Water Heating Performance Comparison of Heat Pump Water Heater, Flat Plate Solar Collector and LPG Boiler Systems for North Cyprus Climate Conditions

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ABSTRACT

This work comparatively investigates three different water heating technologies, used in residential buildings, for a particular location, climate and certain amount of hot water usage. Investigated technologies are Solar Water Heater (SWH), Heat Pump Water Heater (HPWH) and Indirect Gas Heater (IGH). Annual energy analysis simulation is performed by employing EnergyPlus software. It is an open source program, developed by the USA Department of Energy, and used in many researches and projects. Energy simulations are performed for Cyprus weather conditions, by utilizing weather file for Larnaca city (34.9003° N, 33.6232° E). It is considered that in a residential building there is one family with five people and each person consumes 50 L of hot water every day. Total capacity of the hot water tank is assumed to be 250 L. After annual simulation, the results in terms of energy consumption for SWH, HPWH and IGH are found to be 8.05 GJ, 4.08 GJ and 11.95 GJ respectively. This values are used in economic analysis. When comparing SWH with IGH, the results obtained from the economic analyses for Net Present Value (NPV), Savings-to-Investment Ratio (SIR), Internal Rate of Return (IRR) and Simple Payback Period (SPP) are $273, 1.5, 15% and 6.5 years, accordingly. Comparison of HPWH and IGH produced the following values, NPV ($1050), SIR (1.9), IRR (20%) and SPP (4.7). HPWH is compared to SWH and economic analysis results are $807, 2.4, 26% and 3.7 years for NPV, SIR, IRR and SPP respectively. The HPWH is the most economic technology, according to economic and technical analyses results.

Keywords: solar collector, heat pump, gas heater, EnergyPlus, energy simulation-

ÖZ

Bu çalışma, belirli bir yer, iklim ve sıcak su tüketimi için konutlarda kullanılan üç farklı su ısıtıcı cihazının karşılaştırılmasını incelemektedir. Karşılaştırılan su ısıtıcı cihazları: güneş enerjisi sistemi, ısı pompası ve geleneksel gaz yakıtlı sıcak su kazanıdır. Öngörülen cihazların yıllık enerji çözümlemesi ve incelemesi, EnergyPlus adlı enerji çözümleme programı kullanılarak gerçekleştirilmiştir. Energy Plus Amerika Birleşik Devletleri Enerji Bakanlığı tarafından geliştirilen açık kaynaklı bir yazılım olup birçok araştırma ve projede kullanılmaktadır. Bu çalışma Kıbrıs'ın yerel koşulları altında gerçekleştirilmiş olup, enerji simülasyonlarında Larnaka (34.9003 °C N, 33.6232 °C E) şehri için gelştirilmiş iklimsel veri dosyası kullanılmıştır. Bir konutta beş kişilik bir aile olduğu ve her bireyin günlük 50 L sıcak su tükettiği varsayılmıştır. Sıcak su deposunun hacmi, beş kişinin 50 L sıcak su kullanması gerekliliğine dayanarak, 250 L olarak hesaplanmıştır. Yıllık enerji simülasyonu tamamlandıktan sonra, her cihazın enerji tüketimi güneş enerjisi sistemi için 8.05 GJ, ısı pompası için 4.08 GJ ve gaz yakıtlı sıcak su kazanı için 11.95 GJ olmuştur. Bu değerler kullanarak ekonomik analiz gerçekleştirilmiştir. Güneş enerjiisi sistemi ve gaz yakıtlı sıcak su kazanı karşılaştırması sonucunda elde edilen değerler şöyledir NPV ($273), SIR (1.5), IRR (20%) ve SPP (6.5). Isı pompası ve gaz yakıtlı sıcak su kazanı karşılaştırmasından sonra NPV (1050 $), SIR (1.9), IRR (% 20) ve SPP (4.7) değerleri elde edilmiştir. Daha sonra, ısı pompası ile güneş enerjiisi sistemi karşılaştırıldığında NPV=$807, SIR=2.4, IRR=% 26 ve SPP =3.7 sene olarak bulunmuştur.

Çalışmada yapılan enerji ve ekonomik çözümlemelere göre ısı pompasının Kuzey Kıbrıs'ta su ısıtma için uygulanabilecek en verimli cihaz olduğu tesbit edilmiştir.

Anahtar Kelimeler: güneş enerjisi ısıtıcısı, ısı pompası, gazlı ısıtıcı, EnergyPlus, enerji simülasyonu

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LIST OF ABRREVIATIONS

ASCII   American Standard Code for Information Interchange

ASHRAE   American Society of Heating, Refrigeration, and Air-Conditioning

        Engineers

ASME   American Society of Mechanical Engineers

CAD   Computer Aided Design

COP   Coefficient of Performance

DX   Direct Expansion

EU   European Union

GJ   Giga Joules

HP   Heat Pump

HPWH   Heat Pump Water Heater

IDF   Input Data File

IGH   Indirect Gas Heater

IRR   Internal Rate of Return

LPG   Liquefied Petroleum Gas

NPV   Net Present Value

SIR   Savings-to-Investment Ratio

SPP   Simple Payback Period

SWC   Solar Water Collector

SWH   Solar Water Heater

LIST OF SYMBOLS

A	[m^2]	gross area of the collector
a$_{abs}$	[unitless]	absorptance of the absorber plate
C$_p$	[J/kgK]	specific heat
F$_{rac}$	[unitless]	present value for inlet air
F$_R$	[unitless]	an empirically determined correction factor
I$_{solar}$	[W/m^2]	total incident solar radiation (W/m^2)
K$_{\tau\alpha}$	[unitless]	incident angle modifier coefficient
$\dot{m}$	[kg/s]	mass flow rate of the working fluid
$\dot{m}_{source}$	[kg/s]	mass flow rate on the side where source elements are
$\dot{m}_{use}$	[kg/s]	mass flow rate on the side where use elements are
P_{load}	[W]	parasitic electric load set by the user
$P_{parasitic}$	[W]	parasitic electric power
q	[W]	useful heat gain (W)
q$_{heater}$	[W]	additional heat from element or burner
q$_{net}$	[W]	net heat transfer rate to the tank water
q$_{offcycloss}$	[W]	heat exchange to/from the surrounding
q$_{offcycpara}$	[W]	heat gained from off-cycle parasitic loads
q$_{oncycloss}$	[W]	heat exchange to/from the surrounding
q$_{oncycpara}$	[W]	heat gained from on-cycle parasitic loads
q$_{source}$	[W]	heat exchange to or from the source side elements
q$_{use}$	[W]	heat exchange to or from use side elements
R$_{cond}$	[m^2 °C/W]	conductive resistance from absorber to outdoor air through the insulation

R_{conv}	[m^2 °C/W]	convective resistance from absorber to inside glazing
R_{rad}	[m^2 °C/W]	radiative resistance from absorber to inside glazing
T	[°C]	temperature of the tank water
t	[s]	time
T_{air}	[°C]	temperature of the outdoor air
T_{abs}	[°C]	temperature of the absorber plate
$T_{HP,cut-in}$	[°C]	compressor's cut in temperature
$T_{HP,db}$	[°C]	heat pump compressor dead band temperature difference
$T_{HP,set\,point}$	[°C]	set point temperature of a compressor
T_{inlet}	[°C]	dry-bulb air temperature entering to the HPWH
T_{g1}	[°C]	temperature of the outside glazing
T_{g2}	[°C]	temperature of the inside glazing
t_{g1}	[unitless]	transmittance of the first glazing layer
t_{g2}	[unitless]	transmittance of the second glazing layer
$T_{outdoor}$	[°C]	dry-bulb temperature of outdoor air
T_{source}	[°C]	inlet temperature for the source side plant connections
T_{use}	[°C]	temperature of entering fluid for the use side elements
T_{zone}	[°C]	dry-bulb temperature for air exiting the zone
U_L	[W/m^{2}K]	overall heat loss coefficient combining radiation, convection, and conduction terms)
UA_{offcyc}	[W/K]	loss coefficient to the surrounding during operation
UA_{oncyc}	[W/K]	loss coefficient to the surrounding during operation

V	[m^3]	volume of the tank
ρ	[kg/m^3]	density of water
ε_{source}	[unitless]	effectiveness of a heat exchanging device located on a source side
ε_{use}	[unitless]	effectiveness of a heat exchanging device located on a use side
ω_{inlet}	[kg$_{water}$/kg$_{dry\ air}$]	humidity ratio for inlet air to the HPWH
$\omega_{outdoor}$	[kg$_{water}$/kg$_{dry\ air}$]	humidity ratio for outdoor air
ω_{zone}	[kg$_{water}$/kg$_{dry\ air}$]	humidity ratio of air exiting the zone
$(\tau\alpha)$	[unitless]	the product of all transmittance and absorptance terms (unitless)
$(\tau\alpha)_n$	[unitless]	the normal product of all transmittance and absorptance terms (unitless)

Chapter 1

INTRODUCTION

1.1 Background

Modern world is moving towards innovations in technologies with very confident steps, which leads to dramatic situation, lack of energy sources and high prices per unit of energy, all around the world. It is well known, that fossil fuels are the main source of energy. However, using fossil fuels has hazardous effect on all living creatures as well as on atmosphere. As a result, atmosphere becomes polluted by harmful gases like carbon dioxide (CO_2), sulphur dioxides (SO_x) and nitrogen oxides (NO_x). Emission of these gases leads to intoxication of the surrounding air, which causes diseases of breathing system in a human organism [1]. Reducing amount of fossil fuels involved in energy production process, should be the main mission of today's engineers and scientists.

One of the solutions to this problem, is to look into future perspectives of renewable or green energy sources. There is a tremendous amount of energy stored in nature. Despite this fact, efforts put into investigation of renewable sources are not at a level that can allow us totally abandon exploitation of fossil fuels. The fossil fuels are readily available and widely used compared to other energy sources. On the other hand, systems utilizing renewable energy sources are more costly but less harmful to the environment [2, 3].

Developed countries like the USA and EU countries allocate around 20% - 40% of total available energy for dwellings [4]. It is related to increasing level of comfort in residential buildings. In this context, water heating process appears to be one of the main energy consuming area in residential applications, after space heating and conditioning. The energy consumption in the US houses can be viewed in Fig. 1 [5]. The fossil fuels turn out to be the major source of energy for water heating process.
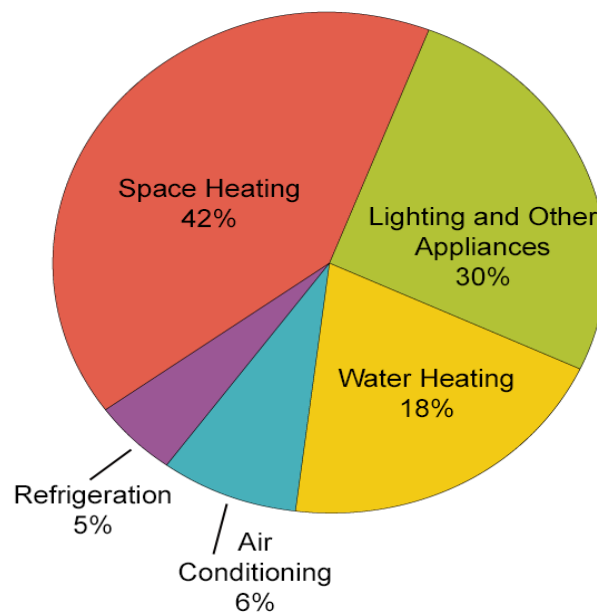
Figure 1: Energy Distribution in US Houses retrieved from Ref. [5]

1.2 Statement of the Problem

Cyprus is the third largest island in Mediterranean Sea, with its typical Mediterranean climate. Cyprus is the leading country in SWH systems, which are installed almost on every house and occupyied 0.82 m^2 per inhabitant [6]. Solar water collectors are the prior and almost free source of energy used for water heating in Cyprus. End user pays only for buying and installing SWH for the first time. Payback period for this devices is in range of 2-4 years, depending on materials and type of the SWH [7]. Problem may occur during cold period of the year, when there

is not enough of solar radiation to heat the water, and the need in hot water reaches its peak. This period of time, starting from mid-November until end of April people are forced to use alternative source of energy rather than just solar water collectors for heating domestic water. Usually, electric resistance heater is a backup source of energy for water heating, during cold period of the year. Unfortunately, dilemmas like high resistance required for the water tank and elevated price per kWh of electricity in North Cyprus, make engineers and users think of alternatives. According to electricity provider (**KIB-TEK**), starting from December 2016 1 kWh of electricity costs 0.52 TL (0.149 $), which is not considered as a low tariff [8]. The essential idea is to look at alternative, less expensive technologies in terms of energy consumption for water heating process, throughout the year.

1.3 Purpose of the Study

There are many alternatives of water heating technologies available all around the world. However, not all of them are popular and feasible. It is based on geographical location of the country and also approach of consumers. For example, in countries with very cold climate conditions utilization of Heat Pumps may not be the best idea, since performance of evaporator side in HPs decreases dramatically. Another reason for not switching from less efficient system to feasible one, is old-fashioned way of thinking in that particular area. People are simply not willing to switch from already tested and applied technologies to the newer and less known ones.

In this study the central goal is to perform energetic and economic analysis of the systems used for satisfying residential hot water needs, based on specific location and climate conditions. Solar water heater is popular technology, which already occupied most of the market in North Cyprus. As alternative technologies HPWH

and IGH systems will be investigated. Heating performance, energy consumption and feasibility analysis will be used for evaluation of all three technologies. Based on results received from simulation, conclusions and advices can be made for end users. There are several objectives to be pursued in this study, they are listed below as follows:

• Performing energy analysis of water heating devices.

• Collecting results of annual simulation.

• Conducting simple economic analysis.

• Deciding on the most effective way of heating domestic water.

1.4 Significance of the Study

Energy profile of Cyprus, illustrated in Fig. 2, mostly consists of oil products and coal, imported from other countries [6]. Opposing` the fact, that there is enough amount of solar, wind and ground energy which can be more than sufficient for satisfying energy needs of citizens. Increased number of researches and promotion campaigns, with strong and reliable information presented to ordinary citizens, can be a key strategy in convincing them to purchase new systems for their needs. This work particularly, is aimed to investigate and present alternative technologies of water heating.

Primary type of energy, used in North Cyprus, is gas and oil products used for power generation. Problem occurs in lack of alternatives for power supply. The prices for electricity are solely controlled   by one organization (*KIB-TEK)*. If the cost of energy per kWh cannot be reduced, than decreasing amount of electricity consumption can be a good strategy.

