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The Capstone Team Project
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Name of Project: *Design and Manufacturing of a Concentrating Collector and its Sub-components for Domestic Hot Water*

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ABSTRACT

Cyprus currently relies heavily on fossil fuels as the main energy source. Fossil fuels such as coal, fuel oil and natural gas are non-renewable energy sources which are estimated to diminish in 50-60 years. Many of the environmental problems the world is facing today such as global warming, air pollution and climate change are accepted to be the consequence of excessive use of fossil fuels. Renewable energy sources, on the other hand, are clean, sustainable and inexhaustible. Utilizing renewable energy sources have several benefits such as preventing global warming, decreasing energy costs and eliminating conflicts between countries. In Cyprus, solar energy holds great potential thanks to long daily sunshine durations. Even though solar energy is not yet used for electricity generation in Cyprus, flat plate solar collectors are widely used for residential water heating. Nonetheless, it is shown that domestic water heating still contributes to a notable part of daily electricity consumption in Cyprus. This project is aimed to find a more efficient solar collector to decrease the use of electricity for water heating purposes. For that reason, the main focus is directed towards concentrating solar collectors since they can reach higher temperatures by concentrating sun light on a focal line. After evaluating different concentrating solar collectors, parabolic trough solar collector is chosen to be designed and manufactured. Main objective for this project was to design a cost-efficient solar collector that supplies hot water with minimum of 40℃ temperature. In the design process, some common properties of parabolic trough solar collectors like continuous sun tracking are eliminated since they would make the system more complicated and costly. In some cases, original design was needed to be modified and different methods were tried because of the unavailability of certain parts in Cyprus and Turkey markets. After testing the collector with three different weather conditions, results have shown that on a cloudy day, water temperature increased by 22.65℃ in 3.5 hours whereas on a sunny day, water temperature increased by 25.48℃ in 4 hours and when the tank was shaded, water temperature rose up to 23.09℃ in 3 hours. The design is cost-efficient and eco-friendly as there is no need for electricity to operate the system.

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ABBREVIATIONS

CAD: Computer-aided design

RCP: Representative Concentration Pathway

ASHRAE: American Society of Heating, Refrigerating and Air Conditioning

ISO: International Standard

NASA: National Aeronautics and Space Administration

PDO: Petroleum Development Oman

IRI: International Research Institute for Climate and Society

WBG: World Bank Group

PV: Photo-voltaic

CPC: Compound parabolic collector

PTC: Parabolic trough collector

NOMENCLATURE

$\dot{m}$	Mass Flow Rate
Nu	Nusselt Number
η	Efficiency
Pr	Prandtl Number
Re	Reynolds Number
V	Velocity
T_i	Inlet Water Temperature
T_o	Outlet Water Temperature
K	Thermal Conductivity
A_a	Aperture Area
A_r	Receiver Area
Q_u	Useful Heat Gain
S	Absorbed Radiation
M	Dynamic Viscosity
H	Heat Transfer Coefficient
C_p	Specific Heat Capacity
Q_{loss}	Heat Loss
C	Concentration Factor
F	Focal point
D_{o1}	Pipe Outer Tubing Outside Diameter
D_{o2}	Pipe Outer Tubing Inside Diameter
D_{i1}	Pipe Inner Tubing Outside Diameter
D_{i2}	Pipe Inner Tubing Inside Diameter

CHAPTER 1 – INTRODUCTION

1.1 Detailed Definition of the Project

This project concerns with the design of a domestic solar water heating system where the main focus of the design is on concentrating solar collectors. Concentrating collectors differ from conventional flat plate solar collectors in a variety of ways. These collectors have two main components which are called receiver and reflector. The reflector focuses sun light on to a smaller area where the receiver is located. This property of concentrating solar collectors allows higher temperatures to be reached which makes them very popular for power generation purposes. Most common types of concentrating solar collectors are:

- Parabolic trough collector
- Compound parabolic reflector
- Power tower receiver with heliostats
- Parabolic dish collector
- Fresnel lens collector

First step of the design process is to choose which concentrating solar collector to design and next steps included choosing what materials to use and carrying out design calculations. Final part of the project includes manufacturing and testing of the prototype. Timing is also an important aspect of the project as the designing and manufacturing should be completed in the period of two semesters.

1.2 Significance of the Project

This project aims to show that there are alternative efficient solar water heating systems that can be implemented in Cyprus residents. Currently, flat plate collectors are widely used in Northern Cyprus for domestic water heating. However, people are still forced to use the electrical heaters as the water is often not heated to desired temperatures. This results in (1) high electricity costs (2) higher peak demand (3) increased carbon emissions. For that reason, using the solar energy in a more efficient way for hot water demand could benefit us and environment immensely.

In order to achieve a sustainable future, energy related environmental problems need to be solved. Utilizing renewable energy sources such as solar energy prevents not only global warming but also prevents air pollution, deforestation, ozone depletion and climate change.

Cyprus has high abundance of sunlight throughout a year which makes it an ideal place for solar energy implementation.

1.3 Detailed Project Objectives

- One of the most important aspects of a solar collector design is temperature of the supplied water. Therefore, the first objective of this project is designing a solar collector that supplies at least 40℃ of hot water. The reason for this particular value is 40-45℃ of hot water requirement in residents.

- The second objective is to have a strong but light structure. When the collector has a light and compact design, it gives flexibility for mounting options. Strength is required for withstanding the outside conditions such that it can withstand strong winds.

- The third objective is to have a cost-efficient design. In order to achieve this objective, materials and assembly methods are required to be chosen carefully. A budget of 1700 TL is chosen for this project.

- The final objective is designing a system that does not require any external energy sources. Therefore, a system that works with a natural water circulation is required to be designed.

1.4 Detailed Project Constraints

The project constraints are as follows:

- First constraint of the design is related to sun tracking system. Concentrating solar collectors require single or multiple axis sun tracking to keep the focal point constant on a receiver. However, for this project, continuous sun tracking is eliminated since it would make the system costly and more complicated. In order to compensate the lack of continuous tracking, collector will be manually adjusted to an optimal angle depending on the location of sun.

- The second constraint is related to the cost of the project. Materials and manufacturing methods are required to be chosen carefully since the project has a certain budget. Therefore, designing a cost-efficient solar collector is aimed.

- Availability of raw materials is another constraint of the project. Since concentrating solar collectors are not common in Cyprus and Turkey, some parts are unavailable in the markets.

- The size of the solar collector is required to be convenient for mounting in residents however it should be large enough to have enough concentration ratio to heat the water to desired temperature in sufficient time.

- Manufacturing the reflector precisely is another constraint of the project. Any defect on the reflector shape can affect the location of the focal point where the sunlight is focused.

1.5 Report Organization

- The first chapter of this report provides information on project objectives, constraints and followed standards.
- The second chapter gives background information on energy related problems and solar energy. It also provides various design solutions for the project objectives and the associated standards.
- The third chapter shows the selected design and design calculations.
- The fourth chapter provides the manufacturing method selection and the detailed manufacturing process.
- The fifth chapter explains the verification plan for the objectives and the standards.
- The sixth chapter provides the results obtained and in the final chapter, conclusion and required future work are explained.
- In the appendices, electronic media, constraints, standards, logbook, project timeline and technical drawings are provided.

CHAPTER 2 – LITERATURE REVIEW

2.1 Background Information

2.1.1 Energy Related Problems

Energy consumption has seen a significant rise due to the increase in the world population and industrial activities. Fossil fuels such as crude oil, natural gas and coal are currently the most commonly used energy sources. However, there are some fundamental problems related to fossil fuel usage. Fossil fuels are limited in supply and are estimated to completely diminish in 50-60 years [1]. As the fossil fuels deplete more, energy prices are going to increase which could possibly cause conflict and war among countries. Fossil fuels also cause environmental problems. Extraction of natural gas and petroleum is done by a method called fracking process. Fracking is believed to cause land degradation and water pollution since the water mixture that is pumped into rock during the fracking process contains potentially harmful chemicals. These could pollute local water supplies near the fracking site and pose a potential threat to the wildlife [2]. Furthermore, burning fossil fuels releases large quantities of greenhouse gases (most notably carbon dioxide) into the atmosphere. As the level of greenhouse gases increases, more heat is trapped in the Earth's surface and average temperature of the Earth's climate system increases.

Global warming and climate change pose a major threat for the future of the Earth. As the temperature of the Earth increases:

- Natural habitats would be affected negatively and numerous animals would face extinction.
- Melting of polar ice caps and water expansion due to higher ocean temperatures would result in higher sea levels; threatening coastal systems and low-lying areas.
- Higher temperatures would worsen the natural disasters including storms, heat waves, floods, and droughts.
- Rising temperatures would increase the air pollution by increasing ground level ozone, also resulting in more intense allergy seasons and spread of insect-borne diseases.

Figure 1 shows the global mean temperature estimates based on land and ocean by NASA Goddard Space Flight Centre. It can be seen that further increase in the global temperatures is estimated [3].

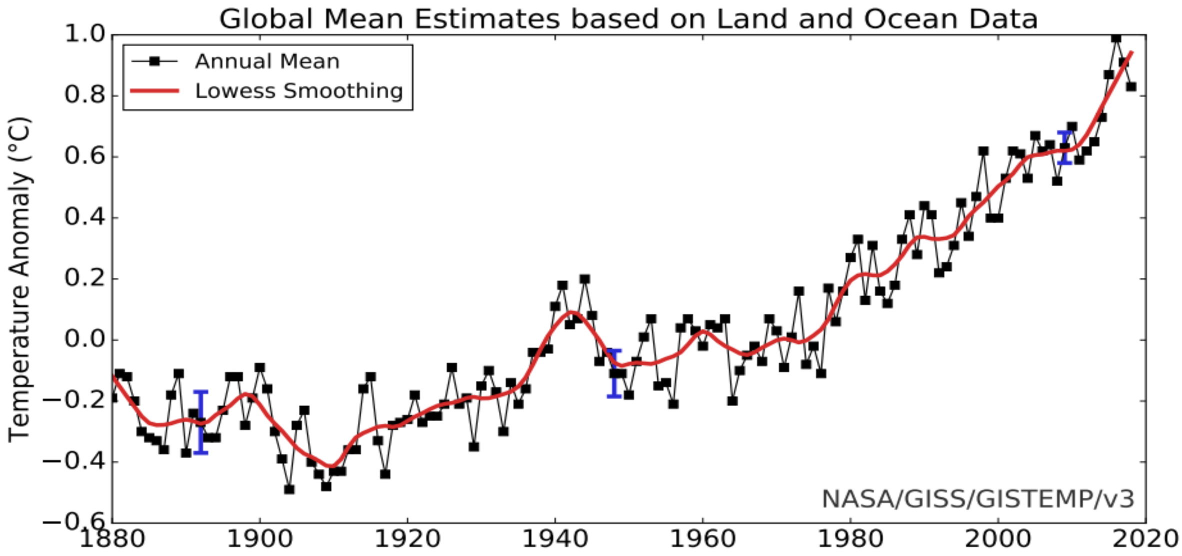


Figure 1. Global Mean Temperature Estimates by NASA Goddard [3].

As the concern for the climate change is increasing, more research and estimates are carried out. Representative Concentration Pathway (RCP) is a set of standards that indicates four different greenhouse gas concentration trajectories. The RCPs include low greenhouse gas emissions (RCP 2.6), two intermediate scenarios (RCP 4.5 and RCP 6.0) and one scenario with very high greenhouse gas emissions (RCP 8.5). Details of these trajectories can be seen in Figure 2 [4].

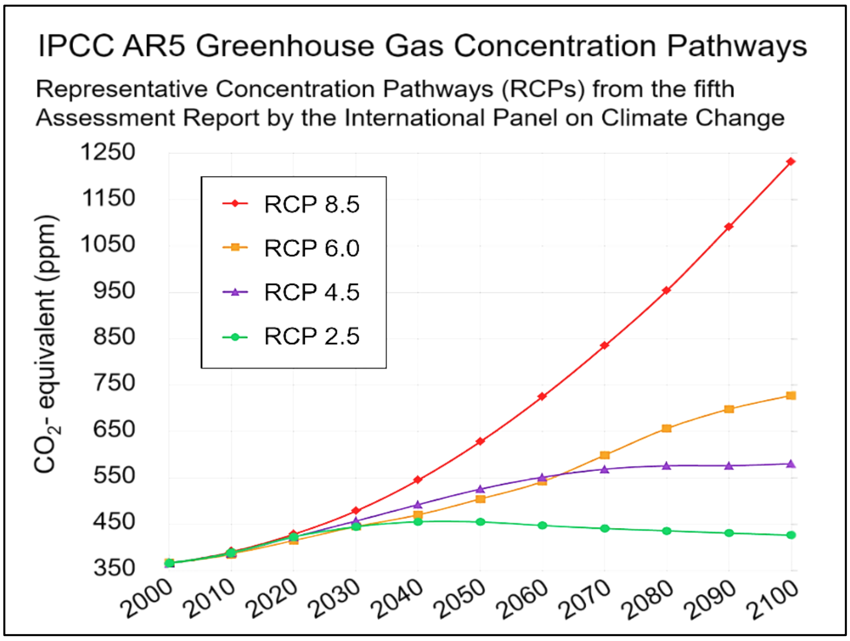


Figure 2. Greenhouse Gas Concentration Pathways from the AR5 by IPCC [4].

According to the resources, International Research Institute for Climate and Society (IRI) and global forecast drought tool of World Bank Group (WBG), it is estimated that in case of RCP 8.5, in Cyprus [5]:

- Mean annual temperature will rise by 2.0°C in 2050 (RCP 8.5, High Emission)
- Mean annual precipitation will fall by -43.3mm in 2050 (RCP 8.5, High Emission)
- Total annual hot days of temperature above 35°C will rise by 11.0 days in 2050 (RCP 8.5, High Emission)

2.1.2 Solar Energy

Future predictions show that serious changes for the Earth's climate is ahead. In order to prevent the life-threatening consequences of global warming, renewable and clean energy utilization is required more than ever. Solar energy is one of the renewable energy sources among others such as wind, geothermal, tidal and biomass. The main advantage of solar energy when compared with other energy sources is that it is completely clean and can be supplied without causing any environmental pollutions. Solar power can be in the form of **electric** or **thermal energy**. In order to obtain electricity from solar energy, an electrical device called photovoltaic (PV) cell is used [6].

PV cells use a chemical and physical phenomenon called photovoltaic effect to generate electricity. The most efficient solar panels on the market today have efficiencies as high as 22.2%, whereas the majority of panels range from 15% to 17% efficiency rating.

Another form of solar power is thermal energy. Heat generation is crucial to the global economy, but it is also an overlooked and growing source of greenhouse gas emissions. Today's industrial heat demand relies mainly on fossil fuels and there is only small use of renewable resources. One of the examples of solar energy utilization for thermal energy in industries:

- MIRAAH SOLAR THERMAL ENERGY PLANT

Even though this project is used for fossil foil recovery by Petroleum Development Oman (PDO), it is accepted as the world's largest solar project. This project is required installation value of $600 million and covers 750 acres of desert in Oman with glass houses. In these glass houses there are parabolic trough concentrating solar collectors which catches sun rays and concentrate the energy to produce steam [7].

Figure 3. Miraah solar thermal energy plant in Oman [7].

PDO intends to use the solar power to produce massive amounts of steam to loosen up the oil and make it flow more easily. PDO used to burn natural gas to generate the steam. It is estimated that Miraah solar thermal energy plant is going to:

- Produce 1021 MW of thermal energy.
- Produce 6000 tonnes of steam each day.
- Save 5.6 trillion BTUs natural gas per year.
- Save 300,000 tonnes of carbon dioxide emissions per year.

2.1.3 Solar Energy in Cyprus

Cyprus is the third largest and populous island of the Mediterranean Sea with an area of 9251 km^2. Cyprus has an average daily global irradiation of 5.4 kWh/m^2. Cyprus also receives an average of 5–6 hours of sunlight per day in winter and 12–13 hours per day in summer which coincides to an average of 2700 to 3500 hours of sunlight duration per year. This is two times more hours of sunshine than in Germany where the annual sunshine durations vary from 1600 to 1800 hours. While Germany is among the leading countries for solar energy utilization, Cyprus still relies heavily on fossil fuels.

Figure 4. Global Horizontal Irradiation Map of Cyprus [5]

Even though Cyprus does not utilize solar energy for electricity generation yet, flat plate solar collectors are widely used in residents for hot water production. However, back up electric water heaters are still widely used, since the water is often not heated up to desired temperatures. It is common for these electric water heaters to have electric heating elements with 3 kW power input which results in high electricity bills and high carbon emissions.

