneficial to cover its relatively expensive initial and maintenance costs.

However, it should be noted that $/TL and oil prices are at their extreme high and low values respectively and are likely that they will be stabilized. Therefore it is worth to investigate the economic feasibility of the Micro-CHP system under stable conditions. $/TL rate and oil prices thus electricity prices in North Cyprus were at their stable values three years ago with $/TL=1.70 and electricity prices 0.84 TL/kWh. In the subsequent section economic feasibility results are presented for the Micro-CHP system when the $/TL and electricity prices were at their stable levels.

6.6 Economic Appraisal of the Micro-CHP System When $/TL and Electricity Prices Were Stable

In the preceding sections it has been showed that under the current conditions the Micro-CHP system is not profitable to be applied. However it is worth to investigate its feasibility under the stable conditions (stable $/TL and electricity prices).

In this section economic feasibility of the Micro-CHP system is carried out again for two modes of operation; system following thermal load of the building and the system following electrical load of the system. All the features used in the economic feasibility calculations in the preceding sections are used here as well except the $/TL and electricity prices. $/TL rate is taken as 1.70 and electricity prices is taken as 0.84 TL/kWh.

In the below tables amount of thermal and electrical energy purchases and corresponding costs and savings are given for the Micro-CHP system and the alternative system for both modes of the operation.

Table 6.6: Energy purchases and savings with the stable $/TL rates and electricity prices for Micro-CHP following the thermal load of the building.

	Micro-CHP (0.27 electrical efficiency)	**Alternative system**	**Savings (Alternative-MicroCHP)**
Electricity (kwh)	407.5	6946.5	6539
Thermal energy (kwh)	20882.4	17228	-3654
Electricity cost (TL)	342	5835	5493
Thermal energy cost (TL)	5409	4462	-946
Total energy (kwh)	21290	24175	2885
Total energy cost (TL)	5751	10297	4546

Table 6.7: Energy purchases and savings with the stable $/TL rates and electricity prices for Micro-CHP following the electrical load of the building.

	Micro-CHP (0.27 electrical efficiency)	**Alternative system**	**Savings (Alternative-MicroCHP)**
Electricity (kwh)	0	6946.5	6946.5
Thermal energy (kwh)	25729.6	17228	-8502
Electricity cost (TL)	0	5835	5835
Thermal energy cost (TL)	6664	4462	-2202
Total energy (kwh)	25730	24175	-1555
Total energy cost (TL)	6664	10297	3633

It is seen in above tables that if the Turkish Lira rate is stable such as it was 3 years ago and the electricity prices were at the same value as 3 years ago the Micro-CHP system can be used to save energy costs. It should be noted that when the system is following the thermal load of the building there is both total energy saving and cost saving. However, this is not the case when the system is following the electrical load of the building. In that case Micro-CHP system is not causing savings in the total energy use however, it causes cost savings.

In order to check if the Micro-CHP system project would be feasible during a period of 20 years economic indicators are evaluated and are given in below tables for two cases, Micro-CHP following the thermal load of the building and Micro-CHP following the electrical load of the building. The spreadsheets for these calculations are given in Appendix F.

Table 6.8: Economic Indicators of the Micro-CHP when it follows the thermal load.

Net Present Value (NPV)	TL 3557
Savings to Investment Ratio (SIR)	1.1
Internal Rate of Return (IRR)	11%
Simple Payback Period (SPP)	8.2

Table 6.9: Economic Indicators of the Micro-CHP when it follows the electrical load.

Net Present Value (NPV)	TL -4405
Savings to Investment Ratio (SIR)	0.9
Internal Rate of Return (IRR)	8%
Simple Payback Period (SPP)	10.3

Reference to the above economic analysis it is noticed that by choosing Micro-CHP using the thermal load, it is deduced that the analysis shows a positive NPV (TL +3557), SIR > 1, IRR > 10% (opportunity cost of capital – discount rate), and SPP of 8.2 years.

On the other hand, while implementing Micro-CHP following the electrical load, the output reflects negative NPV (TL -4405), SIR < 1, IRR < 10% (opportunity cost of capital – discount rate), and SPP of 10.3 years.

In light of the above, the most feasible economical alternative is Micro-CHP following the thermal load because the $/TL

Chapter 7

DISCUSSION AND CONCLUSION

This work investigates the application of a Micro-CHP system for a particular type of residential building i.e. a student accommodation building, for the heating season (November 1st-February 28th) in North Cyprus. The main aim of studying a Micro-CHP installed to a building in North Cyprus is to investigate its applicability under the particular conditions existing in North Cyprus.

Also it is aimed to open a way for promoting the distributed power to lessen the loads on power plants that are working with fossil fuels. This can be done by carrying out a whole system investigation as a case study including economic feasibility study which has been accomplished in this work.

In this work first the building in consideration which is a 400 m^2, 1 storey, 12 occupants student accommodation building is modelled. This is done by generating an Energy Plus model by considering the building fabric thermophysical properties, building electrical capacity and heating and water use systems. The building electrical capacity has been used to select a Micro-CHP system such that the system can meet the buildings peak electrical load. The selected Micro-CHP system (running with LPG) has been included in the Energy Plus model. After the modelling energy simulations carried out for the Micro-CHP system for two scenarios; the system following the thermal load of the building and the system following the electrical load of the building.

The energetic (thermal and electrical) analysis of Micro-CHP for following thermal and electrical loads of the building has been carried out for the heating season. The total thermal and electrical energies produced are 49577.1 MJ and 23521.5 MJ respectively when Micro-CHP follows thermal load of the building. Furthermore, the total thermal and electrical energies produced are 52735.9 MJ and 24987.4 MJ respectively when Micro-CHP follows electrical load of the building. The results show that the production of thermal and electrical energies for both following thermal and following electrical reach its peak by 14680.577 MJ; 13976.505 MJ for thermal load and 6867.433 MJ; 6458.606 for electrical load respectively in January the coldest month in the year.

Finally, an economic feasibility of the system has been done. It has been found that the total energy savings in follow thermal load of the building is 2885 kWh. Nether less, in follow electrical load of the building, the consumption of energy is more than its savings. The total energy savings in follow electrical load is -1555 kWh.

Despite the energy savings, the system wasn’t feasible for the current exchange currency due to high $/TL rate, low oil prices etc. with IRR= 0%, SPP=23.8 years and SIR=0.4. In the past 3 years, when the $/TL rate was stable, and electricity prices were acceptable, the results reached gave a feasible project with IRR=11%, SIR=1.1, SPP= 8.2 years, and NPV=3557 TL.

In the end, Micro-CHP like any other technology is facing some barriers e.g. it needs frequent maintenance every 2880 operating hours, low electrical efficiency (27%), high installation cost etc. Notwithstanding it has more advantages than barriers i.e. low fuel consumption, production of heat and power simultaneously, low CO_2 emissions etc.

REFERENCES

[1] Common, M. (2001). Nebojsa Nakicenovic, Arnulf Grubler and Alan McDonald (eds.), Global Energy Perspectives, Cambridge University Press, Cambridge, 1998. ISBN 0 521 64200 0. *Environment and Development Economics*, *6*(03), 405-412.

