UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

Solar thermal systems for domestic water heating in Cyprus and review of the latest advances

By

KYRIAKOS KOUTSOGIANNIS

Submitted in partial fulfillment of the requirements for the degree of Diploma in Mechanical Engineering at the University of Thessaly

Volos, 2023

UNIVERSITY OF THESSALY

SCHOOL OF ENGINEERING

DEPARTMENT OF MECHANICAL ENGINEERING

Solar thermal systems for domestic water heating in Cyprus and review of the latest advances

By

KYRIAKOS KOUTSOGIANNIS

Submitted in partial fulfillment of the requirements for the degree of Diploma in Mechanical Engineering at the University of Thessaly

Volos, 2023

Approved by the Committee on Final Examination:

Advisor Dr. NIKOLAOS ANDRITSOS

Professor, Department of Mechanical Engineering, University of Thessaly

Member Dr. VASILIS BONTOZOGLOU

Professor, Department of Mechanical Engineering, University of Thessaly

Member Dr. DIMITRIS VALOUGEORGIS

Professor, Department of Mechanical Engineering, University of Thessaly

Date Approved: [February 20, 2023]

Solar thermal systems for domestic water heating in Cyprus and review of the latest advances

KYRIAKOS KOUTSOGIANNIS

Department of Mechanical Engineering, University of Thessaly,2023

Supervisor: Dr. Nikolaos Andritsos
Professor of Operational Research

Abstract

In today's world, climate change and the recent energy crisis have led to an urgent need for societies around the world to transition away from fossil fuels and switch to renewable, more sustainable, and environmentally friendly energy sources. One of the best sources of renewable energy is solar energy, but the current technology hinders its exploitation in full due to various factors but mainly because of the gain-to-cost ratio. However, although solar energy is mostly used for producing electrical energy, it can be exploited for direct heating water using special panels.

Solar thermal heating is mostly used in Mediterranean countries and especially in the island of Cyprus where the solar coverage reaches its maximum in Europe and therefore the production efficiency shows a similar trend. Cyprus is an island in the Mediterranean where solar water heaters are used extensively, in fact, The cabinet of the island encourages and sponsors consumers to install or upgrade old installations with the latest technology which explains why Cyprus has the highest percentage of solar thermal installations per inhabitant. In addition, the new legislation for the construction sector states that part of the house energy must be provided by renewable energy sources.

n this study, the status of solar water heating in domestic use in Cyprus is reported and the latest technologies and innovations are explored to find the most efficient and reliable technologies for future use and further study. Innovative materials and designs that can enhance a solar collector's performance are mentioned. Additionally, environmentally friendly materials that are produced from natural sources and innovative geometries with lower manufacturing costs are stated. Based on the investigated improvements the future of the solar water heating market will keep growing and gain more attention. The state of solar thermal energy in Cyprus is being analyzed to identify the key factors behind the country's success in using solar thermal energy. By pinpointing these factors, other countries could potentially benefit from Cyprus's experience with solar thermal power.

Keywords: Solar water heating, domestic use, Cyprus, solar energy, solar thermal systems, innovations

Ηλιακά συστήματα θέρμανσης νερού οικιακής χρήσης στην Κύπρο και ανασκόπηση των τελευταίων καινοτομιών και εξελίξεων

ΚΥΡΙΑΚΟΣ ΚΟΥΤΣΟΓΙΑΝΝΗΣ

Τμήμα Μηχανολόγων Μηχανικών, Πανεπιστήμιο Θεσσαλίας, 2023

Επιβλέπων Καθηγητής: Δρ.Ανδρίτσος Νικόλαος,
Καθηγητής Επιχειρησιακής Έρευνας

Περίληψη

Στον σύγχρονο κόσμο το ενεργειακό πρόβλημα και η κλιματική αλλαγή ωθούν τον ανθρώπο να σταματήσει να χρησιμοποιεί ορυκτά καύσιμα και να στραφεί σε πιο φιλικές προς το περιβάλλον πηγές ενέργειας, όπως οι ανανεώσιμες πηγές ενέργειας. Μια από τις καλύτερες πηγές ανανεώσιμης ενέργειας είναι η ηλιακή ενέργεια, αλλά η τρέχουσα τεχνολογία εμποδίζει την πλήρη εκμετάλλευσή της. Ωστόσο, αν και η ηλιακή ενέργεια χρησιμοποιείται κυρίως για την παραγωγή ηλεκτρικής ενέργειας, μπορεί να αξιοποιηθεί για την άμεση θέρμανση νερού με τη χρήση ειδικών ηλιακών πάνελ.

Στις μεσογειακές χώρες, η ηλιακή ενέργεια χρησιμοποιείται κυρίως για την παραγωγή ζεστού νερού και ηλεκτρικής ενέργειας. Στο νησί της Κύπρου, οι ηλιακοί θερμοσίφωνες χρησιμοποιούνται ευρέως, αυτό καθιστά την Κύπρο το νησί με την μεγαλύτερη κατά κεφαλήν πυκνότητα ηλιακών συστημάτων θέρμανσης νερού, με 9 στις 10 κατοικίες να διαθέτουν ηλιακή θέρμανση νερού. Το Κυπριακό υπουργικό συμβούλιο προωθεί και χρηματοδοτεί τους καταναλωτές για εγκατάσταση νέων ηλιακών θερμοσιφώνων ή για την αντικατάσταση των πεπαλαιωμένων με πιο προχωρημένης τεχνολογιας. Στην Κύπρο, οι νέοι κατασκευαστικοί νόμοι επιβάλλουν ένα μέρος της ενέργειας του σπιτιού να προέρχεται από ανανεώσιμες πηγές.

Η παρούσα μελέτη καταγράφει την τρέχουσα κατάσταση της ηλιακής θέρμανσης νερού στην Κύπρο και διερευνά τις νεότερες καινοτομίες προκειμένου να προσδιοριστούν οι πιο αποτελεσματικές και αξιόπιστες λύσεις για χρήση στο μέλλον ή για περαιτέρω έρευνα. Η απόδοση ενός ηλιακού συλλέκτη μπορεί να βελτιωθεί με τη χρήση νέων υλικών και σχεδίων, τα οποία περιγράφονται. Αναφέρονται επίσης καινοτόμες γεωμετρίες με χαμηλότερο κόστος κατασκευής και με οικολογικά αποδεκτά υλικά που προέρχονται από φυσικές πηγές. Η κατάσταση της ηλιακής θερμικής ενέργειας στην Κύπρο αναλύεται για να εντοπιστούν οι βασικοί παράγοντες που οδήγησαν την χώρα στην επιτυχία της στη χρήση της ηλιακής θερμικής ενέργειας. Με τον εντοπισμό αυτών των παραγόντων, άλλες χώρες θα μπορούσαν ενδεχομένως να επωφεληθούν από την εμπειρία της Κύπρου με την ηλιοθερμική ενέργεια.

Λέξεις-κλειδιά: Ηλιακά συστήματα θέρμανσης νερού, οικιακή χρήση, Κύπρος, τελευταίες τεχνολοχίες

Contents

LIST OF TABLES

LIST OF FIGURES

1 Chapter 1. INTRODUCTION

Renewable energy sources are recognized as the most important element that is required to achieve a sustainable environment. Today's knowledge of environmental challenges like air and water pollution, the greenhouse effect, and global warming emphasizes the need for energy sources. The domestic-commercial sector consumes approximately more than one-third of the global electricity production. This sector includes households, offices, schools, hospitals, hotels, and other similar types of buildings. The consumption of electricity in this sector is mainly due to the use of heating, air conditioning, and water heating. In addition to that, in 2021 the direct emissions that come from space and water heating in buildings grew by 5.5%, reaching a new high of 2 500 Mt CO_2. The demand for electricity in the domestic-commercial sector is increasing rapidly due to the growing population and rising standards of living.

Renewable energy sources most of the time have zero emissions, so there are no harmful effects on the environment, unlike fossil fuels. For example, solar water heating systems have a low impact on the environment as they do not require any pipelines or drilling, also by relying only on the sun's energy they do not contribute to air pollution or water pollution, which can be harmful to both human health and the environment. By reducing our dependence on fossil fuels and transitioning to renewable energy, we can help reduce global carbon emissions and reduce the negative effects of climate change. Renewable energy sources are often domestically produced, which can reduce the dependence on foreign oil and natural gas, which results in less cost in energy production, and new job opportunities, which leads to the economic growth of a country. Furthermore, it is worth researching ways of improving the current technologies and finding more useful applications. Harnessing solar energy can help the world move toward a more sustainable environment without pollution.

However, despite the progress made in the adoption of solar water heating in Cyprus, there are still some challenges that need to be addressed. For instance, the initial cost of installing a solar water heating system can be relatively high, which may deter some consumers from making the switch. Additionally, there may be some technical and technological problems that do not help consumers to move into solar thermal energy due to performance issues.

In conclusion, the increase in the annually installed surface of solar water heating in Cyprus over the years is a positive sign that more consumers are recognizing the benefits of renewable energy. The government's support through legislation and sponsoring programs has played a crucial role in this development. As the country continues to promote sustainable energy practices, it is important to address any remaining barriers and encourage even more households and businesses to make the transition to renewable energy sources.

1.1 The sun

The sun is a 4.5-billion-year-old star and the core of our solar system. It is the shining star of our solar system, which constantly sends energy and light to the earth and is in the center of our solar system. The sun’s energy supports every life on earth and is responsible for the climate of the earth. It has the shape of a sphere with a diameter of 1,4 million kilometers; the density is said to be 100 times greater than that of water; and it consists mostly of hydrogen and helium. In effect, it operates as a non-stop fusion reactor and is held together by gravitational forces. The most important fusion reaction is hydrogen combining with uranium to form helium. The mass of a helium nucleus is 0.7 percent less than that of four protons, and during fusion, this lost mass is transformed into energy. The planets and all of the debris are all in orbit around the sun thanks to its gravity, which also binds the solar system together. The core's temperature reaches 15 million Celsius and the surface reaches 5,500 Celsius. The distance between the sun and the earth is 150 million kilometers, yet the energy that arrives on earth is enormous. On average, the sun spins on its axis every four weeks. It does not, however, revolve like a solid body, each rotation takes around 30 days for the northern regions and roughly 27 days for the equator. As shown in Figure 1.1 sun can be divided into 3 main layers: the core, where the nuclear reaction happens, the radiative zone, which is the biggest layer, and energy from the core is transported through radiation, as photons bounce off atoms and travel outwards, and the convective zone where energy is transported through convection, as hot gas rises and cool gas sinks (convective zone is where sunspots and solar flares are observed). The photosphere is the name of the outer layer of the sun and is a part of the convective zone, and most of the solar radiation originates from this layer due to its heavily ionized gases' ability to absorb and emit a broad spectrum of radiation.[1], [2],[3]

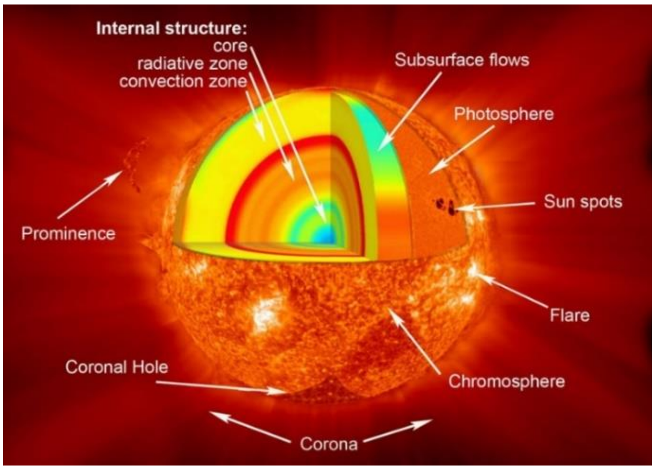

Figure 1.1: Sun’s anatomy (layers)[66]

1.2 Solar irradiance:

Radiation is the energy that a solid, liquid, or gas emits while it is at a specific temperature. This matter has the ability to absorb as well as reflect the radiant energy that is impinging on it. For solar radiation to arrive at the surface of the earth, it has to overcome some obstacles like the atmospheric layer, which modifies the spectrum by absorption and scattering. Long-wavelength radiation normally originates from lower-temperature sources, while short-wavelength radiation often comes from the sun or other high-temperature sources. Radiation that has a wavelength of less than 190 nm is absorbed by atomic and molecular oxygen and nitrogen. Short-wave UV light causes molecular oxygen in the atmosphere to photo-dissociate when it absorbs it, and because of this, ozone is created. Ozone poorly absorbs visible radiation and substantially absorbs longer-wavelength UV between 200 and 300 nm in the Hartley band. The total quantity of energy the Earth receives from the Sun at its zenith varies with the Earth's distance from the Sun and, therefore, the season. When the sun is at its zenith, direct sunlight reaching Earth's surface is approximately 1050 W/m2, but the total amount of sunlight reaching the ground is approximately 1120 W/m2. This is assuming that total extraterrestrial solar radiation is 1367 W/m2. Only a percentage of the total solar energy reaches the earth's surface due to changes in the sun's radiation upon entrance into the atmosphere as mentioned before and due to the enormous distance between the sun and our planet. As shown in figure 1.2, the average distance of about 149.5 million kilometers. [2]

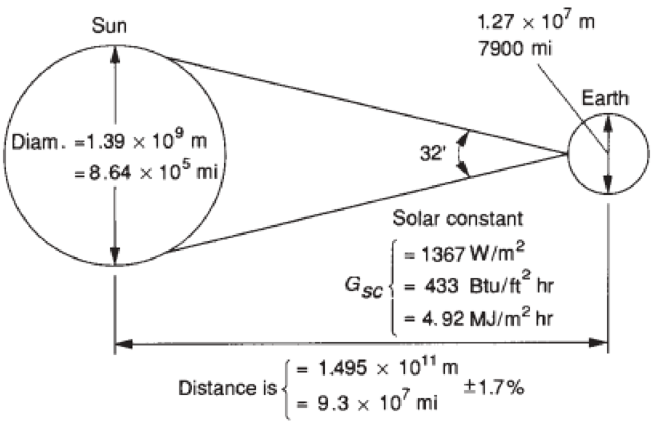

Figure 1.2: Sun and earth relation and solar constant [2]

Solar radiation that reaches the Earth's surface can be divided into three main types based on how it arrives, which can be shown also in figure 1.3:

- Diffuse solar radiation: This is the radiation that eventually makes it to the Earth's surface after repeated route changes, such as those caused by atmospheric gases.

- Direct solar radiation: Without dispersing at all along the way, this kind of radiation passes through the atmosphere and reaches the surface of the Earth.
- Reflected solar radiation: The albedo effect is a phenomenon in which a portion of solar energy is reflected by the earth's surface itself.

Global radiation: Direct, diffuse, and reflected radiation together make up global radiation.