2.2 Concurrent Solutions

2.2.1 Types of Solar Collectors

Solar collectors can be divided into two categories as non-concentrating solar collectors and concentrating solar collectors.

- In the non-concentrating solar collectors, the collector area (the area that intercepts the solar radiation) is the same as the absorber area.
- In the concentrating solar collectors, collector reflects beam radiation on to a smaller area called focal point or focal line.

A. Non-concentrating Solar Collectors

The two most used types of non-concentrating solar collectors are flat plate solar collectors and evacuated tube collectors.

i. Flat Plate Solar Collectors

- Flat plate solar collectors are the most commonly used solar collectors for residential water heating purposes.
- They mainly consist of:
- An enclosure containing a dark coloured absorber plate with fluid circulation passageways.
- A transparent cover to allow transmission of solar energy into the enclosure.

Figure 5. A flat plate solar collector [9].

Working Principle:

- Solar radiation passes through the transparent cover and strikes the absorber plate.
- The absorber plate heats up; changing solar radiation energy into thermal energy.
- The heat is then transferred to liquid passing through pipes attached to the absorber plate.
- Absorber plates are commonly painted with selective coatings, which absorb heat better than ordinary black paint [8].

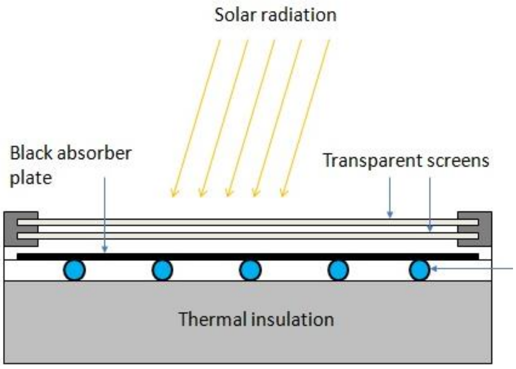


Figure 6. A diagram of flat plate solar collector [2].

ii. Evacuated Tube Collectors

- The Evacuated tube collector consists of a number of parallel glass tubes connected to a header pipe and which are used in place of the blackened heat absorbing plate of flat plate collectors.
- These collectors perform well when sunlight availability is low such as when it is early in the morning or when shaded by clouds. This is enabled since the angle of the sunlight is always perpendicular due to the cylindrical shape of the tubes.
- Evacuated tube collectors have two embedded tubes with vacuum in between. This property decreases the heat loss [10].

Figure 7.Evacuated Tube Collector [11].

- Evacuated tube collectors are made up of a single or multiple row of parallel, transparent glass tubes supported on a frame.
- Each tube consists of a thick glass outer tube and a thinner glass inner tube which is covered with a special coating that absorbs solar energy but inhibits heat loss.
- The tubes are made of borosilicate or soda lime glass, which is strong, resistant to high temperatures and has a high transmittance for solar irradiation.

B. Concentrating Solar Collectors

In this section, two concentrating solar collectors are going to be studied: Compound parabolic collectors and parabolic trough collectors.

i. Compound Parabolic Collector (CPC)

- CPCs are non-imaging concentrators as they do not produce any optical image of the source.

- They can accept solar radiation over a wide range of angles. By using multiple internal reflections, any radiation that is entering the aperture find its way to the absorber surface. This feature allows CPCs to operate without continuous tracking.
- CPCs are characterized by low concentration ratios (<5) and are well-suited for medium-temperature applications (up to 200°C) [12].

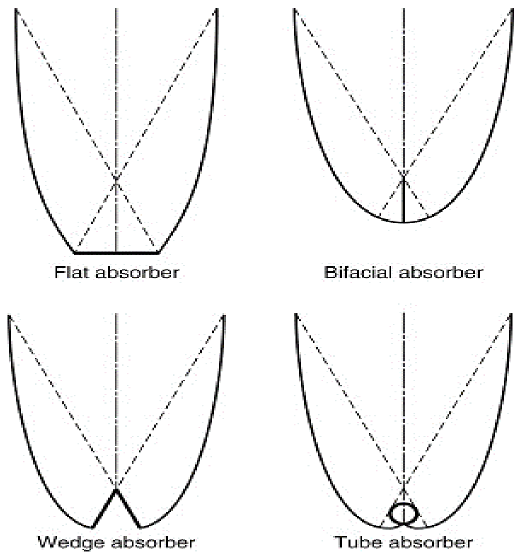


Figure 8. Types of Compound Parabolic Reflectors [13]

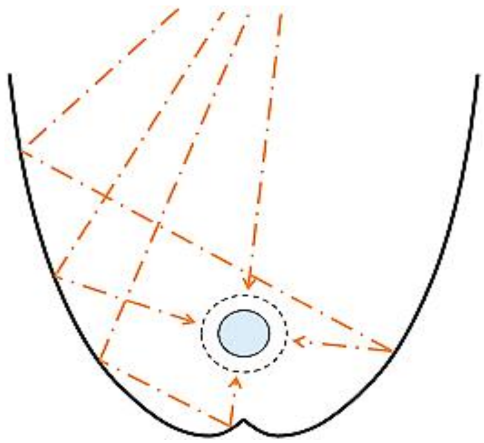


Figure 9. Compound Parabolic Tube Absorber [13]

ii. Parabolic Trough Solar Collectors

- PTCs concentrate the solar radiation on an absorber tube called a receiver that is positioned along the focal line of the reflective trough.
- PTCs can achieve higher temperatures more efficiently than a flat plate collector since the absorbed radiation is concentrated on to a smaller area.
- PTCs often require a sun tracking system to keep the focal line constant on the receiver tube [2].

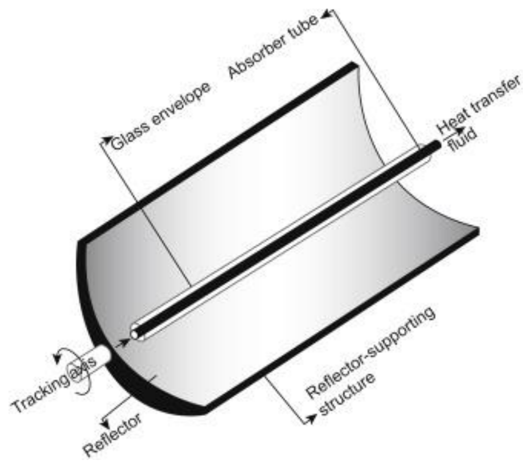


Figure 10. Parabolic Trough Collector Diagram [12].

2.2.2 Solar Water Heating Systems

There are two main types of solar water heating systems as active and passive systems. While solar collectors are designed to absorb the sun light, solar water heating systems are designed to store and deliver the hot water. [14]

A. Active Water Heating Systems

An active system uses a pump and controls to circulate hot water between the collectors and water tank. The system can use a direct or indirect method to circulate the water.

- The direct method circulates the water through the collectors and then back into the storage tank. This method is convenient for mild climates like in Cyprus.
- The indirect method circulates a non-freezing heating fluid through the system. Energy is transferred from this fluid by a heat exchanger to heat the water contained in the storage tank. This method is suitable for climates where air temperature drops below freezing point.

B. Passive Water Heating Systems

A passive system does not use a pump rather relies on natural convection to circulate the water. There are two main types of passive systems: integral collector-storage (ICS) and thermosyphon systems.

- In the ICS systems, the collector and tank are combined into one single unit. Pumps and electronic controls are not required as the hot water is heated and stored within the combined heat storage and collection unit.
- The thermosyphon systems relies on the fact that warm water will rise above the cold water. In thermosyphon systems, the storage tank is located above the collector, so the warm water passively rises into tank as it is heated by the collector.

2.3 Comparison of the Concurrent Solutions

In this section, the previously mentioned design solutions are compared and evaluated by decision matrices.

2.3.1 Concentrating and Non-Concentrating Solar Collectors

The first design consideration for the solar collector is choosing the type of collector. The two main types of solar collectors are concentrating and non-concentrating solar collectors. These two types of solar collectors are compared in Table 1.

Table 1. Comparison of concentrating and non-concentrating solar collectors

Concentrating Solar Collector	**Non-Concentrating Solar Collector**
Higher temperatures can be achieved.	Applications are limited to low temperature uses.
Higher thermal efficiency.	Lower thermal efficiency.
Difficult in maintenance therefore higher maintenance costs.	Simple in maintenance therefore lower maintenance costs.
Uses mainly beam radiation.	Uses both beam and diffuse radiation therefore it could work better in cloudy weathers.
Can be used in power plants and solar furnaces.	Often used for domestic water heating purposes.

Currently in North Cyprus, flat plate collectors (a type of non-concentrating solar collectors) are widely used for domestic water heating. For this project, it is aimed to find a more efficient solar collector that can supply water with higher temperatures.

In Table 2, a weighted decision matrix is presented. Since the thermal efficiency is one of the most important objectives of this project the highest weight is given to thermal efficiency in Table 2 with 40% importance, it is followed by the achieved water temperature rise with 30% importance. Cost and maintenance difficulty have 20% and 10% importance, respectively.

Concentrating and non-concentrating solar collectors are compared in Table 2 and graded out of 100%. These grades are multiplied by the criteria weighting and then summed to give the final grade. Concentrating solar collectors have 81 points whereas non-concentrating solar collectors have 70. Thus, concentrating solar collector is chosen to be manufactured.

Table 2. Decision matrix for concentrating and non-concentrating solar collectors

		Solar Collectors	
Criteria	**Weighting (%)**	**Concentrating**	**Non-concentrating**
Cost	20	60	70
Temperature rise	30	90	70
Thermal efficiency	40	90	65
Maintenance	10	60	90
Total	100	81	70

2.3.2 Parabolic Trough and Compound Parabolic Solar Collectors

After deciding to design a concentrating solar collector, another decision is required to be made regarding to which concentrating solar collector to be designed. Two types of concentrating solar collectors are compared in Table 3.

Table 3. Comparison of parabolic trough and compound parabolic solar collectors

Parabolic Trough Solar Collector	**Compound Parabolic Solar Collector**
Higher concentration ratios can be achieved	Lower concentration ratios can be achieved
Requires sun tracking to keep the focal point constant	Can accept solar radiation from wide range of angles without constant sun tracking
Maintenance is easier	Often requires a glass cover to prevent the accumulation of dust
Relatively easier manufacturability	Difficult to manufacture precisely

It is decided that cost, manufacturability and concentration ratio are the most important factors for selection of the solar collector. Weight of the collector and availability of parts are also important criteria for the selection process. In Table 4, a decision is made for designing a parabolic trough solar collector.

Table 4. Decision matrix for parabolic trough and compound parabolic solar collectors

		Solar Collectors	
Criteria	**Weighting (%)**	**Parabolic Trough**	**Compound Parabolic**
Cost	30	80	70
Manufacturability	20	80	50
Concentration Ratio	25	90	60
Weight	10	70	40
Availability of Parts	15	50	70
Total	100	77	60.5

2.3.3 Active and Passive Solar Water Heating Systems

Another important design decision is choosing which water heating system to use. The two solar water heating systems, Active and Passive, are compared in Table 5.

Table 5.Comparison of active and passive solar heating systems

Active Systems	**Passive Systems**
More expensive to install	Less expensive to install
Requires electricity for the controllers and pump	Works passively with natural convection
There is carbon emission due to electricity consumption	There is no carbon emission
Efficiency is high	In colder areas the efficiency is very low otherwise it is high
High versatility	Low versatility

Cost and electricity required for the system is decided to be the main factors for water heating system selection. Efficiency of the system and manufacturability are also important factors. The decision matrix for water heating system selection is shown in Table 6.

Table 6. Decision matrix for active and passive solar heating systems

		Solar Water Heating Systems	
Criteria	**Weighting (%)**	**Active**	**Passive**
Cost	30	50	90
Efficiency	20	80	80
Electricity requirement	30	0	100
Manufacturability	20	60	80
Total	100	43	89

2.4 Engineering Standards of the Concurrent Solutions

Table 7. Standards of the Concurrent Solutions

Code	**Name**	**Description**
ASHRAE 93-1986	Flat plate solar collectors	Methods of Testing to Determine the Thermal Performance of Solar Collectors. Provides test methods for determining thermal performance of solar energy collectors that use single-phase fluids and have no significant internal energy storage.
EN 12975-1:2006	Compound parabolic solar collector	This European Standard specifies requirements on durability (including mechanical strength), reliability and safety for liquid heating solar collectors. It also includes provisions for evaluation of conformity to these requirements.
ISO 9806:2017	Solar thermal collectors	Specifies test methods for assessing the durability, reliability, safety and thermal performance of fluid heating solar collectors. The test methods are applicable for laboratory testing

CHAPTER 3 – DESIGN and ANALYSIS

3.1 Proposed/Selected Design

Selected design is a parabolic solar collector with an evacuated tube receiver. In this section, main parts of the design are explained with detail. The design is mainly comprised of:

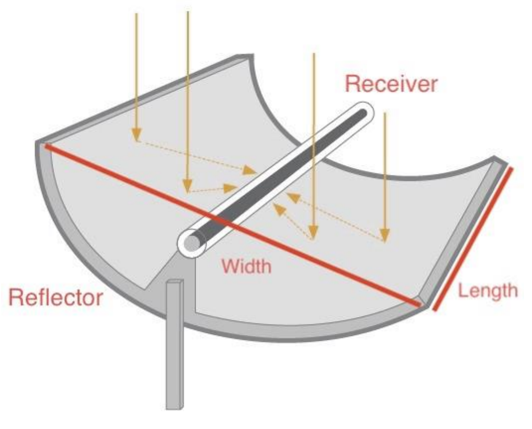
a) Collector
b) Tank
c) Frame

As shown in Table 2 and Table 4, a concentrating collector of type parabolic trough is chosen to be designed. A parabolic trough is comprised of:

a) Reflector
b) Receiver

Reflector is required to be able to reflect sun light effectively on to a focal line where the receiver is located. For this reason, chrome mirror sheet is decided to be used because of its high reflectivity. The size of the reflector decides the performance of the collector. The following table shows reflector dimensions. Focal point of the parabola is calculated with Equation 3.4 in the following pages.

Table 8. Reflector Dimensions

Aperture width	900 mm	
Length	1800 mm	
Rim angle	90°	

The first consideration for the receiver was to use a pipe with glass cover with its both ends being open. Glass cover is essential to decrease heat loss. Hot water could be obtained from the outlet of the pipe and cold water could be supplied by a water pump. However, as a result of the unavailability of these type of pipes in Cyprus and Turkey markets, a different design is considered. For the new design, an evacuated tube is used as a receiver. An evacuated tube consists of two tubes where there is vacuum in between. Evacuated tubes have their one end closed therefore water inlet also acts as the water outlet. Water circulates inside the tube via natural convection. Inner tubing has an aluminium based selective coating with high absorbance and low emittance.

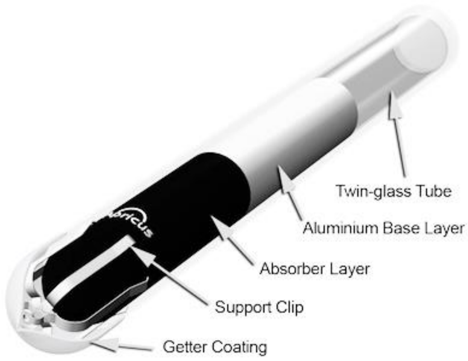


Figure 11. Evacuated Tube [10].

In this design collector area is 1.411 m^2 and receiver area is 0.209 m^2. Ratio of these two areas gives the concentration ratio which is approximately 7. In order to enable natural circulation a tank is required to be connected to the evacuated tube. A frame is designed to support the weight of the collector and tank and to allow the rotation of the collector. A rendered drawing of the whole design is shown in Figure 12.

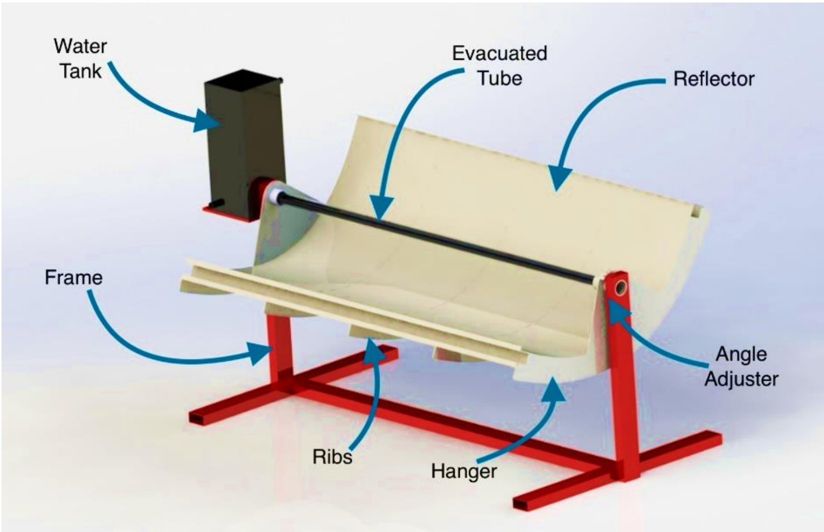


Figure 12. Rendered CAD of the collector

Following figure shows product breakdown structure of this design.

