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Industrial, Energy and Environmental Systems Laboratory.

Life Cycle Assessment and energy - economic - environmental evaluation of evacuated solar collectors with advanced design.

Diploma Thesis

by

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Abstract

In this diploma thesis, a life cycle assessment of evacuated solar collectors and an environmental efficiency study using the SimaPro software is carried out, as well as a detailed study and development of an experimental solar thermal system for heating hot water. The design and construction of this standard device was carried out at the Technical University of Crete and is described in detail.

Acknowledgments

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Dedicated to my father **Lazaros Papadopoulos** and

my uncle Konstantinos Papadopoulos.

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CHAPTER 1

SOLAR ENERGY AND SOLAR SYSTEMS

1.1. Solar radiation and its utilization

The most important supplier of energy for the earth is the sun. The whole of life depends on the sun's energy. It is the starting point for the chemical and biological processes on our planet. At the same time it is the most environmentally friendly form of all energies, it can be used in many ways, and it is suitable for all social systems.

In the core of the sun a fusion process takes place in which pairs of hydrogen nuclei are fused into helium nuclei. The energy thus released is radiated into space in the form of electromagnetic radiation. As the sun is 148 million km from the earth, it radiates only a tiny fraction of its energy to the earth. In spite of this, the sun offers more energy in four hours than the human race uses in a whole year [1].

This energy consists of light, heat, and various wavelengths and radiates into space with power reaching hundreds of thousands of billions of kilowatts. The solar radiation power reaching the Earth is on average 10^{15} W. All the same, only a fraction of the radiation coming from the Sun (direct radiation) reaches the surface of the Earth, about 25%. Besides this percentage, another amount of radiation (25%) reaches the surface by diffusing into the particles of the atmosphere. The rest is either absorbed by ozone, water vapor, air and dust, or returns into space.

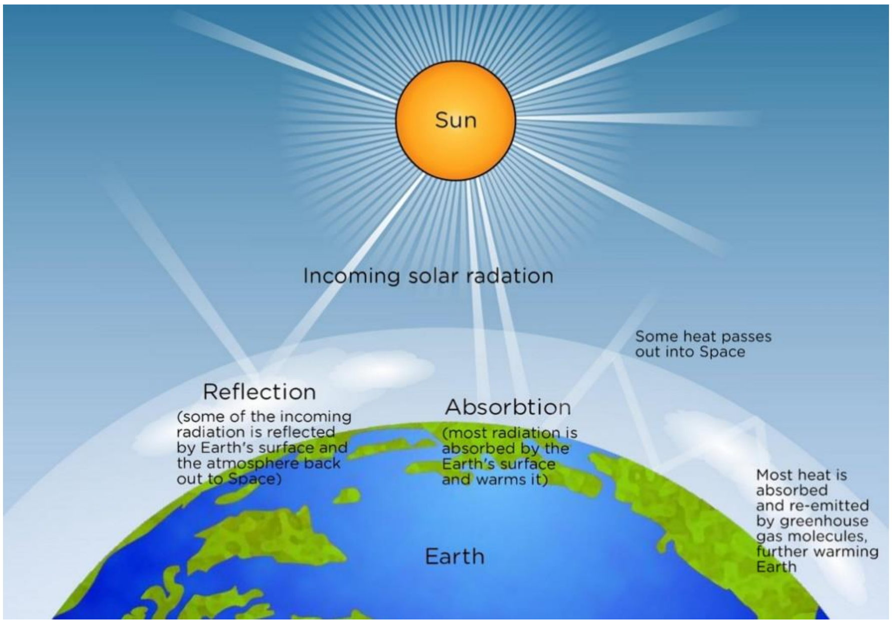


Figure 1.1: Incoming solar radiation [2]

In 24 hours, each square meter of land receives an average of 4-6 KWh of solar energy with an annual radiation of 800-2500 KWh/m^3, almost twice the amount of energy that can ever be obtained from all non-renewable energy sources (oil, gas, coal, etc.). Greece, a country with high sunshine, lends itself to harnessing solar energy, as the average daily energy delivered by the sun is estimated to be 4.6 KWh/m^2 [3].