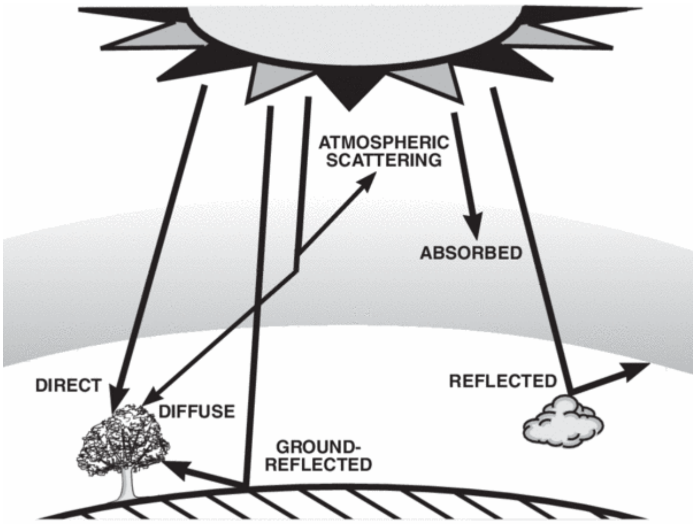

Figure 1.3: Total radiation forms on earth[64]

1.3 Heat Exgange phenomena

1.3.1 Convection Heat Transfer

Convection heat transfer occurs between a limited surface and a fluid when they are at different temperatures. Convection falls into two categories: natural convection and forced convection. With natural convection, the fluid creates movement when it is heated, this occurs because the fluid's density decreases and it gets lighter than the cold fluid in the system. For example, when the hot fluid in a pipe rises and the cooler fluid comes to take its place, this movement causes the fluid to circulate. Forced convection requires a fan or a pump to move the fluid in the system.[1] The convection heat transfer can be measured by equation 1.2:

$$\dot{Q}_{Conv} = hA_s(T_s - T_\infty) \tag{1.2}$$

where $\dot{Q}_{Conv}$ is the convective power, the heat exchange coefficient h, which is inversely correlated with the temperature differential between the heated surface T_s and the surrounding air T_∞. According to Incropera and Dewitt convection heat transfer coefficients can be considered according to Table 1.1:

Process	h [W/m^2-K]
Natural Convection	
Gases	2-25
Liquids	50-1000
Forced Convection	
Gases	25-250
Liquids	100-20,000

Table 1.1: General convection heat transfer coefficient values [1]

1.3.2 Conduction heat transfer

Thermal conduction is the transport of heat through stationary fluids or solids. It takes place inside the body of a solid or between two solids in contact, without the aid of mass movement or mixing. It is the direct microscopic transfer of particle kinetic energy across the border between two systems. This mechanism occurs with lattice vibration and particle collision. Molecular collisions are the main source of heat conduction in stationary fluids, however, in solids, this mechanism is not possible. In a solid with two different temperatures at opposite sides, the hot side undergoes more violent atomic movements, and as a result, the energy is transferred to the cold side. Thermal equilibrium is eventually reached by both sides when all atoms vibrate with the same energy. Metals and fluids are usually stronger thermal conductors than ceramic materials, which have fewer free electrons since electron collision-based conduction is more efficient than lattice vibration-based conduction.[1] The conduction heat transfer can be measured with Fourier's equation (1.3):

$$\dot{Q}_{cond} = kA\frac{dT}{dx} \tag{1.3}$$

where T is the temperature differential between two surfaces separated by a distance dx,k is the corresponding thermal conductivity and A is the cross-sectional area through which the heat is conducted.

1.3.3 Radiation heat transfer

For the majority of technical heat transfer applications in solar water heating, the solar energy is transferred to the collector with radiation. Radiation plays a key role in solar water heating systems, and that is the reason why solar thermal systems are placed on the roof, to be able to capture solar energy through radiation heat transfer. Radiation heat transfer is a type of heat transfer that involves the transfer of energy through electromagnetic waves without the need for a physical medium. This type of heat transfer is responsible for the transfer of energy from the sun to the earth and from hot objects to cooler objects in our daily environment. For all materials with a temperature higher than -273,14 °C, the radiation emittance to its surroundings starts. In radiation heat transfer, heat is transferred in the form of electromagnetic radiation, which can travel through a vacuum or any transparent medium, such as air, glass, or water. The rate of radiation heat transfer depends on the temperature of the emitting object, the surface area of the emitting object, and the distance between the emitting object and the receiving object.

The thermal radiation range consists of ultraviolet (UV) radiation, the entire visible spectrum, and infrared (IR) radiation, which can be further divided into four subcategories. The first subcategory is called the near-infrared (NIR) band, which ranges from 0.7 to 1 µm, while the second is the short-wave IR (SWIR) band, ranging from 1 to 2.5 µm. These spectra are usually produced by object reflections, much like radiation in the visible spectrum, but they are invisible to the human eye and are classified as non-thermal forms of infrared radiation. The mid-wave infrared (MWIR) band spans from 3 to 5 µm, and the long-wave infrared (LWIR) band spans from 7.5 to 14 µm. Both of these radiation bands originate from an object's surface thermal emissions, rather than reflections, and are considered to be the primary sources of thermal radiation.[1]

Radiation heat transfer is an important phenomenon in many industries and fields, including building and construction, heating and cooling, and renewable energy. Understanding the principles of radiation heat transfer can help engineers and scientists design more efficient systems and technologies that harness or manage heat in various applications. The radiative heat transfer interaction between an item and its surroundings is described with regard to wavelength using an equation (1.1):

$$\dot{Q}_{rad} = \sigma \varepsilon_{\lambda} A (T^4 - T_{\infty}^4) \quad (1.1)$$

where A is the surface area of the object, 5.67x10-8 W/m2-K4 is the Stefan-Boltzmann constant, and T is the surrounding temperature.

1.4 Solar water heating

Solar water heating (SWH) is the process of using a solar thermal collector to convert sunlight radiation into heat and then transfer heat to a fluid that flows inside the collector. The collected energy can be used for heating water, or air for later use It can be used for process heating, hot water delivery, distillation, and area heating or cooling in buildings. Solar water heating is considered to be a clean and renewable energy source because some solar thermal collectors do not require a pump or a fan to work, just the sun's radiation.

1.5 Scopus and structure of this study

This study aims to explore the status of solar water heating in Cyprus, as it is one of the leading countries in this area. Also, this study aims to investigate some of the latest technologies and innovative materials that will enhance the solar collector's efficiency.

Cyprus's legislation and the Cypriot Cabinet's sponsors provide an example for other countries with similar climate conditions to use solar water heating in domestic households. Adding some of the investigated new materials and designs to the solar collectors market can encourage consumers to turn to the direction of solar energy, which is a renewable source and environmentally friendly. Innovative materials and geometries can also save on production costs and have a positive environmental impact because of their straightforward designs and accessible natural materials.

The information in this chapter covers the potential for renewable energy that is currently accessible, why solar energy must be used more over time, and the necessity for solar collector technologies to help us harness solar energy. Also, there is an introduction to the sun and the energy that it provides.

Chapter 2 contains an overview of the solar water heating systems used for domestic use. The different types of systems and their working principles and parts are explained.

Chapter 3 includes a status analysis of solar water heating in Cyprus and a detailed explanation of the minimal requirements for a solar water heating system on new residential houses. Furthermore, the results of a questionnaire from 1,000 residential households in Cyprus help to better understand the situation in Cyprus.

In chapter 4, some of the latest and most advanced innovations in solar water heating are presented. It contains new designs and materials that can enhance a solar water heater. Also, some environmentally friendly materials are presented that can be used and have the same or even better results than other traditional materials. It also contains some new and better thermal energy storage systems and high-efficiency photovoltaic thermal solar collectors.

The last chapter of this study contains a conclusion on the situation in Cyprus and what motivates the island's residents to use solar water heating. Also, some of the best innovations and designs presented in the previous chapter are mentioned. Suggestions for further study on some materials and parts that can be improved are also contained in this chapter.

2 Chapter 2. Solar water heating

2.1 Introduction

Solar energy collectors are a unique class of heat exchangers that convert radiation from the sun to heat and transfer that to the circulating fluid, which is usually water or oil. The energy that is collected is transferred to another fluid or to a thermal energy storage tank to be used later. Solar collectors fall into two categories: non-concentrating and concentrating. While the non-concentrating collector has the same area for capturing and absorbing solar radiation, concentrating solar collectors must track the sun to capture and concentrate the sun's radiation to a smaller receiving area through concave reflecting surfaces; this way the radiation flux increases.

2.2 Solar water heating systems (SWHS)

SWHS falls into two categories for domestic use, passive water heating systems, and active solar heating systems:

- Passive solar water heating systems are the type of systems that do not need a pump. Warm fluid spontaneously rises through the solar collectors and into the storage tank. When this occurs, colder water at the storage tank's base is driven out and flows down to the collectors' bottoms where it will be heated.

- Active solar water heating systems (ASWH) circulate the working fluid through the system using one or more pumps, as opposed to passive systems. ASWH can be divided into direct circulation and indirect water heating systems. Direct systems use only one fluid, which circulates through the collector and the storage tank to be headed. Indirect systems use two fluids, the fluid that circulates through the collector to collect heat and then circulates through a heat exchanger inside the storage tank to reject the heat that possesses.

2.3 Solar collector types

For domestic use, stationary collectors are the most common because they are simpler and cheaper than sun-tracking collectors. The three stationary collectors are the flat plate collectors (FPC), the stationary compound parabolic collectors (CPC), and the evacuated tube collectors (ETC). The collectors must face south in the northern hemisphere and north in the southern hemisphere, both directed toward the equator. The best tilt angle for the collector depends on the application and is equivalent to the latitude of the region, with angle variations of 10 to 15 degrees. These types of solar thermal collectors are one of the most popular ways to use the energy from the sun's rays because of their low cost, straightforward construction, and easy usability. Unlike tracking collectors for example parabolic collectors, which require additional consideration for self-shading and wind loading, these collectors are simple to install in buildings with integrated applications.

2.3.1 Flat plate collectors using liquid (FPC)

Flat plate collectors are the most researched technique for producing household water. The solar radiation arrives at the collector and warms a dark surface which transfers the energy to the liquid for later use. A significant amount of solar energy is absorbed by the plate as it collides with the darkened absorber surface of high absorptivity after passing through a transparent cover. This energy is then transferred to the fluid within the tubes to be taken away for storage or consumption. To minimize conduction losses, the side of the casing and the underside of the absorber plate are adequately insulated. The liquid tubes may be an inherent component of the absorbing plate, or they may be welded to the plate. The glass allows for the maximum amount of solar radiation while minimizing the upward loss of heat. The longwave radiation emitted by collector plates is essentially invisible to glass, but when it is absorbed, it raises the temperature of the glass and loses heat by radiation and convection to the environment.[4]

As shown in figure 2.1, a flat plate collector consists of the following main parts:

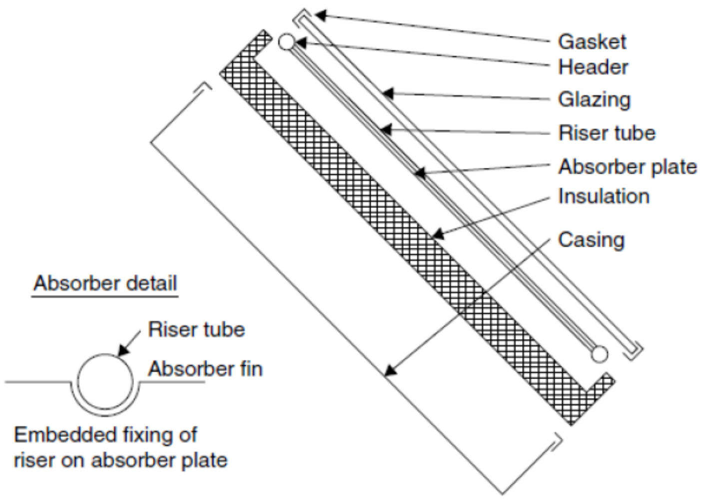

Figure 2.1: Flat plate collector components [65]

- Absorber plate:
  A black surface that can absorb solar energy, is usually made of copper in thin sheets.

- <u>Glazing:</u>
  A transparent glazing cover capable of transmitting radiation made of glass or plastic.
- <u>Interior tubes</u>:
  Pipes that are responsible for the heat transfer fluid inside the collector to remove heat.
- <u>Case</u>:
  A framework that contains and protects the components from dust, water, and moisture.
- <u>Insulation:</u>
  insulation for reducing heat losses with materials with low heat conductivity to reduce heat transfer from the collector’s case to the environment.

Two types of flat plate solar water heating systems are mainly used:

- Close-couple thermosiphon is the most used system for solar water heating. It consists of horizontally mounted storage tanks directly above the solar collectors, together with roof-mounted solar collectors as in figure 2.2. This type of system does not need a pump. Warm fluid spontaneously rises through the solar collector's tubes and into the storage tank. When this occurs, colder water at the storage tank's base is driven out and flows down to the collectors' bottoms where it will be heated.[5], [6]

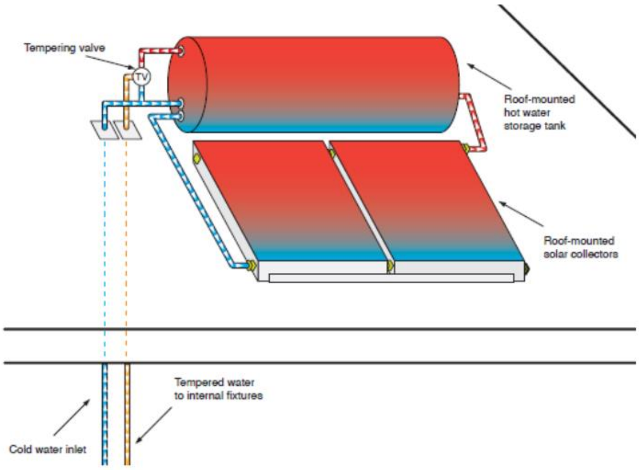

Figure 2.2: Close-couple thermosiphon system[5]

- Split systems: In a split system, the tank is often placed at ground level and below the level of the collectors as shown in figure 2.3. So, a thermostatically regulated pump must be used to move water from the tank to the collectors and back. Solar water heaters can either use a heat exchange fluid to transport heat between the solar collector and storage tank or they can directly transfer heat to water, these two methods of heating the water in storage are referred to as open circuits and closed circuits, respectively.[5], [6]

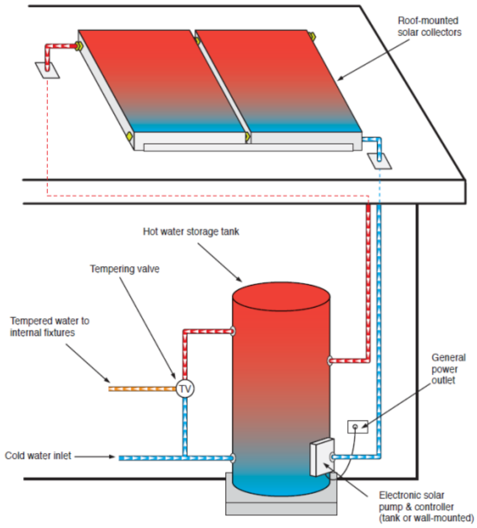

Figure 2.3: Split system[5]

2.3.2 Compound parabolic collectors

CPCs are concentrators without imaging capabilities. These are capable of reflecting all incident radiation to the absorber throughout a wide range. By utilizing a trough with two parabola-shaped portions facing each other, the need to move the concentrator to account for the shifting sun position may be minimized. Any radiation entering the aperture and falling within the collector acceptance angle is reflected numerous times inside until it reaches the absorber surface at the collector's bottom. There are lots of absorber designs available, but the most common is cylindrical; its design is shown in figure 2.4. The absorber is covered with glass to avoid any dust or anything that can reduce the absorber’s reflectivity. For this type of system, the collector must be oriented with its long axis along the east-west direction; this way, the collector must be adjusted every few months for better efficiency and not every few hours. The minimum acceptance angle for stationary CPC collectors deployed in this mode is 47 degrees. Only when the sun is inside the collector's acceptance angle can radiation be collected. CPCs are not so popular for domestic use because of the high temperatures of the fluid.[7]

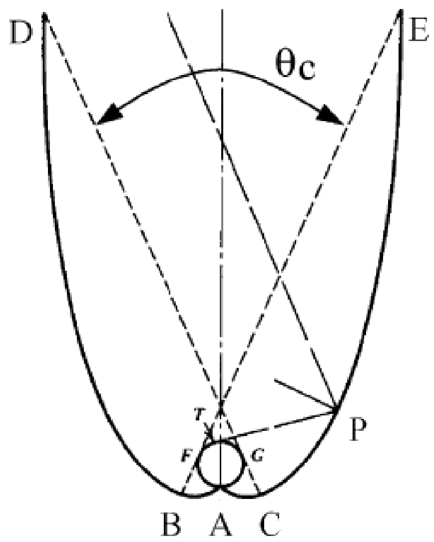

Figure 2.4: Schematic diagram of a compound parabolic collector [7]