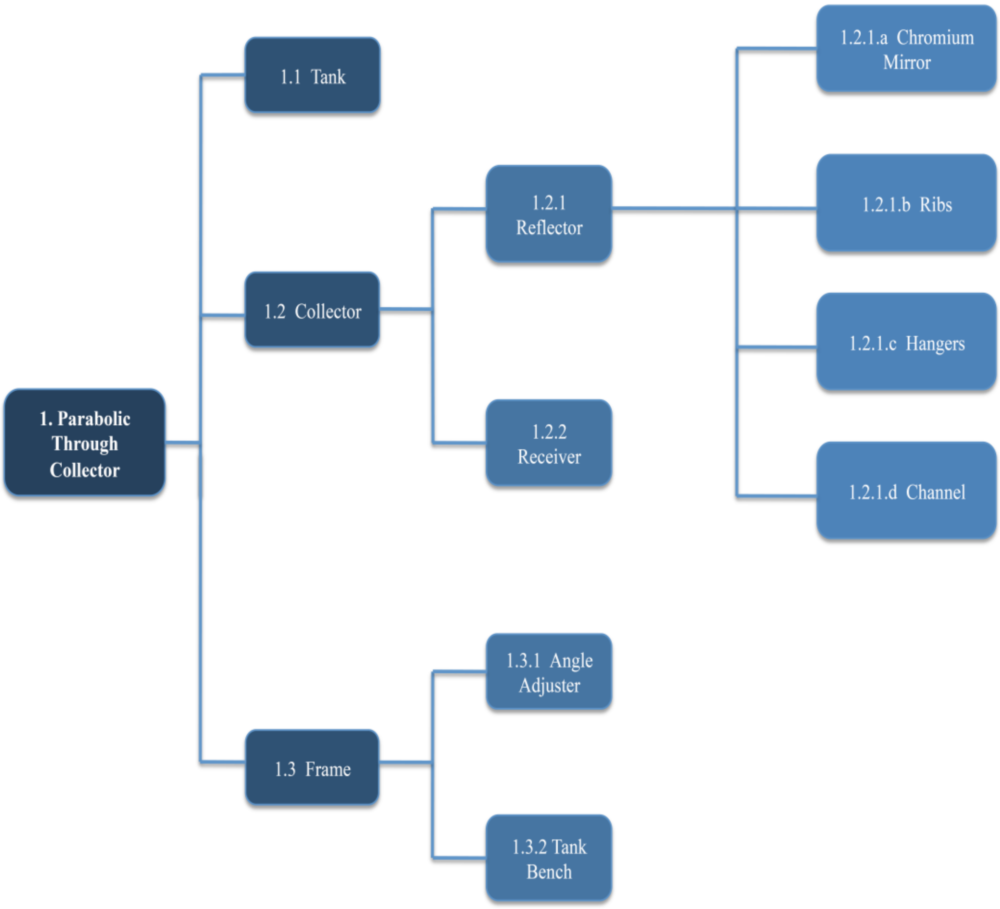


Figure 13. Product Breakdown Structure

3.2 Engineering Standards

Table 9. Design Standards

Code	Name	Description
ISO 9060:1990	Parabolic trough solar collector	Solar energy - specification and classification of instruments for measuring hemispherical solar and direct solar radiation
ISO/TR 10217:1989	Parabolic trough solar collector	Solar energy - water heating systems. Guide to material selection with regard to internal corrosion
UNI EN 12977-1: 2012	Thermal solar systems and components - custom buılt systems - part 1	General requirements for solar water heaters and combisystems. Requirements on durability, reliability and safety of small and large custom-built solar heating systems
BS EN 12977-1:2012	European standards for building solar collectors	Space-heating systems, Safety measures, Durability, Solar power, Domestic, Heating equipment, Solar heating, Water heaters, Solar collectors, Heat exchangers
ISO 9459-1:1993(en)	Active and passive solar water heating systems	Solar heating - domestic water heating systems (This standard includes indoor test method for thermal performance for both solar only systems and solar plus supplementary systems)
GB/T 17049-2005	Evacuated tube solar collector	All-glass evacuated solar collector tubes. (This standard specifies the all-glass vacuum tube solar collector product definition, classification, technical requirements, test methods and inspection rules)

3.3 Design Calculations

In this section, design calculations are presented which includes the calculation of parabola geometry and thermal performance of the designed parabolic trough.

3.3.1 Parabola Geometry Calculations

The selected parabolic trough dimensions are given in Table 10, these parameters are also shown in Figure 14. Evacuated Tube diameters associated to outer and inner tubing are given in Table 11.

Table 10. Collector Parameter Values

Collector Parameter	**Symbol**	**Value**
Aperture width	W	0.9 m
Length of the Collector	L	1.8 m
Rim Angle	Φ	90°

Table 11. Evacuated Tube Parameter Values

Evacuated Tube Parameter	**Symbol**	**Value (m)**
Outer Tubing Outside Diameter	D_{o1}	0.047
Outer Tubing Inside Diameter	D_{o2}	0.0454
Inner Tubing Outside Diameter	D_{i1}	0.037
Inner Tubing Inside Diameter	D_{i2}	0.0354

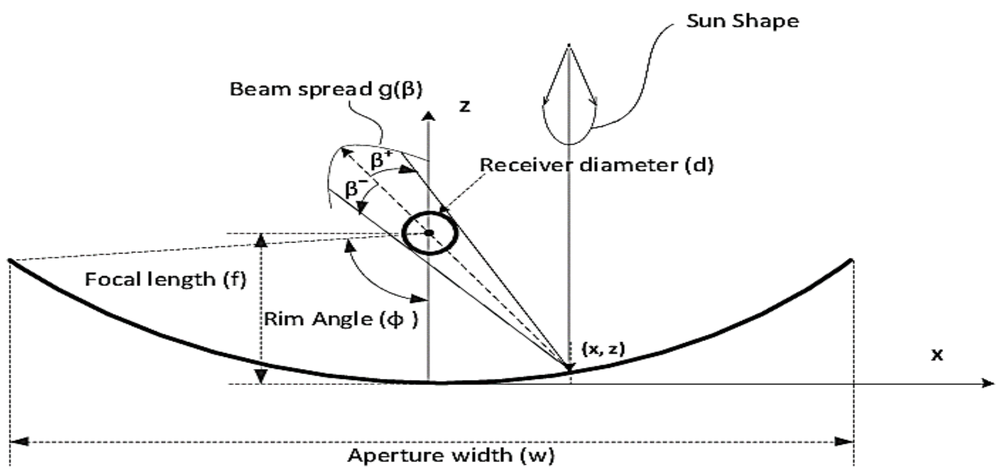


Figure 14. Parabolic Trough Parameters [15].

The following equations are used to calculate collector geometry and results are tabulated in Table 12.

Receiver Area $A_r = \pi \times D_{o1} \times L$ (3.1)

Aperture Area $A_a = (L \times w) - A_r$ (3.2)

Concentration Ratio $C = A_a / A_r$ (3.3)

Focal Point $f = \frac{w}{4\tan(\frac{\varphi}{2})}$ (3.4)

Table 12. Geometry Calculations

Receiver Area	A_r	0.209 m^2
Aperture Area	A_a	1.411 m^2
Concentration Ratio	C	7
Focal Point	f	0.225 m

3.3.2 Thermal Performance Analysis

In this section, useful energy gain, outlet water temperature and collector efficiency are calculated with the following equations:

Useful Energy Gain $Q_u = F_R \times A_a [S - A_r/A_a \times U_L (T_i - T_a)]$ (3.5)

Outlet Water Temperature $T_o = T_i + \frac{Q_u}{\dot{m} C_p}$ (3.6)

Collector Efficiency $\eta = \frac{Q_u}{A_a I_b}$ (3.7)

Where, F_R = Collector heat removal factor, S = Absorbed radiation per unit area of unshaded aperture (W/m^2), U_L = Loss coefficient, T_i = Inlet water temperature (℃), T_o = Outlet water temperature (℃), Ta = Ambient temperature (℃), $\dot{m}$ = Water mass flow rate (kg/s), C_p = Heat capacity of water (J/kg℃), I_b = Effective incident beam radiation (W/m^2)

In order to calculate useful energy gain (Q_u): collector heat removal factor, absorbed radiation and loss coefficient are calculated with the following formula:

Loss Coefficient	$U_L = \frac{Q_{loss}}{A_r(T_r - T_a)}$	(3.8)
Absorbed Radiation	$S = I_b\ \rho\ (\gamma\tau\alpha)_n\ K_{\gamma\tau\alpha}$	(3.9)
Collector Heat Removal Factor	$F_R = F' \times F''$	(3.10)

Where, Q_{loss} = loss heat transfer (W), T_r = temperature of the receiver (°C), T_a = ambient temperature (°C), I_b = hourly incident beam radiation per unit area (W/m^2), ρ = reflectance of the reflector, γ = intercept factor, τ = transmittance of the receiver, α = absorbance of selective coating of the receiver, $K_{\gamma\tau\alpha}$ = incident angle modifier, F' = collector efficiency factor, F''= collector flow factor.

<u>Calculation of Loss Coefficient</u>

In order to calculate the loss coefficient, heat loss is calculated with an iteration method.

Heat loss from receiver to cover by radiation	$Q_{loss} = \frac{\pi D_{i1} L \sigma (T_r{}^4 - T_{o2}{}^4)}{\frac{1}{\varepsilon_r} + \frac{1-\varepsilon_c}{\varepsilon_c}(\frac{D_{i1}}{D_{o2}})}$	(3.11)
Heat loss within the cover by conduction	$Q_{loss} = \frac{2\pi L k_c\ (T_{o2} - T_{o1})}{\ln(\frac{D_{o1}}{D_{o2}})}$	(3.12)
Heat loss from cover to sky by convection and radiation	$Q_{loss} = \pi\ D_{o1}\ L\ h_w\ (T_{o1} - T_a) + \varepsilon_c\ \pi\ D_{o1}\ L\ \sigma\ (T_{o1}{}^4 - T_{sky}{}^4)$	(3.13)

Where, σ = Stefan-Boltzmann constant, T_{o2} = outside tubing inner temperature (K), ε_r = selective coating emittance, ε_c = outer tubing emittance, k_c =thermal conductivity of outer tubing (W/Km), T_{o1} =outside tubing outer temperature (K), h_w = wind heat transfer coefficient (W/m^{2}K), T_a = ambient temperature (K), T_{sky} = sky temperature (K)

Iteration Method Procedure Summary:

Step 1: Having an initial guess for the outside cover temperature.
Step 2: Calculating the heat loss by Equation 3.13.
Step 3: Calculating the inside cover temperature by Equation 3.12.
Step 4: Calculating the heat loss with the calculated inside cover temperature by Equation 3.11.
Step 5: Comparing the heat loss values calculated in Step 2 and Step 4. If the heat loss calculated in Step 4 is lower than heat loss in Step 2 (negative error value), initial guess for the cover temperature was too high and vice versa.
Step 6: Have a second guess for the cover temperature and repeat the procedure.
Step 7: Make a linear interpolation for error value of 0 and find the outside cover temperature.
Step 8: Repeat the procedure with the new cover temperature and calculate the heat loss.

Assumptions:

Table 13. Assumptions for the iteration method

Receiver Temperature	T_r	70℃ = 343 K
Wind Speed	v	2 m/s
Air temperature = Sky temperature	$T_a = T_{sky}$	30℃ = 303 K

The receiver is an evacuated tube with an inner and outer tubing. The inner tubing has a dark coloured selective coating (Al/N). The properties of the evacuated tube are given in Table 14. Inner tube acts as a receiver and outer tube acts as a glass cover which is intended to reduce heat loss.

Table 14. Evacuated tube properties

Property	Symbol	Value
Selective coating surface emittance (receiver surface emittance)	ε_r	0.03
Selective coating solar absorbance (receiver solar absorbance)	α_r	0.92
Outer tubing surface emittance	ε_c	0.80

- The initial guess for the outside cover temperature, T_{co} = 31℃
- Heat loss formula in Equation 3.13 has one unknown which is wind heat loss coefficient, h_w.

Wind heat loss coefficient $h_w = \frac{Nu\ k_a}{D_{01}}$ (3.14)

For flow of air across a single tube in an outdoor environment:

$$Nu = \begin{cases} 0.40 + 0.54\ Re^{0.52} & \text{for } 0.1 < Re < 1000 \quad (3.15) \\ 0.30\ Re^{0.6} & \text{for } 1000 < Re < 50000 \quad (3.16) \end{cases}$$

Reynolds Number $Re = \frac{\rho_a\ v_a\ D_{01}}{\mu_a}$ (3.17)

Where Nu=Nusselt number, k_a = thermal conductivity of air (W/Km), ρ_a = density of air, υ_a = wind speed (m/s), μ_a = dynamic viscosity of air (kg/ms)

At the average temperature of outside cover and air temperatures (31+30)/2 = 30.5 °C:

Density of air = 1.1629 kg/m^3
Dynamic viscosity of air = 1.8704E-5 kg/ms
Thermal conductance of air = 0.026378 W/mK

Re = (1.1629 kg/m^3 x 2 m/s x 0.047 m) / 1.8704E-5 kg/ms = 5844.3

Nu = 0.30(5844.3)$^{0.6}$ = 54.6

$h_w = \frac{54.6\ x\ 0.026378\ W/mK}{0.047\ m}$ = 30.6 W/m^2 K

For 1m of collector length:

Equation 3.13 heat loss value equals to: $Q_{loss} = \pi\ (0.047m)\ (1m)\ (30.6\ W/m^2\ K)\ (304 - 303)\ K + (0.8)\ \pi\ (0.047m)\ (1m)\ (6.67E\text{-}8\ Wm^{-2}K^{-4})\ (304^4 - 303^4)\ K = 5.27\ W$
Equation 3.12 can be arranged to give the inside cover temperature: $T_{02} = T_{01} + \frac{Q_{loss}\ x\ \ln(\frac{D_{co}}{D_{ci}})}{2x\pi xLxk_c} = 304\ K + \frac{5.27\ W\ x\ \ln(\frac{0.047}{0.0454})}{2\pi(1\ m)\ (1.4\ \ W/mK)} = 304.02\ K$
Equation 3.11 heat loss value equals to: $Q_{loss} = \frac{\pi(0.037)(1)(5.67E-8)(343^4 - 304.02^4)}{\frac{1}{0.03}+\frac{1-0.8}{0.8}(\frac{0.037}{0.0454})} = 1.04\ W$
Heat loss values are not equal (1.04 W < 5.27 W), the deviation equals to -4.23 W.

Same procedure is repeated again with a lower cover temperature and then linear interpolation is carried out to find the cover temperature value that gives the same heat loss values for both of the equations. The results are tabulated in Table 15.

Table 15. Results of the iterations

Number of Iterations	Outside Cover temperature (°C)	Inside Cover Temperature (°C)	Q_{loss} by Equation 3.11 (W)	Q_{loss} by Equation 3.13 (W)	Deviation (W)
1	31	31.02	1.04	5.27	-4.23
2	25	24.9	1.074	-26.3	+27.374
3	30.2	30.204	1.1	1.1	0

The Loss Coefficient

$$U_L = \frac{1.1}{\pi(0.037)(1)(343-303)} = 0.237$$

Calculation of Collector Heat Removal Factor

In order to calculate heat removal factor F_R, collector efficiency factor F' and collector flow factor F" are required to be calculated with the following formula.

Collector Efficiency Factor

$$F' = \frac{1/U_L}{\frac{1}{U_L}+\frac{D_{i1}}{h_{fi}D_{i2}}+(\frac{D_{i1}}{2k_r}\ln\left(\frac{D_{i1}}{D_{i2}}\right))} \quad (3.18)$$

Collector Flow Factor

$$F'' = \frac{\dot{m}C_p}{A_r U_L F'}\left[1 - \exp\left(\frac{-A_r U_L F'}{\dot{m}C_p}\right)\right] \quad (3.19)$$

Where, h_{fi} *= heat transfer inside the tube(W/m*^{2}*K),* k_r *= thermal conductance of receiver,* $\dot{m}$*= water mass flow rate (kg/s),* C_p *= specific heat of water*

- Water inside the tube moves with natural circulation, therefore, mass flow rate ($\dot{m}$) is assumed to occur with a slow rate and value of 0.01 kg/s is assumed.
- In order to calculate heat transfer coefficient inside the tube (h_{fi}), Reynolds number is calculated by modifying Equation 3.17.
- Water temperature is assumed as 30°C.