Significance of this study is in comparing three different systems by energy and economic parameters and deciding on which one of them is more feasible.
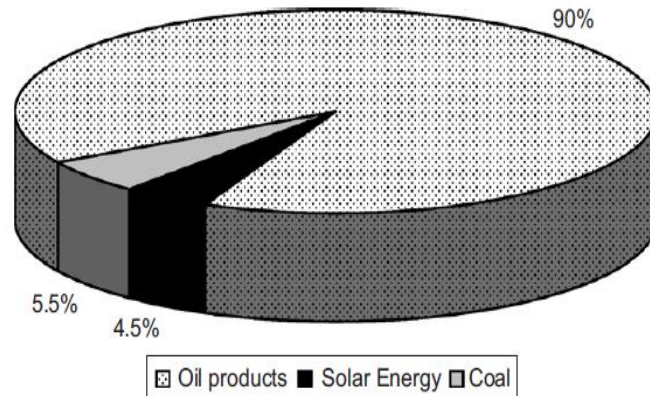
Figure 2: Energy Profile of Cyprus explained in Ref. [6]

1.5 Organization of the Thesis

Whole report is constructed in a way to provide detailed information on devices, modelling and simulation process, acquiring results and performing economic analysis. There are in total seven chapters which describe the research idea and methodologies. First chapter gives brief background on energy profile of Cyprus and underlines importance of the study. Second chapter is literature review, the historical development of water heating technologies are provided. Chapter three is methodology. Chapter four is about modeling and simulation. Simulation process and mathematical calculations involved are presented. Chapter five discusses the results of simulation. Chapter six considers simple economic analysis. Chapter seven is conclusion, where the conclusion in terms of energy consumption for every water heating method is discussed, and future work is mentioned.

Chapter 2

LITERATURE REVIEW

2.1 History of Water Heating

Comfort, is always one of the main objects of concern for the house owners. Nowadays, every modern house in the USA is equipped with water heating technology, ready to supply hot water for 24 hours a day [9]. Water heating process have been attracting curiosity of engineers and scientists for decades. History of water heating goes far back to the ancient time, when Romans started heating water in period of 298 AD – 306 AD, which was later used in bathing. Although, the system was not designed for personal use, this date can be fixed as beginning of water heating technologies [10]. Methods of water heating were not developing so rapidly. The most advanced option until the 19th century was to use stove and pot. Wood and coal were primary sources of heat. In 1868 English painter Benjamin Waddy Maughan invented first prototype of instantaneous gas water heater. However, the design was not following safety requirements, the exhaust gases were tossed out into the room. Then, in 1889 the design of Mr. Waddy was further improved and presented by Edmund Rudd. He has shaped water heater into close form of modern understanding of technology. Water heater by Edmund Rudd is illustrated in Fig. 3 [10].

Figure 3: Instantaneous Water Heater of 1904 as illustrated in Ref. [10]

Water heaters of this form kept being popular until 20th century. Exactly last century was the time when new methods started being investigated. The reason for that, was the high level of pollution of the air by the exhaust gases. In scope of finding a solution to the problem, alternative technologies operating on renewable sources of energy have been introduced. One of the examples of this technologies is the SWH which will be discussed in detail in the following chapters.

In this work three water heating methods, popular in North Cyprus, are discussed. One of them is HPWH, which is quickly occupying market. Another system is SWH, being already widely used. The third technology is IGH, which burns a gas or oil in a boiler and heats a water tank, they are also called indirect-fired hot water heaters.

2.2 Heat Pump Water Heaters

HPWHs are one of the main alternatives for substituting fossil fuel powered water heating methods. These devices took their place in a market in late 20th century, when urgency in substitution to the fossil fuels energy sources has occurred. However, HPWHs could have more attention from engineers and scientists, than they have nowadays. Main reason why this devices are not popular, is their higher purchase and installment costs when compared with conventional resistance water

heaters. Conversion of electricity into thermal energy of resistance water heater heating element can have efficiency of almost 100% [11]. On the other hand, COP for HPWHs is in range between 2-3, which is two or three times more than its competitors [12]. This phenomena can be explained by the energy generating strategies of these technologies. Resistance water heaters generate heat by directly converting electricity input into heat, so the amount of energy spent is exactly equal to the heat generated. Nonetheless, HPWHs instead of generating heat from energy input, they just transfer heat already available in surrounding low temperature air into the water medium [12]. This is possible by adopting a vapor compression cycle.

2.2.1 Components of HPWHs

HPWHs operate on refrigeration or vapor compression cycle, which is commonly used in heating, refrigeration and air conditioning processes [13]. There are four main components used to construct the entire system. These components are as follows: compressor, condenser, expansion valve and evaporator. Working fluid, is a refrigerant, which passes through all four elements by undergoing changes in phase, pressure and temperature. By considering ideal cycle the refrigerant changes its phase accordingly. First, the working fluid enters compressor where the pressure and temperature rise and it reaches superheated vapor state, process is named isentropic (adiabatic) compression. Then, refrigerant as superheated vapor enters a condenser and gives its heat to surrounding, this allows change state to saturated liquid. After exiting condenser, working fluid passes through expansion valve (or capillary tube), sudden expansion causes rapid pressure and temperature drop, as well as change in state from saturated liquid to saturated mixture. At this point, temperature of the refrigerant is lower than temperature of the refrigerated space or environment from which the heat is to be withdrawn. Last stage occurs in evaporator, here saturated

mixture absorbs heat from the surrounding and leaves as saturated vapor. All of the processes are repeated continuously in order to reach desired temperature of the heated space. Components of an ideal refrigeration cycle with T-S diagram are provided in the following Fig. 4.
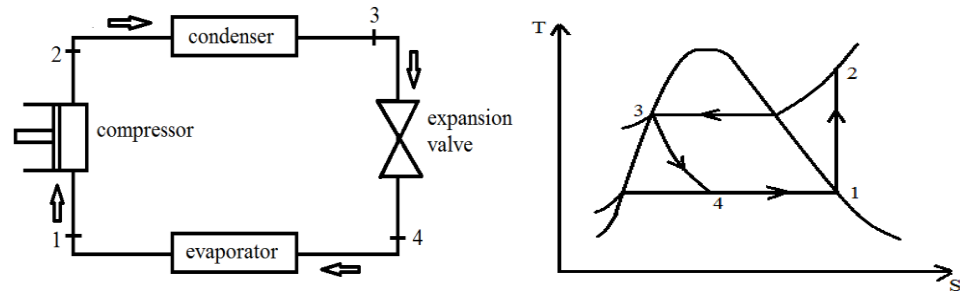
Figure 4: Component and T-S Diagram of Refrigeration Cycle (Carnot cycle)

Besides these main components there are additional elements installed for proper operation of a HPWH. Some of them are; a receiver, a dryer, an oil separator and controlling devices.

2.2.2 Types of HPWHs

As popularity of HPWHs is growing, more and more advancement can be visualised. Attempts to adopt this technology to diverse climate conditions and architectural appearance of the facilities, have lead into occurrence of different types of HPWHs. Two essential types are distinguished to be HPWHs with condensers wrapped right onto the water tank's body (Fig.5 (a)) and condenser to be pumped out of the water tank (Fig.5 (b)), for receiving heat from the condenser. In the first case, HP and water tank must be connected to each other and be located in one zone (rather outdoors or indoors). In second configuration water is pumped out of the water tank through condenser of a HP, which allows separating system into outdoor and indoor units. However, even if the setup is said to be separated into outdoor and indoor units, there

9

are divisions within this configuration called all-in one type (Fig.5 (c)) and split type (Fig.5 (d)) [14]. All of the configurations can be visualized in following Fig. 5.

(a)   (b)

(c)   (d)
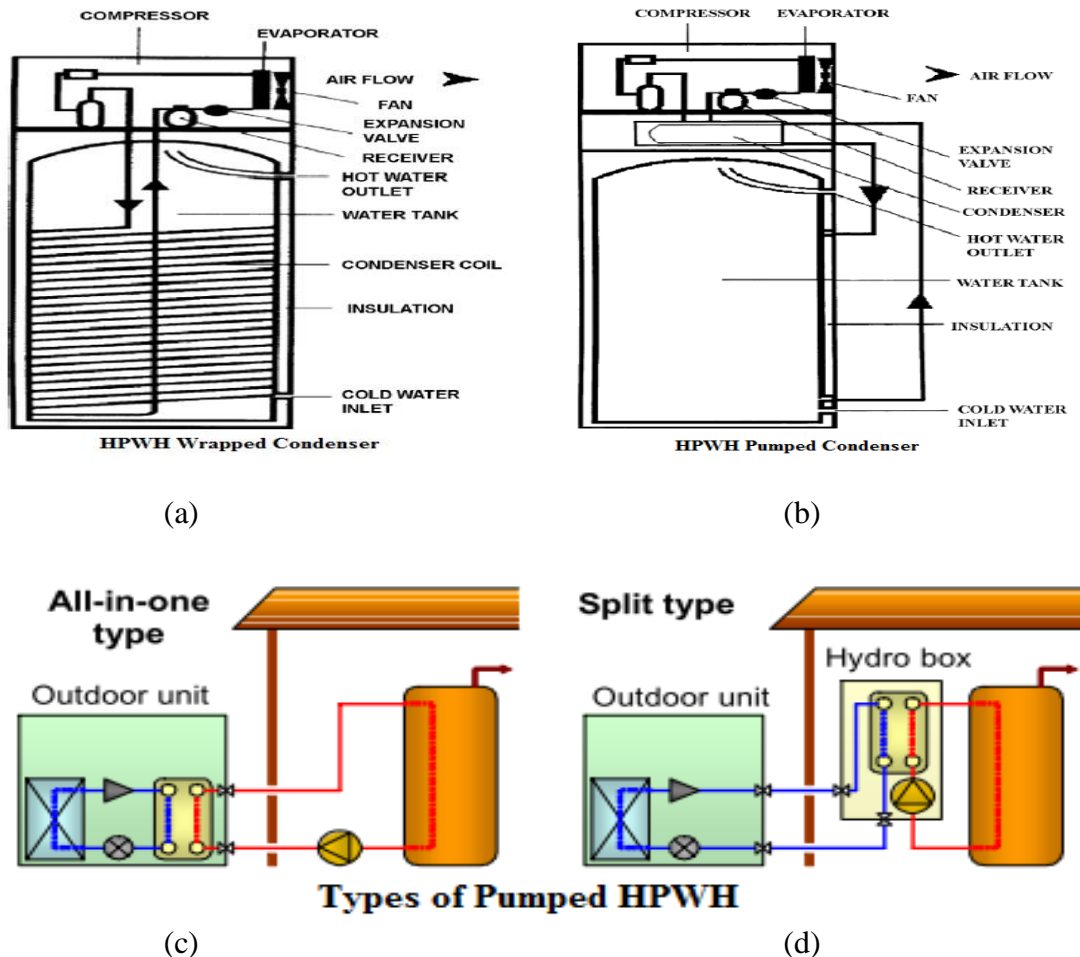
Figure 5: Different Configurations of HPWHs taken from Ref. [14]

2.3 Solar Water Heater

SWHs are widely spread devices used for water heating. As solar energy comes out to be one of the primary types of renewable energy, countries with hot climate conditions conduct more researches on utilization of this free source of energy. Especially, in Mediterranean area the popularity of these devices is undeniable. Interest in solar energy started increasing and showed the growth rate of 30% per every year, starting from 1980s [15]. For example, in 1992 there were already over

140,000 units of solar water collectors installed in Cyprus, which means the ratio of solar collectors per person was 1/5 [16]. In the report prepared by Ministry of Commerce, Industry and Tourism of Cyprus, it is claimed that 91% of facilities were using Solar Water Collectors (SWC), in 1994 [16].

2.3.1 Technology of SWHs

General configuration of SWH contains elements like water tank and a solar panel. There are some models with sun tracking technology, which allows a solar collector plate to follow the movement of a sun during the day and always receive direct beam radiation. The efficiencies of these models are higher than for the non-tracking collectors. However, as more control devices are involved, the prices become higher. In Cyprus almost all of the systems installed do not feature sun tracking technology, since the insolation is at very elevated level. The essential part of the system is a flat plate collector. It is constructed of a sheet metal, usually in rectangular shape, with upper surface glazed. The glazing can be double glass or single glass. It is playing very important role in heating process. When sun radiation passes through the glass cover, it heats the plate and air inside as well. The hot air trapped under the glazing creates greenhouse effect. Under the glass cover, there are tubes, they are attached to the lower metal surface. It is designed in such a way that conduction heat transfer from the plate to the tubes is maximum. Another primary detail in construction of plate is the insulation. Insulating material is located throughout the frame of SWH from all sides except glazing, which allows to decrease heat losses during cold period of time. Water tank is one more principal part of the system. Water tank is also consist of an insulated metal body and it mostly occurs in a cylindrical shape. Cold water is supplied to the SWH, where it is heated inside the tubes of the flat plate

collector and passed to the end user, as hot water. SWHs installed and fully operating in Cyprus can be checked in Fig. 6.
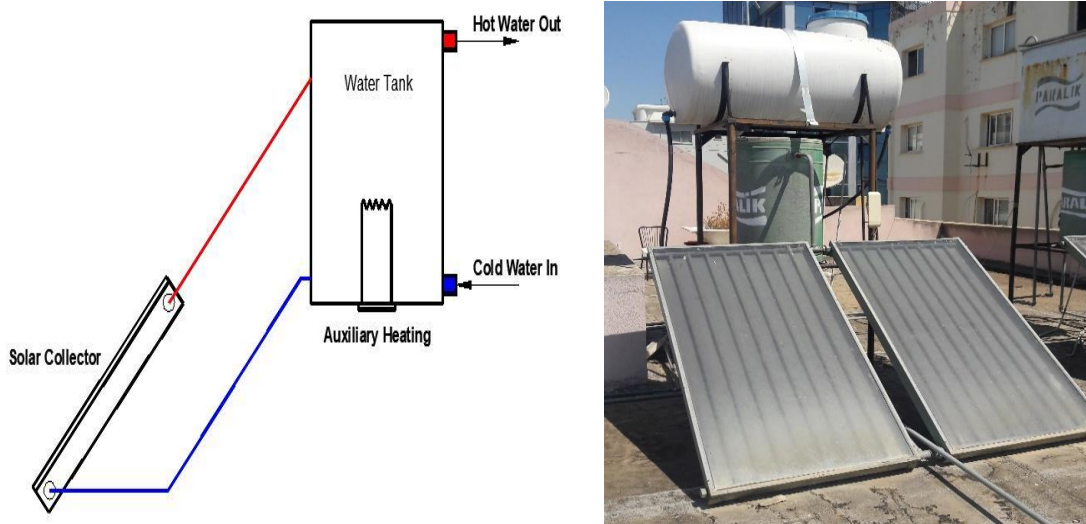
Figure 6: SWHs in Cyprus (Schematic on the Left and Picture on the Right)