2.3.3 Evacuated tube collectors (ETCs)

Evacuated tube collectors were designed to perform in cold climates and on cloudy days, unlike flat-plate collectors. ETCs are made of a heat pipe enclosed in a vacuum-sealed tube, which is like a bulb attached to the manifold. The vacuum-sealed tube is designed to reduce convection and conduction losses, so the collectors are capable of operating at temperatures greater than FPC.ETCs can perform better in total than FPCs because of their higher efficiency due to lower incidence angle acceptance. ETC's distinguishing characteristic is the heat pipe's built-in resistance to freezing and overheating since there is no possibility of evaporation or condensation above the phase-change temperature. [7], [8] The three types of evacuated tube collectors that are mainly used are:

- Water-in glass collectors: this type of collector consists of water pipes that are connected to the storage tank by a single end. The water pipes are made of glass, and they are inside a glass tube with a vacuum as the schematic represents in figure 2.5. The water is transferred through the pipe without any help from a pump. When the water is heated by solar energy the hot water rises to the storage tank and is substituted by the colder. [8]

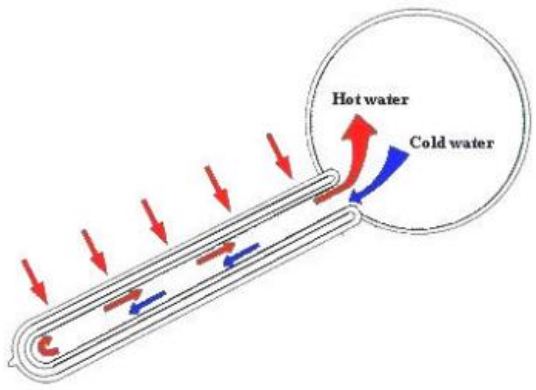

Figure 2.5: Schematic representation of water-in glass collector [63]

- U-type: this type of collector allows thermal fluid to enter the absorber directly, which is placed within the tube vacuum. The absorber is now a tube with fins attached to it and it's made of metal, usually copper. The absorber's surface is painted with black selective paint, to collect greater amounts of solar radiation. The vacuum tube has a single end, where the absorber's inlet and outlet go through, making the shape of the absorber like a "U", as shown in figure 2.6:

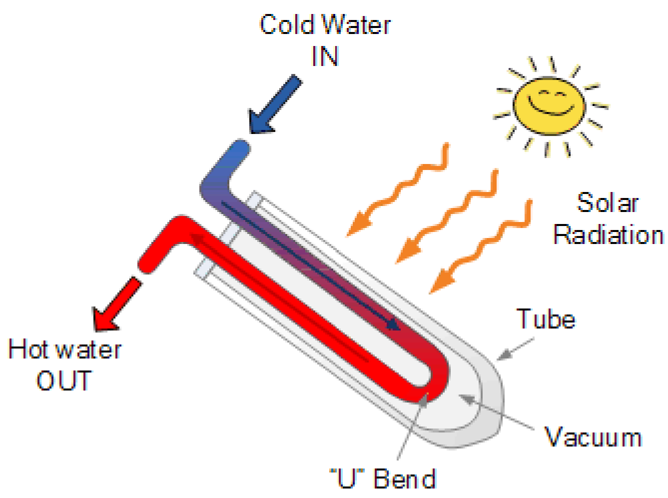

Figure 2.6: Schematic representation of U-type collector[63]

- Heat pipe: The absorber, which is housed inside the tube vacuum, receives the heated fluid directly. The absorber plate is a fin attached to the heat pipe and both are made of copper or aluminum (both very good thermal conductors). The fluids within the heat pipe are methanol or ethanol with water, which are alcoholic solutions that evaporate at low temperatures. The fluid undergoes a cycle in which it evaporates and condenses each cycle, to increase heat transfer efficiency. When the fluid enters the tube and collects the solar heat it evaporates, then the vapor is transferred to the heat exchanger(manifold) to release the heat and condense. The same fluid is then returned to the solar collector and the process is repeated. Inside the manifold water or glycol flows to collect the heat from the tubes. Then the same fluid is transferred to another heat exchanger to transfer its heat to another fluid in the storage tank. A representation of this collector is provided in figure 2.7:

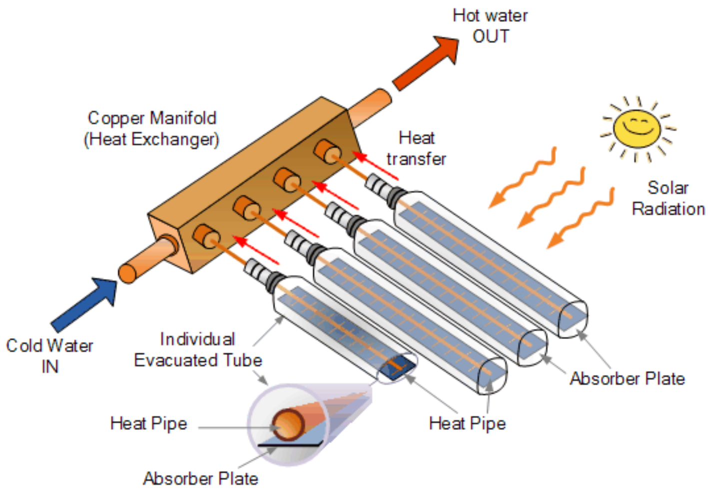

Figure 2.7: Schematic representation of Heat-pipe collector [8]

3 Chapter 3. Cypriot legislation for solar energy and penetration

Cyprus now relies totally on imported fuel to meet its energy needs because it lacks any natural oil resources at the moment. Solar energy is now the best form of energy that is natural and available. Solar energy is used extensively for heating water in households, hotels, and industries. The sum of the total annual radiation in Cyprus is about 1,790 kWh/m^2 per year, about 70% is direct radiation and 30% diffuse. The island receives 9.8 hours of sunshine on average in December and 14.5 hours in June. Most of the installed units are thermosiphonic type, which consists of 2 flat-plate solar collectors with 3 or 4 m^2 for the area of the absorber.

3.1 Legislation for solar water heating for domestic use

According to the decree "On minimum energy efficiency requirements for buildings, 2009", of the Minister of Trade, Industry, and Tourism, the use of solar water heating systems is mandatory in new buildings used as residences. For each system to comply with the law, there is a Solar Systems Technical Guide issued by the Service of Energy of the Ministry of Trade, Industry, and Tourism, which specifies the minimal specifications. In 2009, the minimum specifications based on the CYS ISO 9459-2:1995 standard were for :

- Minimum hot water storage capacity in liters
- Minimum total power of the collectors of the solar water heater in Watts
- The minimum total surface of the collectors of the solar water heater in square meters

The minimum specifications for a Close-couple thermosiphon system based on Solar Systems Technical Guide are shown in table 3.1:

Number of bedrooms	**Minimum hot water storage capacity in liters**	**Minimum total power of the collectors of the solar water heater in Watts**		**The minimum total surface of the collectors of the solar water heater in square meters**
1	90	422	**Or**	1,5
2	150	715		2,6
3	200	990		3,6
4	250	1265		4,6
More than 4 bedrooms	The project designer can specify a solar thermosiphon system that will prove to satisfy the needs of the specific residence.			

Table 3-1: minimum values for a Close-couple thermosiphon system

If the total surface of the solar collector is determined based on the power of the collector, the following equation (3.1) is applied for the minimum total requested surface of the collectors:

$$MTRS = \frac{MTP\ (watts)}{PC\ (\frac{watts}{m^2})} \qquad (3.1)$$

Where:

- MTRS = Minimum total requested surface of the system's collectors in square meters.
- MTP = Minimum total power of the collectors of the solar water heater in Watts for the number of bedrooms based on table 3.1
- PC = Power of the collector in watts per square meter of collector surface

In a case where a Split system is used, the minimum surface area of the solar collectors (in m^2) is corresponding to the total number of bedrooms that are connected to the system when the minimum power per square meter of solar surface collector is 320 Watts. In cases where the solar panels have different power from the 320 watts per square meter, the needed surface for the solar collector is calculated using the equation (3.2):

$$TRS = \frac{NB \times\ 320\ (\frac{Watts}{m^2})}{CP\ (\frac{Watts}{m^2})} \qquad (3.2)$$

Where:

- TRS = total requested surface of solar collector in square Meters
- NB = number of bedrooms
- PC = Collector's power in Watts per square meter of collector surface

The capacity of the storage tank for the hot water in split systems, for apartments and households with one bedroom, is set at 90 liters. For houses and apartments with more than one bedroom the capacity of the storage tank is calculated using the equation (3.3):

$$CST = \left(NB \times 50\ (liters)\right) + 50\ (liters) \qquad (3.3)$$

Where:

- CST = capacity of the hot water storage tank
- NB = number of bedrooms

3.2 Solar water heating status in Cyprus

Cyprus for the past 10-15 years is leading in the sector of the total energy used in domestic houses, with an average of 17% of the total energy being covered by solar thermal collectors. This result comes from the fact that Cyprus is the country with the second highest percentage of installed solar water heating systems per inhabitant (1 m^2 per habitant), with an estimated 93,5% of households, 80% of tourist accommodations, and 53% of hotels having these systems. Specifically, for 2020, the estimated total installed surface of solar panels was 834,339 m2 and the installed capacity was 582 MWth, these numbers may not seem high but Cyprus is an island with less than 1.3 inhabitants. Also, thanks to particular incentives and legislation these percentages keep increasing, for example in 2008 solar water heaters are needed by law for the generation of hot water in all new homes constructed. A few years later in 2017, all newly constructed single-family homes must meet 25% of their energy needs with renewable energy sources like solar water heaters.

For the past years and until today, the Cypriot cabinet sponsors consumers to change the old, low-efficiency solar water heating system with new high-efficiency solar collectors. For example, in 2022 the cabinet approved 600,000 euros in an incentive program to encourage residential owners to replace the old or install new solar collectors. The program gives a €450 subsidy for every integrated solar system installed in a residential house, with an additional €900 available for homes in mountain locations. Also, the program covers the solar collectors and the storage tank too, but there are required specifications that each system must cover. The specification for the new system are:

- If the hot water cylinder can hold up to 200 liters, it is energy class B or higher, if it can hold more than 200 liters, it is energy class C or above.
- Solar panels must be certified by Solar Keymark.
- The solar water heater must be installed by certified contractors whose company is registered in the Register of Small-Scale Installers of RES Systems – Category D: Installers of Solar Thermal Systems.

Cyprus uses fossil fuels to provide 93% of its energy needs, to fulfill this percentage approximately 1000 tons of Mazut are imported, but this comes at a cost because as a member of Europe, there are a lot of energy requirements for every country, and Cyprus does not meet the standards, the results are more taxes and fines. In contrast to the European Union's target of 19% of renewable sources, Cyprus intends to significantly raise this percentage from 13.9% in 2020 to 22.9% in 2030 [9]. The geographical position of the island makes it one of the highest in solar radiation. The climate of the island provides 300 days of sunshine per year, with 60% of sunshine in winter and 90% of sunshine in the summer. With these percentages of yearly sunshine, the number of units installed rises every year, currently is estimated that there are more than 80,000 units installed with more than 750,000 m^2 surface. Even though imported SWH are more robust and better designed for efficiency, Cyrpus has more locally built SWH systems installed. The most used type of SWH is the close-couple thermosyphon which consists of two flat plate collectors with sizes of 160 x 80 cm and 190 x 90 cm [10].

Cyprus's mean daily solar radiation ranges from 2.3 kWh/m2 in December and January, when there is the most cloud cover, to 7.2 kWh/m2 in July, when it is at its highest. The average amount of radiation that is received from areas with typical weather is 1,727 kWh/m^2. There are 1199 kWh/m2 of direct radiation, which makes up 69,4% of the total radiation, and 528 kWh/m2 of diffuse radiation, which makes up 30,6% of the total radiation. [10].

For knowing consumers' perspectives on their solar water heaters or why they haven't installed one yet in their houses, a study was conducted to help understand the situation in Cyprus in 2017 [11]. The data of the study were collected from 1000 residential owners and 77,8% of the owners had already installed a solar water heater. More than half of the owners without SWH, around 51,3%, claimed that they don't have sufficient income to make the installation or the initial cost of installation and purchase is too high. The other percentage without SWH claimed that the house doesn't support the installation, or they don't have access to materials and experts, or for other personal reasons. Furthermore, 56% of the houses without SWH were interested to install one in the near future. The results are shown in figure 3.1:

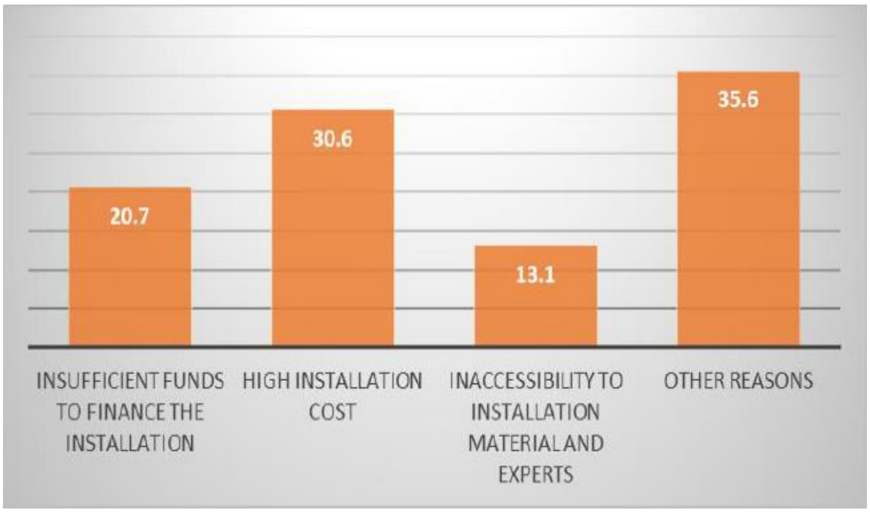

Figure 3.1: Results chart of why residential owners haven't installed SWH.

The owners also stated between which year they installed solar water heating at their homes. Most of the houses were equipped with SWH in the last decade, between 2007 and 2017. The results of the installation date are presented in figure 3.2. The most popular use of the hot water provided by the solar water heater is for bath water, with 86% of the participants in the study agreeing. The other 1.5% is for cooking, 6.6% is for washing clothes and doing the dishes, and the other 5.9% is for other domestic needs. 43 percent of the households stated that the SWH does not provide enough hot water for their needs between the hours of most use, while 12 percent of the households stated that they have plenty of hot water when they need it. One of the main reasons for installing SWH is to minimize the electric bill of each household; half of the houses that participated in the study agreed to that. The majority of the owners are satisfied with the savings and reduced electric bills that the SWH provides; in fact, 84% of the owners are satisfied. Solar water heating is considered a necessary feature for buildings in Cyprus as 82% of the households stated. More than 80% of the residential owners that participated in the study were

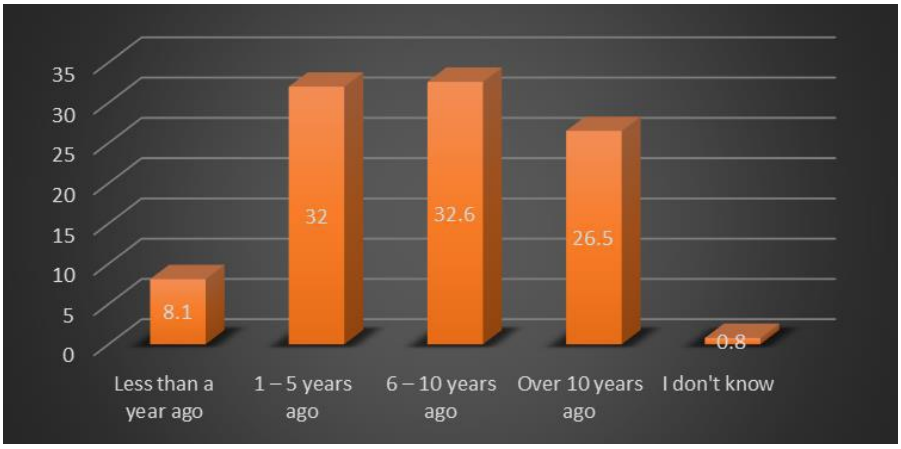

Figure 3.2: Chart of solar water heating date of installation

more than satisfied with the SWH installation, also they are willing to encourage owners to install SWH if they haven't yet.