[2] Siva Reddy, V. M., Kaushik, S. C., & Tyagi, S. K. (2011). Energy and exergy analyses of thermal power plants: A review. *Renewable & Sustainable Energy Reviews*.

[3] Bull, S. R. (2001). Renewable energy today and tomorrow. *Proceedings of the IEEE*, *89*(8), 1216-1226.

[4] Klara, S. M., Srivastava, R. D., & McIlvried, H. G. (2003). Integrated collaborative technology development program for CO 2 sequestration in geologic formations—United States Department of Energy R&D. *Energy Conversion and Management*, *44*(17), 2699-2712.

[5] KKTC Elektirk Kurumu 2015 Yili Toplam U¨retim ve Tu˙ketim Degˇerleri Kib-tek/ Genel Toplam/Kayiplar.

[6] Ben Naceur, S., Barajas, A., & Massara, A. (2015). Can Islamic Banking Increase Financial Inclusion?.

[7] Gillette, S. F. (2004). Market development of microturbine combined heat and power applications. *Cogeneration and Distributed Generation Journal*, *19*(2), 46-59.

[8] Huber, D. G., & Gulledge, J. (2011). *Extreme weather and climate change: understanding the link, managing the risk*. Arlington: Pew Center on Global Climate Change.

[9] Alanne, K., & Saari, A. (2004). Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. *Renewable and Sustainable Energy Reviews*, *8*(5), 401-431.

[10] Jalalzadeh-Azar, A. A., Slayzak, S. J., & Ryan, J. P. (2002). Evaluation of cooling, heating, and power (CHP) for office buildings/Discussion. *ASHRAE transactions*, *108*, 1045.

[11] Blok, K., Worrell, E., Cuelenaere, R., & Turkenburg, W. (1993). The cost effectiveness of CO2 emission reduction achieved by energy conservation.*Energy Policy*, *21*(6), 656-667.

[12] Ahmadi, P., Dincer, I., & Rosen, M. A. (2014). Performance Evaluation of Integrated Energy Systems. In *Progress in Sustainable Energy Technologies: Generating Renewable Energy* (pp. 103-147). Springer International Publishing.

[13] Gillette, S. F. (2004). Market development of microturbine combined heat and power applications. *Cogeneration and Distributed Generation Journal*, *19*(2), 46-59.

[14] Quaschning, V., Kistner, R., & Ortmanns, W. (2002). Influence of direct normal irradiance variation on the optimal parabolic trough field size: A problem solved with technical and economical simulations. *Journal of solar energy engineering*, *124*(2), 160-164.

[15] Cengel, Y. A., & Boles, M. A. (1994). Thermodynamics: an engineering approach. *Sea*, *1000*, 8862.

[16] Sanchez, M. C., Brown, R. E., Webber, C., & Homan, G. K. (2008). Savings estimates for the United States Environmental Protection Agency's ENERGY STAR voluntary product labeling program. *Energy policy*, *36*(6), 2098-2108.

[17] Gillette, S. F. (2004). Market development of microturbine combined heat and power applications. *Cogeneration and Distributed Generation Journal*, *19*(2), 46-59.

[18] Capehart, B. L., Turner, W. C., & Kennedy, W. J. (2006). *Guide to energy management*. The Fairmont Press, Inc.

[19] Handbook, A. S. H. R. A. E. (2001). Fundamentals. *American Society of Heating, Refrigerating and Air Conditioning Engineers*, *Atlanta*, *111*.

[20] Beausoleil-Morrison, I., & Kelly, N. J. (2007). Specifications for modelling fuel cell and combustion-based residential cogeneration device within whole-building simulation programs.

[21] Pulkrabek, W. W. (1997). *Engineering fundamentals of the internal combustion engine* (No. 621.43 P8).

[22] Adamczyk, A. A., & Lavoie, G. A. (1978). *Laminar head-on flame quenching-a theoretical study* (No. 780969). SAE Technical Paper.

[23] Lund, H., & Mathiesen, B. V. (2009). Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050.*Energy*, *34*(5), 524-531.

[24] De Paepe, M., D'Herdt, P., & Mertens, D. (2006). Micro-CHP systems for residential applications. *Energy conversion and management*, *47*(18), 3435-3446.

[25] Hitaka, T., Matsui, C., & Sakai, J. I. (2007). Cyclic tests on steel and concrete-filled tube frames with Slit Walls. *Earthquake Engineering & Structural Dynamics*, *36*(6), 707-727.

[26] Masina, M., & Ciavola, P. (2011). Analisi dei livelli marini estremi e delle acque alte lungo il litorale ravennate. *Studi costieri*, *18*, 87-101.

[27] Handbook, A. S. H. R. A. E. (2001). Fundamentals. *American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta*, *111*.

[28] Handbook, A. F. (2009). American society of heating, refrigerating and air-conditioning engineers. *Inc.: Atlanta, GA, USA*.

[29] Williams, E. (2004). Energy intensity of computer manufacturing: Hybrid assessment combining process and economic input-output methods.*Environmental science & technology*, *38*(22), 6166-6174.

[30] Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., ... & Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and buildings*, *33*(4), 319-331.

[31] Hobbs, B. F., & Meier, P. (2012). *Energy decisions and the environment: a guide to the use of multicriteria methods* (Vol. 28). Springer Science & Business Media.

[32] Oh, S. C., & Hildreth, A. J. (2016). Energy Simulation Using EnergyPlus™ for Building and Process Energy Balance. In *Analytics for Smart Energy Management* (pp. 199-244). Springer International Publishing.

[33] Cengel, Y. A., & Boles, M. A. (1994). Thermodynamics: an engineering approach. *Sea*, *1000*, 8862.

[34] D*ä*umler K.-D., Grundlagen der Investitions- und Wirtschaftlichkeitsrechnung. 11. Edition, Verlag Neue Wirtschafts-Briefe, Berlin, 2003

[35] Babst, F., Alexander, M. R., Szejner, P., Bouriaud, O., Klesse, S., Roden, J., ... & Trouet, V. (2014). A tree-ring perspective on the terrestrial carbon cycle.*Oecologia*, *176*(2), 307-322.

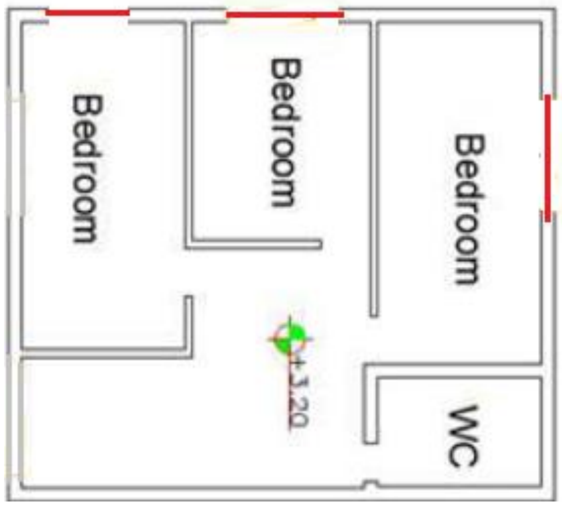
[36] Kelly, N., Hawkes, A. D., Dodds, P. E., Staffell, I., & Pfenninger, S. (2015). 14 Technical and economic modelling of microgeneration. *Domestic Microgeneration: Renewable and Distributed Energy Technologies, Policies and Economics*, 319.