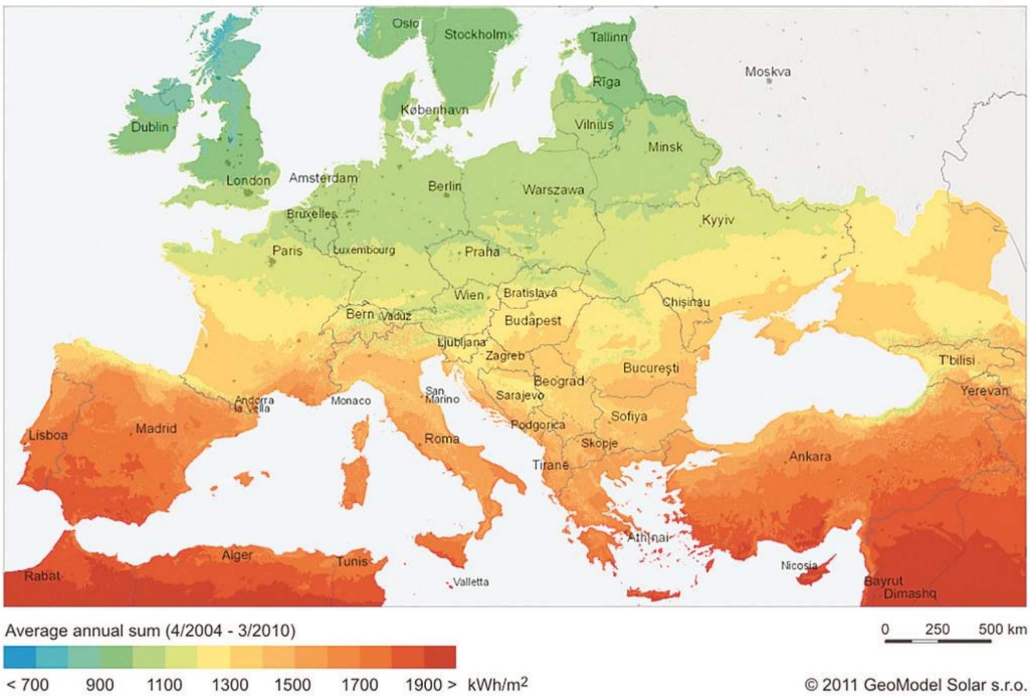


Figure 1.2: Average annual radiation in Europe

Solar radiation can be exploited in several ways:

1. by the direct generation of electricity via photovoltaic cells or PV cells. These systems convert solar energy directly into electricity with efficiency exceeding 15%, with beneficial conditions to achieve even better efficiency.

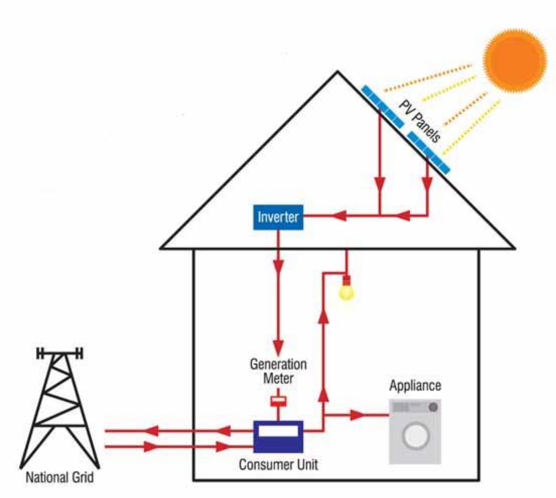


Figure 1.3: Example of application of a photovoltaic system in a house [4]

2. with passive solar systems, which are mainly building blocks, that make use of the heat laws. They collect solar energy, store it in form of heat and then distribute it in space. With glass or other transparent material, they can box heat indoors and combine with architectural lighting techniques, offering solutions for both winter heating and summer air conditioning.

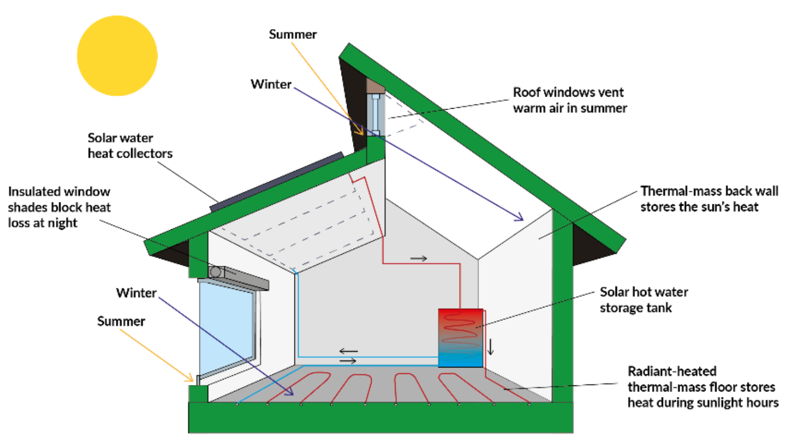


Figure 1.4: Example of application of a passive system in a house [5]

3. with the active thermal systems which we will deal with. They collect the sun's radiation with the solar collectors and convert it into heat. This heat is stored in an insulating tank.