Reynolds Number

$$Re = \frac{4\dot{m}}{\mu \pi D_{i2}} \quad (3.20)$$

$$Re = \frac{4\,(0.01)}{(0.798E-3)\pi(0.0354)}$$

$$= 451 < 2300 \text{ (Laminar flow)}$$

Assuming constant surface temperature gives the following equation:

Nusselt Number

$$Nu = \frac{h_{fi}D}{k} = 3.66 \quad (3.21)$$

Equation 3.21 can be used to calculate the heat transfer coefficient inside the tube:

$$h_{fi} = (3.66 \times 0.615) / 0.0354 = 63.6$$

$$F' = \frac{1/0.237}{\frac{1}{0.237} + \frac{(0.037)}{(63.6)(0.0354)} + \left(\frac{0.037}{2(160)}\ln\left(\frac{0.037}{0.0354}\right)\right)} = 0.996$$

$$F'' = \frac{(0.01)(4180)}{\pi(0.037)(1)\,(0.237)(0.996)}\left[1 - \exp\left(\frac{-\pi(0.037)(1)\,(0.237)(0.996)}{(0.01)(4180)}\right)\right] = 0.999$$

Heat Removal Factor equals to:

$$F_R = 0.996 \times 0.999 = 0.995$$

Calculation of The Absorbed Radiation

In order to calculate the absorbed radiation (S) by the collector, the following properties are required.

Table 16. Properties of the reflector and receiver

Transmittance of the outer tubing of the receiver	τ	0.93
Reflectance of the reflector	ρ	0.94
Absorbance of the selective coating of the receiver	α	0.92

Intercept factor (γ) and incident angle modifier ($K_{\gamma\tau\alpha}$) values are assumed to calculate the absorbed radiation.

Intercept factor is the fraction of the reflected radiation that is incident on the absorbing surface of the receiver and it is assumed as 0.94. Incident angle modifier is assumed as 1.

Intercept factor	γ	0.94
Incident angle modifier	$K_{\gamma\tau\alpha}$	1

- As stated in Solar Engineering of Thermal Processes book by John Duffie:

  "The effective incident solar radiation measured on the plane of the aperture I_b includes only beam radiation for all concentrators except those of low concentration ratio (i.e. perhaps 10 or below) since part of the diffuse radiation will be reflected to the receiver."

- Since the collector we designed has a concentration ratio of 7, effect of the diffuse radiation is included.
- In order to calculate total effective incident solar radiation, I, test day is assumed to be carried out on 15 May at between 1:00-2:00 PM in Famagusta and hourly radiation is going to be estimated from daily radiation data.
- Daily average value for May in Cyprus $\overline{H}$ = 25 MJ/m^2 is used to estimate the hourly value at 1:00-2:00 pm.

Ratio of hourly total to daily total radiation (r_t):

$$r_t = I/H \tag{3.22}$$

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\sin\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \tag{3.23}$$

Where the coefficients a and b calculated by:

$$a = 0.409 + 0.5016\sin(\omega_s - 60) \tag{3.24}$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60) \tag{3.25}$$

In equation 3.21, ω is hour angle in degrees for the midpoint of the hour which the calculation is made and ω_s is sunset hour angle.

Hour angle $\qquad \omega = 15.\ (\text{solar time} - 12) \qquad$ (3.26)

hour angle is negative before solar noon, positive after solar noon.

Sunset hour angle $\qquad \omega_s = \cos^{-1}(-\tan\varphi . \tan\delta) \qquad$ (3.27)

Where φ is latitude which is 35° for Famagusta and δ is declination and equals to 18.8° for 15th of May.

For 1:00-2:00 PM:

Hour angle equals to: $\omega = 15 \times 1.5 = 22.5°$
Sunset hour angle equals to: $\omega_s = \cos^{-1}(-\tan\varphi \tan\delta) = \cos^{-1}(-\tan(35)\tan(18.8)) = 103.8°$
Coefficients a and b equals to: a = 0.75618 and b = 0.33096

- By putting these values into Equation 3.21, ratio of hourly total to daily total radiation is calculated as $r_t = 0.12$.
- By using Equation 3.20, total hourly radiation between 1:00-2:00 PM in Famagusta is estimated as I = 0.12 x 25 MJ/m^2 = 3 MJ/m^2 which is equivalent of 833.3 W/m^2
- Finally absorbed solar radiation is calculated by putting all the values in Equation 3.9: S = 833.3 x 0.94 x 0.93 x 0.92 x 1= 670.2 W

Since all the values are calculated, **useful energy gain (Q_u)**, **outlet water temperature (T_o)** and **collector efficiency (η)** can be calculated with Equations 3.5, 3.6 and 3.7, respectively.

Table 17. Design Calculation Results

Useful Energy Gain	Q_u = 0.995 x 1.411 [670.2-0.209/1.411 x 0.237 (20-30)]	941.4 W
Outlet Water Temperature	T_o = 20 + 941.4/ (0.01 x 4180)	42.5 ℃
Collector Efficiency	η = 941.4/ (1.411 x 833.3)	78.4 %

3.4 Cost Analysis

Table 18. Bill of Materials

Item	Part no.	Name	Quantity	Cost Per Item	Total
1	1.1	Tank	1	90 TL	90 TL
2	1.2.2	Evacuated tube	2	25 TL	50 TL
3	1.2.1.a	Chrome mirror	(120mm x 180mm)	230 TL	230 TL
4	1.2.1.b/c	Hanger & Ribs	2	250 TL	250 TL
5	1.2.1.d	Channel	2	20 TL	40 TL
6	1.3	Frame	1	750 TL	750 TL
7		Paint	1	60 TL	60 TL
8		Anti-rust paint spray	1	20 TL	20 TL
					1490 TL

CHAPTER 4 – MANUFACTURING

4.1 Manufacturing Process Selection

There are four parabolic trough manufacturing methods have been chosen to be discussed in this section.

Table 19. Decision Matrix of Manufacturing Process

	Weight %	Conventional Method	Carpenter Method	FRP Method	Non-Conventional Method
Precision	40	1	8	8	9
Manufacturability	40	9	8	6	5
Weight	20	5	5	8	7
Total %	100	5	7.4	7.2	7

4.1.1 Conventional Method

This method is the easiest manufacturing method among the four methods since it can be carried out in a local workshop with simple tools. Also, it does not require high manufacturing skills therefore it can easily be carried out by students. However, it also produces non-precise parabolic shapes and therefore decreases the efficiency of the system. A short summary of the procedure of this method is as follows.

- A sketch of the whole area of the parabola is drawn with aperture width and length and longitudinal and latitudinal lines are drawn on it.
- A vertical lift of focal length is provided by a bar. Thereafter the corresponding length of each strip is calculated.
- Now the bar is marked for the calculated length and then cut.
- The strips are hammered to take the shape of the parabola using sectoral base of the bar.
- The strips are then welded together to form the visualized grid and attached to the outer longitudinal strips.
- The frame is covered by a metal sheet. After the sheet is fixed on the inner frame then aluminium sheet foil is applied on it in longitudinal strip.
- After this the support strips for the receiver tube and structure.

4.1.2 Carpenter Method

This method requires higher manufacturing skills when compared to the conventional method. The tools used are the ones that found in a carpenter shop as the name suggests. This method produces a more precise parabolic shape.

- The parabolic shape is drawn on the graph sheet using the parabola equation for the decided rim angle and focal length and the graph drawn is pasted on the wood to be used.
- The wood is cut by the hand saw and the final shape is reached by a wood router, metal smoothing plane or file.
- Metal sheet is then nailed on the wood where it takes the shape of the parabola. A wooden strip is then placed on the back side of the sheet for holding structure.
- Holes are drilled with the size of receiver tube diameter to hold the receiver tube at the focal line.
- The glasses are cut in the shape of small rectangles since it is hard to find parabolic shape mirrors.
- The glasses are then pasted on complete sheet length using the synthetic resin.
- The receiver tube is fixed and coated with black chrome.

4.1.3 FRP Method

This method is aimed to manufacture a lighter reflector. Its main difference is it uses FRP (fibre reinforced plastic) instead of a metal sheet.

- The shape of the parabola is drawn on the thin plywood.
- This shape is cut to create a pattern and filed to reach its desired shape.
- Once the frame is ready, a pile of plaster of Paris is made and frame is moved to get the mould.
- The mould is allowed to dry. Once dried then wax polish is applied on the mould.
- Fibre sheets are applied on complete mould and then it is coated with the resin.
- The mix is allowed to dry and then the complete parabolic shape base is removed from the mould, which is ready to be used again.
- The reflective surface is achieved by applying aluminium foil or any other reflective film and resin on the surface.
- The same method is applied to create the tracking mechanism and support structure.

4.1.4 Non-Conventional Method

This method requires high skilled manufacturing and also gives the most precise results since the parabolic shape is manufactured as a single piece. Also, it uses glass as the material for parabola.

- A micro-sheet of glass is drawn from a glass melt.
- A reflective layer is placed on one surface of the micro-sheet.
- A first flexible backing layer, such as fiberglass, is bonded to the reflective layer.
- The combination of the micro-sheet with the reflective layer and the first backing layer is formed over a mandrel which is in the form of a parabolic cylinder.
- A honeycombed layer, with a second fiberglass backing layer, is then bonded to the first backing layer.
- The product produced by the previous steps is then cured so that it stays in the desired configuration after it is removed from the mandrel.

4.2 Detailed Manufacturing Process

In this section, manufacturing processes of each part of the design is explained with detail.

4.2.1 Manufacturing of the Parabolic Trough

For the manufacturing of the parabolic trough, a method similar to the previously mentioned carpenter method is chosen. Parabolic trough contains the following components:

- A chromium mirror sheet
- Ribs for supports
- Channels for connecting ribs and chromium

A chromium sheet of 120 x 180 cm is used and brought to shape of the parabola by the help of ribs. These ribs are manufactured from metal and cut by laser cutting machine in order to increase the accuracy and strength of the collector. Their shape is determined via the parabolic equation we have. These ribs are connected together by channels with welding.

Figure 15. Rib and Hanger

Figure 16. Ribs after assembling with channels

Ribs are then painted with anti-rust paint. After this procedure, chromium mirror sheet is carefully placed on top of the rims and pushed from top to take the shape of the parabola. Chromium sheet is fixed with the help of channels and screws.

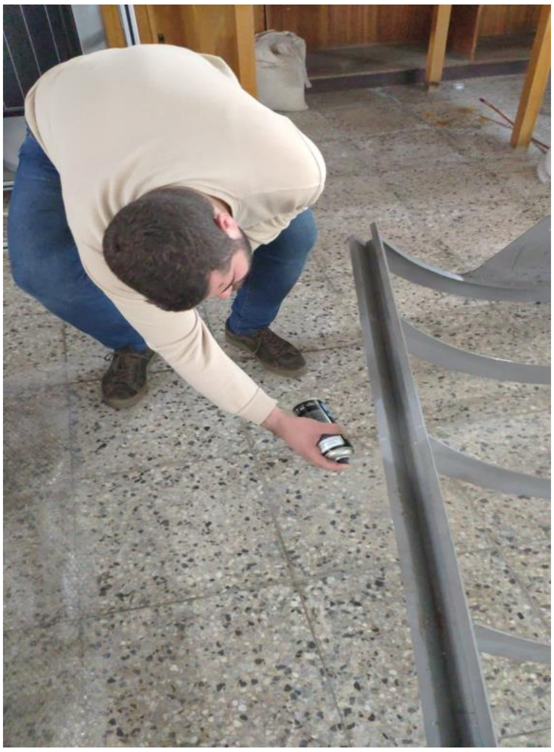


Figure 17. Painting with anti-rust paint

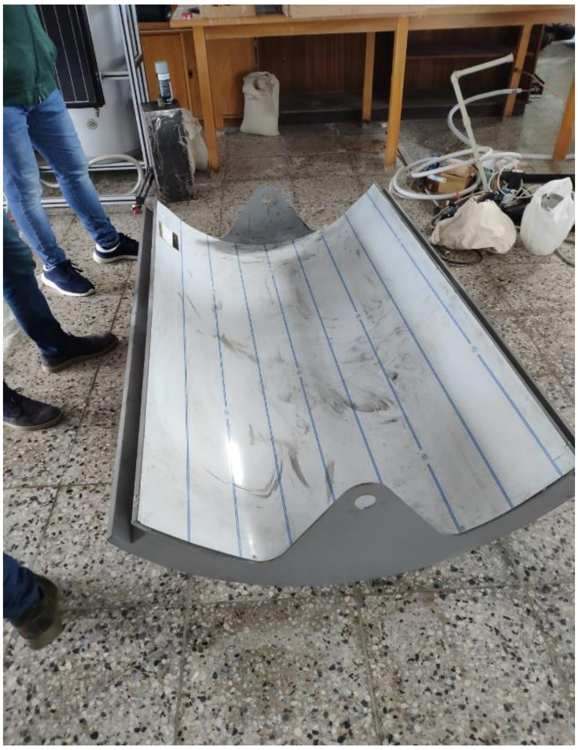


Figure 18. Chromium mirror after attachment

After the painting, evacuated tube is placed on the collector. A 20-litre water tank is mounted to test the water circulation inside the evacuated tube.

Figure 19. Performance test of the tank and evacuated tube

Figure 20. Temperature measurement of water

Without removing the protective film of the chromium mirror, collector is placed outside and temperature of the water increased up to 35°C.

4.2.2 Manufacturing of the Frame

A frame is constructed to support the collector and to allow it to turn and stop at a particular angle. 40x80 mm profile iron bars are used and welded together. Circular iron bars are mounted on the frame to hold the collector and evacuated tube in place. Tank is also fixated to the frame.

Figure 21. Frame after welding

Figure 22. Cylinder parts for holding the collector in place

After placing the chromium mirror on to the frame, evacuated tube is also placed carefully and secured with plastic bearings. Then, protective film over the chromium mirror is removed. A tap is placed to the tank water outlet and tank is filled with water.

Figure 23. Collector after being attached to the frame

Figure 24. Mechanism to adjust the collector angle

Figure 25. Collector after full assembly

CHAPTER 5 – PRODUCT TESTING

5.1 Verification of the Objectives of the Report

In order to test the first objective of the design which is achieving 20 ℃ water temperature rise, three different experiments are carried out. It is decided to test performance of the collector with three different weather conditions. It is tested in cloudy and clear weathers. Additionally, it is tested on a clear day while the tank is shaded in order to minimize the direct heat gain of the tank. Angle of the collector is kept constant in all the experiments. The experiments are carried out at thermal sciences laboratory of Eastern Mediterranean University. Following figure is drawn to show the setup of the experiments.

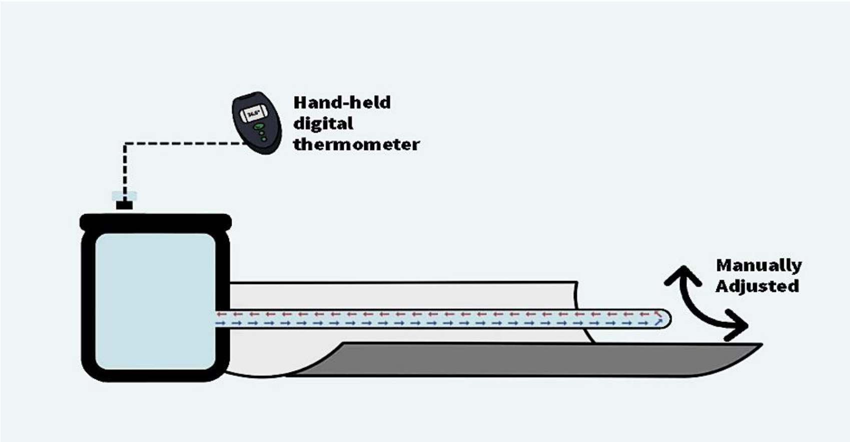


Figure 26. The testing set-up

Testing procedure is as follows for all three experiments:

- Finding the optimal angle for the collector to face.
- Cleaning the pipe and collector.
- Filling the tank with water.
- Placing the temperature sensor inside the tank.
- Setting the device to measure the temperature of the water inside the tank with 30 minutes interval.

- A pyranometer is set up to measure solar radiation and another sensor is used to measure ambient temperature.