[37] Beausoleil-Morrison, I., & Kelly, N. J. (2007). Specifications for modelling fuel cell and combustion-based residential cogeneration device within whole-building simulation programs.

[38] Ahmadi, P., Dincer, I., & Rosen, M. A. (2014). Performance Evaluation of Integrated Energy Systems. In *Progress in Sustainable Energy Technologies: Generating Renewable Energy* (pp. 103-147). Springer International Publishing.

APPENDICES

Appendix A: Building Architectural Plan



Appendix B: Features of Micro-CHP Unit Under Study

A.1 Technical Micro-CHP in study specifications

It has been decided to select a Micro-CHP with an electrical output of 5.5kW. The Micro-CHP unit height (to top casing) is 1000mm, width is 720mm, depth is 1060 and its weight is 530kg. The thermal output of this technology can reach without condenser up to 12.5kW, with the presence of a condenser maximum up to 15.5kW. The efficiency can reach without the installation of a condenser up to 79%; with the presence of a condenser up to 92%. The gas supply pressure for the system is 20mbar, with the l gas input of 2.13 m^3/h.

It is designed for an operating service life 80000 hours and service maintenance intervals of 2880 hours. The 5.5kW Micro-CHP is almost noise free (52-56 dBA) at 1 meter from casing. The heating flow and heating return temperatures are 80°C 70°C respectively. The electrical connections of the system are:

- 3 phase supply onto 20A type 'C' circuit breakers: 2.5mm
- Equipotential bonding to main earth: 10mm.

Appendix C: MCRO-CHP Use and Source Side Schematic

The system under study is composed of three loops: source side loop, use side loop, and packaged terminal air conditioner loop.

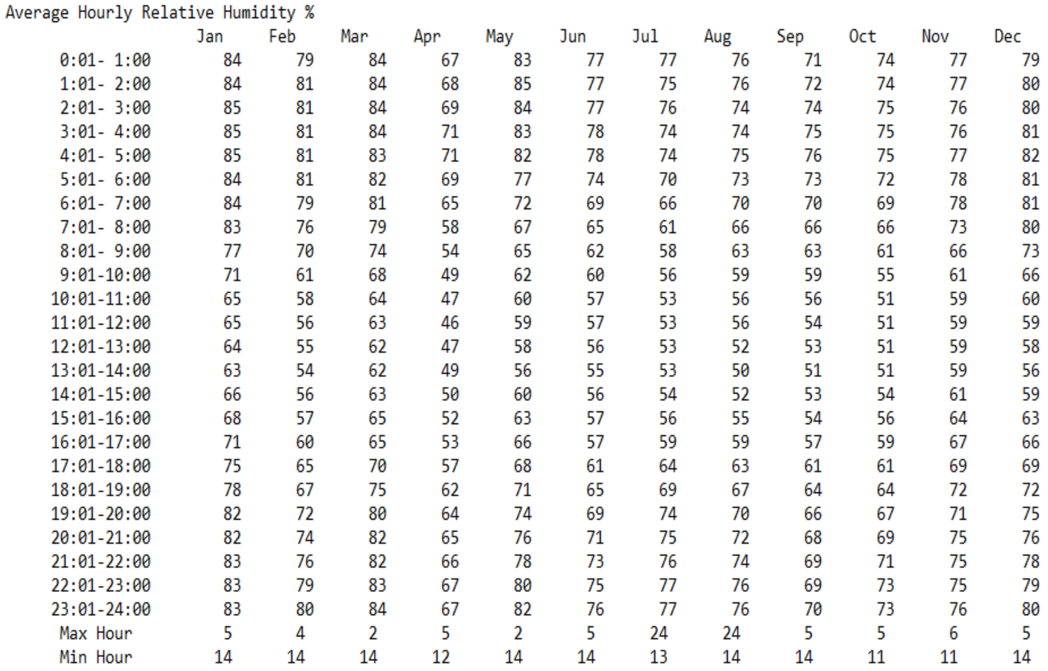
In the source side, the water is delivered to supply splitter by a pump. At the exit of the supply splitter water enters to the Micro-CHP system and heated up. It should be noted here that the other exit of the supply splitter is entering to the bypass pipe. Bypass pipes are used to bypass the main components in the case of the use of main component is not required. Thus they ensure the circulation of the fluid through the bypass pipe instead of the main component when the main component is not used. Once the water is heated in the Micro-CHP it enters the supply mixer and then it is delivered to the water heater via pipes and a splitter. The circulating water heats the water stored in the water heater and then exits and goes to the pump.

The water heater in use side supplies the hot water to the pipes through a mixer. The pipes drive the hot water to the splitter which splits the flow to the source hot water (hot water using items such as shower), bypass pipe, and the PTAC heating coil. Subsequently the water enters the mixer and then to a pump through the pipe. The pump delivers the water into a splitter and finally to the water heater.

Finally, in PTAC side, the PTAC heating coil delivers the energy in the hot water to the air which is forced through the heating coil by a fan. The heated air is then introduced to the zone. The zone exhaust air enters an air mixer which reliefs some of the air and lets in some outside fresh air. The mixed air then is introduced back to the PTAC heating coil. The cooling coil in the system is not operating as the system under study is for the heating season.

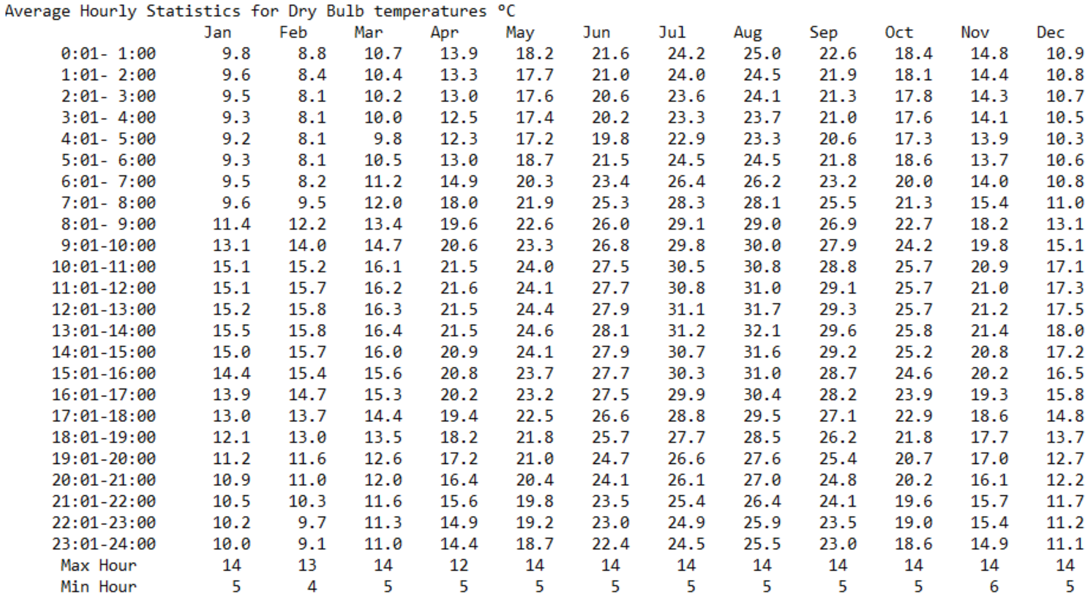
Appendix D: Weather Data of Larnaca from Energy Plus.