2.3.2 Types of SWHs

Based on installation conditions and application there are different arrangements of SWHs. In this work, two primary divisions of these devices will be considered, one is called **active** and other **passive**. Active system is distinguished with additional pump, used to circulate water in the system. Active systems in turn can be divided in two subcategories, direct circulation system and indirect circulation system. On the other hand, passive system does not require a pump but rather than that it relies on heat driven convection ability of hot water to move up, pressure is enough to circulate water through water tank [7]. Passive systems as active ones have subdivisions named integral collector – storage passive system and thermosyphone system. In the following Fig.7.
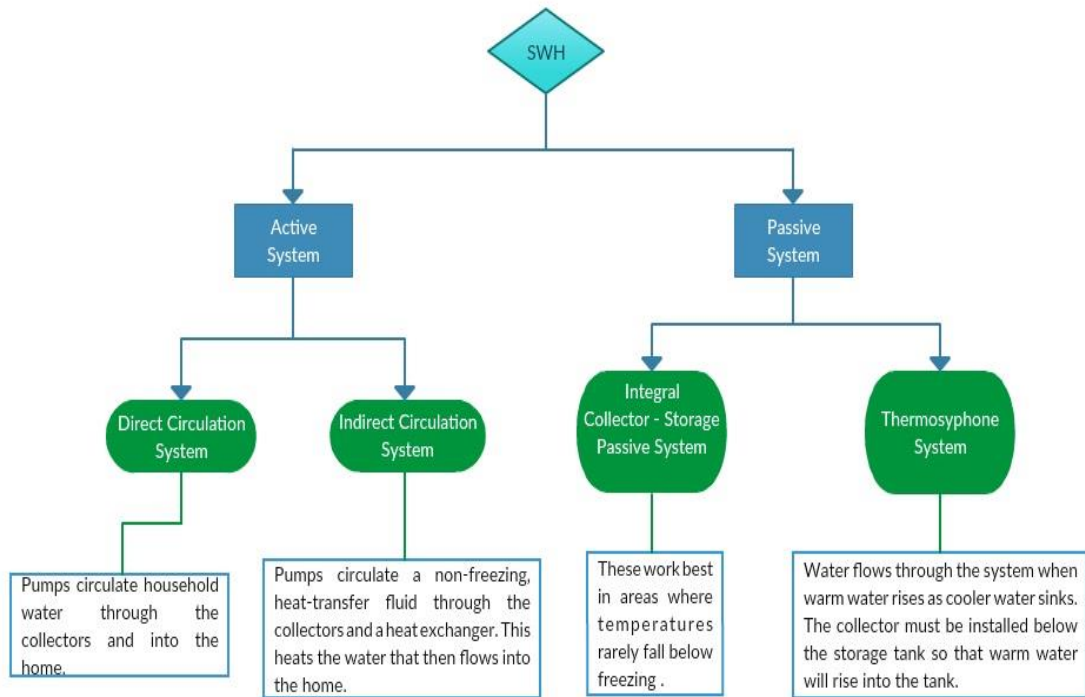
Figure 7: Types of SWHs

2.4 Indirect Gas Heaters (IGH)

Indirect gas water heaters are not of main interest in this study, since they contribute to air pollution and greenhouse effect. Nonetheless, they are still popular in Cyprus as an alternative method of water heating. Hence, performance of this device with annual energy consumption will be analysed, in order to choose the most convinient method of water heating used in North Cyprus. In particular model of IGH there is a separate boiler located outside of the water tank, which operates on LPG. Another component is of course a water tank. Heat exchanger is integrated with water tank in order to execute heat transfer process. Fig. 8 illustrates setup for an IGH.
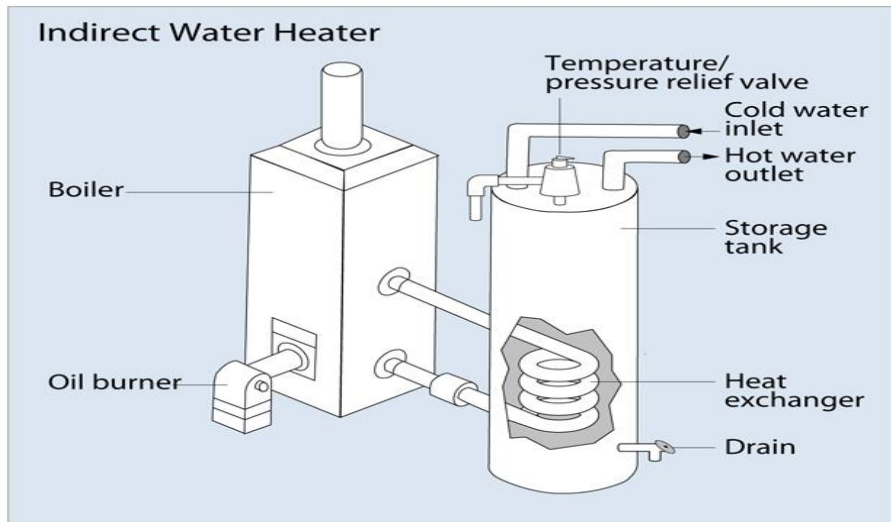
Figure 8: Indirect Water Heater taken from Ref. [17]

2.5 Comparison of Thechnologies for North Cyprus Conditions

Besides mentioned above technologies of water heating, there are many more worthy of attention and investigation. Several of new ideas and methods are implemented all around the world. Many reaserches conducted on analyses of SWHs operating in Cyprus Conditions. However, there is no any broad study related to comparison of the most popular water heating technologies in order to identify the favorite and effective one. Many users switch from gas water heaters and solar water collectors to HPWHs . On the other hand, ordinary citizens in North Cyprus are following advertisements of the companies and tendency to switch from one technology to another, without any reliable and solid facts to support the effectiveness of those devices. The main purpose of this study is to fill the gap in knowledge with solid, reliable information on effective method of annual water heating. In order to achieve the objective, simulations were run on EnergyPlus software with weather data files of Cyprus.The results of simulation are tabulated and presented.

Provided tables give information on some of the studies conducted on all three water heating technologies (see Table 1,2,3). Information on authors, type of study, specific goals and methods is tabulated.

Table 1: Review on Previous Studies of HPWH

System	NO	Study	Type of Study	Cost, Savings	Efficiency	Energy Analysis	PBP
HPWH	1	[18]	Theor.	For EF=2 LCC=$3135 $130 saved			22.5
	2	[12]	Theor.	Cost $250	COP=3.0 27K BTU		
	3	[19]	Exper.	Lifetime (10years) $1982		reduced by 4.3% ± 1.8%	
	4	[20]	Review	Lifetime (10years) $900 saved	COPs 0.08 -1.08, 1.7-6		
	5	[21]	Theor.	243 L $2400 saved			3.6

Table 2: Review on Previous Studies of SWH

System	NO	Study	Type of Study	Costs, Savings	Efficiency	Energy Analysis	PBP
SWH	1	[16]	Exper. TRNSYS		79.7%		5
	2	[7]	Review				2
	3	[15]	Review	Lifetime (10years) $514-$527 saved			
	4	[22]	Exper.	120 -150 $/m^2			6.5-9

Table 3: Review on Previous Studies of IGH

System	NO	Study	Type of Study	Cost, Savings	Efficiency	Energy Analysis	PBP
IGH	1	[23]	Exper. CFD Fluent		92%		
	2	[21]	Theor.	Lifetime Cost $5600			4
	3	[11]	LCC $225-$425	Install. Cost $879.12	>78%		

Chapter 3

METHODOLOGY

3.1 Introduction

This study presents the comparison of three different methods of water heating, by considering weather conditions of North Cyprus. Quantitative method was decided to be applied for this research. The objective of the study requires the use of strong analysis tools, with ability of providing solid and precise results. The methodology followed in this study is presented in Fig. 9.
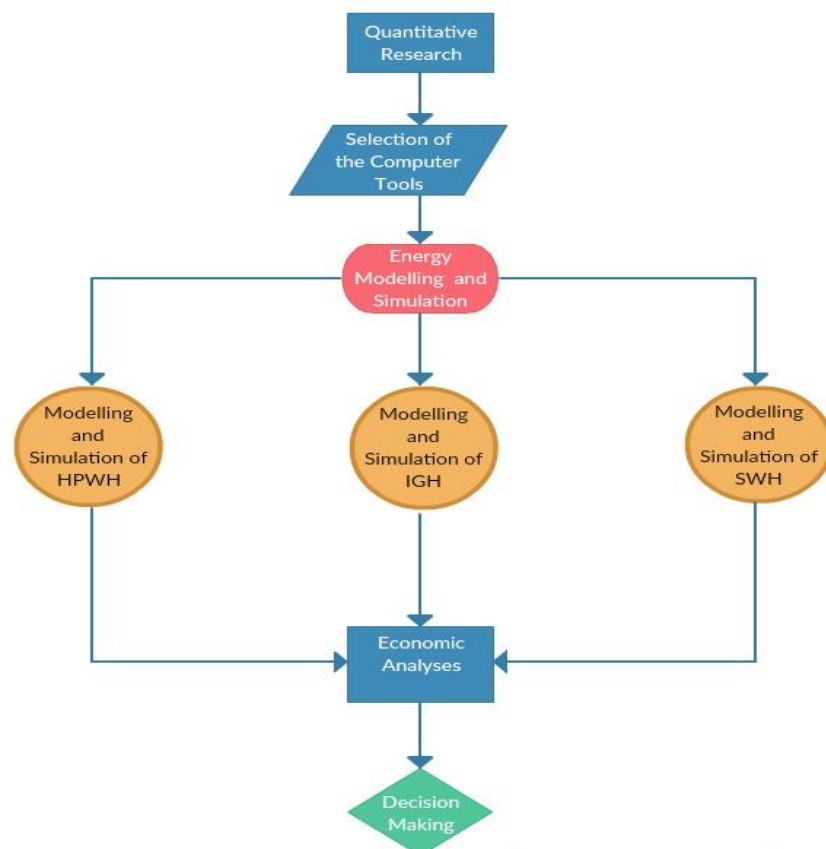
Figure 9: Research Methodology Flowchart

3.2 Methods of Research

There are two types of research methods, qualitative and quantitative. Qualitative research is directed towards using questionnaires and evaluating different opinions about any particular topic. This type of study considers conducting surveys and observing details for an extended period of time, which allows a researcher to analyze the subject and make precise conclusions. Other method of study is named as quantitative. This method deals with numbers, experiments and solid data. Most of the works in engineering field are conducted using quantitative method. This study is using quantitative method as well.

3.3 Selection of the Computer Tools

After deciding on a research method, appropriate and precise tools should be utilized. Computers nowadays have very powerful tools designed to solve iterative problems. This is the main reason to use computer simulation in performing energy analysis. Software named EnergyPlus was employed to complete iterative simulation process. One storey building with dimensions of $10 \times 15 \times 3$ m^3, located in Famagusta city is considered. Geometrical modelling of the building was performed in SketchUp software, which has plugins compatible with EnergyPlus program. Construction materials are chosen in a way, to realistically represent building type existing in North Cyprus. Fig. 10 illustrates building with dimensions, constructed in SketchUp software. The materials employed in a building can be seen in Table 1. Shading analysis and seasonal weather changes are taken into account by utilizing weather files, available on free of charge bases on web page of US Department of Energy. Simulation was performed by detailed tuning of input data, related to every system separately. Totally, there are three different type of systems analysed by using EnergyPlus. These systems are HPWH, IGH and SWH.
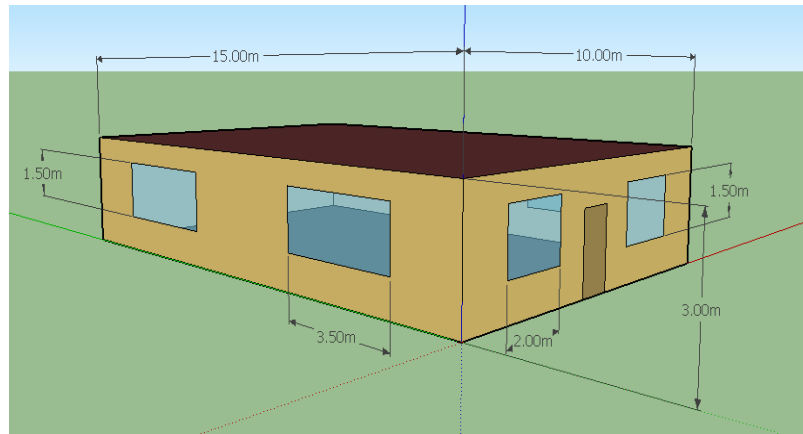
Figure 10: Drawing of One Storey Building in North Cyprus

Table 4: Materials employed in the building

Section	Floor	Roof	Wall	Window	Door
Materials	•I02 50mm insulation board •M15 200mm heavyweight concrete	•M11 100mm lightweight concrete •F05 Ceiling air space resistance	•M01 100mm Brick •I02 50mm insulation board •F04 Wall air space resistance •G01a 19mm gypsum board	•Clear 3mm •Air 13mm •Clear 3mm	•F08 Metal Surface •I01 25mm insulation board

The same building will be used with different water heating devices assigned to it. Also, the same hot water tank size is to be considered, with volume of $0.250\ m^3$. It should be noted that, from these three methods of water heating only the HPWH will be placed into the building (located in a loft) and will take indoor air as the heat sink. During annual simulation, the temperature change inside the facility will affect water heating performance of HPWH. In case of solar water collector and indirect gas water heater the devices will extract heat from distinct sources. For example SWH uses solar energy in order to heat water and for the case of IGH, LPG is used as an

energy source.

3.3.1 SWH System Description

Solar water heater system is first candidate to be studied. This system has the greatest market share in North Cyprus. The main type of SWH used in Cyprus, is passive thermosiphon system. Their arrangement consists of two flat plate collectors with area of 1.5 m^2 each, thus total area is $3m^2$. Double glazing cover on top of the collector is assumed. Although, SWHs with fixed collectors are less efficient than their competitors with sun tracking technology, the big massive positive point is their lower price for purchasing and instalment. Lower efficiency can be neglected, since the amount of sun radiation is plenty on the Island. Also proper arrangement in instalment can allow the system to perform better. Positioning of these flat plate collectors requires engineering approach in calculating the most effective tilt angle. This angle, usually denoted by θ, can be described as the best positioning, at which solar radiation strikes perpendicularly the surface of the flat plate collector [24]. Nevertheless, during the winter there might be need for auxiliary, electric resistance heating, to satisfy the hot water needs. Considering that electricity prices in North Cyprus are relatively high, energy bills are expected to be high enough to consider replacing this system with the better one.

3.3.2 LPG Boiler System Description

Next, indirect gas water heaters are to be analysed in EnergyPlus. These devices are mostly used in industry, factories and hotels. In residential water heating this technology is less popular than SWHs but it is still used. The main reason of studying IGHs is to analyse energy utilization of a gas, since it might be cheaper than electricity in North Cyprus. Setup consists of a LPG boiler, located outside of the building zone, and hot water tank attached to it. The nominal capacity of boiler is

auto sized and capacity of water tank is set to 250 litres for each simulation. The fuel is chosen to be LPG, however, auxiliary heating of water tank can be used when there is no enough heat generated by burning petroleum gas inside the boiler.