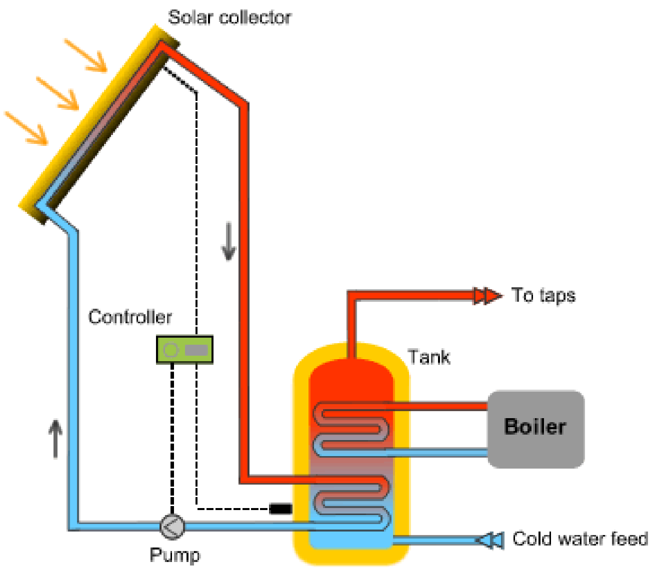


Figure 1.5: Example of application of an active system in a house [6]

1.2. Active methods of harnessing solar energy

Active thermal systems are divided into two major categories, air and liquid systems. The main difference is the way solar energy amasses in the solar collector. In air systems, energy is absorbed through air, while in fluid systems some fluid is used for this process. Air systems comprise a minor part of the world market (0.4% in 2014), as their collectors are less efficient than liquid systems. They are also not easily combined with air conditioning systems and the cost of heat storage is expensive [6] [7].

The most widespread use of active thermal systems is for space or water heating. They collect sun radiation and convert it to low temperature heat. In this way they can be used wherever low temperature heat is required, such as:

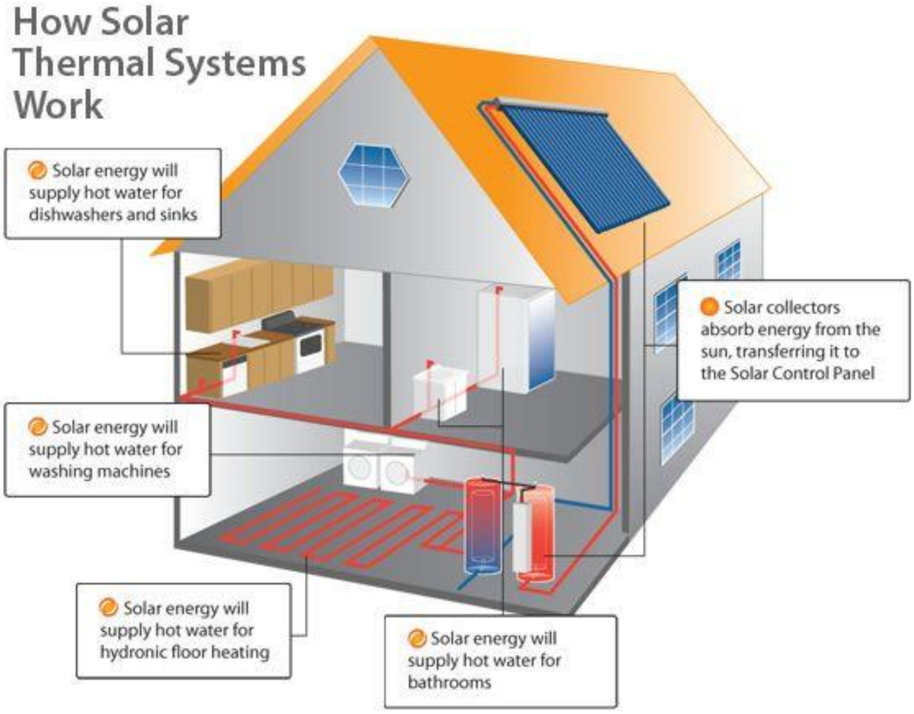
- for domestic water heating
- for space heating or cooling
- for pool heating

- for various industrial processes and agricultural applications (desalination, drying of products, distillation processes) [8]

Finally, another application that has been very popular in recent years is **hybrid systems**, which combine the production of domestic hot water and space heating. This use of systems can be considered very efficient, especially in Greece, if combined with proper design /construction of buildings (good insulation, exploitation of passive solar benefits, etc.).
In general, the efficiency of active thermal systems has improved significantly in recent years, and as result Greece is ranked second in the European ranking of countries with the most installed square meters of solar panels. The established surface of each kind of solar panels reaches 316,000 m^2 (2017 data) [9].