Table D.1: Hourly Relative Humidity for Larnaca.



```
Average Hourly Relative Humidity %
                Jan     Feb     Mar     Apr     May     Jun     Jul     Aug     Sep     Oct     Nov     Dec
   0:01- 1:00    84      79      84      67      83      77      77      76      71      74      77      79
   1:01- 2:00    84      81      84      68      85      77      75      76      72      74      77      80
   2:01- 3:00    85      81      84      69      84      77      76      74      74      75      76      80
   3:01- 4:00    85      81      84      71      83      78      74      74      75      75      76      81
   4:01- 5:00    85      81      83      71      82      78      74      75      76      75      77      82
   5:01- 6:00    84      81      82      69      77      74      70      73      73      72      78      81
   6:01- 7:00    84      79      81      65      72      69      66      70      70      69      78      81
   7:01- 8:00    83      76      79      58      67      65      61      66      66      66      73      80
   8:01- 9:00    77      70      74      54      65      62      58      63      63      61      66      73
   9:01-10:00    71      61      68      49      62      60      56      59      59      55      61      66
  10:01-11:00    65      58      64      47      60      57      53      56      56      51      59      60
  11:01-12:00    65      56      63      46      59      57      53      56      54      51      59      59
  12:01-13:00    64      55      62      47      58      56      53      52      53      51      59      58
  13:01-14:00    63      54      62      49      56      55      53      50      51      51      59      56
  14:01-15:00    66      56      63      50      60      56      54      52      53      54      61      59
  15:01-16:00    68      57      65      52      63      57      56      55      54      56      64      63
  16:01-17:00    71      60      65      53      66      57      59      59      57      59      67      66
  17:01-18:00    75      65      70      57      68      61      64      63      61      61      69      69
  18:01-19:00    78      67      75      62      71      65      69      67      64      64      72      72
  19:01-20:00    82      72      80      64      74      69      74      70      66      67      71      75
  20:01-21:00    82      74      82      65      76      71      75      72      68      69      75      76
  21:01-22:00    83      76      82      66      78      73      76      74      69      71      75      78
  22:01-23:00    83      79      83      67      80      75      77      76      69      73      75      79
  23:01-24:00    83      80      84      67      82      76      77      76      70      73      76      80
   Max Hour      5       4       2       5       2       5      24      24       5       5       6       5
   Min Hour     14      14      14      12      14      14      13      14      14      11      11      14
```