3.3.3 HPWH System Description

In EnergyPLus software HPWHs are designed in different manner than previously mentioned SWH and IGH systems. HPWH is modelled as a composite item which includes hot water tank, direct expansion coil and a fan. Direct expansion coil has a hot water coil, coil for air, compressor, and pump used for pumping water through the cycle [25]. Similarity of this device with the rest two water heating methods is that all of them have a water tank, with same capacity and material construction. More detailed information on simulation process will be provided in the following chapters.

3.4 Energy Consumption

Computers assist researchers in developing correct method of collecting and testing the input information in such a manner that the results have great impact on already existing knowledge or future studies. The main goal of the following study is to figure out the most relevant method of residential water heating within specific climate conditions. In order to do so, there should be a criteria which these systems will satisfy. This criteria is the energy consumption in terms of electricity and fuel (petroleum gas). Cutting down energy usage results into reduction of bills. The primary objective of using annual simulation, is to detect system which utilizes less energy for supplying hot water. Energy is measured in Gigajoules for period of one full year.

3.5 Economic Analyses and Decision

After obtaining the results related to energy consumption of all three systems, it is

time to make additional economic analyses which will help in making decision on the most effective and appropriate technology of water heating. There are four methods to be used in economic analysis. These methods are Net Present Value (NPV), Savings-to-Investment Ratio (SIR), Internal Rate of Return (IRR) and Simple Payback Period (SPP).

Chapter 4

MODELING AND SIMULATION

4.1 Energy Simulation

Energy simulation is essential in analysis of any particular project in engineering field. It allows to control the required parameters and get reliable results. Advantages of computer simulation software are obvious. First of all, they make iterative, continuous calculations possible within seconds. Secondly, they provide researcher with precise and reliable results. Another privilege is in controlling the inputs and outputs, by the user.

There are many different types of energy simulation software available for free of charge as well as payed ones. However, there are few good programs used for various systems at the same time. One of them is EnergyPlus, it was briefly discussed in previous chapter. It was chosen for performing analysis of three different types of systems. Prior to begin working in EnergyPlus, the drawing of the house with shadings is prepared in SketchUp software, since the simulation process in EnergyPlus starts with creating a 3D model.

4.2 SketchUp

In the past, 3D design was very complex and time consuming. Related software were available only for professionals and research institutes. Someone who would like to obtain skills of 3D modelling should have studied for years at universities. However, everything has changed in the beginning of the twenty first century,

when programmers started developing new tools for architectural and engineering purposes. The main goal was to reduce complexity of 3D modelling and rendering by designing more user friendly interface. SketchUp program was developed exactly in this period of time, when there was an acute need in reliable, strong and user friendly software. It possesses all advanced visualization capabilities proposed by expensive and complex computer-aided design (CAD) packages, while providing more plain and user-friendly interface which also comprises rapid sketching of any shape and design [26]. In addition, there is a wide range of online, free base library of 3D drawings, which can be downloaded directly to the software from the 3D Warehouse. Users are allowed to share their own models as well as to download already existing ones, for free [27].

The primary distinction of SketchUp software, which makes it popular among architects, engineers and designers, is its user friendly interface. Very complex shapes and models can be drawn with very simple tools and even people who does not have engineering or architectural background can easily learn and use SketchUp. There are two versions of this program, available. One of them is free of charge and it is named "SketchUp Make". It starts with 30 days of trial and later continues for free if the user agrees with conditions. Another option is to purchase "SketchUp Pro" with more specific and powerful tools, although this version is not for free and requires payment [19]. Start-up window and working space of newest version "SketchUp Pro2017" are provided in the following Fig. 11.
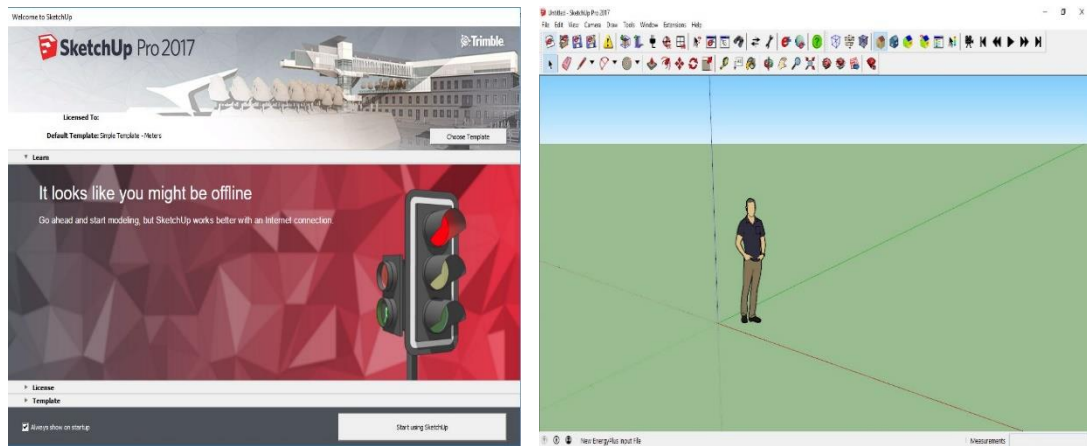
Figure 11: Start-up Window and Working Space of "SketchUp Pro 2017"

Persisting with simulation process, after completing designing buildings and shadings in SketchUp, as it was shown on Fig. 9, next step is to integrate created file with EnergyPlus software. In order to do so, existing file should be saved with IDF (Input Data File) extension.

4.3 EnergyPlus

The roots of this program go deep into late 1970s and early 1980s, when software developers started paying more interest to the energy reduction of energy consumption. After detailed analysis, it was proven that the main demand of energy comes on buildings and residential applications. That is the time, when two leading and competing programs were developed, one was BLAST (Building Loads Analysis and System Thermodynamics) and other was DOE-2 (Department of Energy). These programs are still in use, although there are few professionals who are qualified enough to work on them. It is related to programing language used, which is the older version of FORTRAN. Learning these two programs is time consuming and complex as well [28]. As time has passed, coding of BLAST and DOE-2 had become very challenging and costly. In 1998 both of these platforms released their last version and stopped development. Then, US Department of Energy decided to buy

BLAST and combine it with DOE-2 and as a result EnergyPlus program came into existence. It was completely written in Fortran 90, by considering best tools and capabilities of older BLAST and DOE-2 programs [29]. However, new platform appeared to be more flexible for integrating with other software like TRNSYS and SPARK [29]. EnergyPlus has two main components, "EP-Launch" and "IDF Editor" which are used in data acquiring and simulation.

4.3.1 EnenrgyPlus EP-Launch

This component has such important futures like opening text editor of input files, drawing files, output files and weather file [30]. Input files and weather files for specific location are browsed and added to EP-Launch. Weather files include information on environmental temperature, wind speed and wind direction, along with additional notes. This component is required for starting the simulation and collecting the results. Results are retrieved by specifying outputs in IDF editor.

4.3.2 Input Data File Editor (IDF-Editor)

IDF-Editor is another essential component of EnergyPlus, used in controlling and shaping the simulation conditions. Inputs are interred in simple ASCII text coding, by only typing the words. Also, all of the simulation tunings are possible in this component. Output types and number of outputs are again specified in this component.

4.4 System Topology in EnergyPlus

EnergyPlus follows a definite pattern during simulation process. It is the way of structuring and organising things in such a manner that all the components are connected to each other in sequential order. Ordering any process is essential in understanding the things in any field and subject. This ordering may be called a topology or diagram. In these diagrams all components follow some logical order

and represent a conceptual diagram, with lines connecting elements to each other [31]. In EnergyPlus, system diagrams are not consist of lines only, as it is for other topologies. There are elements representing levels and the highest one is a loop or "PlantLoop".

4.4.1 PlantLoop in EnergyPlus

Loops are the highest level of component connections of the system in EnergyPlus. As it is denoted in "PlantApplicationGuide" document file, in order to satisfy cooling and heating loads of a system, the working fluid is circulating in paths called loops [32]. These loops accommodate all the components like, pumps, bypass pipes, water tanks and etc. Additional to that, all loops are divided into demand and supply sides. Demand side of the loop is passive and it consumes the energy. On the other hand, there is supply side, it is active, has a pump on its very first branch and provides energy to the demand side. Every loop comprises following elements: nodes, branches, components and connectors. Short information on all of the mentioned elements is provided bellow.

   • **Nodes** – are in shape of circles and denote the input and output points of branches and components.

   • **Branches** – are mid-level elements used for constructing loops in EnergyPlus. Their starting and ending points are restricted by nodes. Branches must contain at least one component. On the diagrams branches are denoted with blue colour lines.

   • **Components** – are known as the low-level elements of the loop. They represent physical components like boilers, chillers, water tanks, pipes and etc.

   • **Connectors** – are the mid-level elements which are used in connecting

various branches in the loop. In general, there are two distinguish types of connectors, connector-splitters and connector-mixers. As it can be guessed from the names, splitters are used to split one branch into two or more branches. On the contrary, mixers merge separated branches into one. On the loop diagram the connectors are denoted by green lines.

Loops with all of the segment described above are called PlantLoop in EnergyPlus.

4.4.2 PlantLoop of Solar Water Heater (SWH)

Solar water heater (or solar water collector) comprises hot water tank, cold water tank and flat plate collector. However, diagram representation involves only hot water tank and flat plate collector, as it is shown in following Fig. 12.

Node NO	Node Name
1	Pump In Node
2	Pump Out Node
3	Water Tank In Node
4	Water Tank Out Node
5	Supply Bypass In Node
6	Supply Bypass Out Node
7	Supply Out Pipe In Node
8	Supply Out Pipe Out Node
9	Dem In Pipe In Node
10	Dem In Pipe Out Node
11	Collector In Node
12	Collector Out Node
13	Dem Bypass In Node
14	Dem Bypass Out Node
15	Dem Out Pipe In Node
16	Dem Out Pipe Out Node

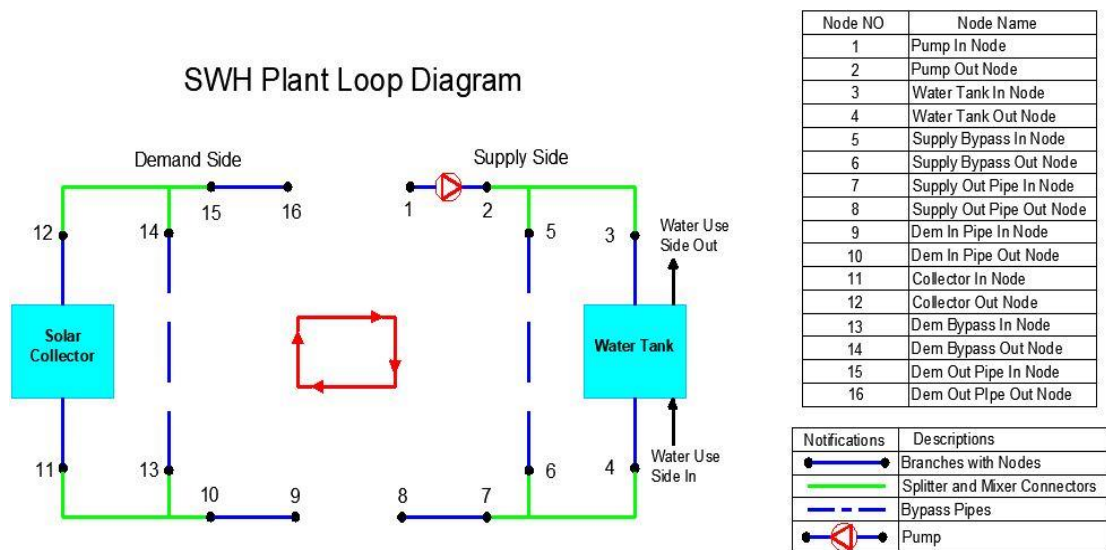| Notifications	Descriptions
	Branches with Nodes
	Splitter and Mixer Connectors
	Bypass Pipes
	Pump

Figure 12: PlantLoop for Solar Water Heater

All information on PlantLoops is demonstrated on this particular diagram as well as on the following diagrams of other systems. Table on the right side provides information on node names and components, existing in the loop. There are two parts of the loop named demand side and supply side.

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4.4.3 PlantLoop of Indirect Gas Heater (IGH)

Indirect gas heater or LPG boiler system is constructed exactly in the same manner the previous device, with only difference to be the components of supply and demand side. In contrary to the SWH diagram, here supply side is not water tank anymore, but the boiler. Water tank, is labelled as component of demand side. The rest of the information is same, Fig. 13 provides details.

Node NO	Node Name
1	Supply Pump In Node
2	Supply Pump Out Node
3	Boiler In Node
4	Boiler Out Node
5	Supply Bypass In Node
6	Supply Bypass Out Node
7	Supply Out Pipe In Node
8	Supply Out Pipe Out Node
9	Dem In Pipe In Node
10	Dem In Pipe Out Node
11	Water Tank In Node
12	Water Tank Out Node
13	Dem Bypass In Node
14	Dem Bypass Out Node
15	Dem Out Pipe In Node
16	Dem Out Pipe Out Node

Notifications	Descriptions
	Branches with Nodes
	Splitter and Mixer Connectors
	Bypass Pipes
	Pump

Figure 13: PlantLoop for Indirect Gas Water Heater

4.4.4 System Diagram of Heat Pump Water Heater (HPWH)

HPWH's design does not have a loop related to the system, since in EnergyPlus this device is presented as a compound object. However, it can be modified by adding hot water consuming elements to the use side of the HPWH. For example, if it would be considered that there is a water usage by some appliances like shower, sink, closet and etc., then same device would have to involve a PlantLoop. In this particular study, there are following objects which comprise the HPWH, direct expansion coil (Coil:WaterHeating:AirToWaterHeatPump:Pumped), a fan and water tank (WaterHeater: Mixed). Composition of DX coil was described in primary sections

29

[25]. Diagram of the HPWH is provided in Fig. 14.
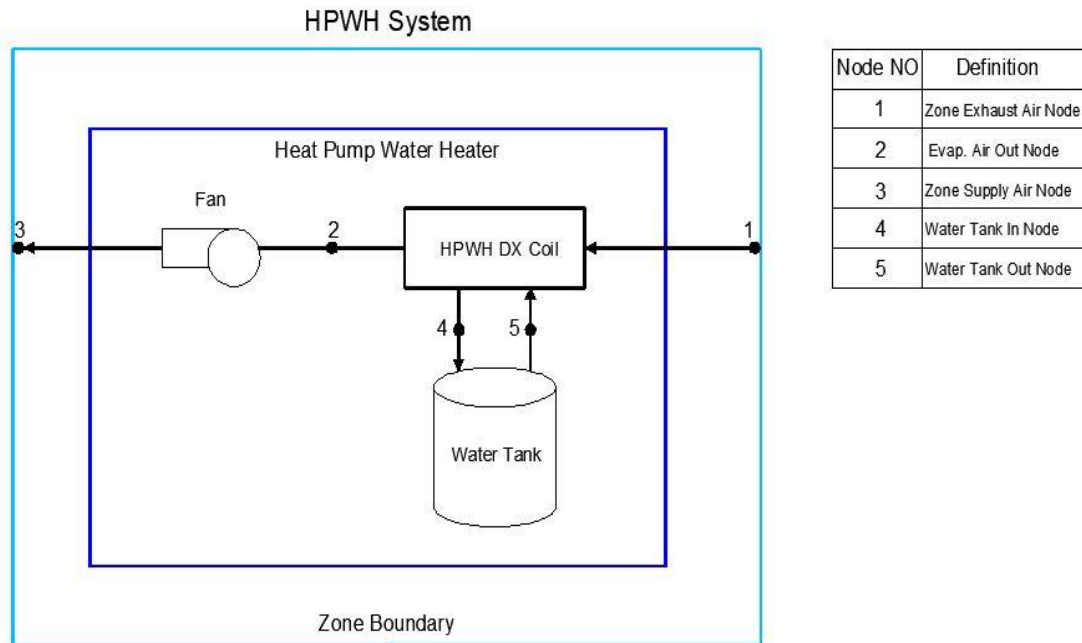
Figure 14: System Diagram of HPWH

Term zone here represents the inside of the building. Node number one is showing air entering and node number three air exiting the HPWH.