1.3. Description of solar thermal system operation

The solar collector mounted on the roof converts the light that penetrates its glass panes (short-wave radiation) into heat. The collector is therefore the link between the sun and the hot water user. The heat is created by the absorption of the sun's rays through a dark-coated, usually metal, plate – the absorber. This is the most important part of the collector. In the absorber is a system of pipes filled with a heat transfer medium (usually water or an antifreeze mixture). This takes up the generated heat.
Collected together into a pipe it flows to the hot water store. In most solar water heating systems – by far the most commonly used type of solar thermal systems – the heat is then transferred to the domestic water by means of a heat exchanger. The cooled medium then flows via a second pipeline back to the collector while the heated domestic water rises upwards in the store. According to its density and temperature, a stratified system is set up in the store: the warmest water is at the top (from where it leaves the tank when the taps are turned on) and the coldest is at the bottom (where cold water is fed in) [1].



1.4. Types of solar thermal systems

The solar thermal systems, depending on how the solar collector and storage tank are connected, are divided into two major categories:

• thermosiphonic or passive solar water heaters

• forced circulation type or active solar water heaters

In thermosiphonic or passive solar water heaters, the hot water storage tank must be located at a point higher than the collectible surface. In this way the circulation of the fluid is achieved due to the pressure difference created in the circuit. Thus, without a pump, the continuous flow of the heated medium from the hottest point (collector) to the coldest (water tank) is achieved until the two points reach similar temperatures. This principle of operation of the natural flow systems is called **the principle of the thermosyphon** [10].

The most well-known of these systems are solar water heaters and are the most widespread in Greece as they are manufactured in capacities of 150-300 liters and can meet the needs of a home for hot domestic use, with relatively high efficiency and rapid damping.

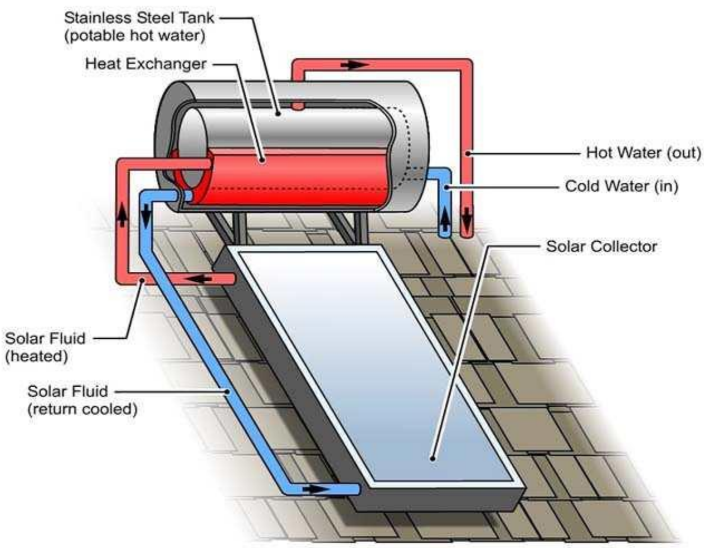


Figure 1.6: A passive solar water heater

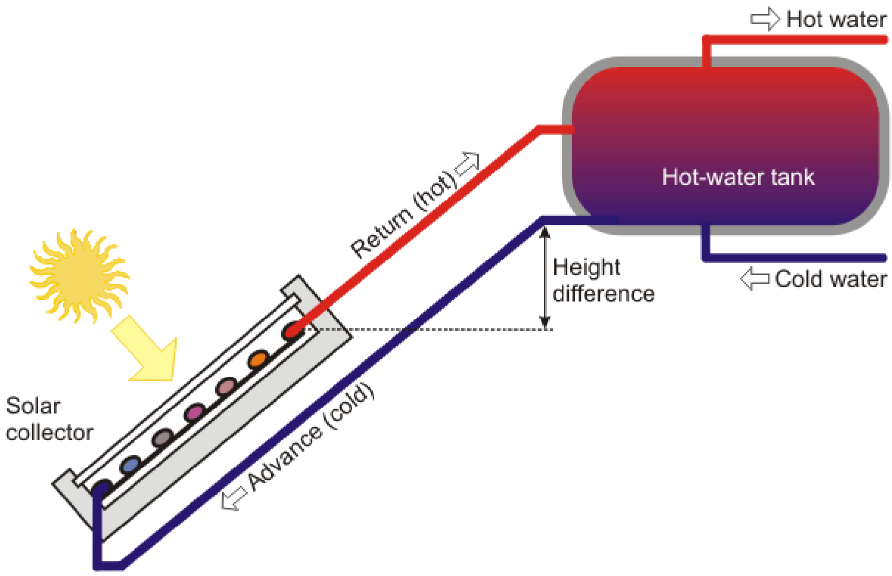


Figure 1.7: A typical arrangement of a thermosyphon system [10]