The annually installed surface of solar water heating in Cyprus is shown in figure 3.3. As the graph shows in 2012 there is a descent in the installation of solar water heating, this is because between 2012 and 2013 there was an economic crisis, which was the largest financial crisis that Cyprus has ever faced. For that reason, lots of constructions and buildings were put on hold. A few years later, in 2017 when the economic crisis was over and also the legislation for new buildings stated that 25% of a building's energy must be from renewable sources, the annual installed surface for that year increased enormously. Also, for the next years and until today the annual installed surface keeps increasing, and if we compare 2011 and 2021, after 10 years the annually installed surface has increased more than 2.5 times. These results show that in Cyprus every year more consumers turn to solar water heating thanks to the legislation and the sponsor programs of the Cypriot cabinet.

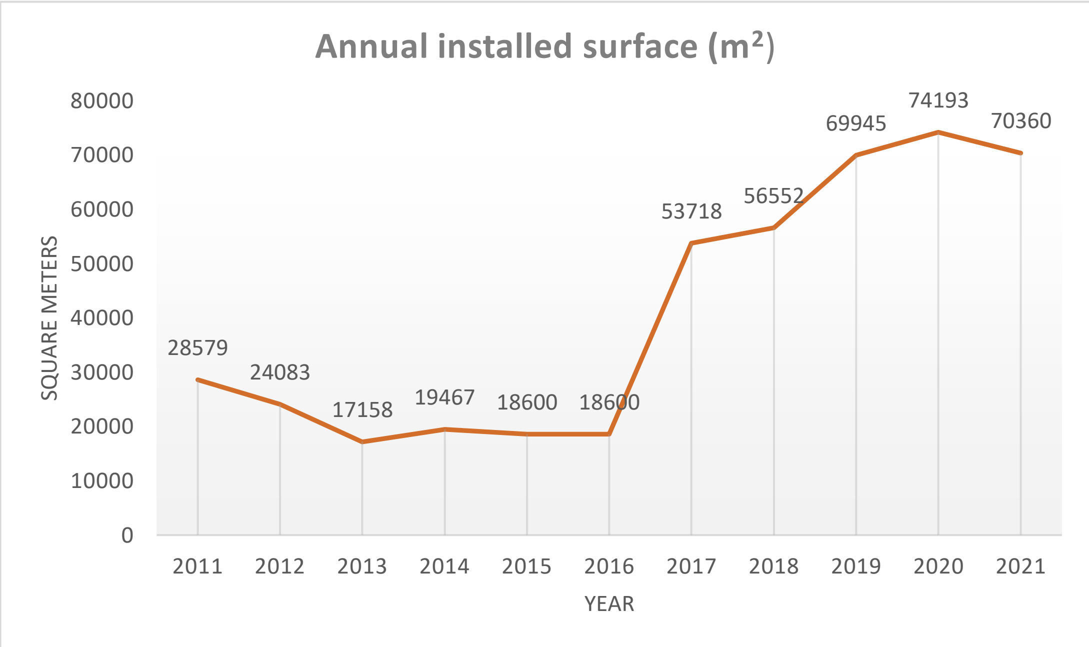

Figure 3.3: Annually installed surface of solar thermal collectors in Cyprus

4 Chapter 4. Latest advances and innovations

Solar thermal systems have drawn significant interest from the scientific community, due to their great efficiency and capacity to provide inexpensive home and industrial heating during the past few decades. In this chapter, there is a review of the latest studies for innovations and advances in solar water heating.

4.1 Functional elements

4.1.1 Absorber

The absorber is considered to be a core component of solar collectors and a lot of research has been done to maximize its performance. The thermal performance mostly depends on the design features and the material properties, and because of that lots of absorber plates and materials have been tested. The parabolic shape is one of the most effective absorber plate profiles because it produces more heat per unit volume than other geometries. Kundu[12] proposed an unusual recto-trapezoidal (RT) shaped fin in place of a rectangular fin design and according to the findings of the simulation, the RT profile absorber plate fin had a higher heat transfer rate per unit volume than other profiles.

To sustain function, an absorber must be unaffected by both internal and exterior corrosion since metal absorbers are more susceptible to corrosion. Since polymer-based absorbers are non-corrosive, lightweight, less expensive, and simpler to make, their use has grown in the last decade. For example, ethylene propylene diene monomer(EPDM) is a good substance that can tolerate prolonged exposure to sunlight thanks to recent advancements in polymer technology [13] A dual-purpose nanocomposite film for efficient solar thermal energy conversion and storage was created by Shang et al. [14]. By incorporating Phase Change Materials (PCMs) and some gold nanoparticles into the polyvinyl alcohol matrix through hydrogen-bonding interactions, this nanocomposite film was made. When comparing the thermal storage efficiency of the di-functional nanocomposite film to that of conventional films, the authors found a 201% improvement, demonstrating a significant increase in energy storage capacity.

The shape of the absorber is proved to be important for optimizing the heat transfer coefficient. Hassanzadeh et al. [15] investigated the optical and thermal performance of a pentagon absorber in a medium-temperature solar thermal collector, both mathematically and experimentally. According to measurements, the suggested solar collector has shown exceptional results, with an optical efficiency of 64% and a thermal efficiency of 50% at 200 °C, only with stationary optical tracking. This idea can be applied to compound parabolic concentrators with the pentagon absorber sealed in a vacuum tube, as shown in

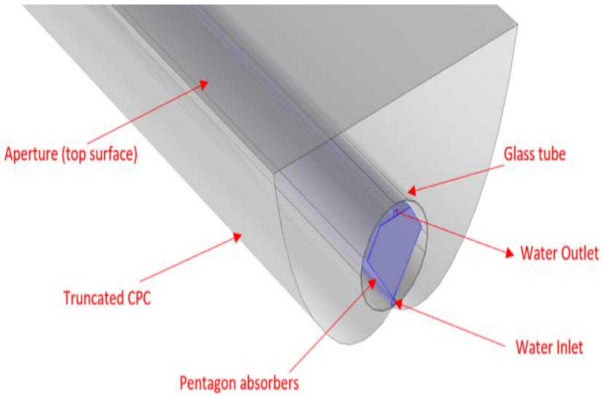

Figure 4.1: Schematic representation of a pentagon absorber[15]

figure 4.1. Another study analyzed the shape of the absorber with circular, elliptical, and semi-circular heat pipes, filled with water at ratios of 10%, 20%, and 35%. The study showed that a heat pipe with an elliptical cross-section has a higher gain in thermal energy because of the larger area of the heat pipe.

An interesting solution for reducing the heat loss of an evacuated tube collector was suggested by Zhang et al.[16]. They investigated the adoption of a heat shield beneath the absorber of an evacuated tube like the representation in figure 4.2, the heat shield is a practical and cost-effective tool for limiting heat loss and optimizing optical efficiency, and overall thermal performance, according to their calculation findings. This technical innovation enhanced the collector's thermal performance, particularly at higher operating temperatures. At high operating temperatures, the thermal efficiency increased to 55%. In comparison to a collector without a heat shield, the collection efficiency is around 31.5% higher.

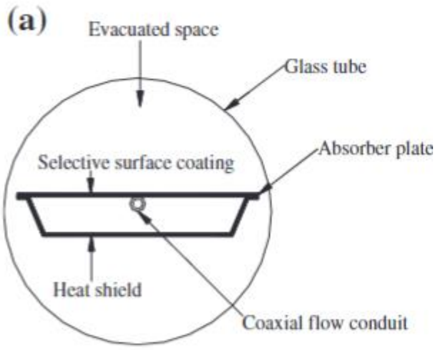

Figure 4.2: Schematic representation of evacuated tube collector with heat shield [16]

4.1.2 Collector ducts

The collector's efficiency is determined to a large extent by the internal pipes. The riser and the header pipes are the main pipes in the collector, they are usually made from copper and their diameter determines the flow and the friction which the flow produced from the thermosiphonic effect must overcome. The riser pipe is the most crucial one because it absorbs the heat from the absorber and transfers it to the heat transfer fluid, so its diameter can change the solar collector efficiency. The impact of the diameter of these pipes was investigated by Kalogirou [17] on flat plate collectors with simulations for diameters ranging from 6mm to 35mm and slopes of 20° to 90°. As a result, the best system was found to include a header pipe that is 22 mm in diameter, with 20 riser pipes that are 8 mm in diameter, angled at 45 degrees. On the other hand, the system's performance is more affected by the distance between the collector's top and the storage tank's bottom, this results in a better performance of the system when the distance is reduced.

The manifold header of the evacuated tube solar collectors can increase significantly the thermal power of the solar collector based on the study of Rybár et al. [18]. In this study, they investigated two evacuated tube solar collectors, one of which had a conventional manifold header and another one with a modified interior using a metal foam structural element as shown in figure 4.3. The effect of the metal foam proved to be significant to the increase of the collector's thermal power, as the results of the test showed an increase in thermal power from 85,2W to 201,8W per 1 m^2 area of the collector and an increase in the performance improvement factor from 1,14 to 3,20.

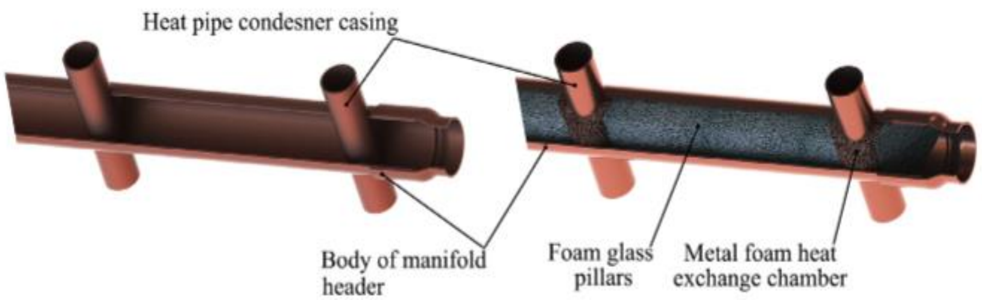

Figure 4.3: Modified header manifold with metal foam structural element [18]

A revolutionary micro-channel heat pipe array (MHPA) for a flat plate solar collector was created and investigated to develop a high-efficiency heat transfer unit [19]. The MHPA resembles a thin aluminum plate with several separate micro-channel heat pipes within it, these channels are like micro fins which are created by the grooves on the metal plate as shown in figure 4.4. The size of the heat pipe is 60 mm in width and 3 mm in thickness. The MHPA's main key elements which are responsible for heat transfer are the evaporator section and condenser section. Inside the micro-channels, specifically at the peripheral surface of the channel, the phase transition occurs. Under the influence of capillary force, the working fluid inside the evaporator section's micro-channel congeals into the meniscus. The meniscus thin film can be separated into the equilibrium, the evaporating part, and the intrinsic part. At the evaporating thin film, the fluid evaporates and turns into saturated vapor, and then, in response to the pressure differential, the fluid starts to flow upward from the evaporator portion to the condenser section. After the vapor condenses, liquid forms on the condenser section and creates a thin film across the inner surface. This results in heat transfer due to the condensing liquid film, the internal surface of the condenser section, and the vapor-liquid interface. At last, the condensing film finds its way back to the evaporator section in the center of the groove. After testing, the MHPA's maximum instantaneous efficiency reached 80%, and after comparing this system with other conventional ones, the MHPA's maximum instantaneous efficiency was at least 25% over the conventional systems. Also, the collector is reliable because if a micro-channel stops working it doesn't affect the overall system. The main material is aluminum which is cheaper than copper so the initial cost of the collectors isn't high, this makes the MHPA collector even more attractive to customers. This is one of the best solar collectors that can be used today.

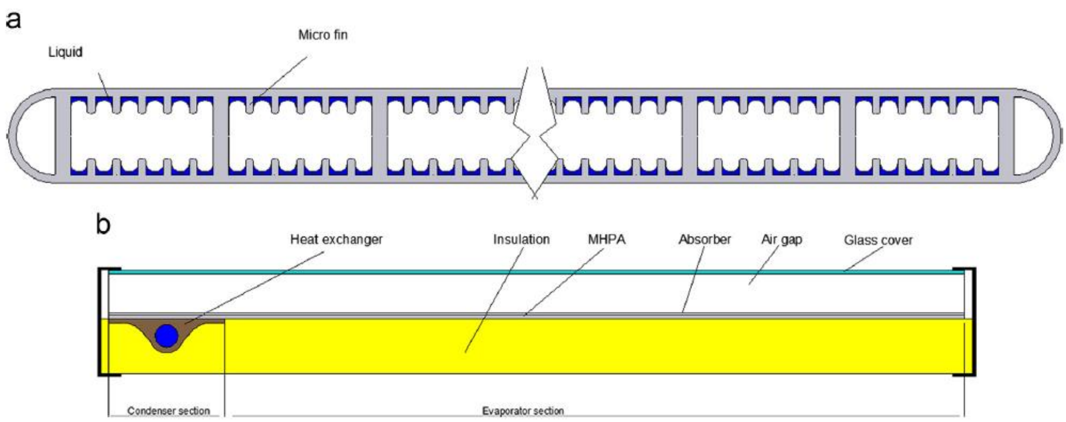

Figure 4.4: a)Schematic representation of MHPA and b) cross-section of MHPA-FPC [19]

In practical applications, the micro-channels might not be the most reliable as the channels can be blocked with time, and a fair amount of heat will be lost. A different design was created by Del Col et al. [20] with a prototype design of a flat plate collector with a roll-bond aluminum absorber. The transfer medium which is liquid flows inside the roll-bond plate. The roll-bond procedure utilizes a unique sandwich bonding method to produce canalized panels. Two aluminum sheets are sandwiched together using a unique hot-cold rolling method. Before joining the aluminum sheets together, the required channel design is printed using an unusual ink on the inner surface of a sheet. The ink prevents the welding of the inner surfaces where it is applied. By expanding air at high pressure, the unwelded network of channels can finally be raised. After testing the roll-bond aluminum collector it was found that this collector has higher efficiency than the standard copper collectors. Also, the collector was tested with different coatings like a black coating and a semi-selective coating, and the black coating proved to be better for efficiency. The advantage of this collector over the standard copper collector is the lowest cost for the build due to the use of aluminum and the unlikeliness of cracks or blocks in the tubes.

The price for a solar collector is between €1000 and €3000, and for some customers, this price may seem too much, especially in countries with tropical weather where the temperature and the sun's solar irradiance are high, and the need for the most advanced solar collector is unnecessary. An interesting design using polymeric materials like Low-Density Polyethylene (LDPE) tube for a collector duct has been created and tested. The collector is made from a single long LDPE tube that runs through the case in series as shown in figure 4.5, the diameter of the hose is larger than usual due to pressure drop problems. The collector's tube is covered with transparent plastic materials like air-packed LDPE and polyester thin films which helps with heat losses, protect the tube, and absorb solar radiation better. With this design, some of the main components can be eliminated and the cost of the overall collector can be highly reduced. For example, the storage tank is no longer needed because of the tube's large diameter and huge length, a tube 100 meters in length and 1,5 inches in diameter can hold around 106 liters of hot water, so the water that is inside the tube is plenty for a family house. Similarly, the absorbing plate is not needed, and the tube collects the solar irradiance without the help of special metals and coatings. Also, the insulation and the glazing cover are replaced by LDPE and polyester thin films, and the casing and hydraulic joints are much more simple and cheaper. By reducing the main components the collector is becoming simple and cheap, this collector can be built with 60 or 70 euros which is way less than a conventional flat plate collector. The collector during summer can reach temperatures of 70°C-80°C and during winter 35°C -40°C. The peak efficiency of the collector is 80% and the average is 64%. The bigger the diameter of the hose the lower the peak temperature, so the customers can choose the diameter of the tube to meet their standards. The biggest drawback of this design is at night or when it becomes cloudy the water's temperature is reduced fast because of the heat losses. The future of this collector is promising due to the low cost, with some modifications to the transparent tube and the glazing to reduce heat losses or to gain more solar irradiance, the collector can be a low-cost solution for countries with hot climates [21].