4.5 Modelling Process

Modelling process is essential in any project or any simulation. First of all, there are some international and local standards to be considered in order to begin the modelling process. For example, ASHRAE standards for piping, heating, cooling and etc. Standard values are tested and approved by the engineers and scientists. Each field has its own standards to be followed. For example, there are standards for electrical engineers called IEEE and standard developers for mechanical engineers, named ASME. ASME is one of the well-known organization developing codes of standards related to art, science and mechanical engineering practice [33].

Another step, is to make some logical and relevant assumptions about the project

30

details. In this work, there are assumptions related to building, number of people and water usage pattern. Table 1 lists assumptions which are made in this study. Based on information in Table 1, one floor residential house with family of five people is assumed to be located in Larnaca city. Also, there is one solar collector located on the roof of the house.

Table 5: Assumptions for Building

Assumption	NO of Floors	Type of Building	Location	No of People	NO of Energy Zones	No of Collectors
Value	1	House	34°55′N 33°38′E	5	1	1

To design a system which will operate efficiently, based on a real life hot water usage pattern, the operation schedule was developed for all three water heating devices. This pattern considers two periods of time, winter-season operation and summer-season operation. Winter period in Cyprus starts in mid-November and continues up to end of April. The rest of the time is considered as summer season, starting from 1st of May and prolonging until 14th of November. Two distinctive system operation schedules are provided in Tables 6 and 7. Moreover, based on activities of the house owners, there are different water consumption schedules for weekdays and all other days, which include Saturdays, Sundays and Holidays. Simulation considers annual operation of one complete year.

Table 6: Equipment Operation in Winter

Period of Time	05:00-07:30	09:00-12:00	11:00-15:00	14:00-17:00	17:00-20:00	20:00-22:00
Weekdays	ON	-	ON	-	ON	-
Weekends	-	ON	-	ON	-	ON

Table 7: Equipment Operation in Summer

Period of Time	05:00-07:30	10:00-12:00	12:00-15:00	17:00-20:00	18:00-20:00
Weekdays	ON	-	ON	-	ON
Weekends	-	ON	-	ON	-

These tables provide information on working pattern of all three methods of residential hot water supply. Empty cells are representing hours when systems are not operating. These tables provide information on particular period of the day, when systems are running.

As it was specified above, there are standards to be followed when designing any project or conducting an experiments. Standards allow engineers and scientists to stay in a safe side and construct a system which will be safe and reliable. There are standards for domestic hot water as well. It is based on a fact that hot water can cause sizzling, when the temperature is higher than 40 °C. The risk of skin burning increases rapidly above this temperature. However, skin burning also depends on time of contact with hot water and type of skin, but in general the values are like in following Table 8 [34].

Table 8: Hot Water Standards for Appliances

Application	Bidet	Washbasin	Shower	Unassisted Bath Fill
Temperature (°C)	38	41	41	44

In order to fit into these standard values, the output hot water temperature is set in interval between 38 °C – 50 °C. Extra five degrees are added in order to compensate skin sensibility difference and possibility of mixing hot and cold water by means of mixing valve.

4.6 Modelling of Solar Water Heater

Every simulation software has its own mathematical model used to perform analyses and provide the results. Moreover, every system has its own expressions and mathematical equations. There are two main components of SWH, operating under provided weather conditions and hot water supply schedules. One of them is flat plate solar collector with object name *SolarCollector:FlatPlate:Water.* Another object involved in SWH construction, is the hot water tank named *WaterHeater:Mixed.*

4.6.1 Mathematical Module of Solar Collector

Modelling of flat plate solar collector in EnergyPlus is based the ASHRAE standards, Duffie and Backman. Developed model is acceptable for glazed and unglazed flat plate solar collectors [35]. Mathematical module of SWH includes following segments: *solar and shading calculations, thermal performance, incident angle modifier and outlet temperature.*

• **Solar and Shading Calculations -** Standard EnergyPlus surfaces are utilized for Calculation of beam, diffused and reflected radiations on surface of the collector. Shading effect of nearby staying buildings and objects is also taken into account.

• **Thermal Performance -** Ratio of useful heat gain of the solar collector fluid over total incident radiation fallen onto gross surface area of the collector.

$$\eta = \frac{\left(\frac{q}{A}\right)}{I_{solar}} \tag{1}$$

Where:

q = useful heat gain (W)

A = gross area of the collector (m^2)

I_{solar} = total incident solar radiation (W/m^2)

Note: Efficiency is valid only if condition $I_{solar} > 0$ is satisfied

Relationship between characteristics of a glass, absorption plate, and climate conditions for particular area can be verified by equation of energy balance on flat plate with two double glazing.

$$\frac{q}{A} = I_{solar}\tau_{g1}\,\tau_{g2}\,\alpha_{abs} - \frac{T_{abs}^4 - T_{g2}^4}{R_{rad}} - \frac{T_{abs} - T_{g2}}{R_{conv}} - \frac{T_{abs}^4 - T_{g2}^4}{R_{rad}} \tag{2}$$

Where:

t_{g1} = transmittance of the first glazing layer (unitless)

t_{g2} = transmittance of the second glazing layer (unitless)

a_{abs} = absorptance of the absorber plate (unitless)

R_{rad} = radiative resistance from absorber to inside glazing (m^2 °C/W)

R_{conv} = convective resistance from absorber to inside glazing (m^2 °C/W)

R_{cond} = conductive resistance from absorber to outdoor air through the insulation

(m^2 °C/W)

T_{abs} = temperature of the absorber plate (°C)

T_{g2} = temperature of the inside glazing (°C)

T_{air} = temperature of the outdoor air (°C)

Equation above can be rearranged in the following manner:

$$\frac{q}{A} = F_R\,[I_{solar}(\tau\,\alpha) - U_L\,(T_{in} - T_{air})] \tag{3}$$

Where:

F_R = an empirically determined correction factor (unitless)

$(\tau\,\alpha)$ = the product of all transmittance and absorptance terms (unitless)

U_L = overall heat loss coefficient combining radiation, convection, and conduction

terms (W/m^{2}K)

T_{in} = inlet temperature of the working fluid (°C)

Substituting all this values into equation (1) will give following,

$$\eta = F_R \left(\tau \, \alpha \right) - \ F_R \, U_L \, \frac{(T_{in} - T_{air})}{I_{solar}} \tag{4}$$

Note: all of the formulas used in modelling section are retrieved from "Engineering References" document of EnergyPlus software [35].

• **Incident Angle** – Transmittance of solar collector glass changes when the incident angle of radiation varies. It is normal to expect higher transmittance of the glass at beam (perpendicular) radiation of sunlight. In cases when the radiation reaches surface of the collector's glass at unknown or off-normal angles the transmittance of the glass should be changed by coefficient called incident angle modifier. It is presented by the following formula.

$$K_{\tau \, \alpha} = \frac{(\tau \, \alpha)}{(\tau \, \alpha)_n} \text{ (unitless)} \tag{5}$$

Where:

$K_{\tau \, \alpha}$ = incident angle modifier coefficient (unitless)

$(\tau \, \alpha)$ = the product of all transmittance and absorptance terms (unitless)

$(\tau \, \alpha)_n$ = the normal product of all transmittance and absorptance terms (unitless)

• **Outlet Temperature** – Outlet temperature can be acquired by calculating useful heat gain (q) out of following equations (2) and (3). It is found from the following formula.

$$\frac{q}{A} = \dot{m} c_p \left(T_{out} - T_{in} \right) \text{ (W/m}^2\text{)} \tag{6}$$

Where:

$\dot{m}$ = mass flow rate of the working fluid passing through collector (kg)

C_p = specific heat of working fluid (J/kgK)

From above equation it is possible to derive outlet temperature,

$$T_{out} = T_{in} - \frac{q}{\dot{m} c_p \, A} \text{ (°C)} \tag{7}$$

4.6.2 Mathematical Module of Water Tank

In EnergyPlus there are two available types of water tanks representing two scenarios in real life, one of them is mixed and the other is stratified. Mixed water tank is easier to design, since it has less inputs to be specified and neglects stratified structure of hot water in a tank. Thus, the heat is considered to be equally distributed across the tank and same temperature can be measured at any point. This dissertation looks only into energy modelling of the mixed water tank, so the energy balance equation is given as;

$$\rho V c_p \frac{dT}{dt} = q_{net} \text{ (W)} \tag{8}$$

Where:

ρ = density of water (kg/m^3)

V = volume of the tank (m^3)

Cp = specific heat of water (J/kgK)

T = temperature of the tank water (°C)

t = time (s)

q_{net} = net heat transfer rate to the tank water (W)

The total heat transfer rate (q_{net}) is denoted as a sum of gains and losses caused by different heat transfer methods.

$$q_{net} = q_{heater} + q_{oncycpara} + q_{offcycpara} + q_{oncycloss} + q_{offcycloss} + q_{use} + q_{source}$$

$$\text{(W)} \tag{9}$$

Where:

q_{heater} = additional heat from element or burner (W)

$q_{oncycpara}$ = heat gained from on-cycle parasitic loads (W)

$q_{offcycpara}$ = heat gained from off-cycle parasitic loads (W)

$q_{oncycloss}$ = heat exchange to/from the surrounding (W)

$q_{offcycloss}$ = heat exchange to/from the surrounding (W)

q_{use} = heat exchange to or from use side elements (W)

q_{source} = heat exchange to or from the source side elements (W)

Here $q_{oncycloss}$ *and* $q_{offcycloss}$ are defined as:

$$q_{oncycloss}=UA_{oncyc}(T_{amb}-T) \text{ (W)} \tag{10}$$

$$q_{offcycloss}=UA_{offcyc}(T_{amb}-T) \text{ (W)} \tag{11}$$

Where:

UA_{oncyc} = loss coefficient to the surrounding during operation (W/K)

UA_{offcyc} =loss coefficient to the surrounding during operation (W/K)

Here q_{use} and q_{source} can be defined by the following equations,

$$q_{use}=\varepsilon_{use}\dot{m}_{use}c_p (T_{use}-T) \text{ (W)} \tag{12}$$

$$q_{use}=\varepsilon_{source}\dot{m}_{source}c_p (T_{source}-T) \text{ (W)} \tag{13}$$

Where:

ε_{use} = effectiveness of a heat exchanging device located on a use side (unitless)

$\dot{m}_{use}$ = mass flow rate on the side where use elements are (kg/s)

T_{use} = temperature of entering fluid for the use side elements (°C)

ε_{source} = effectiveness of a heat exchanging device located on a source side (unitless)

$\dot{m}_{source}$ = mass flow rate on the side where source elements are (kg/s)

T_{source} = inlet temperature for the source side plant connections (°C)

Substituting all these values into original differential equation will result in following,

$$\dot{m}C_p \frac{dT}{dt} = q_{heater} + q_{oncyc} + q_{offcyc} + UA_{oncyc}(T_{amb}-T) +$$

$$UA_{offcyc}(T_{amb}-T) + \varepsilon_{use}\dot{m}_{use}c_p (T_{use}-T)\varepsilon_{source}\dot{m}_{source}c_p (T_{source}-T)$$

$$\tag{14}$$

Separating all terms not related to temperature T to one side and terms related T to the other side, yields to the following equation:

$$\frac{dT}{dt} = \left[\frac{1}{\dot{m}C_p}\left(q_{heater} + q_{oncyc} + q_{offcyc} + UA_{oncyc}T_{amb} + UA_{offcyc}T_{amb} + \right.\right.$$

$$\left.\left.\varepsilon_{use}\dot{m}_{use}C_p\,T_{use} + \varepsilon_{source}\dot{m}_{source}C_p\,T_{source}\right)\right] + \left[\frac{-1}{\dot{m}C_p}\left(UA_{oncyc}UA_{offcyc} + \right.\right.$$

$$\left.\left.\varepsilon_{use}\dot{m}_{use}C_p + \varepsilon_{source}\dot{m}_{source}C_p\,\right)\right]T \tag{15}$$

The differential equation now has the form:

$$\frac{dT}{dt} = a + bT \tag{16}$$

This equation is solved in order to find out the final temperature of the water in the tank. Heat balance equation of water tank is provided here and the same procedure applies to the rest two systems.