Another category of passive solar systems, in addition to solar water heaters, are the integrated collector storage systems **ICS (Integrated Collector Storage),** which has undergone a lot of research in recent years to improve their performance. These systems combine the collector with the storage tank in one unit. More specifically, a water tank is enclosed in a well-insulated box, and the storage surface acts as an absorber. Cold water is pumped to the bottom of the tank, while hot water is taken from the top. The advantage of these systems is that they do not require piping, separate storage tanks and other components, and do not require large installation space. However, they are not yet popular because of the high heat loss at night and when the weather is cloudy [11].

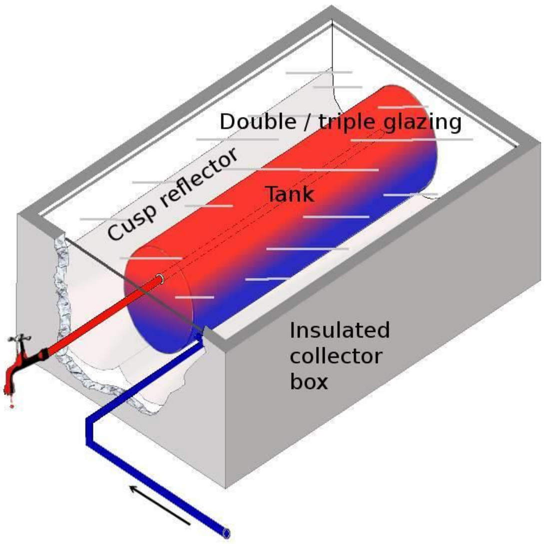


Figure 1.8: An ICS system [12]

In **forced circulation solar systems**, the solar collector is usually located away from the storage tank. Electric pumps, valves and control systems are used to circulate the heated medium. Many times, a differential thermostat is also used to command the pump to start the flow of fluid into the pipes when the water temperature of the collector is higher than the water temperature at the bottom of the tank. Otherwise, the pump will not start and there is no flow.

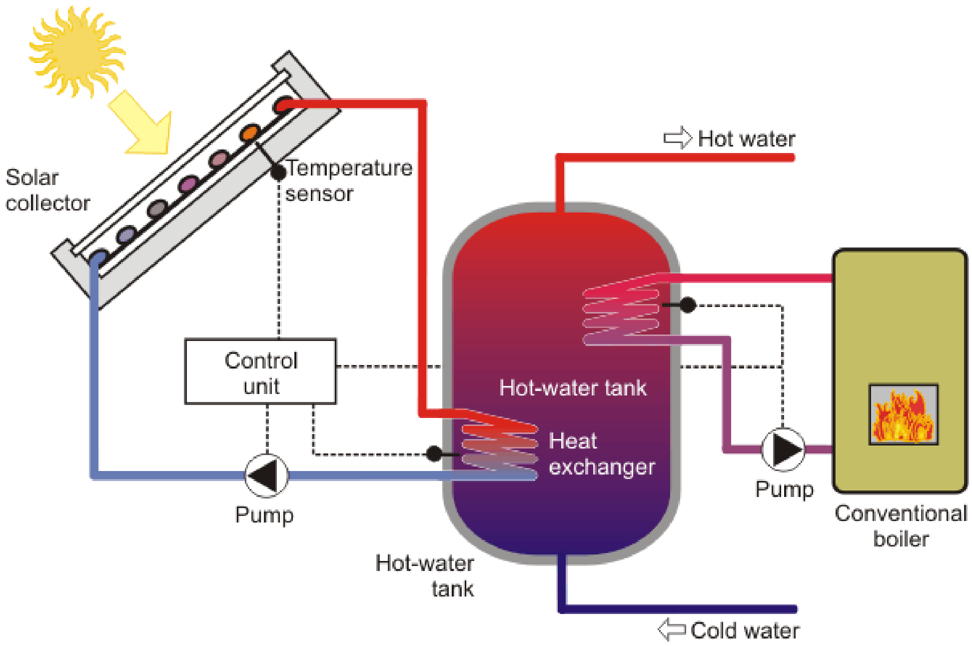


Figure 1.9: A double-cycle system with forced circulation with a boiler for back-up heating [10]

These systems are most often used to meet greater water needs (e.g. gyms, apartment buildings, hotels, large detached houses), are fully automated, require minimal maintenance and when they are combined with a backup source, meet up to 100% the needs for hot water [10].