Table D.2: Hourly Statistics for Dry Bulb temperatures for Larnaca.



```
Average Hourly Statistics for Dry Bulb temperatures °C
                Jan      Feb      Mar      Apr      May      Jun      Jul      Aug      Sep      Oct      Nov      Dec
   0:01- 1:00    9.8      8.8     10.7     13.9     18.2     21.6     24.2     25.0     22.6     18.4     14.8     10.9
   1:01- 2:00    9.6      8.4     10.4     13.3     17.7     21.0     24.0     24.5     21.9     18.1     14.4     10.8
   2:01- 3:00    9.5      8.1     10.2     13.0     17.6     20.6     23.6     24.1     21.3     17.8     14.3     10.7
   3:01- 4:00    9.3      8.1     10.0     12.5     17.4     20.2     23.3     23.7     21.0     17.6     14.1     10.5
   4:01- 5:00    9.2      8.1      9.8     12.3     17.2     19.8     22.9     23.3     20.6     17.3     13.9     10.3
   5:01- 6:00    9.3      8.1     10.5     13.0     18.7     21.5     24.5     24.5     21.8     18.6     13.7     10.6
   6:01- 7:00    9.5      8.2     11.2     14.9     20.3     23.4     26.4     26.2     23.2     20.0     14.0     10.8
   7:01- 8:00    9.6      9.5     12.0     18.0     21.9     25.3     28.3     28.1     25.5     21.3     15.4     11.0
   8:01- 9:00   11.4     12.2     13.4     19.6     22.6     26.0     29.1     29.0     26.9     22.7     18.2     13.1
   9:01-10:00   13.1     14.0     14.7     20.6     23.3     26.8     29.8     30.0     27.9     24.2     19.8     15.1
  10:01-11:00   15.1     15.2     16.1     21.5     24.0     27.5     30.5     30.8     28.8     25.7     20.9     17.1
  11:01-12:00   15.1     15.7     16.2     21.6     24.1     27.7     30.8     31.0     29.1     25.7     21.0     17.3
  12:01-13:00   15.2     15.8     16.3     21.5     24.4     27.9     31.1     31.7     29.3     25.7     21.2     17.5
  13:01-14:00   15.5     15.8     16.4     21.5     24.6     28.1     31.2     32.1     29.6     25.8     21.4     18.0
  14:01-15:00   15.0     15.7     16.0     20.9     24.1     27.9     30.7     31.6     29.2     25.2     20.8     17.2
  15:01-16:00   14.4     15.4     15.6     20.8     23.7     27.7     30.3     31.0     28.7     24.6     20.2     16.5
  16:01-17:00   13.9     14.7     15.3     20.2     23.2     27.5     29.9     30.4     28.2     23.9     19.3     15.8
  17:01-18:00   13.0     13.7     14.4     19.4     22.5     26.6     28.8     29.5     27.1     22.9     18.6     14.8
  18:01-19:00   12.1     13.0     13.5     18.2     21.8     25.7     27.7     28.5     26.2     21.8     17.7     13.7
  19:01-20:00   11.2     11.6     12.6     17.2     21.0     24.7     26.6     27.6     25.4     20.7     17.0     12.7
  20:01-21:00   10.9     11.0     12.0     16.4     20.4     24.1     26.1     27.0     24.8     20.2     16.1     12.2
  21:01-22:00   10.5     10.3     11.6     15.6     19.8     23.5     25.4     26.4     24.1     19.6     15.7     11.7
  22:01-23:00   10.2      9.7     11.3     14.9     19.2     23.0     24.9     25.9     23.5     19.0     15.4     11.2
  23:01-24:00   10.0      9.1     11.0     14.4     18.7     22.4     24.5     25.5     23.0     18.6     14.9     11.1
   Max Hour      14       13       14       12       14       14       14       14       14       14       14       14
   Min Hour       5        4        5        5        5        5        5        5        5        5        6        5
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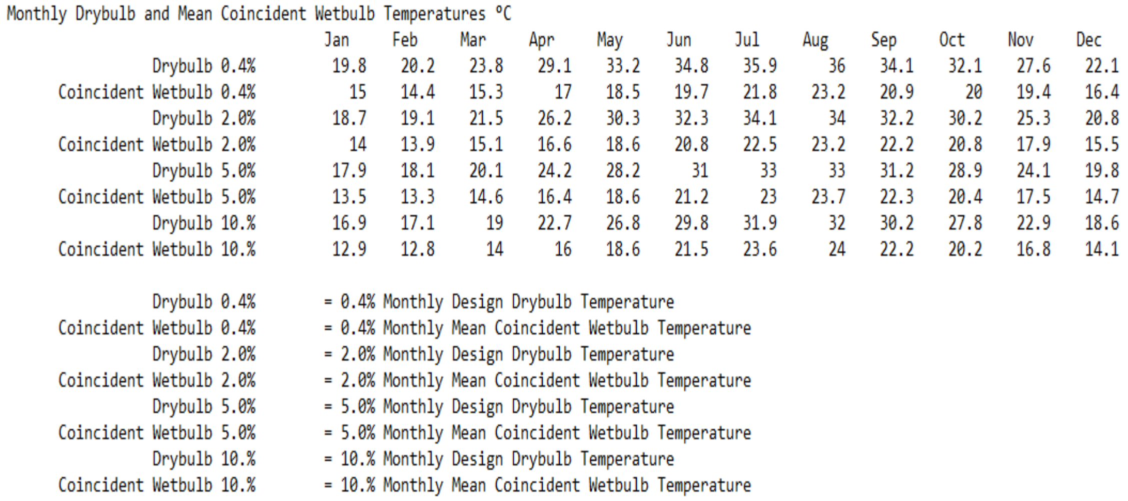
Table D.3: Monthly Statistics for Dry Bulb and Wet Bulb Temperatures for Larnaca.

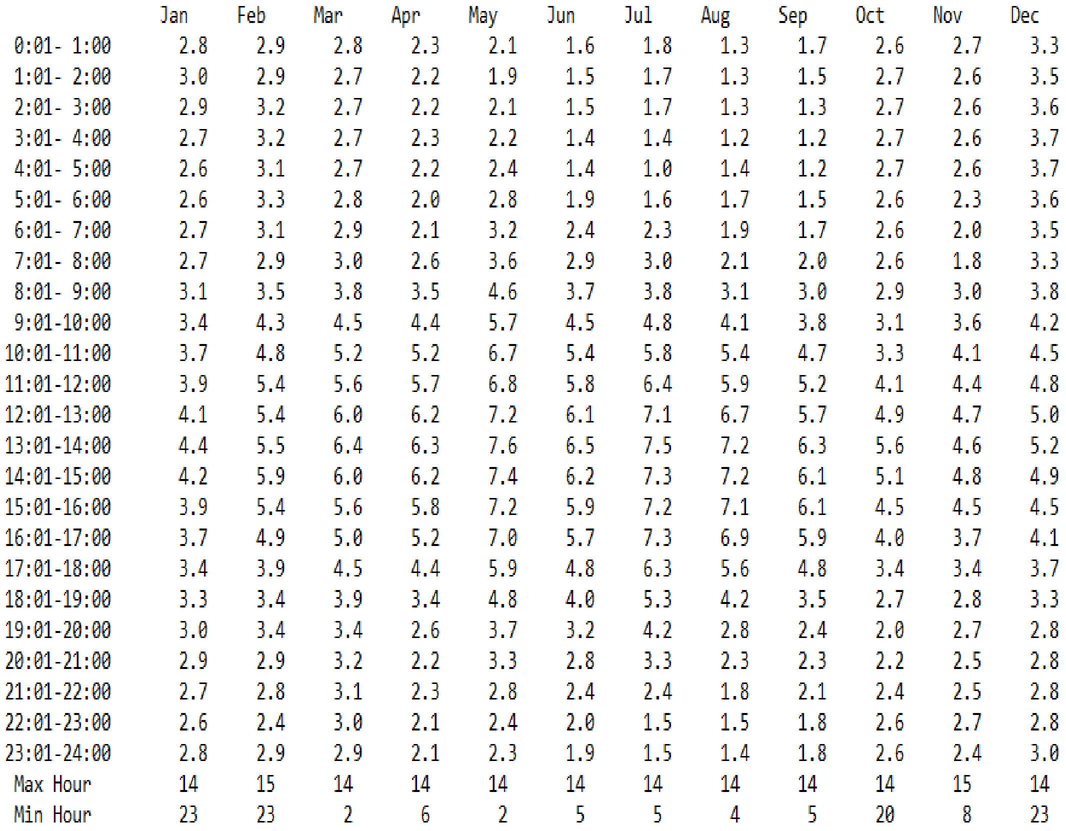


Monthly Drybulb and Mean Coincident Wetbulb Temperatures °C