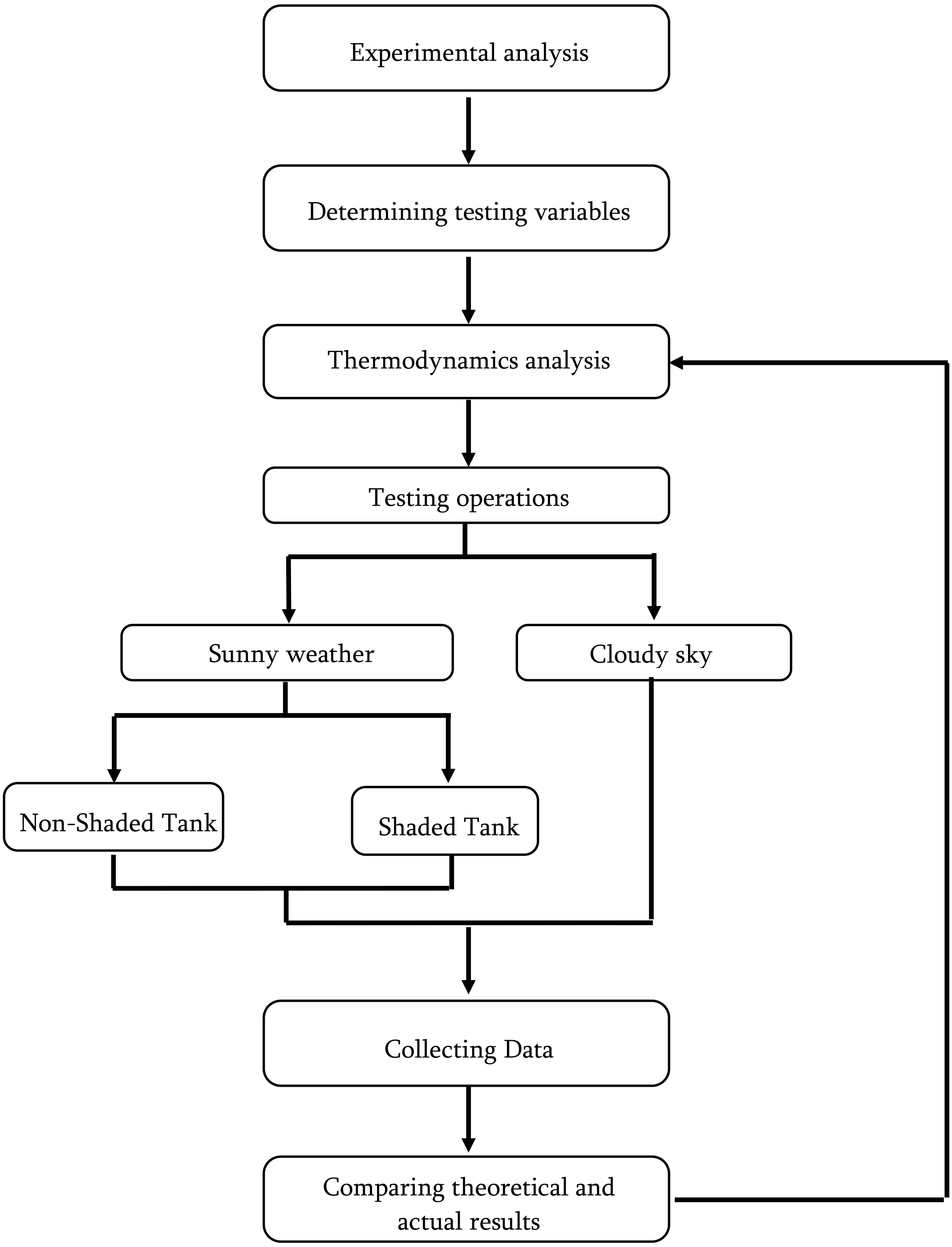


Figure 27.The Testing Procedure

The tests showed that 20℃ of water temperature rise is achived in all three conditions and details of the results are provided in Chapter 6. After the completion of the project, the objectives are all verified which are summarised as follows.

- Temperature rise of 20℃ is reached in three different conditions
- Cost of the whole design has not exceeded the budget of the project
- The system works without any need to a pump
- Collector is light and can withstand outside conditions

5.2 Verification of the Applied Engineering Standards

The following figure shows closed loop setup for liquid heating flat plate solar collector from ASHRAE Standard 93-2003.

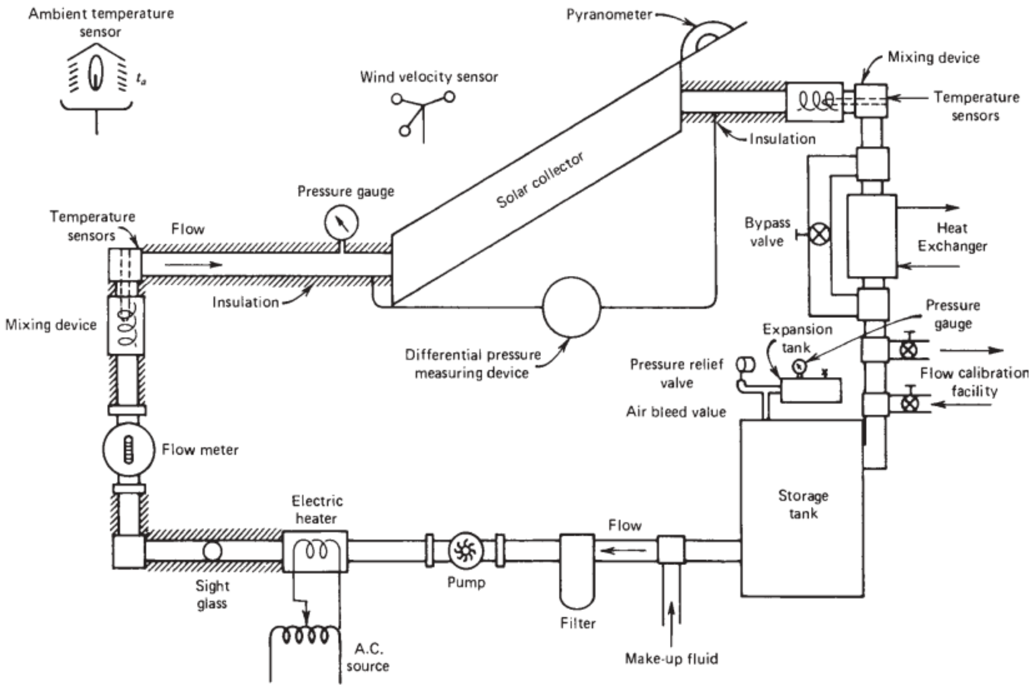


Figure 28. Closed loop setup for liquid heating flat plate solar collector [15].

In this project, we tried to follow some sections of this ASHRAE standard testing procedure such that temperature sensors are used to measure ambient and water temperatures. In our testing procedure, however, flow meter and wind velocity sensors are some of the devices that were not included in our experiments.

CHAPTER 6 – RESULTS and DISCUSSIONS

6.1 The Results

In this section, the results of three experiments are presented.

6.1.1 Cloudy Weather Data

An experiment is carried on 18.05.2019 when the weather was cloudy. Temperature of the water inside the tank is measured for 6.5 hours with 30-minute intervals. The results are tabulated in Table 20. At 10:00 temperature of the water was 22.2℃ and it reached the peak at 13.30 with 44.85℃.

Table 20. Cloudy weather water and ambient temperature data

Time (min)	Hour	Water Temperature (℃)	Ambient Temperature (℃)
0	10:00	22,2	25
30	10:30	23,9	25
60	11:00	25,45	25
90	11:30	27,4	25
120	12:00	30,25	26
150	12:30	36,4	26
180	13:00	42,62	26
210	13:30	44,85	26
240	14:00	41,82	26
270	14:30	36,74	26
300	15:00	35,41	26
330	15:30	32,95	25
360	16:00	31,87	25
390	16:30	31,5	25

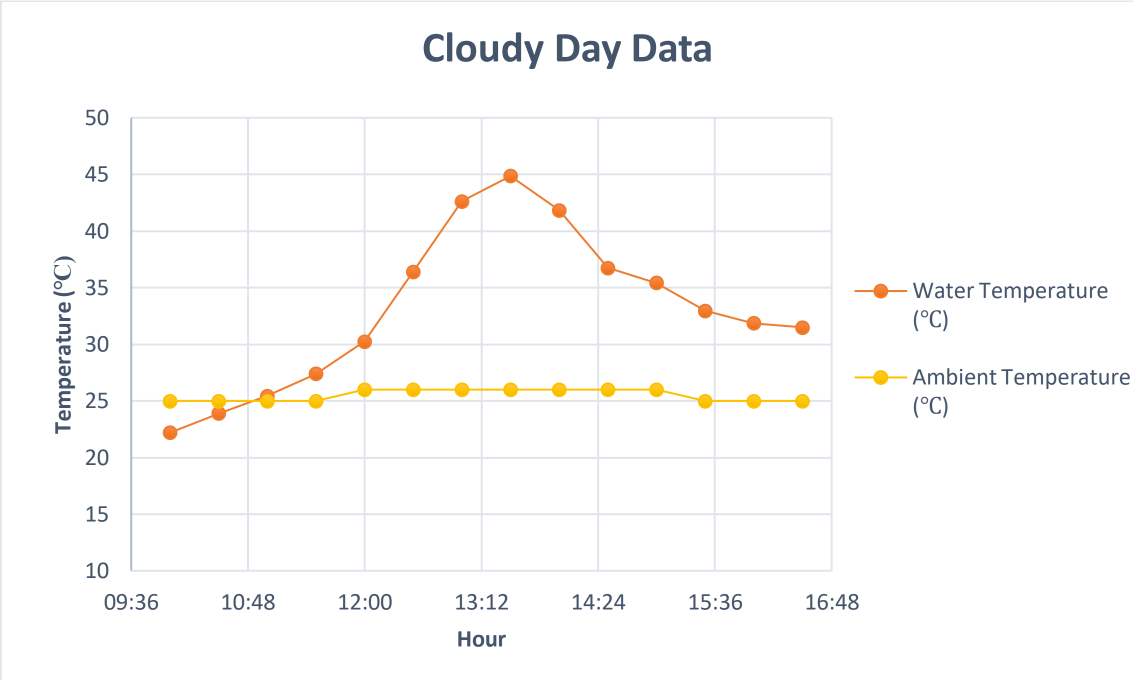


Figure 29. Water and ambient temperature against time in a cloudy day

6.1.2 Clear Day Data

Another test is carried on 21.5.2019 when the weather was sunny. Temperature of the water inside the tank is measured for 6.5 hours with 30-minute intervals. The results are tabulated in Table 21. At 10:00 temperature of the water was 25.75℃ and it reached the peak at 14.00 with 51.23℃.

Table 21. Clear sky-water temperature data

Time (min)	**Hour**	**Water Temperature (℃)**	**Ambient Temperature (℃)**
0	10:00	25,75	27
30	10:30	28,48	27
60	11:00	31,74	27
90	11:30	33,32	27
120	12:00	35,8	28
150	12:30	40,88	29
180	13:00	44,27	30
210	13:30	48,63	31
240	14:00	51,23	31
270	14:30	48,32	31
300	15:00	46,8	31
330	15:30	46,15	30
360	16:00	45,21	29
390	16:30	44,74	28

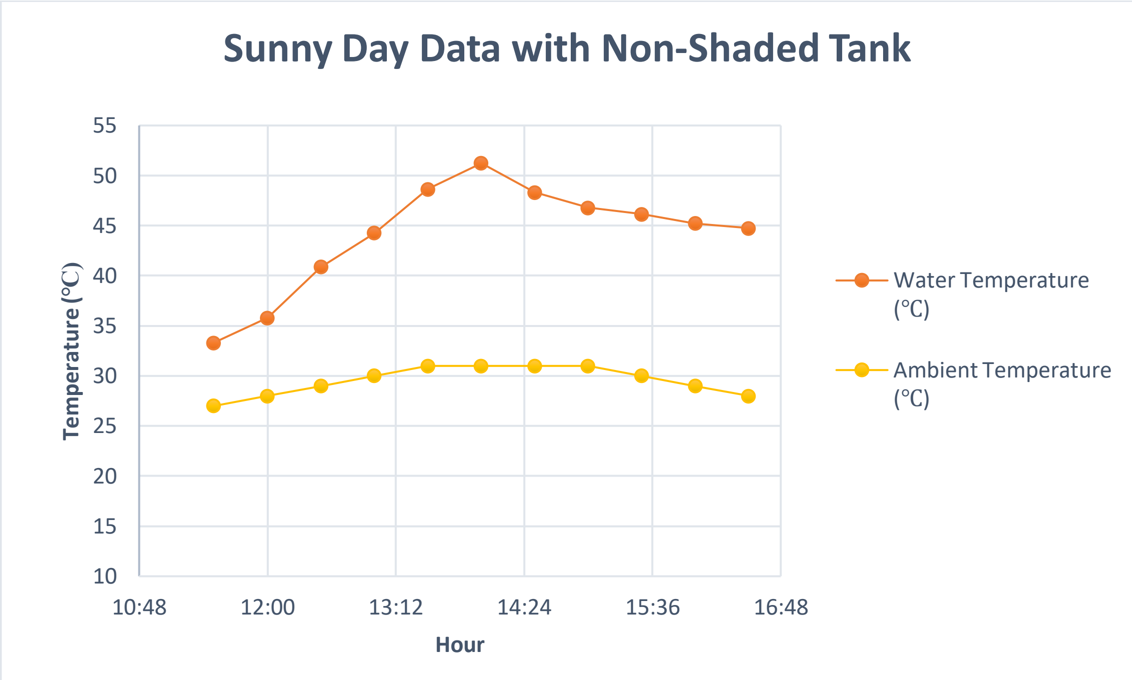


Figure 30. Water temperature against time on a sunny day

6.1.3 Clear Day with Shaded Tank Data

Final test is carried on 22.5.2019 when the weather was sunny. In order to see only effect of the collector on the water temperature tank is shaded. Temperature of the water inside the tank is measured for 6.5 hours with 30-minute intervals. The results are tabulated in Table 22. At 10:00 temperature of the water was 25.85℃ and it reached the peak at 13.00 with 48.94℃.

Table 22. Clear day with shaded tank temperature data

Time (min)	Hour	Water Temperature (℃)	Ambient Temperature (℃)
0	10:00	25,85	27
30	10:30	28,65	27
60	11:00	34,25	28
90	11:30	37,58	29
120	12:00	42,59	31
150	12:30	46,26	30
180	13:00	48,94	30
210	13:30	47,61	30
240	14:00	47,23	30
270	14:30	45,23	30
300	15:00	42,12	30
330	15:30	40,32	30
360	16:00	40,12	29
390	16:30	39,25	28

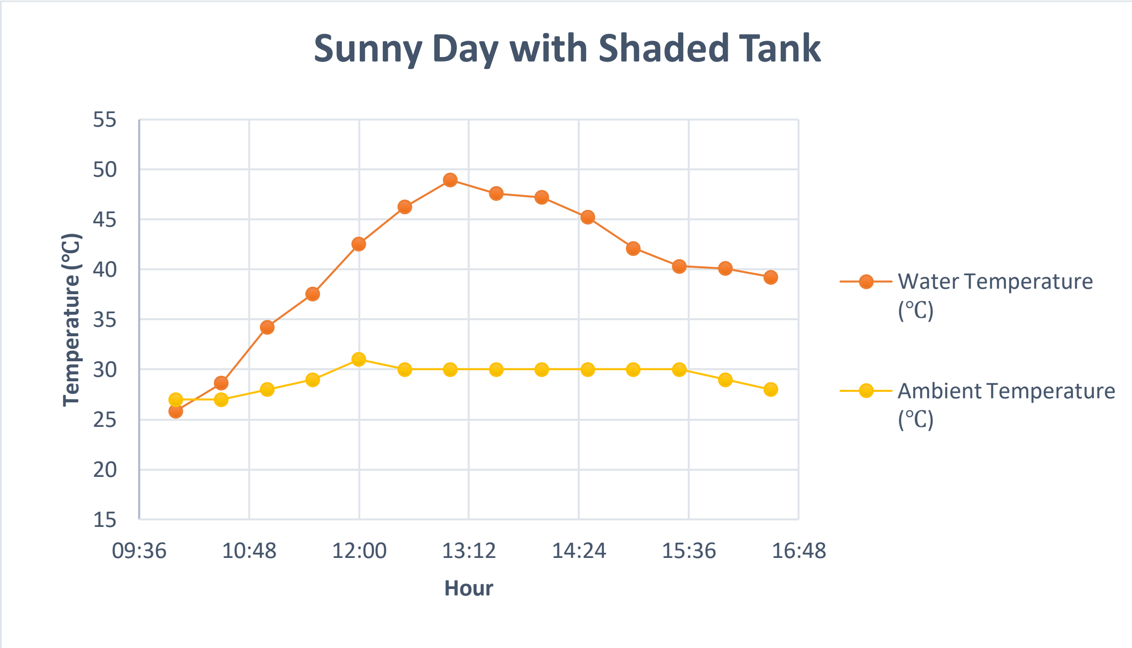


Figure 31. Water temperature against time on a sunny day with shaded tank

The following figure shows the results of the all three experiments in one graph.