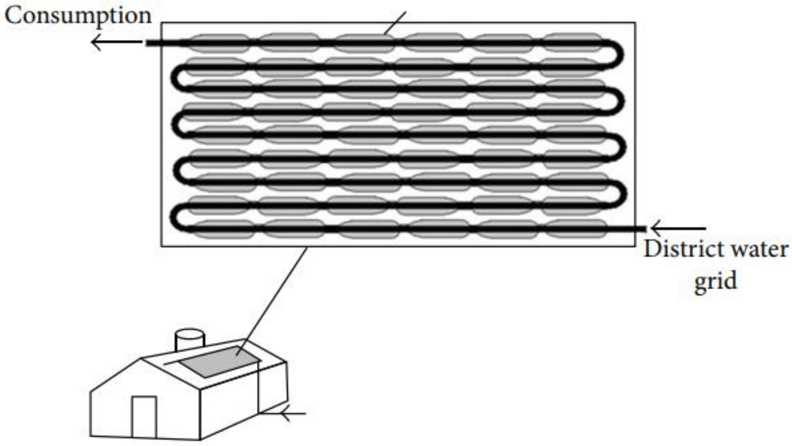

Figure 4.5: Schematic drawing of the hose collector mounted on the roof [21]

A high-performance novel duct type was created and tested on different collector types by Sharma et al. [22]. A mini-channel evacuated solar collector with the absorber enclosed in an evacuated glass envelope. The fluid flows inside parallel tubes with a diameter of 3 mm, unlike conventional tubes with a diameter of 25 mm, and a U-shaped configuration. The mini-tubes are spaced by 1mm and they are connected directly to the absorber, also the absorber has no fins attached and has a selective coating on the outside. The heat is transferred to the transfer fluid faster due to an increased contact surface between the tube walls and the transfer fluid, resulting in higher efficiency of the overall system. The collector's main drawback might be at low temperatures when the fluid is cold or when the solar irradiance is low the pressure drop inside the ducts is too high and a pump might be needed for the collector to reach an operating point. Another disadvantage is the problem with blocked channels as salts could block channels, a solution is the use of distilled water in a closed system as an indirect system. The use of mini channels was also tested on flat plate collectors by Mansour [23] but this time with a square shape, with a 2 mm hydraulic diameter and 4mm pitch. This collector showed a 16,1% higher heat removal factor than conventional collectors, and also reached an instantaneous efficiency of 92%. Both collectors equipped with mini channels should be designed with a higher water flow rate because the thermal efficiency increases. Mini-channel-based flat plate collector was tested using nanofluids as a heat transfer medium, with 25nm nanoparticle size and volume fractions up to 4%. The tested nanofluids had a higher heat transfer coefficient compared to water, but the one with the highest was the

Al_2O_3/water nanofluid. The increase in nanoparticles in the water mixture increases the outlet temperature, so Cu/water had the highest outlet temperature, but had the lowest efficiency. The highest efficiency is gained from SiO_2/water nanofluids but with this nanofluid, the entropy generation increases more, entropy generation usually is reduced when nanofluids are used except SiO_2/water nanofluids [24].

4.1.3 Transparent glass cover

The glass cover is used to limit the loss of heat from the solar panel to the environment. Glass with low iron has solar transmittance of 90% which is excellent, but to increase the thermal efficiency of the collector researchers found that by applying a coating the transmittance of the glass increases and reduces the heat loses, so the total efficiency of the system increases. The easiest way to reduce heat losses is the use of multiple layers of glass, most usually double glazing, with gaps of air as insulation, or by attaching a thin layer of plastic to the glass.

Nowadays most researchers study the use of polymeric materials for coatings. A study of the optical properties of transparent conductive oxides(TCOs) by Ehrmann et al. [25] showed promising results. TCOs can be used on transparent glazing due to their antireflective properties. The thin film is created using a plasma vapor deposition process, which accelerates the ions and deposits them on a target material made of ZnO and Al_2O_3 to create the film, this method is known as magnetron sputtering. The solar transmittance of these layers of glass and film is 85% which is higher than the ordinary ones because of the anti-reflective coating and the low-emitting coating's ability to absorb more energy. The overall efficiency of the collector increases by applying the low-emitting coating up to 77%, a significant increase at low solar irradiance and high temperatures was reported. The low-emitting coating can also help with moisture condensation when it is applied to the outer surface of the glazing cover. The results of transparent conductive oxides are positive and can help to improve the flat-plate collector's efficiency even at temperatures that exceed 100°C.

Low emissivity coatings can reduce the radiative heat losses of glass panes for solar energy utilization but their optical qualities have a significant impact on their efficacy due to their optical qualities that do not always match the application that they are used. Giovannetti et al. [26] considered uncovered, single-glazed, and double-glazed designs while examining the performance of glass with high transmittance and spectrally selective coatings for use in flat-plate panels. The results showed that adding a spectrally selective cover to single-glazed collectors with highly selective absorbers does not equate to increased performance of the collector and the overall collector's efficiency decreases due to the extra optical losses of the coating.

The most used glazing cover is made out of glass, due to its low production cost and its properties to absorb solar radiation. In an attempt to find a more efficient flat-plate solar collector a few other materials were explored and compared with glass. The materials that were tested were polycarbonate, polyethylene, polyvinyl fluoride, polystyrene, and polyester. Using the mentioned materials the influence of solar irradiance, heat removal factor, overall heat loss coefficient, and ambient temperature on the efficiency was measured. Polyvinyl fluoride glazing has the highest efficiency when considering how solar radiance affects efficiency, since Polyvinyl Fluoride has a relatively higher transmissivity compared to the other materials used in the experiment the overall efficiency was expected to be higher. Also, the same result appeared for the variation in intensity the overall efficiency was at its highest when the heat loss coefficient was at its lowest. The heat loss coefficient on efficiency showed that maximum solar irradiance produces approximately the highest efficiency since as solar irradiance increases, a higher temperature gradient will occur and a higher quantity of heat will be transferred to the working fluid. Heat removal factor also affects the heat transfer rate positively, this results in a higher temperature limit of the water at the outlet and an improved solar thermal collector's efficiency[27].

The glazing cover, as mentioned before, is made of glass, but its thickness can cause the solar collector's efficiency to increase or decrease. In order to analyze and find the optimal glass thickness a study was conducted using different glass covers. The test was conducted using 4 flat-plate solar collectors equipped with low iron glasses, all of them with the same properties but with different glass thicknesses. The glass thicknesses that were tested were 3 mm, 4 mm, 5 mm, and 6 mm. The thinner the glass the higher the transmittance due to low reflectance, but it causes losses convection losses to rise. The results showed that glass with a thickness of 4 mm can maximize the solar collector's performance by 7,6% over the other glasses that were tested. With this knowledge, the performance of a solar collector can easily be increased, the only risk that comes with thinner glass is the risk of glass breakage during the installation or due to bad weather conditions [28].

Thin nanostructured films can be applied to the transparent cover to maximize the solar transmittance with the same visible reflectance value, this is because of the lower refractive indices of those films. An example of those films is the nanoporous SiO_2 and the quaternary Mg-F-Si-O film. These films were created by sol-gel dip-coating and then with subsequent thermal annealing in a contaminated area without particles in the air. The refractive index of those films was measured with spectrophotometric analysis. The SiO_2 film with a pore volume fraction of 30% and a pore size of 3 nm was determined to be between 1.32 and 1.35 at a range of 300 nm and 900 nm. The Mg-F-Si-O film's refractive index was even lower at 1.26 and between the range of 300 nm and 900 nm, this was achieved with a ratio of 50% Magnesium and 50% Silicon. Both of the films that were created were highly transparent, the nanoporous SiO_2 spectral transmittance reached 98.5% and the quaternary's Mg-F-Si-O reached 99.5%. As these coatings have incredible properties they also have an issue, the possibility of deterioration caused by hydrocarbon pore-filling, so the use of multilayer stacks can cause the film to be destroyed[29].

The installation of plastic Transparent Insulation Materials (TIMs) as glazing cover or adding the TIM under the transparent glass cover as shown in figure 4.6, can help the collector to reduce thermal heat losses. The effect of TIMs is controversial as they can increase a collector's efficiency at high temperatures due to reduced heat loss, but at lower absorber temperatures the conventional collector can perform better because of the reduced solar energy transmittance due to TIM installation. Although, the reduced solar transmittance can be covered by the amount of heat loss that the transparent insulation can cut off. For flat plate solar collectors the most used TIM products are polymer sheets, cellular profiles, capillaries, polycarbonate honeycombs, and silica aerogel. After testing the flat plate collector with TIM and compared to a traditional one, to benefit from the TIM installation the temperature of the system must reach 51 °C and above. Another advantage of TIMs is the low extinction coefficient, this can help the efficiency because the wider the expansion that the absorber temperature domain has the more efficient the system is [30], [31] [32].

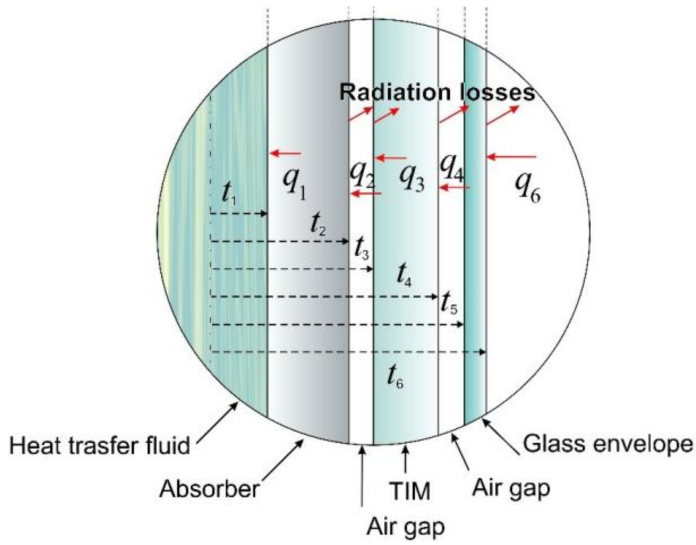

Figure 4.6: Schematic representation of flat plate collector with TIM [32]

4.1.4 Thermal insulation

Thermal insulation is used inside the tank and the collector for the reduction of heat transfer to the environment. We can increase the system's efficiency by reducing heat loss. The most popular insulating materials utilized for these applications are mineral fibers, polyurethane foams, or mineral fiber-polyurethane composite which have greater thermal and mechanical performance. The use of environmentally friendly materials has been most common lately, a study for date palm wood was put to the test in a solar air heater to see how well it performed in comparison to glass wool. The thermal efficiency of insulators with petiole piece, fibers piece, petiole powder, fibers powder, petiole plus gypsum, and fiber plus gypsum characteristics were examined. The findings showed that the collector with date palm wood insulation had a thermal efficiency that was 37.7% greater than that of glass wool insulation. Compared to Petiole's gypsum-insulated collector, the average output air temperature of the glass wool-insulated collector was 7% lower [33].

Another natural material that can be used for insulating the solar collector or the storage tank is coconut noir. Coconut noir is the outside shell of the coconut and is considered to be a natural waste product in most food industries, so there is plenty of quantity available at low cost. The thermal conductivity coefficient of coconut fiber is less than 0,04 W/m K so the panel's made out of coconut noir can have low values of thermal conductivity as 0,160 W/m K. The thermal efficiency of glass wool which is an excellent insulating material is the same as coconut coir. In order to test coconut coir's thermal efficiency it was tested inside a flat plate collector and compared to the same collector which is insulated with polypropylene drinking straw insulation polypropylene. The collector insulated using coconut noir had 13,7% higher thermal efficiency that the other collector with the thermoplastic polymer material. This shows that there are cheaper natural materials available that can replace other more expensive materials like glass wool [34].

Nowadays, the ecology is negatively impacted by increased agricultural output, especially when it comes to the usage of agricultural waste. Two of the most noteworthy byproducts that originate from agricultural waste are rice husks and sunflower stalks. In order to use cleaner technologies and renewable materials an experimental study was conducted, using rice husks and sunflower stalks they created insulating boards for solar thermal collectors. The different insulating boards that they tested were constructed with each one made up of a different ratio of rice husks, sunflower stalks, gypsum as a binding material, and jute thread as a design piece. Before the boards were made separate samples of sunflower stalks and rice husks were dried in the oven at 150 degrees for times between 10 and 120 minutes. After testing each board's thermal conductivity and the solar collector's heating cycle temperatures, the results revealed that the boards made from agricultural waste could be substantially similar to glass wool in terms of heat loss and thermal insulation. These materials can replace traditional materials in the production of thermal insulation boards in a practical way [35].

Upon assembly of the collector, the air moisture that is trapped within will ultimately condense and seep through the insulation. To avoid this problem, silica gel desiccant is used inside porous bags to absorb moisture. The desiccant is also used for the area between the glazings, tiny holes allow trapped air to come into touch with the desiccant through the surface of the spacers facing the gap between the panes. The use of desiccant is necessary to prevent the condensation of water on the glass cover. Moisture can reduce the overall efficiency of the system because of increased heat loss from the glazing cover due to increased thermal conductivity. Additionally, moisture can block solar irradiance from reaching the absorber which is a major problem [36].

Reducing the heat losses from the transparent glass and the collector's casing with the same materials is revolutionary progress. A nanostructured material with excellent solar transmittance and low heat conductivity like silica aerogel granulate can do both and it is ideal to use in a flat plate solar collector. Silica aerogel has a heat transfer coefficient of less than 0,4 W/m^2K and solar transmittance of 88% for 10 mm of stacked bed silica aerogel. The silica aerogel was tested using a flat plate collector filled with aerogel granules and insulated with 1 cm of insulation, the front part of the collector had a heat transfer coefficient of 1,4 W/m^2K and 0,5 W/m^2K at the back. A traditional collector with white glass for glazing and 5cm mineral wood for insulation is managing 2,4 W/m^2K at the front and 0,8 W/m^2K at the back for the heat transfer coefficient. Comparing these values, the estimated heat loss is reduced by 40%, and the collector's size is reduced due to the reduced insulation thickness. The U-value of the overall system is also reduced using the silica aerogel and the difference to a traditional collector is enormous. By increasing the insulation's thickness at the back to 4 cm the heat transfer coefficient can be reduced to 0,15 W/m^2K which is extremely low, to achieve this value using mineral wool as insulation the needed thickness must be more than 25 cm [37].

4.1.5 Thermal energy storage systems

Energy storage is one of the biggest problems in every system that requires storing energy for later use. The storage of thermal energy may be done with a variety of materials, like water, molten salts, thermal oils, and concrete blocks. The most common and ideal material for applications with low temperatures, under 100°C, is water because of its abundance, its high specific heat capacity, and lack of toxicity. When higher temperatures are needed the most suitable materials in liquid form are thermals oils and molten salts, due to their ability to stay in the liquid phase, unlike water.

These days the demand for thermal energy is growing and so is the volume of the systems. Thermal energy storage systems can be placed underground where the outer temperature does not change, this type of system is ideal for seasonal and long-duration storage. The storage medium can be eath materials like rocks and sand or water in a tank. Water systems are made of stainless steel or concrete and must prevent heat losses to the ground, so the tank is surrounded by a thick layer of insulation, the insulation layer is usually made of glass wool, polyurethane, or foam glass, and in some case, it can reach 1 meter of thickness. Similarly, the interior of the tank is coated using geomembranes, bentonite, or clay to avoid any water or vapor from escaping through the tank's walls. They can reach temperatures of 95°C maximum and can last up to 30 years of use. This type of storage system is more suitable for a complex of households and in countries that do not have available solar energy every day. The cost of this system is too high for some consumers. A representation of a water system is shown in figure 4.7.