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Drybulb 0.4%	19.8	20.2	23.8	29.1	33.2	34.8	35.9	36	34.1	32.1	27.6	22.1
Coincident Wetbulb 0.4%	15	14.4	15.3	17	18.5	19.7	21.8	23.2	20.9	20	19.4	16.4
Drybulb 2.0%	18.7	19.1	21.5	26.2	30.3	32.3	34.1	34	32.2	30.2	25.3	20.8
Coincident Wetbulb 2.0%	14	13.9	15.1	16.6	18.6	20.8	22.5	23.2	22.2	20.8	17.9	15.5
Drybulb 5.0%	17.9	18.1	20.1	24.2	28.2	31	33	33	31.2	28.9	24.1	19.8
Coincident Wetbulb 5.0%	13.5	13.3	14.6	16.4	18.6	21.2	23	23.7	22.3	20.4	17.5	14.7
Drybulb 10.%	16.9	17.1	19	22.7	26.8	29.8	31.9	32	30.2	27.8	22.9	18.6
Coincident Wetbulb 10.%	12.9	12.8	14	16	18.6	21.5	23.6	24	22.2	20.2	16.8	14.1

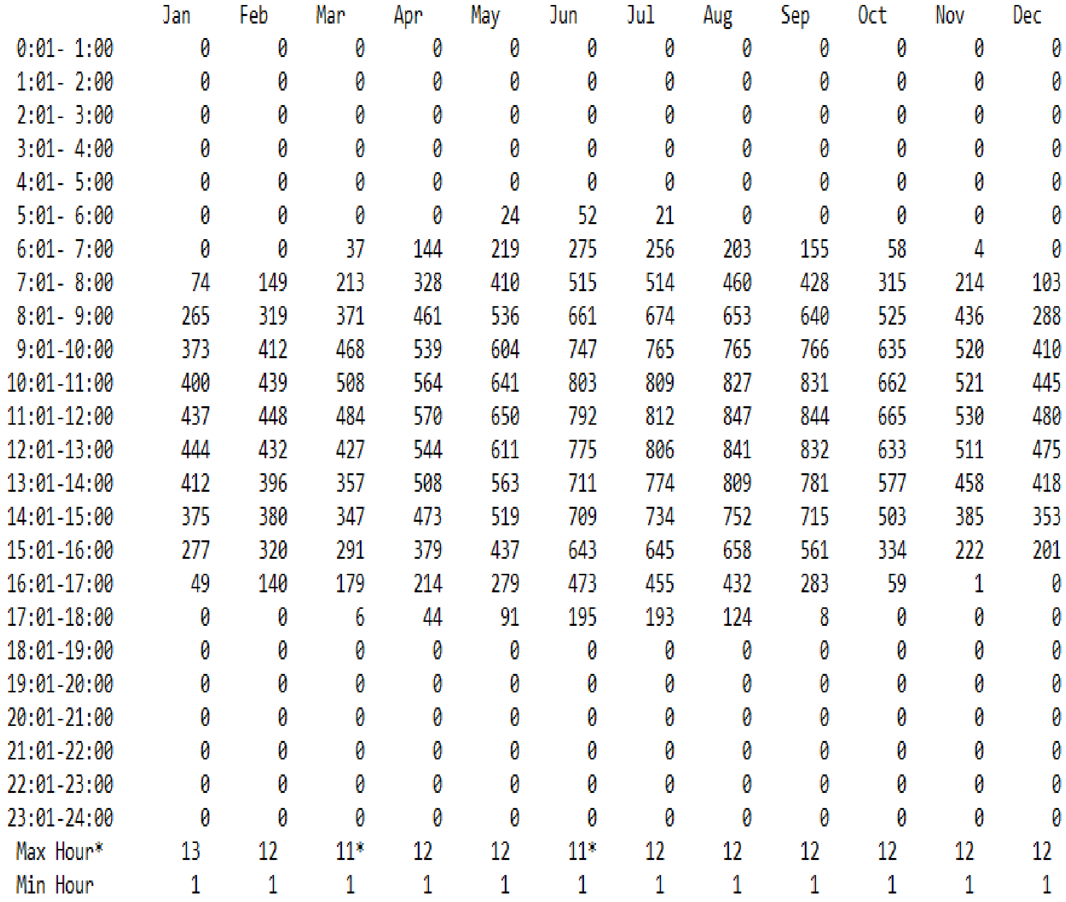
Drybulb 0.4% = 0.4% Monthly Design Drybulb Temperature
Coincident Wetbulb 0.4% = 0.4% Monthly Mean Coincident Wetbulb Temperature
Drybulb 2.0% = 2.0% Monthly Design Drybulb Temperature
Coincident Wetbulb 2.0% = 2.0% Monthly Mean Coincident Wetbulb Temperature
Drybulb 5.0% = 5.0% Monthly Design Drybulb Temperature
Coincident Wetbulb 5.0% = 5.0% Monthly Mean Coincident Wetbulb Temperature
Drybulb 10.% = 10.% Monthly Design Drybulb Temperature
Coincident Wetbulb 10.% = 10.% Monthly Mean Coincident Wetbulb Temperature

Table D.4: Average Hourly Statistics for Wind Speed m/s.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	2.8	2.9	2.8	2.3	2.1	1.6	1.8	1.3	1.7	2.6	2.7	3.3
1:01- 2:00	3.0	2.9	2.7	2.2	1.9	1.5	1.7	1.3	1.5	2.7	2.6	3.5
2:01- 3:00	2.9	3.2	2.7	2.2	2.1	1.5	1.7	1.3	1.3	2.7	2.6	3.6
3:01- 4:00	2.7	3.2	2.7	2.3	2.2	1.4	1.4	1.2	1.2	2.7	2.6	3.7
4:01- 5:00	2.6	3.1	2.7	2.2	2.4	1.4	1.0	1.4	1.2	2.7	2.6	3.7
5:01- 6:00	2.6	3.3	2.8	2.0	2.8	1.9	1.6	1.7	1.5	2.6	2.3	3.6
6:01- 7:00	2.7	3.1	2.9	2.1	3.2	2.4	2.3	1.9	1.7	2.6	2.0	3.5
7:01- 8:00	2.7	2.9	3.0	2.6	3.6	2.9	3.0	2.1	2.0	2.6	1.8	3.3
8:01- 9:00	3.1	3.5	3.8	3.5	4.6	3.7	3.8	3.1	3.0	2.9	3.0	3.8
9:01-10:00	3.4	4.3	4.5	4.4	5.7	4.5	4.8	4.1	3.8	3.1	3.6	4.2
10:01-11:00	3.7	4.8	5.2	5.2	6.7	5.4	5.8	5.4	4.7	3.3	4.1	4.5
11:01-12:00	3.9	5.4	5.6	5.7	6.8	5.8	6.4	5.9	5.2	4.1	4.4	4.8
12:01-13:00	4.1	5.4	6.0	6.2	7.2	6.1	7.1	6.7	5.7	4.9	4.7	5.0
13:01-14:00	4.4	5.5	6.4	6.3	7.6	6.5	7.5	7.2	6.3	5.6	4.6	5.2
14:01-15:00	4.2	5.9	6.0	6.2	7.4	6.2	7.3	7.2	6.1	5.1	4.8	4.9
15:01-16:00	3.9	5.4	5.6	5.8	7.2	5.9	7.2	7.1	6.1	4.5	4.5	4.5
16:01-17:00	3.7	4.9	5.0	5.2	7.0	5.7	7.3	6.9	5.9	4.0	3.7	4.1
17:01-18:00	3.4	3.9	4.5	4.4	5.9	4.8	6.3	5.6	4.8	3.4	3.4	3.7
18:01-19:00	3.3	3.4	3.9	3.4	4.8	4.0	5.3	4.2	3.5	2.7	2.8	3.3
19:01-20:00	3.0	3.4	3.4	2.6	3.7	3.2	4.2	2.8	2.4	2.0	2.7	2.8
20:01-21:00	2.9	2.9	3.2	2.2	3.3	2.8	3.3	2.3	2.3	2.2	2.5	2.8
21:01-22:00	2.7	2.8	3.1	2.3	2.8	2.4	2.4	1.8	2.1	2.4	2.5	2.8
22:01-23:00	2.6	2.4	3.0	2.1	2.4	2.0	1.5	1.5	1.8	2.6	2.7	2.8
23:01-24:00	2.8	2.9	2.9	2.1	2.3	1.9	1.5	1.4	1.8	2.6	2.4	3.0
Max Hour	14	15	14	14	14	14	14	14	14	14	15	14
Min Hour	23	23	2	6	2	5	5	4	5	20	8	23

Table D.5: Average Hourly Statistics for Direct Normal Solar Radiation Wh/m^2



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0:01- 1:00	0	0	0	0	0	0	0	0	0	0	0	0
1:01- 2:00	0	0	0	0	0	0	0	0	0	0	0	0
2:01- 3:00	0	0	0	0	0	0	0	0	0	0	0	0
3:01- 4:00	0	0	0	0	0	0	0	0	0	0	0	0
4:01- 5:00	0	0	0	0	0	0	0	0	0	0	0	0
5:01- 6:00	0	0	0	0	24	52	21	0	0	0	0	0
6:01- 7:00	0	0	37	144	219	275	256	203	155	58	4	0
7:01- 8:00	74	149	213	328	410	515	514	460	428	315	214	103
8:01- 9:00	265	319	371	461	536	661	674	653	640	525	436	288
9:01-10:00	373	412	468	539	604	747	765	765	766	635	520	410
10:01-11:00	400	439	508	564	641	803	809	827	831	662	521	445
11:01-12:00	437	448	484	570	650	792	812	847	844	665	530	480
12:01-13:00	444	432	427	544	611	775	806	841	832	633	511	475
13:01-14:00	412	396	357	508	563	711	774	809	781	577	458	418
14:01-15:00	375	380	347	473	519	709	734	752	715	503	385	353
15:01-16:00	277	320	291	379	437	643	645	658	561	334	222	201