4.7 Modelling of IGH

Indirect Gas Heaters are modelled in EnergyPlus by using following object name *Boiler: HotWater*. It includes a gas burner and water storage, where water is heated and sent to the hot water tank. Presented model only requires entering nominal boiler capacity and thermal efficiency. Fuel type is chosen to be LPG gas. All of the information is retrieved from "EngineeringReferences" document, as well [35]. The model is based on three equations.

$$\text{OperatingPartLoadRatio} = \frac{\text{BoilerLoad}}{\text{BoilerNomCapacity}} \tag{17}$$

$$\text{TheoreticalFuelUse} = \frac{\text{BoilerLoad}}{\text{BoilerNomCapacity}} \tag{18}$$

$$\text{FuelUsed} = \frac{\text{TheoreticalFuelUse}}{\text{BoilerEfficiencyCurveOutput}} \tag{19}$$

Or,

$$\text{FuelUsed} = \frac{\text{TheoreticalFuelUse}}{(\text{NominalThermalEfficiency})(\text{BoilerEfficiencyCurveOutput})} \tag{20}$$

The parasitic electric power is calculated based on the user-defined parasitic electric load and the operating part load ratio. The model assumes that this parasitic power does not contribute to water heating.

$$P_{parasitic} = P_{load}(PLR) \text{ (W)} \tag{21}$$

Where:

$P_{parasitic}$ = parasitic electric power (W)

P_{load} = parasitic electric load set by the user (W)

4.8 Modelling of HPWH

HPWH is designed in different way than the preceding two devices. Distinction of HPWH is in absence of PlantLoop object, since there is no any plant in this particular study. The loop diagram differs from the standard loops, since there no supply and demand side components (see Figure 4.4). There are two objects in EnergyPlus which are related to HPWH. One of them is "*WaterHeater:HeatPump: PumpedCondenser*" , where cold water is pumped from water tank into the compressor and returned back as a hot water. Other one is "*WaterHeater: HeatPump:WrappedCondenser*", here heating coil is submerged into or wrapped around water tank. For the domestic application HPWH with wrapped condenser is more suitable than the pumped one. However, "*WaterHeater:HeatPump: WrappedCondenser*" can only be used with stratified water tank (see Table 5). In order to simplify the task, it is decided to use pumped condenser HPWH.

Table 9: Compatibility of Water Tank and HPWH Types

Type of Water Tank / Type of HPWH	Mixed	Stratified
Pumped Condenser	✓	✓
Wrapped Condenser		✓

Required inputs for HPWHs are: compressor set point temperature schedule and dead band temperature difference. They are independent form the set point temperature schedule and dead band temperature difference for the resistance heater. There is a cut-in temperature for the compressor calculated by subtraction of dead band temperature difference from the temperature of the compressor.

$$T_{HP,cut-in} = T_{HP,set\ point} - T_{HP,dead\ band}\ (°C) \tag{22}$$

Where:

$T_{HP,cut-in}$ = Compressor's cut in temperature (°C)

$T_{HP,set\ point}$ = set point temperature of a compressor (°C)

$T_{HP,dead\ band}$ = Heat pump compressor dead band temperature difference (°C)

DX coil is considered as the prior source of energy used for water heating in HPWH. However, if there is no enough amount of heat generated, then secondary option is used. Second option of water heating is the auxiliary resistance heater element inside the water tank.

First thing to be calculated in simulation, is the condition of entering air, which flows through evaporator. HPWH takes air from the building, since it is located indoors. In order to define the condition of this air, the following calculation can be made.

$$F_{rac} = GetScheduleValue(MixerInletAirSchedule) \tag{23}$$

$$T_{inlet} = T_{outdoor}(F_{rac}) + T_{zone}(1 - F_{rac}) \tag{24}$$

$$\omega_{inlet} = \omega_{outdoor}(F_{rac}) + \omega_{zone}(1 - F_{rac}) \tag{25}$$

Where:

F_{rac} = present value for inlet air

T_{inlet} = dry-bulb air temperature entering to the HPWH (°C)

$T_{outdoor}$ = dry-bulb temperature of outdoor air (°C)

T_{zone} = dry-bulb temperature for air exiting the zone (°C)

ω_{inlet} = humidity ratio for inlet air to the HPWH (kg/kg)

$\omega_{outdoor}$ = humidity ratio for outdoor air (kg/kg)

ω_{zone} = humidity ratio of air exiting the zone (kg/kg)

Chapter 5

INPUTS AND ENERGYPLUS SIMULATION RESULTS

5.1 Inputs and Outputs in EnergyPlus

In EnergyPlus, inputs and outputs of the simulation are slightly different from each other. Inputs are in special utility which is defined as Input Data File (IDF) and has extension *example.idf*. Inputs and outputs are in simple text form written in ASCII code [29]. Although the method of inputting information in EnergyPlus is easy, engineering or scientific background is required. Rather than that, there should be a third party software where it is possible to create input file for simulation process [29]. For example, there is a program called DesignBuilder, which makes it possible to design complex buildings and HVAC systems and insert them into EnergyPlus as an input file [36]. This software allows users to create a building with lightning, shading, and energy zones already available as a template. Detailed energy analysis of a building can be performed by architects and civil engineers as well as mechanical engineers. Input details for each simulation, as well as the results, are provided in this chapter.

In this thesis the results of simulation are expected to provide information on annual electricity and fuel consumption, summed up as GJ (Giga Joules) of energy.

5.2 Inputs and Results for SWH

Solar water collector is designed as an active system, with pump causing water to go through the flat plate collector, water tank and return back to the initial. This process

happens in predefined pattern, which is set by the user. Flat plate collector was described previously in chapter three of this work. However, the input parameters for water tank and operation schedule are not discussed. Modelling of the flat plate collector is the easiest part, since there are no many controlling parameters, which will affect the simulation process. On the other hand, water tank is the key component to control the output result and to design the most efficient device. Two essential objects in EnergyPlus are tuned in modelling of water tank. These objects are as follows: *WaterHeater:Mixed* and *WaterHeater:Sizing*. First one is directly related to the water tank and second one controls amount of water to be heated throughout the year.

5.2.1 Inputs in WaterHeater:Mixed

Particular object will be applied to all three systems exactly with the same design and parameters. There is no need in describing *WaterHeater:Mixed* object in later sections. Inputs to the water tank are provided in IDF file and have two sections named "Filed" and "Object". First one denotes the parameters and it is predefined by the software. The other one is the variable entered by the user. There are some parameters already provided by the developers of the program. Some non-numeric values have to be specified in "Object" section. For example the name of the water tank is chosen to be "Water Tank", the ambient temperature indicator is set to the zone inside the building, with object name "Building". There are also three very important schedules, used in controlling the temperature of hot water inside the tank, inlet temperature of cold water and periods of hot water extraction. They are named "*hot water tank setpoint t. sch.*", "*WaterExtraction*" and "*ColdWaterSupplyTemp*", respectively. They are designed in object called "*Schedule:Compact*".

Another important section is related to supplementary heater, which is resistance

electric heater, it will operate in periods when there is no enough heat supplied by the main source (SWH, HPWH and IGH). Rest are the numeric values, they can be seen from Table 6.

Table 10: Numeric Inputs for Water Tank

Field	Tank Vol.	Dead Band Temp. Diff.	Max. Temp. Limit	Heater Max. Cap-ty	Heater Thermal Effii-cy	Peak Use Flow Rate	Source Side Design Flow Rate
Object	0.250	5	90	1500	1	0.00005	0.00005
Units	m^3	°C	°C	W	-	m^3/s	m^3/s

Water tank volume is decided based on assumption that every person will consume 50 litres of hot water per day. Dead band temperature is known as the lower limiting temperature of the tank, when water temperature is dropped by 5 degrees the system will start operating and increasing temperature up to set point temperature of 50 °C. Maximum temperature limit, is the theoretical maximum, up to which water can escalate. Next in the table, is the heater maximum capacity, it is set to be 1500 W, based on a fact that water heater tanks operating in Cyprus have the same value. Peak use flow rate and source side design flow rate are set to be the same, since they represent amount of hot water supplied and consumed.

5.2.2 Inputs in WaterHeater:Sizing

This is the object in EnergyPlus used for sizing the system for hot water consumption. It defines the base point, according to which the device will produce hot water. In this special case, option "*PerPerson*" is selected. It allows to declare storage capacity during annual simulation. As an assumption it is considered that there are five people in the family and each person requires 0.045 $m^3/person$ of water storage. To be on the safe side, it is decided to design water tank volume to be

$0.250 \ m^3$.

5.2.3 Results for SWH Simulation

Annual simulation for all three methods of water heating is performed for 8760 hours or 365 days. Total amount of water consumed by SWH system is 98.54 m^3 or 98540 litres. Cold water is supplied to the tank with temperature range of 10-15 °C in winter and 15-25 °C in summer. Lower value is for morning time and higher value for the afternoon. Entering water with temperatures mentioned above should be raised up to 50 °C and supplied to the demand side. However, hot water outlet temperature of the tank appears to be in the interval of 38-49 °C during simulation. In order to increase water temperature up to required level, there is electric resistance heater and solar water collector, operating throughout the year. Analysis of the energy consumption are evaluated according to the annual electricity usage of the system. In terms of energy, SWH device consumes 8.05 GJ per year. It includes electricity utilized by pumps, which is 0.15 GJ and resistance water heater with value of 7.9 GJ. Pumps have a capacity of 417.36 W and resistance water heater element has capacity 1500 W for the peak value of each. SWH reduces great amount of energy consumption. The solar collector efficiency ranges from 3% up to 52% (hourly), throughout the year.

EnergyPlus provides results in output excel file for annual simulation, so providing all of the results is not an easy task. In order to show some reasonable results it is decided to pick the hottest and coldest days in a year. Temperature change of the cold water during twenty four hours is to be shown. Water enters the tank where it mixes with hot water supplied by SWH. Also electric resistance heating element provides additional heat, to raise water temperature up to set point. All of the

information is provided in Figure 15 and Figure 16, down below.
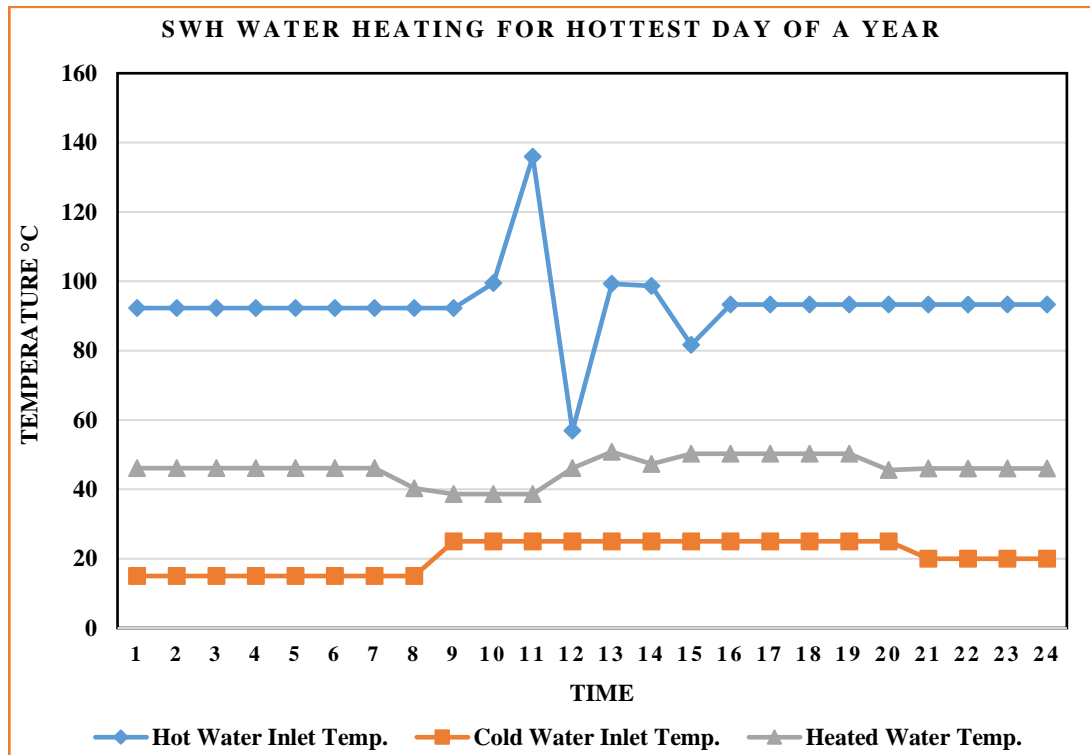
Figure 15: Water Heating For the Hottest Day in a Year, Weekday

Since figure above provides information for the hottest day in a year, the temperature of entering water is above hundred degrees Celsius at one point. However, when it mixes with cold water at 15-25 degrees, the outlet temperature reaches maximum of 50 °C. SWH does not operate until $9\!:\!30^{AM}$ and after $15\!:\!00^{PM}$, it is clearly seen from the figure, at times of operation the temperature of hot water decreases. The horizontal axis shows time starting from $01\!:\!00^{AM}$ and up to $24\!:\!00^{AM}$. Vertical axis, on the other hand, illustrates values for temperature in degrees Celsius. Second figure displays the same information but for the cold day in a year.
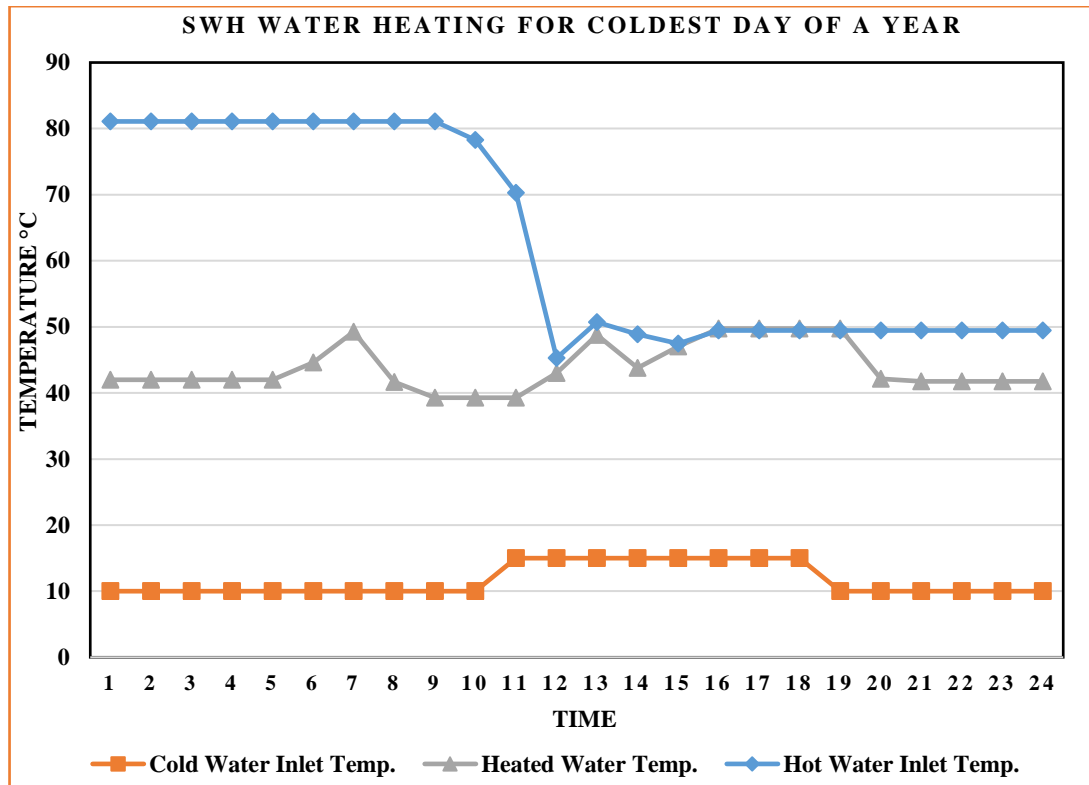
Figure 16: Water Heating For the Coldest Day in a Year, Weekend

As it can be seen the maximum temperature of hot water ranges here from 45 °C up to around 82°C. Nevertheless, the outlet temperature of cold water is still at 50 °C, here involvement of electric resistance heater is more than in previous case. At periods when hot water is extracted by the users, heated water temperature decreases up to 38 °C, as it can be seen from middle line on a graph. Water is drawn from a system in time periods of $7{:}00 - 7{:}30^{\mathrm{AM}}$, $13{:}00 - 13{:}30^{\mathrm{PM}}$ and $19{:}00 - 19{:}30^{\mathrm{PM}}$.