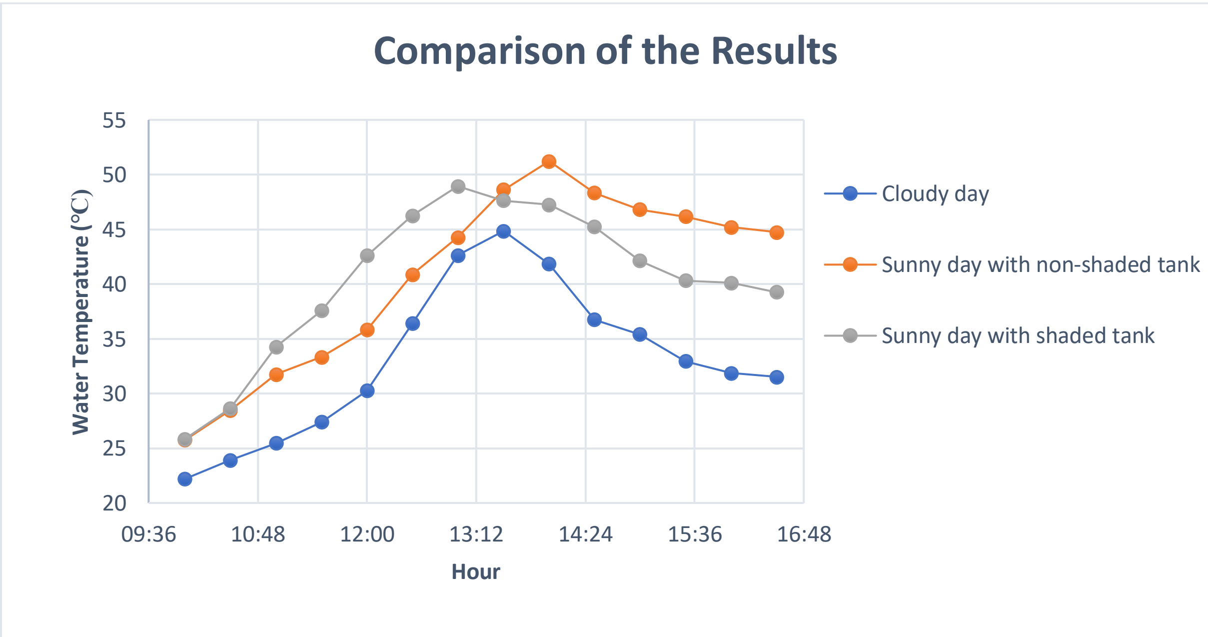


Figure 32. Comparison of the results

6.2 The Engineering Standards

The design and calculations of the collector followed the (European Standards) EN 12975-1: 2006 + A1 2010 thermal solar systems and components - solar collectors: general requirements

And the testing followed the (The American Society of Heating, Refrigerating and Air-Conditioning Engineers) ASHRAE Standard 93-2003 and (The International Organization for Standardization) ISO 9459-1: 1993(R2018) solar heating - domestic water heating systems - performance rating procedure using indoor test methods.

Moreover, for the frame construction followed BS EN 10219-2:2006 (the British adoption of a European (EN) standards) cold formed welded structural hollow sections of non-alloy and fine grain steels.

6.3 Constraints

- Some assumptions are required to be made related to the mass flow rate and inlet water temperature since they are difficult to measure.
- Lack of continuous tracking reduces the efficiency of the collector.
- Manufacturing the parabola precisely is practically difficult.
- Some parts are unavailable in Turkey and Cyprus markets which resulted in certain design changes.
- Manual tracking mechanism is restricted to certain angles.
- High cost of materials in North Cyprus markets.

CHAPTER 7 – CONCLUSIONS and FUTURE WORKS

7.1 Conclusions

In this project, we aimed to design a solar collector that can heat water efficiently without any need of external source. Cyprus with its great solar energy potential is an excellent place to learn and research solar energy systems. With this project, we had the opportunity to do research about energy related global problems and learn the significance of renewable energy utilization. We learned how to design a solar collector with certain constraints. Manufacturing and testing of the collector is also used as a great learning tool.

After the tests, results showed that:

- On a cloudy day, water temperature increased by 22.65℃ in 3.5 hours.
- On a sunny day, water temperature increased by 25.48℃ in 4 hours.
- On a sunny day where the tank is shaded, water temperature increased by 23.09℃ in 3 hours.
- In all 3 experiments, water temperature reached over 40℃ less than or equal to 4 hours.

Additionally:

- The cost of the design has not exceeded the budget we have. With a cost of 1570 TL, we were able to purchase parts and manufacture the collector.
- The whole design has a strong structure, weight is low with approximately 40 kg without the frame.
- The system operates without any external power source and works with natural water circulation.

It can be concluded as that we have achieved the project objectives and have gained knowledge about solar energy and its importance in Cyprus.

7.2 Future Works

- In order to improve this design, a single axis tracking system or a better manual angle adjuster could be designed. This could significantly increase the efficiency of the collector.
- A tank with greater volume could be added to this design to make it more feasible for domestic usage.
- In order to compare the performance of different variations of the same design, different pipes could be added to the collector and tests can be repeated to find the best outcome.
- In order to prevent the constant maintenance need, a glass cover or automated cleaning system could be added.
- Tests can be repeated in different seasons or with different angles to analyse the performance of the collector.
- Another method to produce the parabolic shape can be found to produce the shape more precisely.
- A tank with better insulation is required to keep the water heated for longer time.

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APPENDIX A: ELECTRONIC MEDIA

The following figure shows the project poster.

Figure 33. Project Poster

For more information please visit our website: https://umuratan96.wixsite.com/solarcollector This website contains videos and photos of our design for demonstration purposes. Following figure shows the main page of the project website.

Figure 34. Main page of the project website

APPENDIX B: CONSTRAINTS

B.1 Economic:

- The price of a similar design available in Chinese market is $1,000. However, in our design, it is aimed that the group use using maximum $500. Therefore, our design would suffer from cost limitations.
- As an unexperienced team, it is highly possible to make a design error, thus the possible loss of economic resources.
- It is necessary to consider that the potential impact of the design to Northern Cyprus' economy therefore, it would become a competitive alternative against the electricity.
- Designs for public use need to consider high maintenance cost in terms of cleaning dust, changing broken and rusty parts and general care.
- Due the economical limitations, the group is limited the cheapest product available in Turkish and Northern Cypriot markets.
- Because of the deadline and time limited the group's ability to produce better solutions for existing problems.

B.2 Environmental:

- The manufacturing process of the design would not produce dangerous materials for the landscape.

B.3 Political:

- Design is different than the Northern Cyprus government's main energy policies which are photovoltaic solar panels and thermic central.

B.4 Ethical:

- The design is used the products implicitly using patent protected designs and concepts.
- Products use materials that have better appearance but are toxic
- The design is fully based for profit
- Products for secrete survey of personal private life

B.5 Health and Safety:

- Hazardous materials in manufacturing are being used in the design without considering environment and workers
- Products require the use of non-recyclable materials
- Products use materials that have better appearance but are toxic
- Products for infants/children require special safety considerations

B.6 Manufacturability:

- The concept is designed entirely by students, which would have led many manufacturing mistakes.
- The design is highly optimistic in its calculations about efficiency-manufacturing cost ratio.
- Design is assumed that it would be perfectly symmetrical therefore statically balanced.
- The parabolic though is planned and calculated as a perfect shape, which would be impossible to manufacture.
- Weight of the final product was not considered as a high priority.
- The reflector chromium sheet is planned to be bended over the structure. If any welding is needed, it is not considered.
- Expect the MDF and pipe parts of the design, painting is not considered. Thus, it would create future problems.

B.7 Sustainability:

- In a long run, it is suspicious that parabolic through solar power would compete against fossil fuels and other renewable and unrenewable energy sources.
- Because of the complexity of the parabolic design, the life of the concept could be smaller than its competitors.
- Consideration of actual environmental factors like the temperature of source water, the temperature and radioactivity of the sun are highly changeable variables.
- All parts of the design are needed to have a similar designed life span to sustain its efficiency.
- Reliability and durability of the product's is questionable due to the complexity.

APPENDIX C: STANDARDS

C.1 Design and Manufacturing Standards:

ISO/TR 10217:1989. Solar Energy-Water heating systems-Guide to material selection with regard to internal corrosion.

EN 12975-1:2006 D A1:2010. Thermal solar systems and components-Solar Collectors-Part 1: General requirements.

EN 12977-1:2012. Thermal solar systems and components-Custom-built systems-Part 1: General requirements for solar water heaters and combi systems.

C.2 Testing Standards:

ANSI/ASHRAE Standard 93, 2010. Methods of Testing to Determine the Thermal Performance of Solar Collectors

ISO 9806-1:1994, 1994. Test Methods for Solar Collectors, Part 1: Thermal Performance of Glazed Liquid Heating Collectors Including Pressure Drop.

ISO 9806-2:1995, 1995a. Test Methods for Solar Collectors, Part 2: Qualification Test Procedures.

ISO 9806-3:1995, 1995b. Test Methods for Solar Collectors, Part 3: Thermal Performance of Unglazed Liquid Heating Collectors (Sensible Heat Transfer Only) Including Pressure Drop.

ISO 9553:1997. Solar energy-Methods of testing preformed rubber seals and sealing compounds used in collectors.

ISO 9808:1990. Solar water heaters-Elastomeric materials for absorbers, connecting pipes, and fittings-Methods of assessment.

EN 12977-2:2012. Thermal solar systems and components-Custom-built systems-Part 2: Test methods for solar water heaters and combi systems.

EN 12977-3:2012. Thermal solar systems and components-Custom-built systems-Part 3: Performance test methods for solar water heating stores

APPENDIX D: LOGBOOKS

D1: Logbook of Umur Atan

Umur Atan 140050

01/10/2018	Meeting withe the supervisor to discuss the selected capstone project
01/10/2018	Meeting with the group to discuss project plan
02/10/2018	Preparation of project timeline
22/10/2018	Researching background information
06/11/2018	Proposing and selecting designs
06/11/2018	Meeting with supervisor to discuss chapter 1 and chapter 2
21/11/2018	Started on cost analysis
04/12/2018	Preparing the testing plan to verify the objectives
01/12/2018	Preparing the Engineering drawings
09/12/2018	Researching the verified plan according to engineering standards
10/12/2018	Writing detailed constrains
10/12/2018	Meeting with supervisor to discuss design calculations and specifications
12/12/2018	Meeting with supervisor to discuss latest work on the project
01/02/2019	Started the manufacturing process of the collector (hangers, ribs and channels)
12/02/2019	Attached the chromium mirror into the chassis of the collector
14/02/2019	Researching alternatives for the receiver with both ends open

12/03/2019	Researching evacuated solar tubes
27/03/2019	spray painting the collector with anti-rust paint
04/04/2019	First test of the collector
30/04/2019	Designing an angle adjuster to allow manual turning
07/05/2019	Designing the frame
09/05/2019	Manufacturing the frame
13/05/2019	Assembling all of the collectors part together as a whole system
16/05/2019	First test of the collector without the protective film on the chromium mirror
17/05/2019	Data analysis of the first testing
18/05/2019	2nd testing and data recording
02/05/2019	Testing and recording data in a different weather
22/05/2019	Testing with shaded tank

D2: Logbook of Sondos Elgabroun

Sondos Elgabroun 1700470

01/10/2018	Meeting withe the supervisor to discuss the selected capstone project
01/10/2018	Meeting with the group to discuss project plan
10/10/2018	Started on report organization
26/10/2018	Researching and writing about the comparisons of concurrent solutions
06/11/2018	Meeting with supervisor to discuss chapter 1 and chapter 2
21/11/2018	Started on cost analysis
04/12/2018	Preparing the testing plan to verify the objectives

09/12/2018	Preparing the logbooks
10/12/2018	Meeting with supervisor to discuss design calculations and specifications
12/12/2018	Meeting with supervisor to discuss latest work on the project
01/02/2019	Started the manufacturing process of the collector (hangers, ribs and channels)
12/02/2019	Attached the chromium mirror into the chassis of the collector
14/02/2019	Researching alternatives for the receiver with both ends open
12/03/2019	Researching evacuated solar tubes
27/03/2019	spray painting the collector with anti-rust paint
04/04/2019	First test of the collector
30/04/2019	Designing an angle adjuster to allow manual turning
07/05/2019	Designing the frame
09/05/2019	Manufacturing the frame
13/05/2019	Assembling all of the collectors part together as a whole system
16/05/2019	First test of the collector without the protective film on the chromium mirror
17/05/2019	Data analysis of the first testing
18/05/2019	2nd testing and data recording
02/05/2019	Testing and recording data in a different weather
22/05/2019	Testing with shaded tank

D3: Logbook of Melisa Menteşoğulları

Melisa Menteşoğulları 15330083

01/10/2018	Meeting withe the supervisor to discuss the selected capstone project
01/10/2018	Meeting with the group to discuss project plan
23/10/2018	Researching for concurrent solutions
06/11/2018	Meeting with supervisor to discuss chapter 1 and chapter 2
14/11/2018	Doing the calculations for the design
26/11/2018	Researching for manufacturing processes for the design
01/12/2018	Writing the details of the manufacturing processes
01/12/2018	Preparing the Engineering drawings
10/12/2018	Meeting with supervisor to discuss design calculations and specifications
12/12/2018	Organizing the project report
12/12/2018	Meeting with supervisor to discuss latest work on the project
01/02/2019	Started the manufacturing process of the collector (hangers, ribs and channels)
12/02/2019	Attached the chromium mirror into the chassis of the collector
14/02/2019	Researching alternatives for the receiver with both ends open
12/03/2019	Researching evacuated solar tubes
27/03/2019	spray painting the collector with anti-rust paint
04/04/2019	First test of the collector
30/04/2019	Designing an angle adjuster to allow manual turning
07/05/2019	Designing the frame
09/05/2019	Manufacturing the frame
13/05/2019	Assembling all of the collectors part together as a whole system

16/05/2019	First test of the collector without the protective film on the chromium mirror
17/05/2019	Data analysis of the first testing
18/05/2019	2nd testing and data recording
02/05/2019	Testing and recording data in a different weather
22/05/2019	Testing with shaded tank
24/05/2019	Finalizing the technical report

D4: Logbook of Hüseyin Göktaş

Hüseyin Göktaş 120905

01/10/2018	Meeting withe the supervisor to discuss the selected capstone project
01/10/2018	Meeting with the group to discuss project plan
08/10/2018	Writing the detailed definition of the project
18/10/2018	Researching on the significance of the project
06/11/2018	Meeting with supervisor to discuss chapter 1 and chapter 2
15/11/2018	Researching for materials
21/11/2018	Started on cost analysis
24/11/2018	Searching for manufacturing processes to apply to the project
10/12/2018	Meeting with supervisor to discuss design calculations and specifications
12/12/2018	Meeting with supervisor to discuss latest work on the project
01/02/2019	Started the manufacturing process of the collector (hangers, ribs and channels)
12/02/2019	Attached the chromium mirror into the chassis of the collector
14/02/2019	Researching alternatives for the receiver with both ends open

12/03/2019	Researching evacuated solar tubes
27/03/2019	spray painting the collector with anti-rust paint
04/04/2019	First test of the collector
30/04/2019	Designing an angle adjuster to allow manual turning
07/05/2019	Designing the frame
09/05/2019	Manufacturing the frame
13/05/2019	Assembling all of the collectors part together as a whole system
16/05/2019	First test of the collector without the protective film on the chromium mirror
17/05/2019	Data analysis of the first testing
18/05/2019	2nd testing and data recording
02/05/2019	Testing and recording data in a different weather
22/05/2019	Testing with the tank shaded