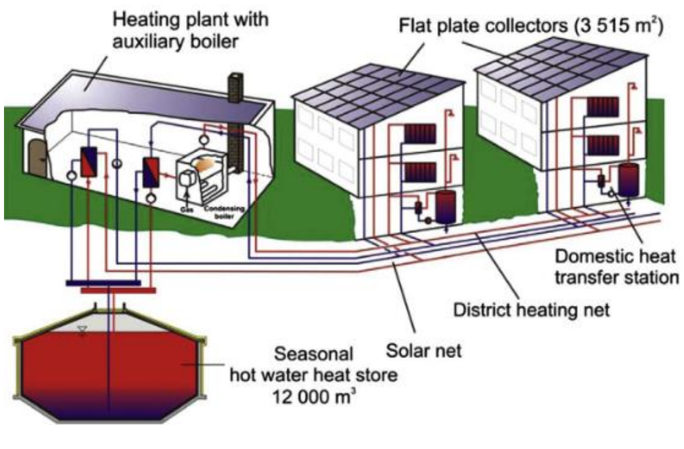

Figure 4.7: Representation of a water tank seasonal system connected to a block of houses [38]

A useful system for energy storage is the borehole system, this type of system can only be used when the ground has a high specific heat, and high thermal conductivity but with the lowest hydraulic conductivity possible. This system requires the ground to be drillable to depths of 30-100m, which is extremely difficult. Inside the drilled holes a vertical tube heat exchanger is placed, and the space between the heat exchanger and the borehole is filled with high thermal conductivity materials like bentonite, portland, cement, silica sand, and others.

The surface of the hole is covered with thermal insulation materials to prevent heat losses. This type of system has a high initial cost and without the proper study on the ground it cannot be installed, so the overall cost tends to increase for this type of system. Furthermore, this thermal energy storage system is ideal for countries with cold weather and long winters. [38]

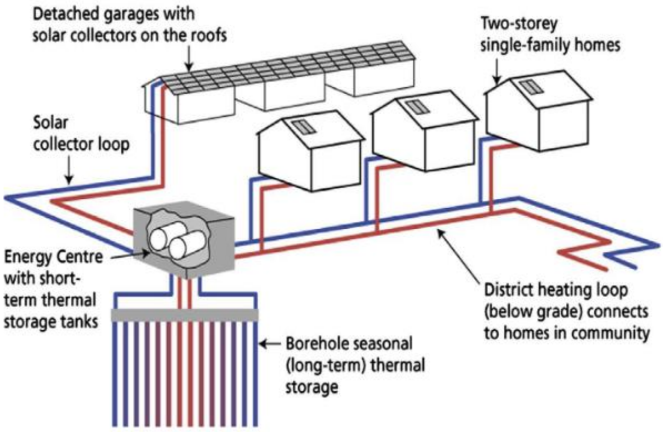

Figure 4.8: Representation of a pit-type seasonal system connected to a block of houses [38]

The use of phase change materials is gaining lots of interest in the last few years due to their ability to store enormous amounts of thermal energy, for example, the concrete's sensible heat capacity is around 1.0 kJ/kg K and paraffin's wax which is an example of PCMs' is 154 kJ/kg K [39]. Traditional storage tanks with water suffer from great amounts of heat loss and their large size does not help at all. Storage tanks using phase change materials can be smaller as the needed water volume is significantly smaller. PCMs can also help the absorbance and release of heat continuously and more stably. Also, another advantage over water is that the PCMs do not boil like water, this saves the tank from lots of problems and can store even more heat at higher temperatures. The use of PCMs in water tanks is currently under investigation because there are some problems with their use that do not help, for example, some of them are corrosive, and there is also the problem of supercooling and phase separation when they change phase [40].

Latent heat integration with household solar water heaters is a technology that was discovered years ago, but its economic viability has not been helpful at all.PCMs have the ability to hold enormous amounts of latent heat because of their phase-change behavior, the only problem that exists today is their short life and high initial cost. An interesting approach to solving this problem was made by Minh Tri Luu [41], who created a latent heat storage system that can store energy like a battery and merge it with a domestic solar water heater, this way the old water tank was removed as it was no longer needed. The latent heat battery (LHB) is a heat exchanger with a tube shape and consists of copper tubes and PCMs. The hot water flows through the tubes and the PCMs surrounding the tube's external surface collects the heat, as in figure 4.7. After putting the solar system together a yearly simulation took place in Australia, the results showed that by using the latent heat battery the overall system uses 86.6% less fossil fuel than a conventional system, and also increased the solar heater's fuel-saving 97,4% compared to the 81,7% that the conventional domestic solar heater's with sensible heat has.

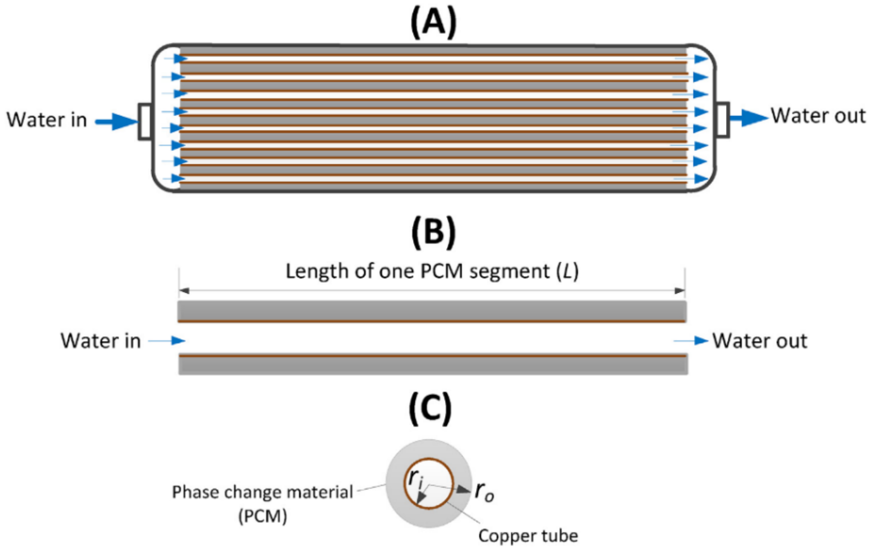

Figure 4.9: (A) Schematic diagram for latent heat battery, (B) front-view of a PCM segment, (C) side-view of a PCM segment [41]

By inserting PCMs inside the collector the need for a storage tank can be eliminated if the need for storage isn't high. Special stearic acids were developed in order to increase thermal conductivity, heat release capabilities, and heat transfer performance. Stearic acid and expanded graphite with a 6 % mass percentage were mended via melting impregnation. The final mixture showed a great thermal conductivity, 9,6 times higher than the original stearic acid, and with a value of 2,5 W/ mK. Furthermore, this composite proved to be the most effective for solar water heating as the melting time was 63,3 % lower than the stearic acid and the heat release time 3.6 times faster [42].

The short life of PCMs and the high initial cost can be lowered by optimizing the water flow. A study proved that by testing a shell-tube thermal energy storage system with paraffin wax at different flow rates the total life cycle cost can be reduced. The solar collector system that was tested consists of two storage tanks, one filled with PCMs and the traditional water storage tank. The system was designed this way to be able to control the flow that goes through the thermal energy storage while the other goes to the water storage tank. By adjusting the flow through the thermal storage tank the exergy and energy efficiencies and costs were calculated. With water flow rates of 0,033 kg/min and 0,167 kg/min the energy efficiencies reached 63,88% and 77,41%, respectively, although the exergy analysis revealed that due to the increased flow, the exergy efficiency decreased from 9,58% to 6,02%. The increase of the flow rate to 0,167 kg/min reduces the total cycle life cost by 45,39$ [43].

One of the main properties of paraffin wax is its low conductivity and high viscosity, this means that it cannot be used as a heat transfer medium, but it cant be mixed with water inside a collector's manifold and help with thermal performance. An experimental study was conducted by Saffa et al. [44] using a new cylindrical evacuated solar collector design with different paraffin wax/water mixtures inside the collector's manifold. The collector consists of a shaped aluminum sheet connected to the tube, the outer tube, the inner tube coated with a selective coating, a wooden insert for insulation, an aluminum sheet that covers the insulation, and the energy storage material. The energy storage material is changed with different water/paraffin wax mixtures. The mixture with 25,28% water performed better and had the highest thermal efficiency.

Another similar study by Naghani et al. [45] with an evacuated tube collector whose heat pipes were connected to a manifold full of phase change materials. The manifold is used as a latent heat thermal energy storage tank, as solar irradiance collected from the absorber is transferred to the PCM tank to heat the domestic water. This is possible due to a finned exchanger inside the manifold. The collector's thermal efficiency was steady between 55% and 60% even at significantly higher flow rates than similar conventional collectors. This collector seems to be ideal for applications when higher flow rates are important, but it can be used for domestic and provided better performance than traditional collectors.

With the same idea but a different approach Abokersh et al. [46], developed a U-pipe evacuated collector but this time the PCM is placed inside the evacuated tube itself. The tubes and the inner glass tube are covered with an aluminum fin to enhance the heat transfer to paraffin wax's low conductivity. The collector's total discharged energy is 47,7% higher than conventional collectors. Also, based on long-term predictions the collector might reach 85,7% annual average efficiency.

4.1.6 Heat transfer medium

Heat transfer using water or a combination of water and ethylene glycol is mostly used in solar collectors for domestic use. To increase the effectiveness of energy systems, new heat transfer fluids have been developed. These fluids combine classic heat transfer mediums such as water, ethylene glycol, and oil with solid nanoparticles of metal or metal oxide smaller than 100nm.

An interesting study was conducted by Mintsa et al. [47] by measuring the thermal conductivity of alumina and copper oxide based nanofluids. This water-based nanofluid was created by combining Al_2O_3 nanoparticles with average sizes of 47 nm and 36 nm, or with CuO nanoparticles with an average size of 29 nm. The experiment showed an increase between 2.0% and 24,0% with the nanofluid which had the CuO nanoparticles in a fraction of volume between 1.0% and 14,0%. The nanofluid with Al_2O_3 performed better with the thermal conductivity reaching an increase of 30,0% in a fraction of volume between 1,0% and 18,0%. Lots of research have been conducted with different combination of nanoparticles and fluids, like ethylene glycol with TiO_2 or Al nanoparticles, and oil-based fluids with Al_2O_3, CuO, ZnO, and Cu nanoparticles. These nanofluids were tested in different temperatures and fractions of volume. The experiment results were promising because all nanofluids showed an increase in thermal conductivity, with the lowest at 8,29% and the highest at 21,76%. Furthermore, the nanofluid's heat transfer coefficient has been examined. A nanofluid was tested in a circular tube with the effect of turbulence flow, using a water-based nanofluid with Al_2O_3 nanoparticles with a 40.0nm diameter. The heat transfer coefficient indicated an improvement of up to 23.0% above the base fluid [48]. Another study by Ziyadanogullari et al. [49] confirmed the high performance of nanofluids in a flat-plate solar collector with the Cu/water nanofluid managing an increase of 87,8% compared to water, with a concentration of 0,2%. The Al_2O_3/water nanofluid showed an increase of 71% and last the TiO_2/water nanofluid with an increase of 52,5%. The nanofluids may look like a perfect replacement for water but due to the increased viscosity the pressure drop increases and leads to other types of losses.

In most heat pumps, freezers, and air conditioners, heat transfer fluids are composed of refrigerants. One of the significant advancements in solar technology is the use of refrigerant-filled solar collectors. Since they have lower boiling temperatures and higher heat capacities than other fluids, refrigerants are more efficient than other heat fluids, especially when it's foggy outside. Numerous studies have been carried out to examine the efficiency of the 2-phase heat transfer technique used in the solar water heating system. For example, the performance of R-11 refrigerant in the thermosyphon collector was tested for domestic use. According to experimental findings, employing a two-phase refrigerant has a greater peak instantaneous efficiency than utilizing hydronic fluid.

Magnesium oxide nanoparticles with a 74,5 nm average size were used for the manufacture of a nanofluid. MgO nanofluid was tested inside an evacuated heat pipe collector and showed an increase compared to water. The increase is based on the increased convective heat transfer coefficient of the nanofluid. Also, the higher the concentration the higher the efficiency of the heat pipe. In addition to that, the thermal performance of the collector is improved by increasing the flow rate[50]. Furthermore, Daghigh and Zandi [51] proved that using MWCNT, CuO, and TiO_2 nanofluids in an evacuated solar collector can improve the collector's efficiency in winter by 25%, 15%, and 7% respectively. Nanofluids have the ability to heat the storage tank's water faster due to higher thermophysical properties, the nanofluids can achieve higher temperatures which means higher heat transfer to the domestic water inside the storage tank.

4.2 Photovoltaic thermal solar collectors

Photovoltaic thermal collectors (PVT) or hybrid solar collectors combine a solar panel and a flat plate solar thermal collector. The solar panel absorbs the sun's radiation and converts it to electricity while the flat plate collector collects the unused heat and the heat from the working solar panel, and transfers the heat to the transfer fluid. This way, the photovoltaic module works at lower temperatures especially when the ambient temperature or the solar energy is too high. The efficiency of the photovoltaic cells improves by removing heat from the cells and lowering the temperature. Lower operating temperatures also have the advantage of extending the lifespan of photovoltaic cells.

The two main categories that photovoltaic cells can be divided into based on design are photovoltaic thermal liquid collectors and photovoltaic thermal air collectors. The PVT air collectors instead of using liquids like water use air to absorb the waste heat from the photovoltaic module. The main advantages over liquid collectors are the simplicity of the structure and lower cost. PVT collectors can reach temperatures up to 95 degrees.

The development of photovoltaic thermal collectors in the last few years has grown extensively due to their ability to combine two forms of energy and achieve higher efficiency than the two systems separated. Interesting research was conducted by Erdil et al. [52] who tested PVT liquid collectors using water and composed of two photovoltaic modules. The study took place In Cyprus and according to the island's households, the minimum system for the electrical demand is ten PV modules. The system with the two modules lost 11,5% of its electrical energy for water circulation, absorption, and reflection of the glass. This may sound a lot but for a typical household in Cyprus, this percentage of electrical energy loss equals 1% of the daily required energy. The study also showed that in less than 2 years it can recover the investment for the updated system.

A new type of hybrid solar collector was developed and tested by Liang et al. [53]. The PVT solar collector was filled with graphite as shown in figure 4.10, to check whether the efficiency of the collector increased. After testing it side by side with a conventional PVT collector the PVT collector filled with graphite showed a higher mean value of electrical efficiency at 1.29 while the highest electrical efficiency reached 7.2%. Also, a huge difference was recorded in the backplane temperature due to solar radiation, with a temperature difference of 16.74% between the two collectors.

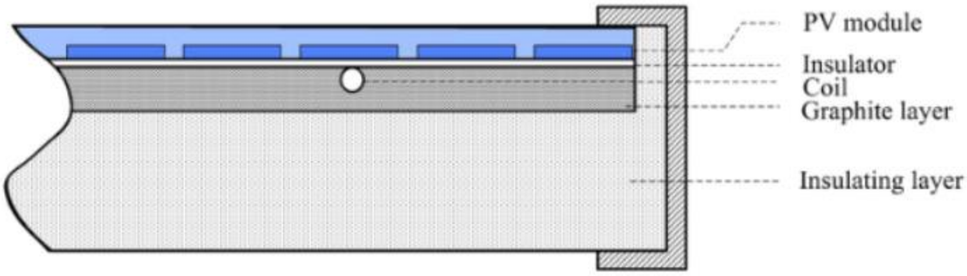

Figure 4.10: Schematic part sectioned view of PVT solar collector filled with graphite [53]

In contrast to the traditional hybrid system, Tuafek et al [54]. researched a new PVT solar collector system with water that improved both thermal and electrical efficiency. The monocrystalline photovoltaic module for the PVT system has a 0.33m width and a 1.29m length, and it is installed inside an absorber made of galvanized steel. Due to the unique design of the absorber, it can contain fluids like water, glycol, and others. The system is insulated on all sides with glass wool, as shown in figure 4.11. The thermal efficiency of the collector was tested according to the ASHRAE standards 93-86 and the efficiency was between 50% and 80%, this ensures that this novel PVT collector system is more effective than the conventional one, whose efficiency does not surpass 50%.