5.3 Inputs and Results of HPWH

In EnergyPlus heat pump water heater is simulated in slightly different manner than the other two devices. The only common object between all of the systems is the presence of water heater tank, with the same input parameters listed above. There are two distinct objects tuned in a way to produce logical results, under simulation conditions, close to the ones of SWH. As in case with other inputs, there are some

numerical and non-numerical sections to be filled as an input. Two objects related to HPWH are "*WaterHeater:HeatPump:PumpedCondenser*" and "*Coil:WaterHeating: AirToWaterHeatPump:Pumped*". First one was discussed in chapter four, so the details are to be neglected here. Second object of EnergyPlus, is one of the types of DX coils.

5.3.1 Inputs in WaterHeater:HeatPump:PumpedCondenser

This particular object models an air-source heat pump for water heating where the cold water is pumped out of the tank, through a heating coil and returned to the tank as hot [25]. Inputs are mainly aimed to control simulation process by considering schedules for availability of the device, and compressor set point temperature. Object names for this two schedules are as follows: "*PlantEquipmentOperationScheme*" and "*CompressorOperation Schedule*" respectively. Other non-numerical inputs include names of the inlet and outlet nodes for water tank and zone air. The rest of the important numerical inputs are provided in Table 11.

Table 11: Numerical Inputs for HPWH

Field	Dead Ban Temp. Diff.	Comp. Min. Operation Air Temp.	Comp. Max. Operation Air Temp	Condenser Water Flow Rate	Evap. Air Flow Rate
Object	5	10	48.89	0.00005	1.00695
Units	°C	°C	°C	m^3/s	m^3/s

Dead band temperature here has the same meaning as in SWH, it is the lower temperature limit up to which compressor does not operate. When the temperature of compressor drops more than by 5 °C it automatically starts working again, until the temperature reaches 50 °C. In HPWH case the set point temperature of compressor is higher than the value for water tank, otherwise the simulation stops and shows error message related to the cut-in temperature. Compressor minimum operation air

temperature is the smallest possible ambient air temperature where compressor can perform efficiently. On the contrary, the compressor maximum operation air temperature denotes the value of the highest ambient air temperature for high efficiency related to compressor. Water flow rate through condenser has the same velocity as peak use flow rate in water tank object and has value of 0.00005 m^3. It is chosen in order to equate supply and demand sides of water flow. The last one is the evaporator air flow rate. This field defines the amount of air to be forced by a fan, through evaporator coils.

5.3.2 Inputs in Coil:WaterHeating:AirToWaterHeatPump:Pumped

Coils play very essential role in designing water heating-cooling and HVAC systems. It acts as a template in simulation process, since it includes many components of the model. For example, DX coil contains input fields for condenser, evaporator, fans and water pump. Alphabetic inputs in this case involve input and output node names of evaporator and condenser. Some of the important numeric inputs include rated condenser water flow rate (0.00115525 m^3/s), condenser water pump power (150 W), capacity of the heater used in a crankcase (100 W) and highest surrounding temperature for crankcase (10 °C). Other, principal numerical inputs are shown on Table 12.

Table 12: Inputs for DX Coil

Field	Rated Heating Capacity	Rated COP	Rated Sensible Heat Ratio	Evap. Inlet Dry-Bulb Air Temp	Evap. Inlet Wet-Bulb Air Temp	Cond. Inlet Water Temp.
Object	3000	4	0.85	29.44	22.22	50
Units	W	-	-	°C	°C	°C

Rated heating capacity is related to the compressor's performance and appears to be

one of the key fields which can affect the results of simulation. Rated COP is the ability of the device to transfer input energy into useful work and it means that the efficiency is 400%. HPWH do not create energy but rather than that it transfers available heat from one space to another. Sensible heat ratio is the fraction of sensible cooling capacity to total cooling capacity, at given conditions. The value must be higher than 0.5 and less than 1.0. Dry bulb and wet bulb temperatures of evaporator inlet air should be higher than 5 °C. Condenser inlet water temperature should be higher than 25 °C.

5.3.3 Results for HPWH Simulation

Annual simulation hours are exactly the same as in case of SWH and have value of 8760 hours. The upper limit for outlet temperature of the tank has increased up to 50 °C, since the compressor set point temperature is set to this value. Results of energy consumption are almost half of the ones observed for SWH. Total energy consumption in terms of electricity is equal to 4.08 GJ. Electricity usage by resistance electric heater has reduced up to 0.0 GJ, and HPWH energy consumption accounts for 3.32 GJ. Since HPWH model includes pump and compressor, their used up electricity energy is within 3.32 GJ. Moreover, there are fans which contribute in energy utilization and have annual value of 0.75 GJ. At their peak, capacities of fan and HPWH reach values of 400 W and 3400 W, respectfully. By following the example of the results section for SWH, the same data is provided for HPWH, starting with hottest day as first Figure 17 and continuing with the coldest day in Figure 18.
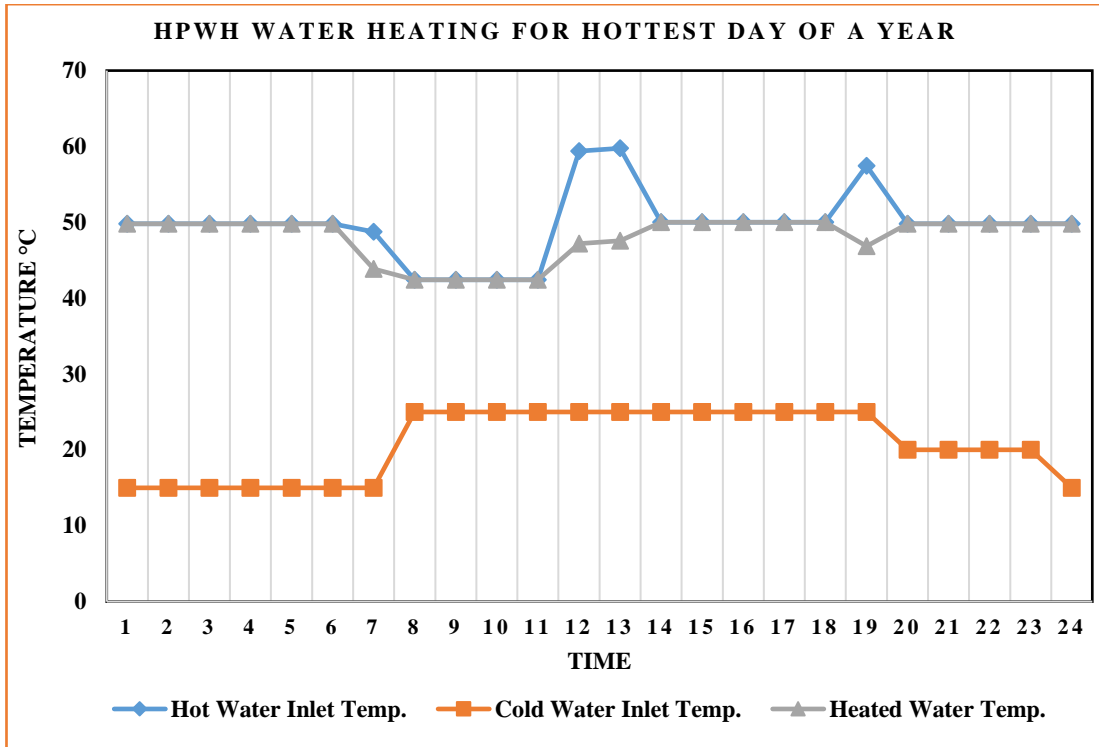
Figure 17: Water Heating For the Hottest Day in a Year, Weekday

Results for HPWH are different compared to SWH. It is related to the working principle of device. In HPWH the compressor is set to 50 °C that is why it tries to operate within that condition. However, as it is seen from both tables, the temperature can reach up to 60 °C, at some points. That is related to fact that once HPWH reaches provided set point temperature for the compressor, it tries to operate within that boundary condition. Results for the coldest day represents same type of information.
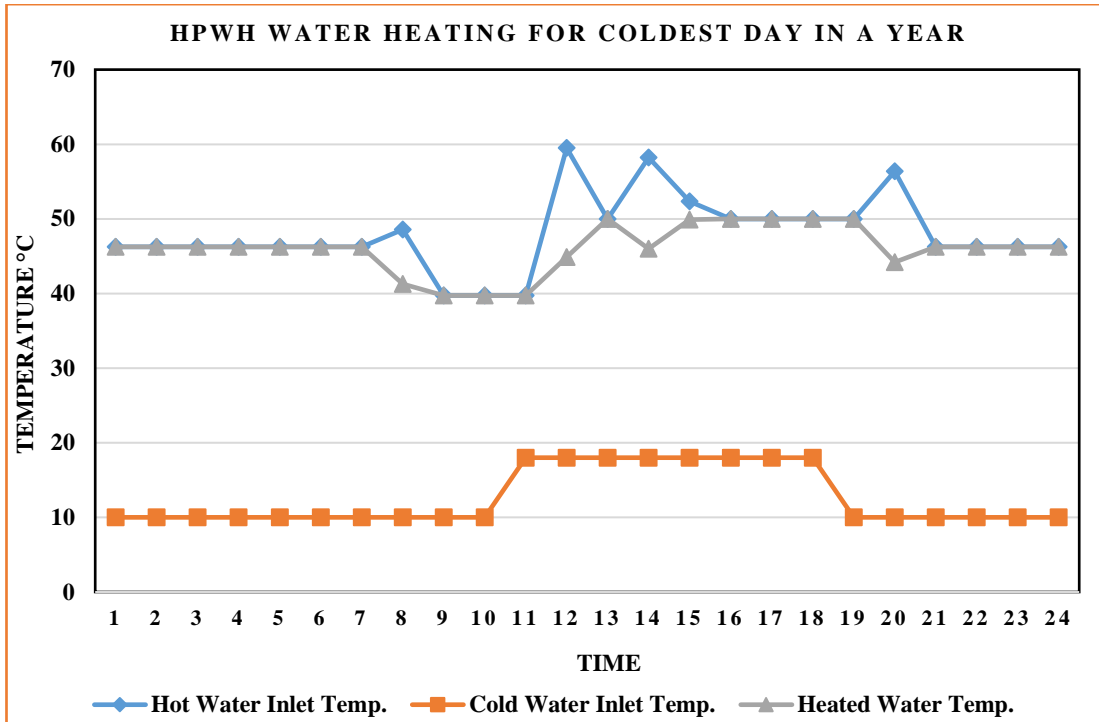
Figure 18: Water Heating For the Coldest Day in a Year, Weekday

During coldest day, the minimum temperature of heated water drops below 40 °C at some point. Cold water enters at 10-18 °C during the day. On the other hand, since HPWH is very efficient device, the required temperatures are reached without difficulty.

5.4 Inputs and Results of IGH

For Indirect Gas Heater there is only one main EnergyPlus object, except water tank, which requires input data from the user. This object is called "*Boiler:HotWater*". It uses different types of fuel in water heating process. In order to imitate real life device operating in particular area, it is expected to implement everything. The popular fuel type in Cyprus is coal and natural gas, since coal is not an option to be used with boiler, it is preferred to choose LPG gas. Its price is cheaper than petrol and gasoline.

5.4.1 Inputs in *Boiler:HotWater*

There are no many inputs required for this object. For example, there is no any schedule directly attached to the object. However, boiler water inlet and outlet nodes are connected to the water tank, which in turn has the schedules for water temperature and operation pattern. There is section called "Nominal Capacity", it requests capacity of a boiler in watts. After trying out some general capacities like 3500 W or 7000 W, it was decided to leave this object auto sized, which in a results excel file shows the value of 1569.21 W, during peak use. It is the most optimal solution, in order to produce an appropriate result. Except these alphabetic objects, there are some numerical as well. Table 9 provides more information.

Table 13: Numeric Inputs for LPG Boiler

Field	Nominal Thermal Efficiency	Optimal Capacity	Design Water Out. Temp.	Design Water Flow Rate	Water Out. Max. Temp. Limit
Object	0.8	1569.21	60	0.00005	99.9
Units		W	°C	m^3/s	°C

Nominal heating efficiency is related to the heating capacity of the burner. The values can range between 0 and 1. Provided input for this object is retrieved from "*InputOutputReferences*" file. Design temperature of exiting water is related to the boiler outlet condition of a water. Design water flow rate is the same as in preceding devices. Water outlet upper (or maximum) temperature limit is the highest value that water can reach.