D5: Logbook of Karim Ben Alashher

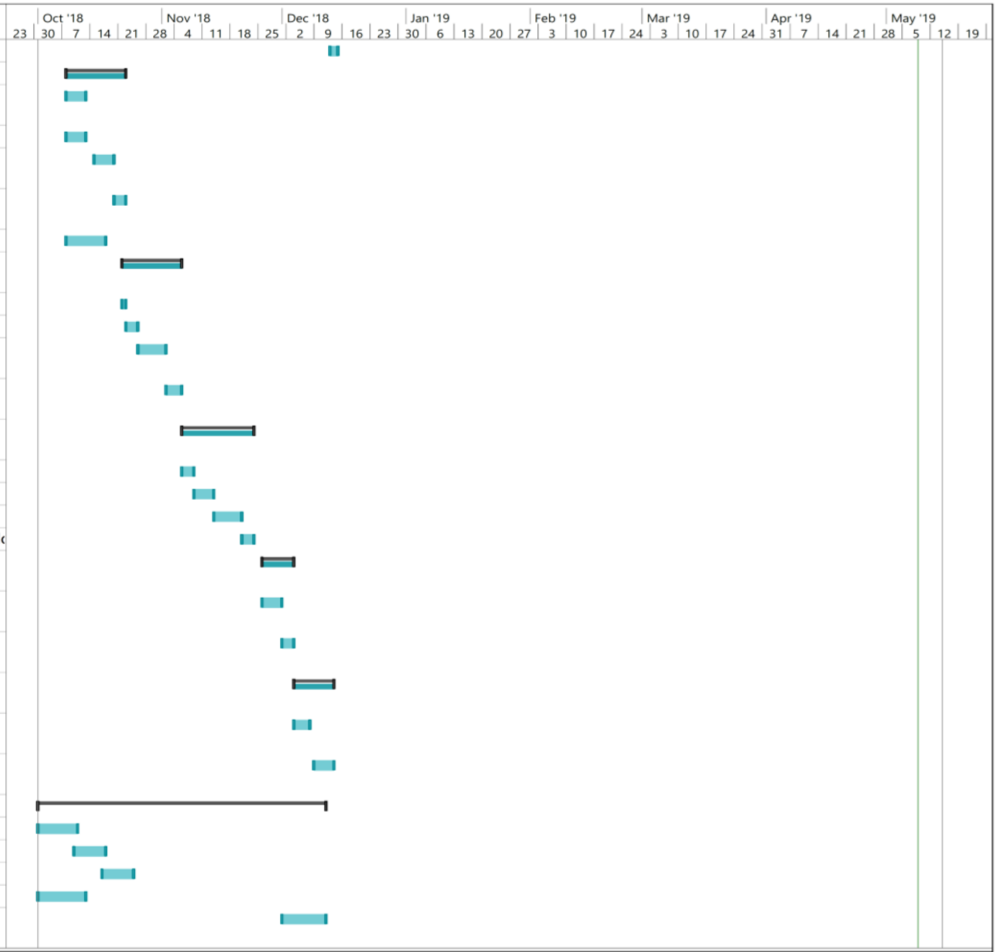
Karim Ben Alashher 15700690

01/10/2018	Meeting withe the supervisor to discuss the selected capstone project
01/10/2018	Meeting with the group to discuss project plan
15/10/2018	Writing detailed project objectives
20/10/2018	Writing detailed project constrains
02/11/2018	Researching Engineering standards for the concurrent solutions
06/11/2018	Meeting with supervisor to discuss chapter 1 and chapter 2
09/11/2018	Preparing Engineering standards for the design
04/12/2018	Preparing the testing plan to verify the objectives
09/12/2018	Researching the verified plan according to Engineering standards

10/12/2018	Meeting the supervisor to discuss design calculations and specifications
12/12/2018	Meeting the supervisor to discuss latest work on the project
01/02/2019	Started the manufacturing process of the collector (hangers, ribs and channels)
12/02/2019	Attached the chromium mirror into the chassis of the collector
14/02/2019	Researching alternatives for the receiver with both ends open
12/03/2019	Researching evacuated solar tubes
27/03/2019	spray painting the collector with anti-rust paint
04/04/2019	First test of the collector
30/04/2019	Designing an angle adjuster to allow manual turning
07/05/2019	Designing the frame
09/05/2019	Manufacturing the frame
13/05/2019	Assembling all of the collectors part together as a whole system
16/05/2019	First test of the collector without the protective film on the chromium mirror
17/05/2019	Data analysis of the first testing
18/05/2019	2nd testing and data recording
02/05/2019	Testing and recording data in a different weather
22/05/2019	Testing with shaded tank

APPENDIX E: PROJECT TIMELINE

ID	Task Mode	Task Name	Duration	Start	Finish	Assigned to
1		ABSTRACT	2 days	Thu 12/13/18	Fri 12/14/18	Melisa
2		**CHAPTER 1 - INTRODUCTION**	**11 days**	**Mon 10/8/18**	**Mon 10/22/18**	
3		1.1. Detailed definition of the project	5 days	Mon 10/8/18	Fri 10/12/18	Huseyin
4		1.2. Significance of the pro	5 days	Mon 10/8/18	Fri 10/12/18	Huseyin
5		1.3. Detailed project objectives	5 days	Mon 10/15/18	Fri 10/19/18	Karim
6		1.4. Detailed project constraints	2 days	Sat 10/20/18	Mon 10/22/18	Karim
7		1.5. Report Organization	8 days	Mon 10/8/18	Wed 10/17/18	Sondos
8		**CHAPTER 2 - LITERATURE REVIEW**	**11 days**	**Mon 10/22/18**	**Mon 11/5/18**	
9		2.1. Background informati	1 day	Mon 10/22/1	Mon 10/22/18	Umur
10		2.2. Concurrent solutions	3 days	Tue 10/23/18	Thu 10/25/18	Melisa
11		2.3. Comparisons of the concurrent solutions	5 days	Fri 10/26/18	Thu 11/1/18	Sondos
12		2.4. Engineering standards of the concurrent	2 days	Fri 11/2/18	Mon 11/5/18	Karim
13		**CHAPTER 3 -DESIGN and ANALYSIS**	**14 days**	**Tue 11/6/18**	**Fri 11/23/18**	
14		3.1. Proposed/Selected de	3 days	Tue 11/6/18	Thu 11/8/18	Melisa
15		3.2. Engineering standards	3 days	Fri 11/9/18	Tue 11/13/18	Karim
16		3.3. Design calculations	5 days	Wed 11/14/1	Tue 11/20/18	Melisa
17		3.4. Cost analysis	3 days	Wed 11/21/1	Fri 11/23/18	mur&Huseyin&Sondo
18		**CHAPTER 4 – MANUFACTURING PLAN**	**6 days**	**Mon 11/26/18**	**Mon 12/3/18**	
19		4.1. Manufacturing process selection	5 days	Mon 11/26/18	Fri 11/30/18	Melisa
20		4.2. Detailed manufacturing process	2 days	Sat 12/1/18	Mon 12/3/18	Melisa
21		**CHAPTER 5 - PRODUCT TESTING PLAN**	**8 days**	**Tue 12/4/18**	**Thu 12/13/18**	
22		5.1. Verification plan of the objectives of the	4 days	Tue 12/4/18	Fri 12/7/18	Umur
23		5.2. Verification plan of the applied engineering	5 days	Sun 12/9/18	Thu 12/13/18	Umur&Sondos
24		**APPENDIX**	**52 days**	**Mon 10/1/18**	**Tue 12/11/18**	
25		APPENDIX A: Constraints	8 days	Mon 10/1/18	Wed 10/10/18	Karim
26		APPENDIX B: Standards	6 days	Wed 10/10/1	Wed 10/17/18	Karim
27		APPENDIX C: Logbook	6 days	Wed 10/17/1	Wed 10/24/18	Sondos
28		APPENDIX E: Project Timel	10 days	Mon 10/1/18	Fri 10/12/18	Umur
29		APPENDIX F: Engineering Drawings	8 days	Sat 12/1/18	Tue 12/11/18	Melisa&Umur

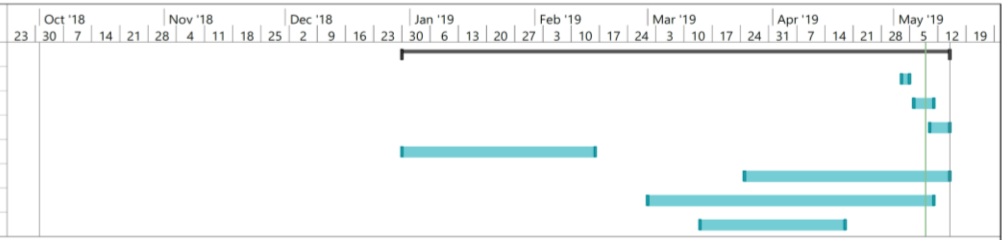


Project: Gantt_Chart_Capstone
Date: Thu 5/9/19

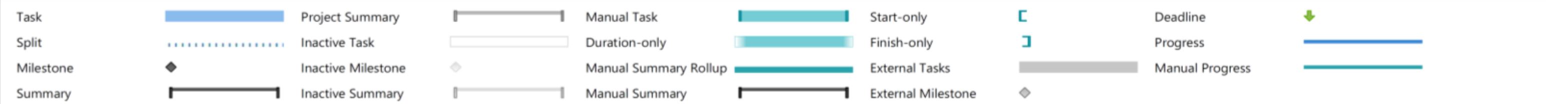
Task | Split | Milestone | Summary | Project Summary | Inactive Task | Inactive Milestone | Inactive Summary | Manual Task | Duration-only | Manual Summary Rollup | Manual Summary | Start-only | Finish-only | External Tasks | External Milestone | Deadline | Progress | Manual Progress

Page 1

ID	Task Mode	Task Name	Duration	Start	Finish	Assigned to
30		**CAPSTONE 2**	**97 days**	**Sun 12/30/1**	**Tue 5/14/19**	
31		Website	2 days	Fri 5/3/19	Sat 5/4/19	Umur
32		Presentation Slide	5 days	Mon 5/6/19	Fri 5/10/19	Umur
33		Poster	3 days	Fri 5/10/19	Tue 5/14/19	All
34		Manufacturing	36 days	Sun 12/30/1	Fri 2/15/19	All
35		Testing	37 days	Mon 3/25/19	Tue 5/14/19	All
36		Re-Organization of the Rep	51 days	Fri 3/1/19	Fri 5/10/19	Melisa
37		Re-Calculations	26 days	Thu 3/14/19	Thu 4/18/19	Melisa

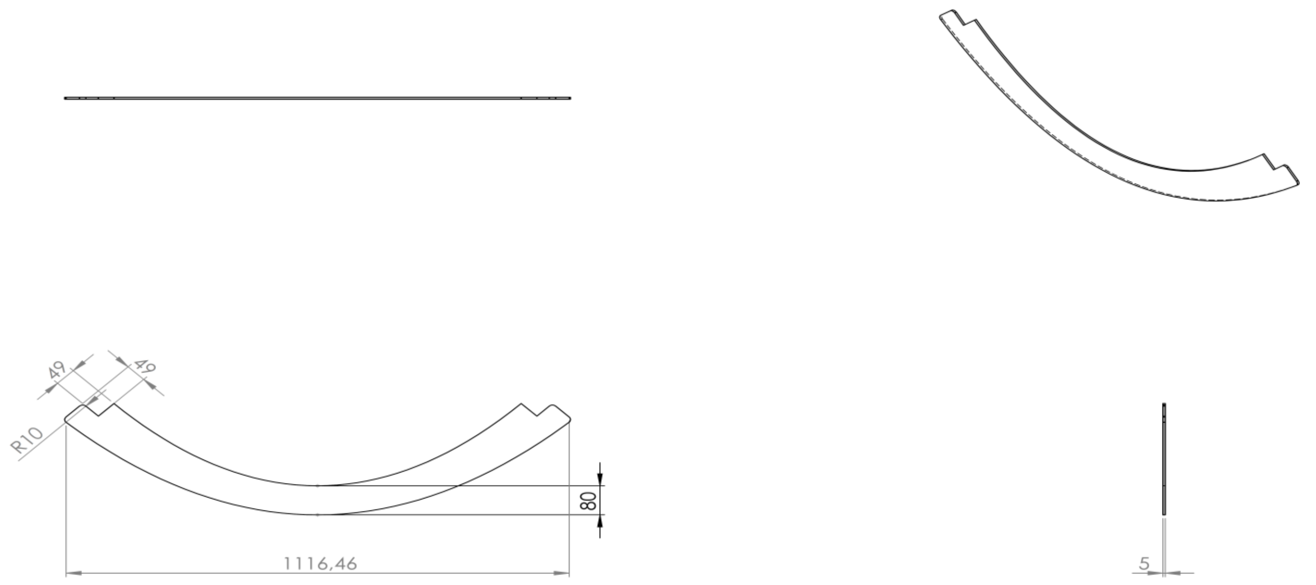


Project: Gantt_Chart_Capstone
Date: Thu 5/9/19



Page 2

APPENDIX F: ENGINEERING DRAWINGS



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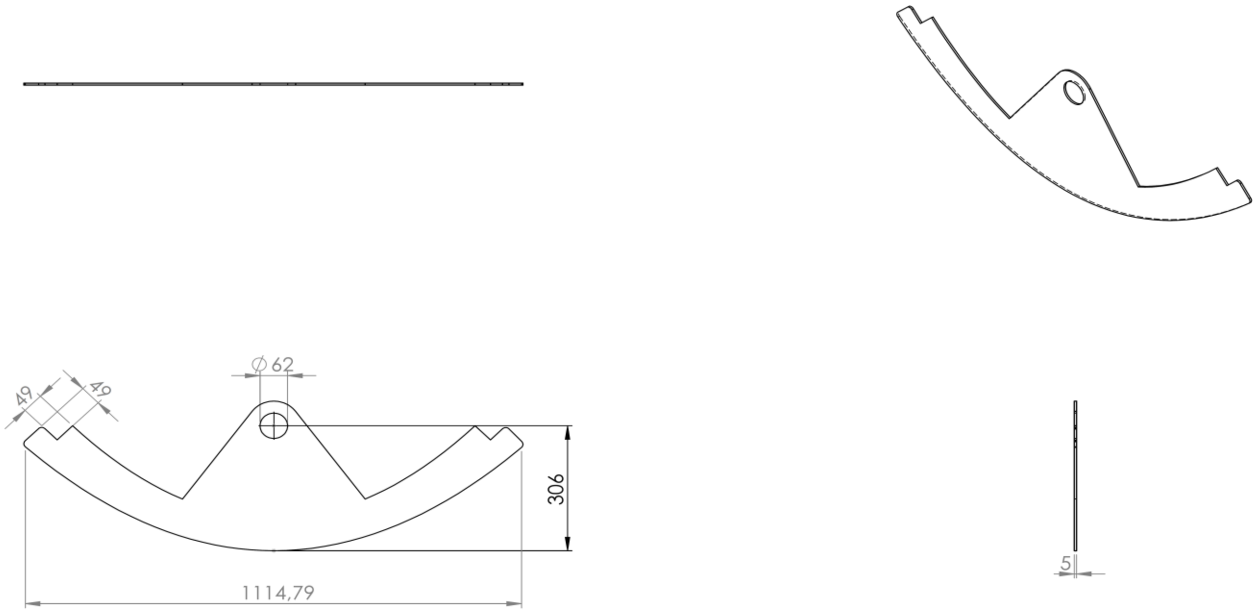
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:10	RIB			DRAWING NO 1