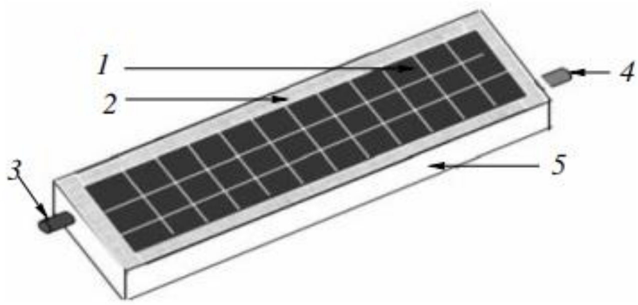

Figure 4.11: Schematic representation of the new hybrid collector prototype, with 1. photovoltaic cells, 2. heat insulation, 3. entry of the coolant, 4. exit of the coolant, 5. galvanized iron steel structure [54]

The design of the PVT collector can change the thermal efficiency of the overall system. A study recently showed that changing the panel configuration of the system can help the thermal collector gain more energy and also help the photovoltaic module produce more energy. To identify which panel layout gives the optimum performance in terms of ideal PV efficiency and available thermal energy, many combinations of different water flow rates and panel configurations have been examined. Regardless of the chosen configuration, configurations using the highest water flow rates resulted in higher system efficiency. The high flow rates might be better for overall system efficiency but this results in low inlet temperature and outlet temperature because there is not enough energy for the fluid to collect. This means that the heat transfer fluid can only be used for preheating applications. Furthermore, the results of the study were promising and revealed that for the vertical design, the available energy is 675.46 kWh/m^2 per year, and for the horizontal design, the available energy is 691.04 kWh/m^2 per year, while the photovoltaic modules obtained an efficiency of 4.74% and 5.44%, respectively [55].

After all this research and studies on photovoltaic thermal solar collectors, the easiest way to enhance the performance of the collector is to optimize the design of the overall system. The optimization of the PVT collectors includes the following variables, the number of collector tubes, the mass flow rate, the collector's angle, azimuth and material, and the storage tank volume. After testing the different combinations using computer software the optimal control settings are with copper collector plate material, collector azimuth due south, mass flow rate 0.01 kg/s-m^2, 12 collection tubes, collector angle 25°, and storage tank volume to area ratio 123. The collector with the optimal parameters reached electrical efficiency of 14.29% and thermal efficiency of 44.96% which are 1.55% and 10.9% higher than the standard system respectively. [56]

4.3 Innovative designs

A new dual-purpose solar collector that provides hot water and air simultaneously has been created and tested. The collector is made from a traditional flat plate collector after some modifications like changing the absorber and the air gap in the interior. The absorber consists of L-shaped aluminum fins and there are 13 copper tubes welded at the bottom of every fin as shown in figure 4.12. The fins are lined up under the glass for the air to flow through them and under the glazing cover and collect the heat. The collector's air channels closed when the water is circulating through the collector because there isn't enough heat supply to heat the air and water simultaneously. Similarly, the water tubes are closed during the air heating to avoid water circulation, when the water is heated starts circulating due to density difference, this way the heat stays in the absorber's fins and is collected with the airflow. The collector can be used only as an air heater or as a water heater, this depends on the demand for air and water in each household. The collector has a 50% average efficiency for water heating and a 55% of average efficiency for air heating. The efficiency of air heating can be increased with lower airflow rates. This type of collector is suitable for winter as the warm air that it produces can heat a household when hot water is not needed or when the water reaches a temperature limit, for example, 50°C is enough for bathing and other home needs [57].

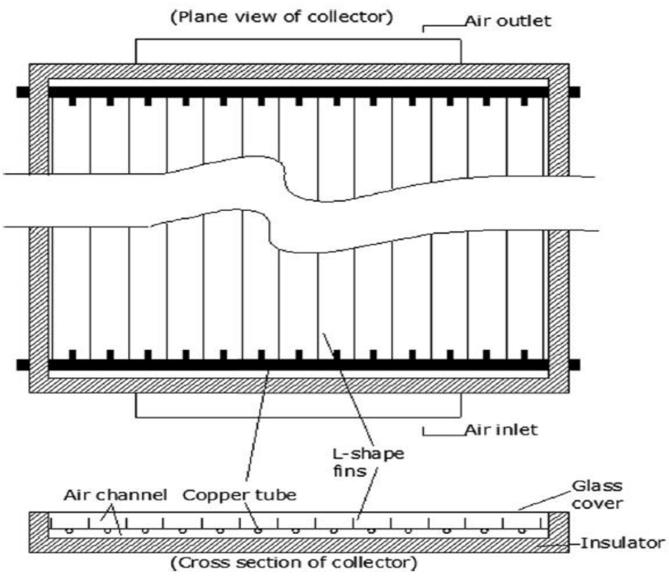

Figure 4.12: Schematic drawing of air and water collector and cross-section [57]

An integrated collector storage solar water heater (ICSSWH) with a unique design has been created to lower the initial cost of the system by simplifying the design and increasing the performance. This type of collector consists of a cylindrical tank placed inside a stationary compound parabolic concentrating reflector trough. The tank is placed across the center of the trough to absorb the reflecting radiation. While building ICSSWH three types of collectors were tested with three different acceptance angles, the first with 180°, the second with 90°, and the third with 60°. The results showed that in the lower range of temperature/irradiance, the most efficient ICSSWH is the first with an acceptance angle of 180° and daily mean efficiency ranging between 0,42 and 0,53. On the contrary, at higher ranges of temperature/irradiance, the second ICSSWH with an acceptance angle of 90°

performed better with a higher mean efficiency of 0,46. The ICSSWH can heat water up to 95°C but that depends on the solar irradiance and the storage tank size. The installation is easier and simpler because of the compact size and the no need for any attachments like flat plate collectors. The biggest drawback of ICSSWH is during the night when there is no solar irradiance the heat losses are enormous because the storage tank has no insulation. To reduce heat loss at night, the easiest way is to apply a nanostructured coating to the glazing cover or by installing a transparent cover made from transparent insulation materials (TIMs), of course, this will not eliminate the problem [58].

4.4 Integrated solar thermal collectors

Integrated solar collectors are usually used in modern houses or when there isn't enough space for other collector types. These collectors are integrated inside buildings outside walls or on the roof as a part of it, most of the time they place on the south-oriented part of the roof and walls. They have high efficiency but the main advantage is the way they are hidden, someone cannot identify or spot the collector easily.

A new innovative design for an integrated solar collector has been constructed especially for households who don't have the option to install a collector inside walls or the roof. The new concept places the solar collector inside a gutter, this way the collector cannot be seen from the ground. The gutter with the collector can be installed easily all around the house and can also collect rainwater from the roof like a proper gutter. The collector inside the gutter is built based on flat plate collectors, it consists of a glazing cover, the hot and cold tube, a selective absorber, and insulation at the bottom as shown in figure 4.13. Attached to the absorber there are 2 tubes the hot tube and the cold tube, the cold water that leaves from the tank flows inside the cold tube which is attached to the absorber plate. After the cold water passes through the lower tube it starts to warm up and then the water flows through the hot tube which is the upper one and collects the heat from the absorber to heat up. The collector's instantaneous efficiency reached 60% and when collectors are installed around the roof's perimeter the collectors may be more than enough for a single household [59].

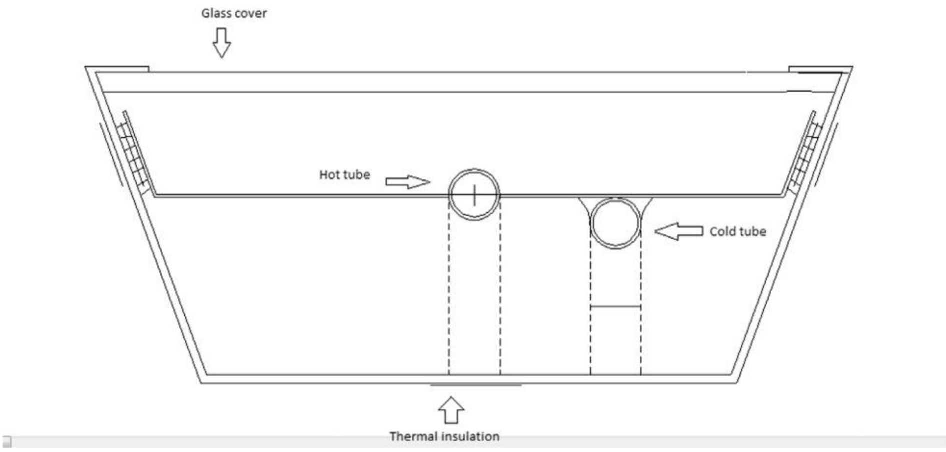

Figure 4.13: Scheme of integrated solar collector (cross-section) [59]

Concrete is ideal for heating storage due to its ability to hold an enormous amount of energy, so the use of concrete matrix in an integrated solar storage collector has been constructed and tested. The use of concrete matrix for storage eliminates any problem with leaks, it is easy and simple to make, it can be produced locally, and does not cost as much as other solar collectors used for domestic water heating. The collector consists of a highly transparent glazing cover, a thin concrete layer with 40 mm of thickness, and copper tubes that are integrated inside the concrete, the casing, and the thermal insulation. The absorber is painted with a black coating to help the concrete to absorb more solar radiation. This integrated solar storage collector is ideal for warmer climates as it is not the most efficient, but the lower cost and the elimination of maintenance make it a long-life ideal collector. The collector was tested during winter time and the results showed that has a daily efficiency of 32% and can provide a household with 140-180 liters of water at a temperature between 42 and 46°C. This efficiency number for the winter season is very similar to other traditional solar systems and confirms that this solar system can produce 80% of the annual hot water requirements of a household. Similar to other integrated solar thermal systems the biggest drawback is the heat losses during the night, as the absorber acts as storage the heat losses are massive due to no insulation. This collector can be installed into a house wall which can be aesthetically attractive [60].

Another innovative solar integrated collector storage system with the collector used as a storage unit was created and analyzed. This time, the collector consists of just four cylindrical pipes made out of stainless steel. Also, the overall system is composed of transparent glazing, insulation by a polyurethane layer, and the casing which is made of a galvanized aluminum alloy as shown in figure 4.14. This is an open-system collector, so when the collector absorbs solar radiation the water inside the stainless steel pipes rises towards the outlet which is at the top of the pipe. Then the hot water stays at the top of the pipe and is ready for consumption. The low efficiency at thermal conversion doesn't make this kind of system attractive to consumers. As the hot water leaves the collector cold tap water enters, this mixing of cold water with the heated water reduces the temperature of the hot water too fast. The prototype collector was put to a 3 days test to check the maximum temperature of the water, the results showed that with solar irradiation of 868 $W/m^{2,}$ the water reached 46,9°C. The collector is compact and can be integrated into walls, and like other integrated collectors the heat losses during the night are high [61].

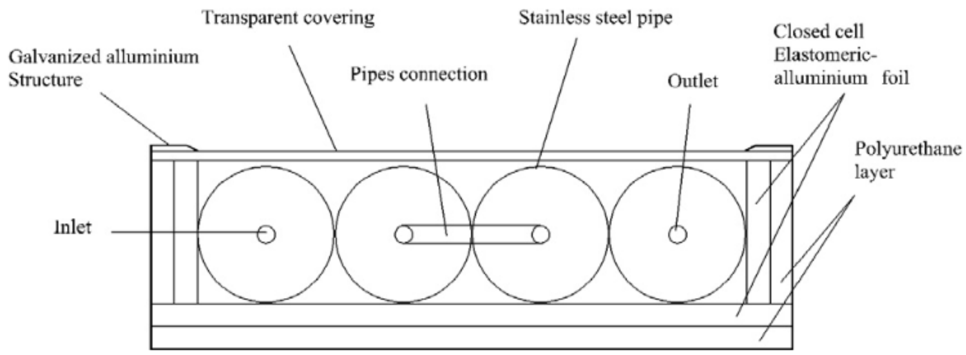

Figure 4.14: Schematic drawing of a solar-integrated collector storage system [61]

A new style of flat plate collector made exclusively from ceramic materials has been designed to be a part of a building. The absorber is made with ceramic raw materials like quartz, clay, sand, feldspar, and a V-Ti black ceramic coating which is made from the tailings of vanadium extraction. The V-Ti black ceramic coating is an ideal material for solar absorption, after testing, the solar absorptance of this coating is between 0,93-0,97. The production of ceramic collectors it's easier and faster than conventional flat plate collectors, first, the ceramic materials are mixed with water and ground until they reach the desired thickness, then the milled mixture is placed inside the plaster molds, after this procedure the collector is created and continues to the next step which is drying out and spraying on the V-Ti black ceramic coating. For the final procedure, the ceramic collectors are calcined at a temperature of 1210°C for a specific time. The wavy black pattern of the absorber makes the collector suitable for buildings' roofs and balcony railings as it can be aesthetically nice to look at. The collector usually is placed inside an alloy frame which protects the ceramic absorber with the help of a transparent cover, but the alloy frame can be swapped with a concrete frame in cases where the collector acts as a balcony rail. Because of the unusual installation locations, the heat transfer fluid is transferred by a pump, but for roof installations, it can be transferred naturally. The most effective heat transfer fluids for ceramic collectors are antifreeze or liquids with the same properties. The cost of the ceramic collector is much less compared to flat plate collectors made from aluminum and copper, also the house building cost is reduced as the ceramic collectors are a part of the balcony railing or part of the roof. The collectors were tested for their thermal efficiencies, the collector on the balcony's efficiency was 47,1% while the collector’s on the roof was higher than 50%. A huge advantage of ceramic collectors is their ability to last more than 50 years, which is more than double compared to traditional solar water heaters [62].

5 CONCLUSIONS – SUGGESTIONS FOR FURTHER STUDY

This study presents a status development and policy of solar water heaters for domestic use in Cyprus. It also presents some of the latest the most efficient technologies of every main component of solar water heaters for domestic use that have been developed in the last years.

Solar thermal collectors are used extensively on the island of Cyprus, especially thermosiphonic types like flat plate collectors. Cyprus has the highest percentage of solar water heating systems per inhabitant, with 1 m^2 per inhabitant, this is because the households with installed solar thermal collectors are about 93,5%. On the island, legislation on newly constructed houses demands the installation of solar water collectors with specific minimum requirements based on house members. Also, newly constructed houses must cover 25% of their energy needs with renewable energy, this is possible with the use of solar water heaters. Furthermore, the Cypriot cabinet encourages people to replace their outdated, inefficient solar water heaters with more advanced solar collectors.

In the modern world that we live in every country, environmental sustainability and economic development are two of the main objectives. Environmental development can be achieved by natural resource utilization which provides renewable energy. The sun's energy is the best natural resource and with the right equipment, it can be harnessed to a great extent. This can be achieved using the latest and most efficient solar water heaters, they are mostly used in domestic houses to provide hot water for everyday applications and needs. Solar water heaters are studied every day by scientists all around the world, to enhance the performance of the system. It has been proved that expensive materials and complicated designs that are difficult to manufacture cannot always enhance the performance of the solar system. Also, the use of materials with low environmental impact appears to take place on solar thermal collectors.

The efficiency increase based on some of the mentioned innovations has reached almost a 30% high. The glazing cover coating like nanostructured films and selective coating made from transparent conductive oxides can enhance the transmittance of the glazing cover by up to 99,5%. In addition to that they can also reduce heat losses from the transparent cover. The thermal efficiency increases by almost 38% by using date palm wood as a thermal insulation material. Also coconut noir can enhance thermal efficiency to a great value. Collector duct design and materials proved that also increase thermal efficiency, the mini-channels on a flat-plate collector reached an instantaneous efficiency of 92% and also increased the heat removal factor by more than 16,1% compared to traditional flat-plate collectors.