5.4.2 Results for LPG Boiler

Total amount of water passed through the LPG boiler, during annual simulation is equal to 98.54 m^3. Compared to other water heating methods there will be two types of fuel involved in results, one of them is again electricity and there is additional

LPG consumed. Electricity utilization is belong to pump. During annual simulation for one year, pump and LPG gas consumptions are 0.07 GJ and 11.88 GJ, respectively. Amount of LPG used directly depends on "Nominal Capacity", in case of decreasing this parameter, the amount of spent gas increases and vice versa. At peak value indicators being 20.24 W, and 1569.21 W for pumps, resistance water heaters and LPG gas respectively. Last system behaves as SWH, in sense that cold water outlet and hot water inlet temperatures are not the same. Moreover, temperatures are changing logically, under given conditions, as it is in other two cases. Figs. 19 and 20 provide all information on temperature changes for the hottest and coldest days in a year.
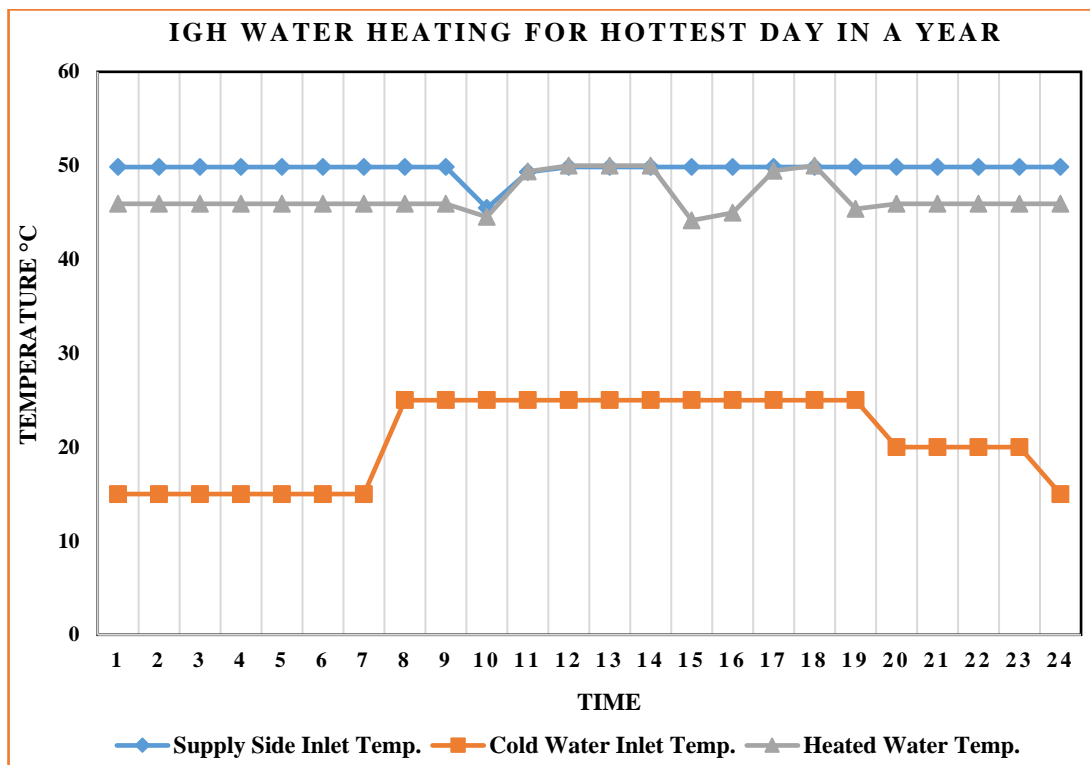

Figure 19: Water Heating For the Hottest Day in a Year, Weekday

As it is seen from above figure, the temperature of hot water entering the water tank is set to 50°C. Temperature drops only at times of water extraction from the system. As for the heated water temperature, it ranges between 45-50°C.
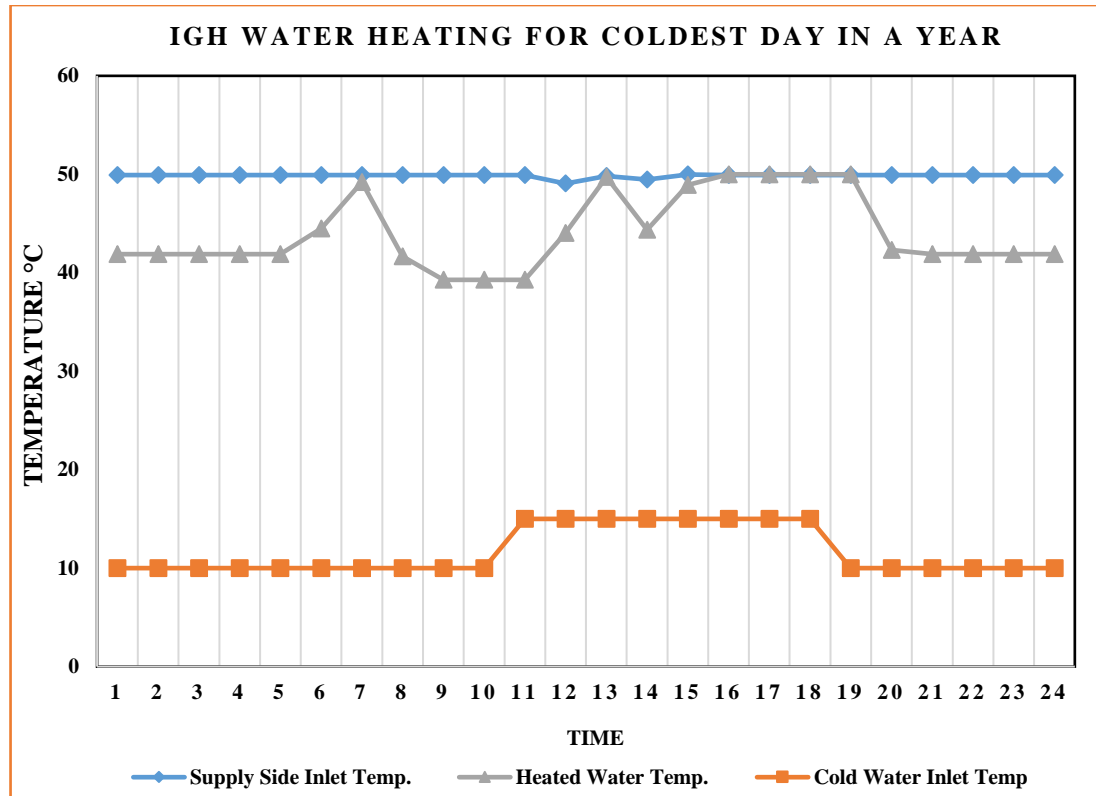
Figure 20: Water Heating For the Coldest Day in a Year, Weekend

Figure for coldest day shows lower temperatures. Heated water temperature ranges between 38-50°C, which is a very good result considering the fact that cold water enters at 10-18°C. Also, the hot water inlet temperature is almost constant at 50°C.

5.5 Discussion and Comparison

Provided above information on capacities, temperature limits and water usage pattern is only one of the scenarios which are possible in real life. All the assumptions are made based on a fact that there are five people in a family and the building is located in particular area. However, there are many other options available in designing a water heater system. For example, if the number of people are to be increased the

same systems might act in a different manner. Also, the energy consumption scheme could be changed if larger amount of water was heated. Another option can alter the results in terms of feasibility, this is the prices for electricity and other types of fuels, like propane or natural gas. For comparing results of all three systems, it is better to put all of them into one single table (see Table 14).

Table 14: Simulation Results

Types \ Methods	Electric Resist. Heater	Pumps	Fans	LPG	HPWH	Total
SWH	7.9	0.15	-	-	-	**8.05**
HPWH	0	-	0.75	-	3.32	**4.08**
IGH	0	0.07	-	11.88	-	**11.95**
Units	*GJ/year*	*GJ/year*	*GJ/year*	*GJ/year*	*GJ/year*	*GJ/year*

As it is can be seen from the table, in terms of energy consumption HPWH takes it's deserved first place, second position goes to SWH and the last is the IGH. Although, total result for IGH is the highest in terms of energy it is impossible to tell that this device is less efficient than the rest. It is based on a fact, that generally LPG gas is less expensive than electricity. In order to decide on the most efficient technology among SWH, HPWH and IGH the additional analysis should be applied. Another thing to be considered is the COP of HPWH, which is 4. If the rated heating capacity of HPWH to be increased, the total amount of energy consumption may drop even further. For example, if the rated heating capacity is to be assumed 7000 W, the electricity utilization will decrease up to 1.89 GJ, which is very significant. Electric resistance element has the bigger energy consumption value than a pump in SWH. However, in HPWH and IGH the electric resistance contribution is zero.

Chapter 6

ECONOMIC ANALYSIS

6.1 Introduction

The results of the energy analysis process are the energy consumption values for each system in GJs. It should be noted that for the SWH and HPWH the type of consumed energy is electricity, whereas for IGH some portion is heat (obtained from burning LPG).

The main goal of this study is to compare the considered systems and decide which one is the most feasible. In order to do this an economic analysis method which is life cycle cost analysis was employed. This method considers parameters, such as initial costs of the devices, annual (yearly) costs and savings, residual values etc.

6.2 Methods of Economic Analysis

In the economic analysis the following economic indicators are considered: Net Present Value (NPV), Savings-to-Investment Ratio (SIR), Simple Payback Period (SPP) and Internal Rate of Return (IRR). These indicators are widely used for assessing the projects and their results are reliable.

6.2.1 Net Present Value

The NPV is one of the most used indictor utilized in economic analyses. A feasible project should have NPV value greater than zero. Projects with zero or negative NPV values are said to be not feasible. Description of NPV is as follows: it is equal to the difference of sums for present value of incomes (savings) and present value of

outcomes (costs). Present Value (PV) is the value or amount of money at present time (or at time 0). NPV is expressed as:

$$NPV = \sum PV_{AS} - \sum PV_{LCI} \tag{26}$$

Where:

PV_{AS} = present value of annual savings

PV_{LCI} = present value of life cycle cost

The PV is the future value of the project at the present time, and it is possible to calculate it by using the following expression:

$$PV = \frac{FV}{(1+i)^n} \tag{27}$$

Where:

FV = future value

i = interest rate

n = number of years

6.2.3 Simple Payback Period

The SIR is the ratio of sum of present value of savings to the sum of present value of costs. The feasibility of the project is confirmed if the SIR result is greater than one, otherwise project is not feasible. Formula for SIR is given as:

$$SIR = \frac{\sum PV_{AS}}{\sum PV_{LCI}} \tag{28}$$

6.2.4 Internal Rate of Return

IRR is the value of interest rate (i) at which the present values of the savings is equal to the present value of costs. Also, at this value of interest rate the SIR = 1 and NPV = 0.

6.3 Inputs for Economic Analysis

Any spreadsheet program can be used for economic analysis. In this work Microsoft excel is employed. Performing economic analysis requires to input the necessary parameters. In this study these are; the initial cost of the devices, period of time for analysis, annual savings, interest rate, LPG and electricity prices.

6.3.1 Initial Cost

The prices of the devices, are retrieved from online sources. The sources used in this work enable to choose the specifications and ordering options. The initial costs of the each system including shipping and instalment are as follows: HPWH is $1200[37], SWH is $600 [38] and IGH is $500 [39].

6.3.2 Other Inputs

Period of analysis is assumed to be 15 years. The interest rates in North Cyprus is taken as 8% which is a common figure. The price for electricity is $ 0.149, and price for one litre of LPG gas is $ 0.925 [40]. The maintenance of the systems is assumed as $20, $20 and $50 (every five years) for SWH, HPWH and IGH respectively.

The annual savings of a system should be evaluated based on an old technology. In this work the old technology is the IGH and SWH. It is assumed that the last maintenance was done to it two years before the present time. The annual savings obtained by the systems are presented in the following section.

6.4 Calculations

The energy consumptions are 8.05 GJ, 4.08 GJ and 11.95 GJ for SWH, HPWH and IGH respectively. 1 litre of LPG produces 26 MJ of heat energy when burned. 1kWh of electricity corresponds to 3.6 MJ. By using these values together with the electricity and LPG prices given before the total energy prices are found to be 422.65

$/year, 168.87 $/year and 329.76 $/year for IGH, HPWH and SWH, respectively. Then, the annual savings become $253.78 ($422.65 – $168.87) and $92.89 ($422.65 – $329.76), for HPWH and SWH respectively compared with IGH. The residual value for each device at the end of 10th year is assumed to be 10% of initial cost. Thus the residual values are $ 120, $60 and $50, for HPWH, SWH and IGH respectively.

6.5 Results of Economic Analysis

The input and output fields for the old (existing) and new (competitor) technologies can be seen in following Fig. 21 and Fig. 22.

Life Cycle Cost Analysis
Input

Input in BLUE cells only.

TABLE 1
Life Cycle Investment Schedule, from Steps 1, 2, and 3

Year	New	Old	Net Amount
0	$1,200		$1,200
1			$0
2			$0
3		$50	–$50
4			$0
5	$20		$20
6			$0
7			$0
8		$50	–$50
9			$0
10	$20		$20
11			$0
12			$0
13		$50	–$50
14			$0
15	$20		$20
16			$0
17			$0
18			$0
19			$0

Figure 21: Inputs for Economic Analysis in Excel

Figure 22: Outputs for Economic analysis in Excel

Considering IGH to be the old system and comparing it with SWH and HPWH gives the results tabulated in Table 15 and Table 16.

Table 15: Results of Comparing HPWH (challenger) and IGH

Methods	NPV	SIR	IRR	SPP
Results	$1050	1.9	20%	4.7

Table 16: Results of Comparing SWH (challenger) and IGH

Methods	NPV	SIR	IRR	SPP
Results	$273	1.5	15%	6.5

From these tables it is clear that IGH is not feasible when compared to SWH and HPWH, since in both cases the values of NPV is greater than zero and SIR is greater than one. However, this information is not enough for deciding on the most efficient technology. Thus, HPWH and SWH should be compared and checked. In this case the SWH is to be chosen as an old device and HPWH as competitive one. The annual saving here will be $160.89 ($ 329.76-$168.87). The results for this comparison are tabulated in Table 17.

Table 17: Results of Comparing HPWH (challenger) and SWH

Methods	NPV	SIR	IRR	SPP
Results	$807	2.4	26%	3.7

As it can be seen, in this comparison the HPWH appears to be the most efficient, again the value of NPV is greater than zero and value of SIR is greater than one. This index is satisfying the condition of choosing more feasible project, in this case, it is HPWH.

Chapter 7

CONCLUSION

7.1 Conclusion

In this work three domestic water heater systems are investigated in energy and economical point of view. These systems are IGH, SWH and HPWH. IGH and SWH systems are used as the benchmark for evaluating the savings occurred when other systems are employed instead of them.

EnergyPlus software is used in simulation process. The annual results are acquired in GJs of energy. After simulation, HPWH, SWH and IGH have the following values for energy consumption: 4.08 GJ, 8.05 GJ and 11.95 GJ, respectively. Using this results and economic analyses methods it is possible to decide on the most efficient water heating technology.

When HPWH is compared to the IGH, the results are $1050, 1.9, 20% and 4.7(years) for NPV, SIR, IRR and SPP, respectively. Comparison of SWH and IGH results in $273, 1.5, 15%, 6.5 (years) for NPV, SIR, IRR and SPP methods accordingly. Last comparison is performed for SWH and HPWH. The results are $807, 2.4, 26% and 3.7 for NPV, SIR, IRR and SPP, respectively. These results prove that HPWHs are more feasible than SWH and IGH.

It is becoming common approach to switch from conventional gas water heaters to

other alternatives such as instantaneous water heaters, HPWHs and SWHs. In North Cyprus mainly hotels and restaurants are currently switching from IGHs to HPWHs and to SWHs. Solar water heaters are the devices which are easy to purchase, install and maintain in North Cyprus. On the other hand, HPWHs' popularity increased in recent years. This is related to their high COP thus, low energy consumption. Another advantage of HPWH technology is that, they are capable of not only to heat water but also heat spaces via fan coils.

7.2 Future Work

This work investigated three different scenarios of certain configurations i.e. solar collector system with electrical auxiliary heater (SWH), heat pump with auxiliary heater (HPWH) and indirect gas heater (IGH). It is thought that combining SWH with HPWH system, to feed the preheated water by solar collector to the water tank of a HPWH can reduce the energy consumption drastically. Another option for further reducing energy consumption could be coupling of SWH and IGH. These configurations is thought to be valuable for future work.

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