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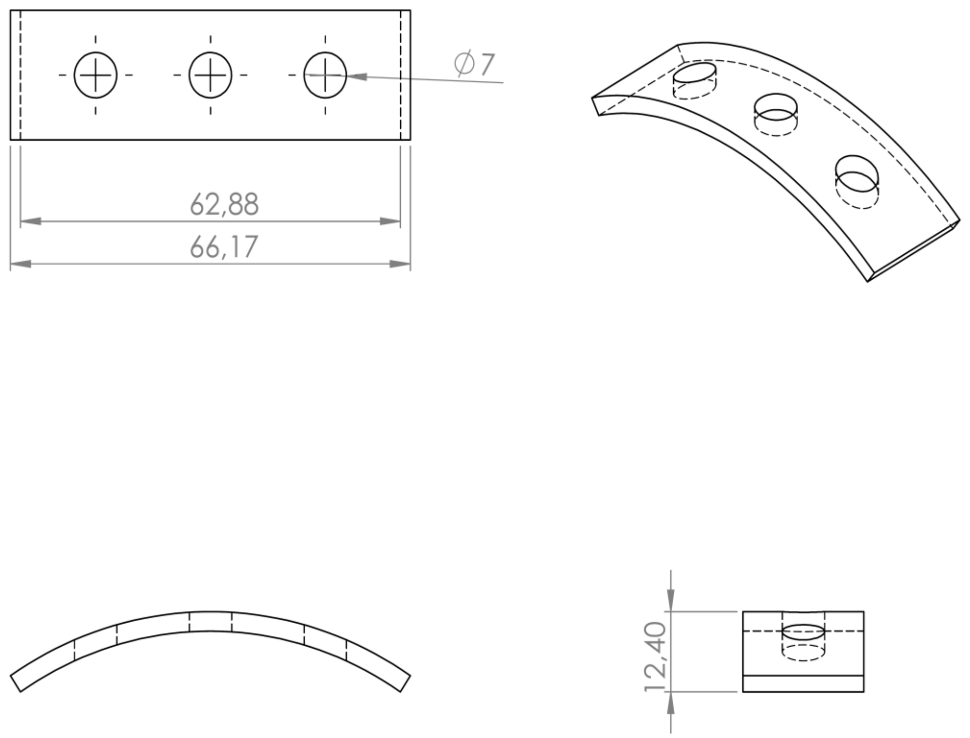
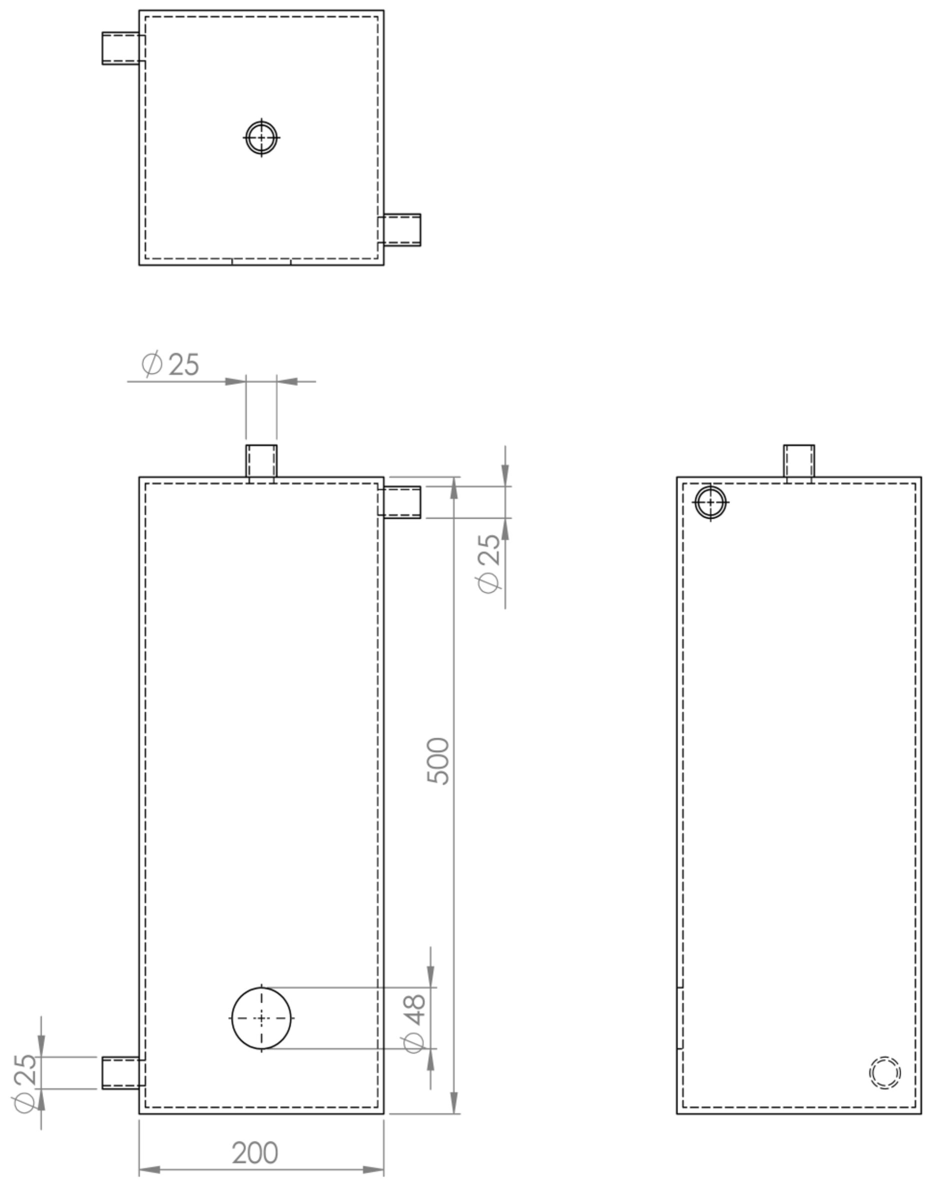
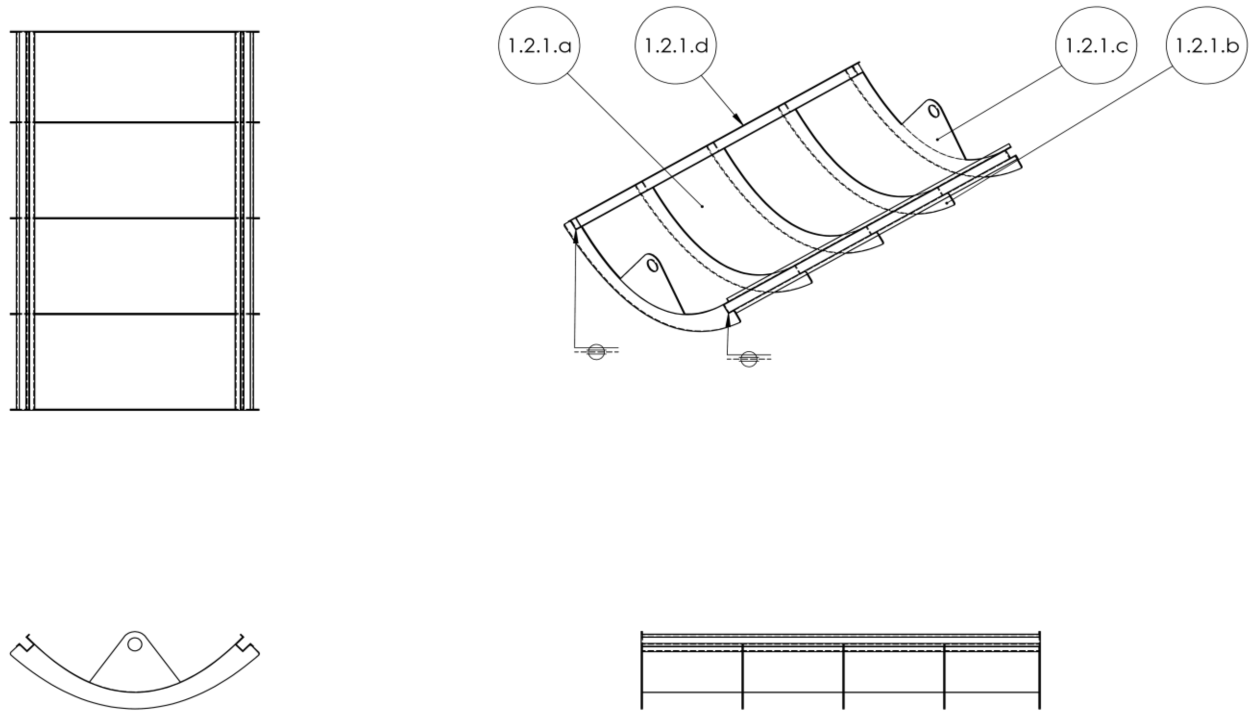
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:10	HANGER			DRAWING NO 2



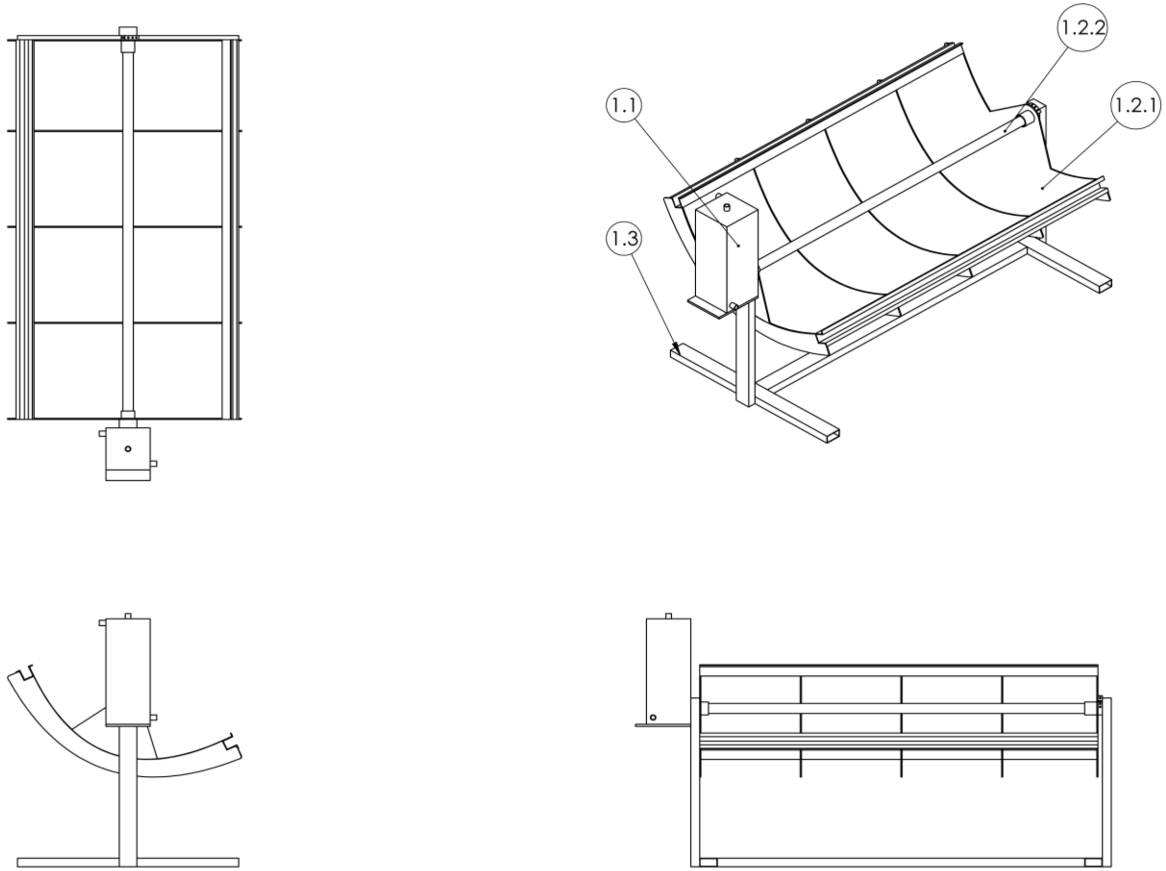
	NAME	DATE	SIGN	EMU
DRW. BY	MELISA	16-05-19	M.M.	
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:1	ANGLE ADJUSTER			DRAWING NO 3



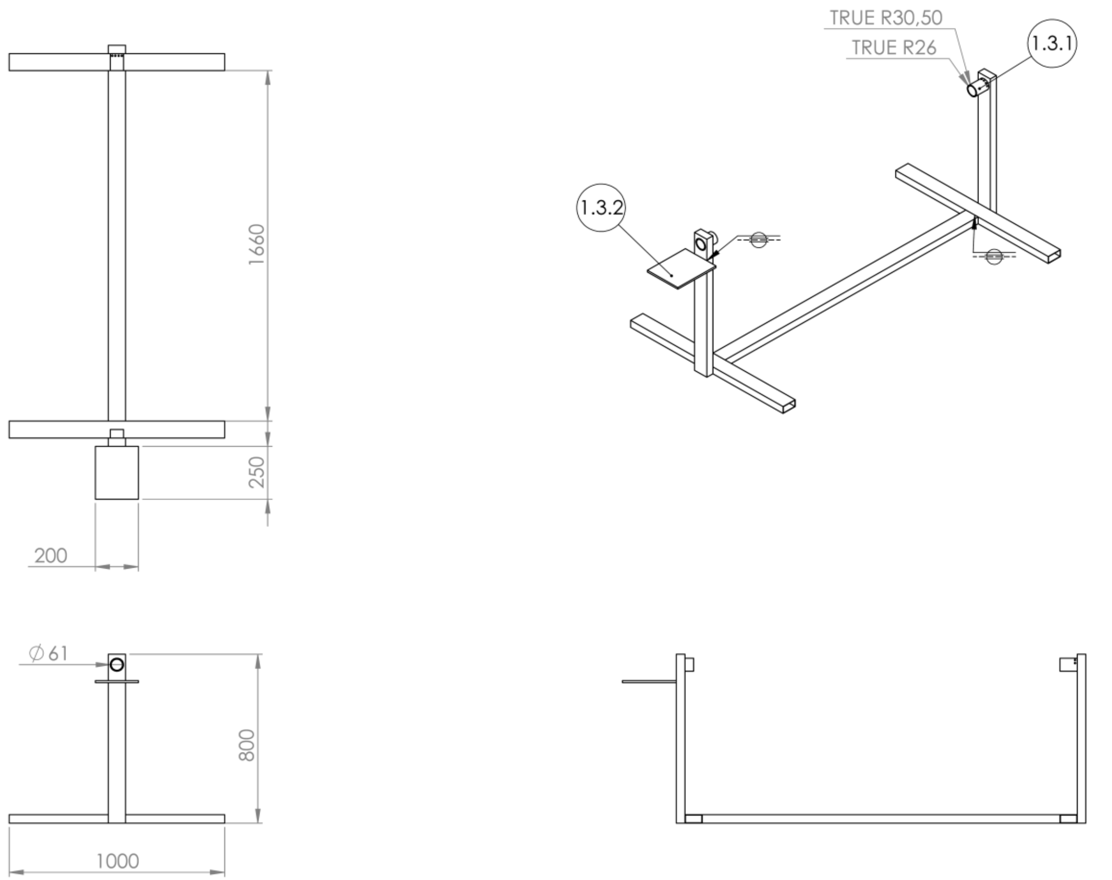
	NAME	DATE	SIGN	EMU
DRW. BY	MELISA	16-05-19	M.M.	
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:5	TANK			DRAWING NO 4



	NAME	DATE	SIGN	
DRW. BY	MELISA	16-05-19	M.M.	EMU
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:20	REFLECTOR ASSEMBLY			DRAWING NO 5



	NAME	DATE	SIGN	
DRW. BY	MELISA	16-05-19	M.M.	EMU
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:20	COLLECTOR ASSEMBLY			DRAWING NO 6



	NAME	DATE	SIGN	
DRW. BY	MELISA	16-05-19	M.M.	EMU
CHK. BY	UMUR	17-05-19	U.A	
SCALE 1:20	FRAME ASSEMBLY			DRAWING NO 7

APPENDIX G: ECONOMIC ANALYSIS

Economic analysis of parabolic trough concentrating collector for domestic water heating:

An electric water heater uses around 3 kW & assuming that people use it 2 times a day throughout the year. The current unit price of electricity depending on the time of the day are:

	Time	Unit price
1	09:00 - 18:00	1.29 TL/kWh
2	18:00 - 23:00	0.98 TL/kWh
3	23:00 - 09:00	0.65 TL/kWh

Electricity unit price is expected to show an increase of 5% per year. Considering the discount rate (g) and inflation rate (i) are 18.5% and 24% respectively. The payback period would be;

The parabolic trough solar concentrating collector costs around 1500 TL with an additional cost for installing in a house and attaching a 150-litre tank and insulating the tank during winter the total cost would be around 3000 TL.

$\dot{Q} = \dot{m}\, C_p\, \Delta T$

$\dot{m} = \frac{\dot{Q}}{C_p\, \Delta T} = \frac{3000\ W}{(4180\ J/kg℃)\ (20℃)}$ = 0.036 kg/s

Tank capacity: 150L = 150 kg

t = $\frac{150\ kg}{0.036\ kg/s}$ = 4166 sec = 70 mins

(The electrical water heater takes a little over 1 hour to heat the water in the tank since we assumed that electric heater is operated two times in a day, operation time is taken as 2 hours per day)

Yearly electrical consumption:

3kW x 2 hr/day x 365 day/year = 2,190 kWh/yearly

2190 kWh x 1.29 TL/kWh = 2825 TL/yearly

Present worth factor

r = $\frac{(i+g)}{(1-g)} = \frac{(0.185+0.24)}{(1-0.185)}$ = 0.521

PWF = $\frac{1}{(1+r)^n} = \frac{1}{(1.521)^n}$

Year	PWF
0	1
1	0.657
2	0.432
3	0.284
4	0.186

Savings:

Year	Unit price increasing	Yearly revenue
1	1.29	2825 TL/yearly
2	1.35	2956.5 TL/yearly
3	1.41	3087.9 TL/yearly
4	1.48	3241.2 TL/yearly

year	PWF	Capital cost	cum. Costs	Savings	Cum. savings
0	1	3000	3000	-	-
1	0.657	-	3000	1856	1856
2	0.432	-	3000	1277.2	3133.2
3	0.284	-	3000	876.9	4010
4	0.186	-	3000	602.8	4612.9

Payback period is 2 years.