Some main components of the mentioned solar water heaters can be investigated more to enhance the performance of the collector or the storage capabilities. This may be possible by using new materials with higher transmittance values and lower reflectance for the glazing cover. Also, the initial cost discourages a lot of customers from installing solar water heating, so examining more affordable and flexible manufacturing techniques and using natural materials that are cheaper may avoid this problem. Furthermore, studying new designs can help reduce the cost of a collector, with more simple design the manufacturing cost is reduced. A more expensive solution to enhance the performance of the solar collector is by examining solar tracking systems, by tracking the sun more solar irradiance will always reach the collector, so this can improve the efficiency of the overall solar system. Improving nanofluids with higher heat transfer coefficients and more stability during different temperatures will increase the performance of the collector by far. Heat transfer can also be enhanced by studying new materials and designing absorbers with geometries that can transfer the heat to the transfer fluid fastest.

The collected solar energy that is transferred to the storage tank is most usually used at times when there is no solar energy available, for example in most domestic houses the demand for hot water is in the morning before work or at night after work. By studying new materials like phase change materials the energy capacity of the storage tank can be increased and so the energy that is available for later use. Also, exploring new insulation materials that can reduce overnight heat loss will help too. Using natural materials can reduce the cost of a storage tank too.

The most potential in the future is shown from the hybrid photovoltaic thermal collectors. They might be the most expensive in this study but can provide a household with two types of energy, electrical and thermal energy. By studying new designs and materials to transfer the heat from the photovoltaic panel to the transfer fluid, the temperature of the panel can be reduced, which results in higher electrical and thermal output. Examining new manufacturing ways may reduce the cost of the PVT and become attractive to customers.

6 REFERENCES

[1] Armijo KM, Shinde SL. Heat Transfer Phenomena in Concentrating Solar Power Systems, Sandia National Laboratories, California, 2016

[2] Duffie JA, Beckman WA. *Solar engineering of thermal processes*, 4th Edition, Wiley & Sons, New Jersey, 2013

[3] Foster R., Ghassemi M., Cota M. SOLAR ENERGY Renewable Energy and the Environment, CRC Press Taylor & Francis Group, Florida, 2010

[4] Kalogirou S. (2003) The potential of solar industrial process heat applications. Applied Energy, 76 (4), 337–361.

[5] (2014) Product Profile: Solar Water Heaters, Equipment Energy Efficiency (E3) program of the Australian Government and New Zealand Government. [https://www.energyrating.gov.au/sites/default/files/2020-06/product-profile-solar-water-heaters-august-2014.pdf, retrieved 17/9/2022]

[6] Kalogirou S. (2003) The potential of solar industrial process heat applications. *Appl Energy*, 76 (4), 337–361.

[7] Kalogirou SA. (2004) Solar thermal collectors and applications. *Progress in Energy and Combustion Science*, 30, 231–295.

[8] Evangelisti L, de Lieto Vollaro R, Asdrubali F. (2019) Latest advances on solar thermal collectors: A comprehensive review. Vol. 114, *Renewable and Sustainable Energy Reviews*, 114

[9] Fountoulakis I, Kosmopoulos P, Papachristopoulou K, Raptis IP, Mamouri RE, Nisantzi A, et al. (2021) Effects of aerosols and clouds on the levels of surface solar radiation and solar energy in Cyprus. *Remote Sensing*, 13(12), 2319

[10] Kalogirou S. (1997) Solar water heating in Cyprus: current status of technology and problems. *Renewable Energy*, 10 (1), 107-112

[11] Bamisile O, Babatunde A, Dagbasi M, Bamisile OO, Babatunde AA, Wole-Osho I. (2017) Assessment of solar water heating in Cyprus: Utility, development and policy. *INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH*, 7 (3), 1448-1453

[12] Kundu B. (2002) Performance analysis and optimization of absorber plates of different geometry for a flat-plate solar collector: a comparative. *Applied thermal engineering,* 22 (9), 999-1012

[13] O'brien-Bernini FC, Mcgowant JG. (1984) PERFORMANCE MODELING OF NON-METALLIC FLAT PLATE SOLAR COLLECTORS. *Solar Energy,* 33, 305-319

[14] Shang M, Zhang S, Li N, Gu X, Li L, Wang Z. (2017) Di-functional nanocomposite films for efficient conversion and storage of solar energy. *Solar Energy Materials and Solar Cells,* 164,188–192.

[15] Hassanzadeh A, Jiang L, Winston R. (2018) Coupled optical-thermal modeling, design and experimental testing of a novel medium-temperature solar thermal collector with pentagon absorber. *Solar Energy*, 173, 1248–1261.

[16] Zhang X, You S, Ge H, Gao Y, Xu W, Wang M, et al. (2014) Thermal performance of direct-flow coaxial evacuated-tube solar collectors with and without a heat shield. *Energy Convers Management,* 84, 80–87.

[17] Kalogirou SA. (2014) Flat-plate collector construction and system configuration to optimize the thermosiphonic effect. *Renew Energy*, 67, 202–226.
[18] Rybár R, Beer M, Cehlár M. (2016) Thermal power measurement of the novel evacuated tube solar collector and conventional solar collector during simultaneous operation. *Measurement*, 88, 153–64.
[19] Deng Y, Zhao Y, Wang W, Quan Z, Wang L, Yu D. (2013) Experimental investigation of performance for the novel flat plate solar collector with micro-channel heat pipe array (MHPA-FPC). *Applied Thermal Engineering*, 54 (2),440–449.
[20] del Col D, Padovan A, Bortolato M, Dai Prè M, Zambolin E. (2013) Thermal performance of flat plate solar collectors with sheet-and-tube and roll-bond absorbers. *Energy,* 58, 258–269.
[21] Juanicó LE, di Lalla N. (2013) A New Low-Cost Plastic Solar Collector. *ISRN Renewable Energy*,2013 (4), 1–10.
[22] Sharma N, Diaz G. (2011) Performance model of a novel evacuated-tube solar collector based on minichannels. *Solar Energy*, 85(5), 881–90.
[23] Khamis Mansour M. (2013) Thermal analysis of novel minichannel-based solar flat-plate collector. *Energy*, 60, 333–343.
[24] Mahian O, Kianifar A, Sahin AZ, Wongwises S. (2014) Performance analysis of a minichannel-based solar collector using different nanofluids. Energy Convers Management, 88, 129–138.
[25] Ehrmann N, Reineke-Koch R. (2012) Selectively coated high efficiency glazing for solar-thermal flat-plate collectors. *Thin Solid Films*, 520, 4214–4218.
[26] Giovannetti F, Föste S, Ehrmann N, Rockendorf G. (2014) High transmittance, low emissivity glass covers for flat plate collectors: Applications and performance. *Solar Energy*, 104, 52–9.
[27] Dondapati RS, Agarwal R, Saini V, Vyas G, Thakur J. (2018.) Effect of Glazing Materials on the Performance of Solar Flat Plate Collectors for Water Heating Applications. *Materials Today: Proceedings 5*, 5, 27680-27689
[28] Bakari R, Minja RJA, Njau KN. (2014) Effect of Glass Thickness on Performance of Flat Plate Solar Collectors for Fruits Drying. *Journal of Energy*, 1–8.
[29] Hody-Le Caër V, de Chambrier E, Mertin S, Joly M, Schaer M, Scartezzini JL, et al. (2013) Optical and morphological characterisation of low refractive index materials for coatings on solar collector glazing. *Renew Energy*, 53, 27–34.
[30] Dowson M, Harrison D, Craig S, Gill Z. (2011) Improving the thermal performance of single-glazed windows using translucent granular aerogel. *International Journal of Sustainable Engineering*,4 (3),266–80.
[31] Dowson M, (2022) Transparent insulation. Buro Happold, [https://www.designingbuildings.co.uk/wiki/Transparent_insulation, retrieved 20/12/2022]
[32] D. Osorio J, Rivera-Alvarez A, Girurugwiro P, Yang S, Hovsapian R, C. Ordonez J (2017) Integration of Transparent Insulation Materials into Solar Collector Devices, *Solar energy, 147, 8-21*
[33] Nadir N, Bouguettaia H, Boughali S, Bechki D. (2019) Use of a new agricultural product as thermal insulation for solar collector. *Renew Energy*, 134, 569–578.

[34] Khaw V, Hwa Chong C, Hosseini Fouladi M, Chuen KW, Qian CW, Hwa CC, et al. (2015) Effect of using coconut fibre and polypropylene for thermal insulation in a flat plate collector. *Journal of Engineering Science and Technology*, 41-49

[35] da Rosa LC, Santor CG, Lovato A, da Rosa CS, Güths S. (2015) Use of rice husk and sunflower stalk as a substitute for glass wool in thermal insulation of solar collector. *J Cleaner Production, 104*, 90–97.

[36] Alghoul MA, Sulaiman MY, Azmi BZ, Wahab M abd. (2005.) Review of materials for solar thermal collectors. *-Corrosion Methods and Materials,* 52, 199–206.

[37] Reim M, Körner W, Manara J, Korder S, Arduini-Schuster M, Ebert HP, et al. (2005) Silica aerogel granulate material for thermal insulation and daylighting. *Solar Energy*, 79, 131–139.

[38] Alva G, Lin Y, Fang G. (2018) An overview of thermal energy storage systems. *Energy*,144, 341–378.

[39] Shukla A, Buddhi D, Sawhney RL. (2009) Solar water heaters with phase change material thermal energy storage medium: A review. *Renewable and Sustainable Energy Reviews,*13, 2119–2125.

[40] Xie L, Tian L, Yang L, Lv Y, Li Q. (2017) Review on application of phase change material in water tanks. *Advances in Mechanical Engineering*.,9 (7), 1-13

[41] Luu MT, Milani D, Nomvar M, Abbas A. (2017) Dynamic modelling and analysis of a novel latent heat battery in tankless domestic solar water heating. *Energy Build*, 152, 227–242.

[42] Li C, Zhang B, Xie B, Zhao X, Chen J, Chen Z, et al. (2019) Stearic acid/expanded graphite as a composite phase change thermal energy storage material for tankless solar water heater. *Sustainable Cities and Society*, 44, 458–464.

[43] Mahfuz MH, Anisur MR, Kibria MA, Saidur R, Metselaar IHSC. (2014) Performance investigation of thermal energy storage system with Phase Change Material (PCM) for solar water heating application. *International Communications in Heat and Mass Transfer*, 57, 132–139.

[44] Riffat S, Jiang L, Zhu J, Gan G. (2006) Experimental investigation of energy storage for an evacuated solar collector [Internet]. Vol. 1, *International Journal of Low Carbon Technologies*, 1 (2), 139-148

[45] Naghavi MS, Ong KS, Badruddin IA, Mehrali M, Silakhori M, Metselaar HSC. (2015) Theoretical model of an evacuated tube heat pipe solar collector integrated with phase change material. *Energy,* 91, 911–924.

[46] Abokersh MH, El-Morsi M, Sharaf O, Abdelrahman W. (2017) On-demand operation of a compact solar water heater based on U-pipe evacuated tube solar collector combined with phase change material. *Solar Energy*, 155, 1130–1147.

[47] Mintsa HA, Roy G, Nguyen CT, Doucet D. (2009) New temperature dependent thermal conductivity data for water-based nanofluids. *International Journal of Thermal Sciences*, 48 (2), 363–71.

[48] Heyhat MM, Kowsary F, Rashidi AM, Alem Varzane Esfehani S, Amrollahi A. (2012) Experimental investigation of turbulent flow and convective heat transfer characteristics of alumina water nanofluids in fully developed flow regime. *International Communications in Heat and Mass Transfer*, 39 (8), 1272–1278.

[49] Ziyadanogullari NB, Yucel HL, Yildiz C. (2018) Thermal performance enhancement of flat-plate solar collectors by means of three different nanofluids. *Thermal Science and Engineering Progress,* 1(8), 55–65.
[50] Dehaj MS, Mohiabadi MZ. (2019) Experimental investigation of heat pipe solar collector using MgO nanofluids. *Solar Energy Materials and Solar Cells*, 191, 91–99.
[51] Daghigh R, Zandi P. (2019) Improving the performance of heat pipe embedded evacuated tube collector with nanofluids and auxiliary gas system. *Renew Energy*, 134, 888–901.
[52] Erdil E, Ilkan M, Egelioglu F. (2008) An experimental study on energy generation with a photovoltaic (PV)-solar thermal hybrid system. *Energy,* 33 (8), 1241–1245.
[53] Liang R, Zhang J, Ma L, Li Y. (2015) Performance evaluation of new type hybrid photovoltaic/thermal solar collector by experimental study. *Applied Thermal Engineering*, 75, 487–492.
[54] Touafek K, Haddadi M, Malek A. (2009) Experimental study on a new hybrid photovoltaic thermal collector. *Applied Solar Energy*, 45(3),181–186.
[55] Colangelo G, Romano D, Tina GM. (2015) Performance evaluation of a new type of combined photovoltaic-thermal solar collector. *Journal of Solar Energy Engineering*, 137 (4).
[56] Kuo CFJ, Liu JM, Umar ML, Lan WL, Huang CY, Syu SS. (2019) The photovoltaic-thermal system parameter optimization design and practical verification. *Energy Conversion and Management*, 180, 358–371.
[57] Ma J, Sun W, Ji J, Zhang Y, Zhang A, Fan W. (2011) Experimental and theoretical study of the efficiency of a dual-function solar collector. *Applied Thermal Engineering*, 31 (10), 1751–1756.
[58] Souliotis M, Chemisana D, Caouris YG, Tripanagnostopoulos Y. (2013) Experimental study of integrated collector storage solar water heaters. *Renewable Energy*, 50, 1083–1094.
[59] Motte F, Notton G, Cristofari C, Canaletti JL. (2013) Design and modelling of a new patented thermal solar collector with high building integration. *Applied Energy*, 102, 631–639.
[60] Hazami M, Kooli S, Lazâar M, Farhat A, Belghith A. (2010) Energetic and exergetic performances of an economical and available integrated solar storage collector based on concrete matrix. *Energy Conversion and Management*, 51 (6), 1210–1218.
[61] Borello D, Corsini A, Delibra G, Evangelisti S, Micangeli A. (2012) Experimental and computational investigation of a new solar integrated collector storage system. *Applied Energy*, 97, 982–989.
[62] Yang Y, Wang Q, Xiu D, Zhao Z, Sun Q. (2013) A building integrated solar collector: All-ceramic solar collector. *Energy and Buildings*, 62, 15–17.
[63] (2022) Introduction to solar radiation, Newport Corporation of MKS Instruments, [https://www.newport.com/t/introduction-to-solar-radiation, retrieved 10/9/2022]
[64] Md. Kafiul I,Tanvir A,Enamul H.P. (2011) Analysis of Maximum Possible Utilization of Solar Radiation on a Solar Photovoltaic Cell with a Proposed Model. *International Journal of Modeling and Optimization*, 1 (1), 66–69
[65] Kalogirou S, Solar energy engineering: Processes and systems, 2nd Edition, Academic Press, Elsevier, 2014

[66] (2022) The sun, National Aeronautics and Space Administration (NASA), [https://www.nasa.gov/mission_pages/sunearth/science/Sunlayers.html, retrieved 15/8/2022]
[67] (2022) Weiss W, Spork-Dur M, SOLAR HEAT WORLDWIDE, 2022 Edition, AEE - Institute for Sustainable Technologies, IEA Solar Heating & Cooling Programme, [https://www.iea-shc.org/solar-heat-worldwide, retrieved 10/2/2023]
[68] (2022) Solar thermal and concentrated solar power barometer, [https://www.eurobserv-er.org/category/all-solar-thermal-and-concentrated-solar-power-barometers/, retrieved 10/2/2023]