Also, depending on the circulating circuit of the heated medium, there are two types of solar thermal systems:

- direct circulation systems and
- indirect water heating systems.

In **direct circulation systems** (open loop systems), the heated medium is the same as the water for use. They are used in areas with a warm climate, where the possibility of frost is rare, as it is not possible to add antifreeze mixtures (since the heated medium is the water itself). These systems may require a recirculation freeze protection (circulating warm tank water during freeze conditions) and this in return requires electrical power for the protection to be effective. In an open loop system the usable hot water is directly circulated through the heating system [7] [13].

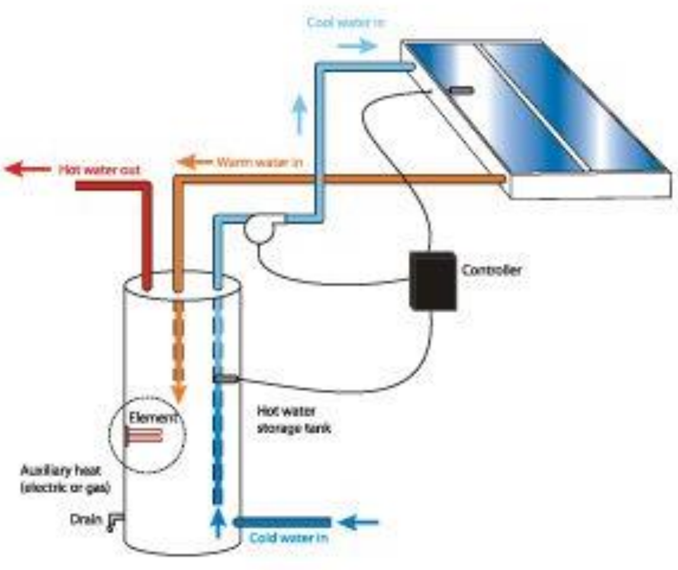


Figure 1.10: A direct water heating system [13]

In **indirect water heating systems** (closed loop), water is heated by a heat exchanger. The heated medium is most often a mixture of antifreeze liquid (glucose) and water, which protects it from frost. The mains water is heated by contact with the spiral tubing of the hot heated fluid, coming from the solar panels. A big advantage of the antifreeze system is that the collectors can be mounted anywhere. These systems are almost the only solution in installations where the climate in the area is very cold [14].

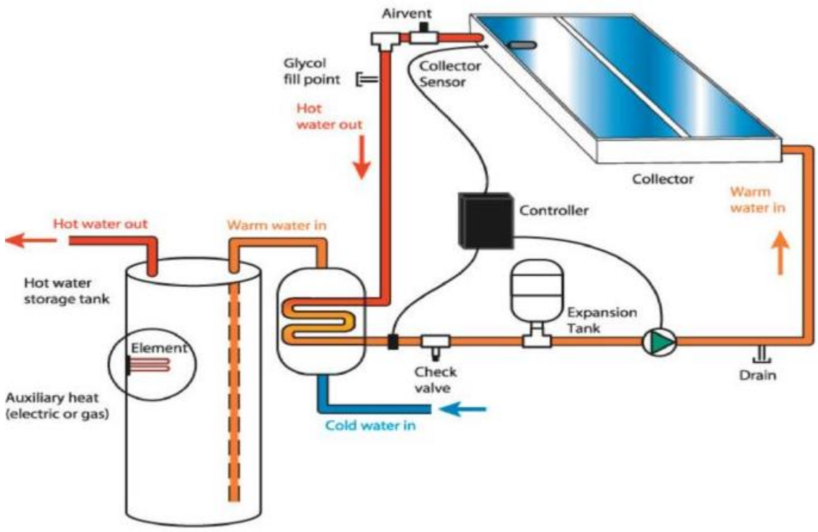


Figure 1.11: An indirect water heating system [13]

Finally, depending on the number of energy sources that can be utilized, solar thermal systems can be distinguished into:

• dual energy solar heating systems

• triple energy solar heating systems

Dual energy systems operate using either solar or electricity. For example, in the event of a cloud, where solar energy is insufficient to heat the water, there is electrical resistance placed inside the storage compartment to provide hot water.