16:01-17:00	49	140	179	214	279	473	455	432	283	59	1	0
17:01-18:00	0	0	6	44	91	195	193	124	8	0	0	0
18:01-19:00	0	0	0	0	0	0	0	0	0	0	0	0
19:01-20:00	0	0	0	0	0	0	0	0	0	0	0	0
20:01-21:00	0	0	0	0	0	0	0	0	0	0	0	0
21:01-22:00	0	0	0	0	0	0	0	0	0	0	0	0
22:01-23:00	0	0	0	0	0	0	0	0	0	0	0	0
23:01-24:00	0	0	0	0	0	0	0	0	0	0	0	0
Max Hour*	13	12	11*	12	12	11*	12	12	12	12	12	12
Min Hour	1	1	1	1	1	1	1	1	1	1	1	1

Appendix E: Current Currency (1$= 2.8TL) calculation

E.1 Micro-CHP Following the Thermal Load

Table E.1: Life Cycle Investment Schedule.

Year	New	Old	Net Amount
0	TL 84000	TL 22400	TL 61600
1	TL 210	TL 210	TL 0
2	TL 210	TL 210	TL 0
3	TL 210	TL 210	TL 0
4	TL 210	TL 210	TL 0
5	TL 560	TL 210	TL 350
6	TL 210	TL 210	TL 0
7	TL 210	TL 210	TL 0
8	TL 210	TL 210	TL 0
9	TL 210	TL 210	TL 0
10	TL 560	TL 210	TL 350
11	TL 210	TL 210	TL 0
12	TL 210	TL 210	TL 0
13	TL 210	TL 210	TL 0
14	TL 210	TL 210	TL 0
15	TL 560	TL 210	TL 350
16	TL 210	TL 210	TL 0
17	TL 210	TL 210	TL 0
18	TL 210	TL 210	TL 0
19	TL 210	TL 210	TL 0

Table E.2: Given Data

Annual Savings	TL 2585
Discount Rate	10%
Analysis period (years)	20
Residual value	TL 10000

Table E.3: Savings Calculations

Year	**Annual Savings**	**PV Annual Savings**
0	TL 0	TL 0
1	TL 2585	TL 2358
2	TL 2585	TL 2150
3	TL 2585	TL 1961
4	TL 2585	TL 1788
5	TL 2585	TL 1631
6	TL 2585	TL 1487
7	TL 2585	TL 1356
8	TL 2585	TL 1237
9	TL 2585	TL 1128
10	TL 2585	TL 1029
11	TL 2585	TL 938
12	TL 2585	TL 856
13	TL 2585	TL 780
14	TL 2585	TL 712
15	TL 2585	TL 649
16	TL 2585	TL 592
17	TL 2585	TL 540
18	TL 2585	TL 492
19	TL 2585	TL 449
20	TL 2585	TL 410
$\sum PV\ Annual\ Savings$	TL 22544	

Table E.4: Investments

Year	Net Life Cycle Investments	PV Life Cycle Investments	Net Cash Flows
0	TL 61600	TL 61600	TL 61600
1	TL 0	TL 0	TL 2585
2	TL 0	TL 0	TL 2585
3	TL 0	TL 0	TL 2585
4	TL 0	TL 0	TL 2585
5	TL 350	TL 321	TL 2235
6	TL 0	TL 0	TL 2585
7	TL 0	TL 0	TL 2585
8	TL 0	TL 0	TL 2585
9	TL 0	TL 0	TL 2585
10	TL 350	TL 139	TL 2235
11	TL 0	TL 0	TL 2585
12	TL 0	TL 0	TL 2585
13	TL 0	TL 0	TL 2585
14	TL 0	TL 0	TL 2585
15	TL 350	TL 88	TL 2235
16	TL 0	TL 0	TL 2585
17	TL 0	TL 0	TL 2585
18	TL 0	TL 0	TL 2585
19	TL 0	TL 0	TL 2585
Residual	TL -10000	TL -1584	TL12584
$\sum$ PV Life Cycle Investments	TL 60464		

E.2 Micro-CHP Following the Electrical Load

Table E.5: Given Data

Annual Savings	TL 1549
Discount Rate	10%
Analysis period (years)	20
Residual value	TL 10000

Table E.6: Savings Calculations

Year	**Annual Savings**	**PV Annual Savings**
0	TL 0	TL 0
1	TL 1549	TL 1413
2	TL 1549	TL 1288
3	TL 1549	TL 1175
4	TL 1549	TL 1072
5	TL 1549	TL 977
6	TL 1549	TL 891
7	TL 1549	TL 813
8	TL 1549	TL 741
9	TL 1549	TL 676
10	TL 1549	TL 617
11	TL 1549	TL 562
12	TL 1549	TL 513
13	TL 1549	TL 468
14	TL 1549	TL 427
15	TL 1549	TL 389
16	TL 1549	TL 355
17	TL 1549	TL 324
18	TL 1549	TL 295
19	TL 1549	TL 269
20	TL 1549	TL 245
$\sum PV\ Annual\ Savings$	TL 13509	

Table E.7: Investments

Year	**Net Life Cycle Investments**	**PV Life Cycle Investments**	**Net Cash Flows**
0	TL 61600	TL 61600	TL 61600
1	TL 0	TL 0	TL 1549
2	TL 0	TL 0	TL 1549
3	TL 0	TL 0	TL 1549
4	TL 0	TL 0	TL 1549
5	TL 350	TL 221	TL 1199
6	TL 0	TL 0	TL 1549
7	TL 0	TL 0	TL 1549
8	TL 0	TL 0	TL 1549
9	TL 0	TL 0	TL 1549
10	TL 350	TL 139	TL 1199
11	TL 0	TL 0	TL 1549
12	TL 0	TL 0	TL 1549
13	TL 0	TL 0	TL 1549
14	TL 0	TL 0	TL 1549
15	TL 350	TL 88	TL 1199
16	TL 0	TL 0	TL 1549
17	TL 0	TL 0	TL 1549
18	TL 0	TL 0	TL 1549
19	TL 0	TL 0	TL 1549
Residual	TL -10000	TL -1584	TL11549
$\sum$ PV Life Cycle Investments	TL 60464		

Appendix F: Past 3years Currency (1$= 1.7TL) Calculation

F.1Micro-CHP Following the Thermal Load

Table F.1: Life Cycle Investment Schedule.

Year	New	Old	Net Amount
0	TL 51000	TL 13600	TL 37400
1	TL 127	TL 127	TL 0
2	TL 127	TL 127	TL 0