Triple energy systems operate like dual energy systems, except that they include another utility. This is the use of hot water, as a heating device, by the central heating boiler. For the triple energy system to function, it is necessary to have adequate infrastructure in the building so that the solar system can be connected to the boiler room [15].

1.5. Storage tank

In a solar thermal system, the solar collector is connected to a storage tank, in which it transfers the heat it produces through the heating medium that flows into the piping. The tank is usually made of steel, with an inner coating for protection against corrosion. The coating consists of special plastic or epoxy paints. If the system is expensive, the storage tank can be copper or stainless steel. The tank exterior has very good insulation, usually made of polyurethane or fiberglass, to minimize heat loss.

Moreover, in storage tanks depending on the type of solar system we use, there is a built-in electrical resistance. In indirect water heating systems, there is a built-in alternator or coil for circulating the heated medium. In the most expensive systems, the tank is double walled (mantle type), in which the heated medium circulates between the two walls. This system offers a larger heat exchange surface and is simple to manufacture.

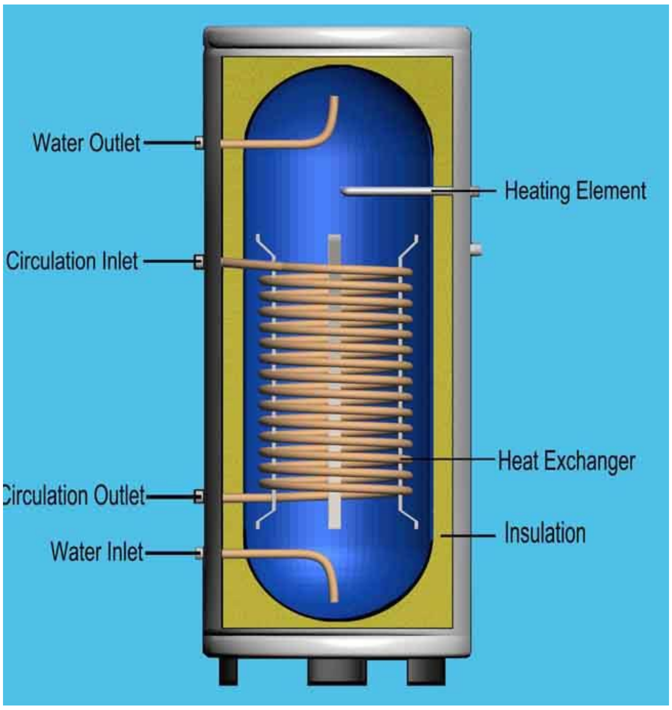


Figure 1.12: Water tank incision [16]

Finally, the capacity of the tank is a function of the collecting surface available. For regular home applications the capacity ranges from 150 to 300 liters and can be mounted horizontally to save space or vertically for better water stratification [17].

1.6. Solar collectors

The solar collector is the most important part of a solar thermal system. Depending on the operating temperature of the system, solar panels are divided into two large categories. At low and medium temperatures, flat geometry collectors are usually used, while at high temperatures solar panels are combined with flat and mirror arrangements. More specifically:

For low and medium temperatures, non-concentrating collectors are used for both hot water use and space heating. These are simple devices whose operation is based on **the principle of the greenhouse**, which develops in the space between the absorption plate and the glass coating. According to this principle, the solar radiation falls on the black absorbent plate increasing its temperature. The plate then emits a large wave of radiation (thermal radiation), but for which there is a glass that covers the plate and is almost opaque. In this way, high-wavelength radiation traps between the plate and the glass, thereby increasing the efficiency of the radiator. The heating medium is circulated in pipes that are in contact with the plate at the back.

On the contrary, for high temperatures, concentrating systems consist of complex devices. Their aim is to achieve high temperatures, either to produce hot water or to produce electricity. The temperatures needed to generate electricity are in the order of over 500 °C. As the gain fluid is heated, it becomes steam and it in turn drives a turbine connected to an electric generator.

The most important factors that ensure maximum efficiency of the solar collector are the high absorption of the plate in the solar radiation, the small emission factor of the long wavelength radiation and the large opacity of the crystal for the second. The materials that offer the best value-for-money are glass and aluminum or copper-colored black (to increase heat conductivity) [8].

1.6.1. Types of solar collectors

As mentioned above, solar panels are divided into two large categories depending on their operating temperature, non-concentrated and concentrated.