3	TL 127	TL 127	TL 0
4	TL 127	TL 127	TL 0
5	TL 340	TL 127	TL 213
6	TL 127	TL 127	TL 0
7	TL 127	TL 127	TL 0
8	TL 127	TL 127	TL 0
9	TL 127	TL 127	TL 0
10	TL 340	TL 127	TL 213
11	TL 127	TL 127	TL 0
12	TL 127	TL 127	TL 0
13	TL 127	TL 127	TL 0
14	TL 127	TL 127	TL 0
15	TL 340	TL 127	TL 213
16	TL 127	TL 127	TL 0
17	TL 127	TL 127	TL 0
18	TL 127	TL 127	TL 0
19	TL 127	TL 127	TL 0

Table F.2: Given Data

Annual Savings	TL 4546
Discount Rate	10%
Analysis period (years)	20
Residual value	TL 10000

Table F.3: Savings Calculations

Year	**Annual Savings**	**PV Annual Savings**
0	TL 0	TL 0
1	TL 4546	TL 4146
2	TL 4546	TL 3781
3	TL 4546	TL 3448
4	TL 4546	TL 3145
5	TL 4546	TL 2868
6	TL 4546	TL 2616
7	TL 4546	TL 2385
8	TL 4546	TL 2176
9	TL 4546	TL 1984
10	TL 4546	TL 1809
11	TL 4546	TL 1650
12	TL 4546	TL 1505
13	TL 4546	TL 1373
14	TL 4546	TL 1252
15	TL 4546	TL 1142
16	TL 4546	TL 1041
17	TL 4546	TL 949
18	TL 4546	TL 866
19	TL 4546	TL 790
20	TL 4546	TL 720
$\sum PV\ Annual\ Savings$	TL 39646	

Table F.4: Investments

Year	**Net Life Cycle Investments**	**PV Life Cycle Investments**	**Net Cash Flows**
0	TL 37400	TL 37400	TL 37400
1	TL 0	TL 0	TL 4546
2	TL 0	TL 0	TL 4546
3	TL 0	TL 0	TL 4546
4	TL 0	TL 0	TL 4546
5	TL 213	TL 134	TL 4333
6	TL 0	TL 0	TL 4546
7	TL 0	TL 0	TL 4546
8	TL 0	TL 0	TL 4546
9	TL 0	TL 0	TL 4546
10	TL 213	TL 85	TL 4333
11	TL 0	TL 0	TL 4546
12	TL 0	TL 0	TL 4546
13	TL 0	TL 0	TL 4546
14	TL 0	TL 0	TL 4546
15	TL 213	TL 53	TL 4333
16	TL 0	TL 0	TL 4546
17	TL 0	TL 0	TL 4546
18	TL 0	TL 0	TL 4546
19	TL 0	TL 0	TL 4546
Residual	TL -10000	TL -1584	TL14546
$\sum$ PV Life Cycle Investments	TL 36088		

F.2 Micro-CHP Following the Electrical Load

Table F.5: Given Data

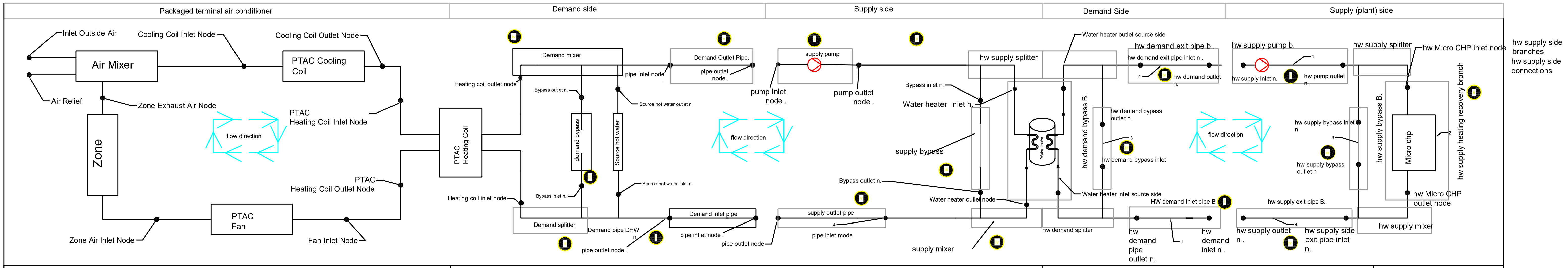
Annual Savings	TL 3633
Discount Rate	10%
Analysis period (years)	20
Residual value	TL 10000

Table F.6: Savings Calculations

Year	**Annual Savings**	**PV Annual Savings**
0	TL 0	TL 0
1	TL 3633	TL 3313
2	TL 3633	TL 3022
3	TL 3633	TL 2756
4	TL 3633	TL 2513
5	TL 3633	TL 2292
6	TL 3633	TL 2090
7	TL 3633	TL 1906
8	TL 3633	TL 1739
9	TL 3633	TL 1586
10	TL 3633	TL 1446
11	TL 3633	TL 1319
12	TL 3633	TL 1203
13	TL 3633	TL 1097
14	TL 3633	TL 1000
15	TL 3633	TL 912
16	TL 3633	TL 832
17	TL 3633	TL 759
18	TL 3633	TL 692
19	TL 3633	TL 631
20	TL 3633	TL 576
$\sum PV\ Annual\ Savings$	TL 31683	

Table F.7: Investments

Year	Net Life Cycle Investments	PV Life Cycle Investments	Net Cash Flows
0	TL 37400	TL 37400	TL 37400
1	TL 0	TL 0	TL 3633
2	TL 0	TL 0	TL 3633
3	TL 0	TL 0	TL 3633
4	TL 0	TL 0	TL 3633
5	TL 213	TL 134	TL 3420
6	TL 0	TL 0	TL 3633
7	TL 0	TL 0	TL 3633
8	TL 0	TL 0	TL 3633
9	TL 0	TL 0	TL 3633
10	TL 213	TL 85	TL 3420
11	TL 0	TL 0	TL 3633
12	TL 0	TL 0	TL 3633
13	TL 0	TL 0	TL 3633
14	TL 0	TL 0	TL 3633
15	TL 213	TL 53	TL 3420
16	TL 0	TL 0	TL 3633
17	TL 0	TL 0	TL 3633
18	TL 0	TL 0	TL 3633
19	TL 0	TL 0	TL 3633
Residual	TL -10000	TL -1584	TL13633
$\sum$ PV Life Cycle Investments	TL 36088		



Source demand side branches
1 - Demand inlet Pipe
2 - Demand splitter.
3 - Demand bypass pipe.
4 - Demand mixer
5 - Demand outlet pipe.

Source supply side branches
1 - supply pump.
2 - supply splitter.
3 - supply bypass pipe.
4 - supply mixer
5 - Supply outlet pipe.

demand side components
1 - demand side in pipe
2 - Water heater source side.
3 - demand side bypass pipe
4 - demand side exit pipe

hw demand side branches
1 - hw demand in pipe branches
2 - hw demand water heater branch
3 - hw demand bypass branch
4 - hw demand exit pipe branch

supply side components
1 - hw circulation
2 - Micro chp
3 - supply side bypass pipe
4 - supply side exit pipe

hw supply side branch
1 - hw supply pump branch
2 - hw supply heat recovery branch
3 - hw supply bypass branch
4 - hw supply exit pipe branch