- Non-concentrated (Low – High Temperatures)
  - Unglazed solar collectors
  - Flat plate solar collectors
  - Evacuated tube solar collectors
- Concentrated (High temperatures)
  - Solar dish Stirling
  - Parabolic trough
  - Fresnel reflectors
  - Solar power towers

- **Unglazed solar collectors**

They are the simplest form of solar panels. They consist of black plastic or metal pipes, which have no insulation, and liquid circulates in them. The most important difference from the other flat-panel collectors lies in the fact that they consist only of the absorber.

Their operation is very simple as, no additional equipment such as storage unit and heat exchanger are required. The water in the tank circulates through the collector, is heated by the sun and is pumped directly back into the tank.

Figure 1.13: Unglazed Solar collector [18]

They are almost always used for swimming pools, where the wanted temperature is relatively low, since the maximum temperature achieved is 20°C above ambient temperature. The surface of the collectors that required is approximately equal to the surface of the pool [19].

- **Flat plate solar collectors**

Flat plate collectors are the main solar energy collection system used for hot water production and space heating applications. Their function is based on the greenhouse effect discussed above. They are usually mounted firmly on the building and in a position (inclination and orientation) depending on the place and season of the year the collector operates.

They consist of four main parts:

- The radiation collection plate (absorption plate), which is available in various types, but is usually black in order to reduce reflections.
- Fluid flow pipes, which either form part of the absorbent plate or are in contact and usually consist of copper.
- The cover of the absorption plate, which is a protective cover of glass or plastic. It is distinguished for its high absorbency (90-95%), the minimum reflection at short wavelengths (5-15%) and maximum reflection at longer wavelengths of solar radiation.
- The frame, which ensures the insulation of the remaining components from the weather phenomena and reduces the losses on the back of the collector.

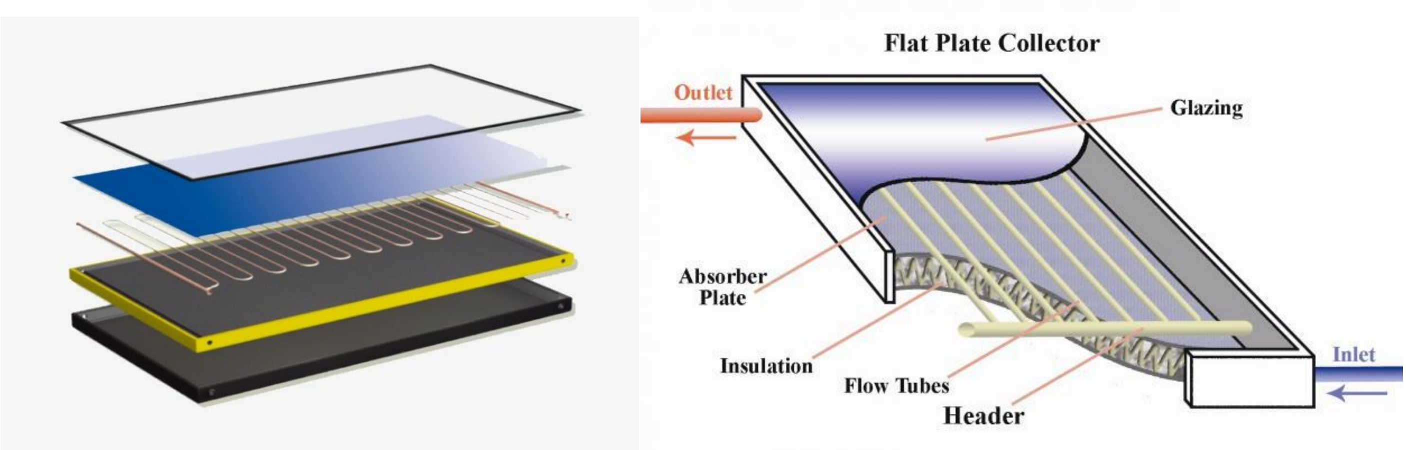


Figure 1.14: Parts of flat plate solar collector [20]

Flat plate solar collectors are used for applications with temperatures up to 150 ° C. In addition to space heating and hot water production, they are also used in applications such as air conditioning and heat production facilities for industrial use [21].

Another subcategory of flat solar panels, which has been developing in recent years, is **selective flat panels**. The selective surfaces have a high degree of absorption and a relatively low emission for solar radiation. The selective collector uses dyes, which absorb a great deal of the emitted radiation. This paint contains titanium and is applied to the metal surface by molecular bombardment. Selective paint gives the collector a distinctive light-blue color. The use of these relatively expensive surfaces is justified only to achieve relatively high temperatures (above 60 °C) and greater degrees of efficiency. Generally, the selective collector maximizes the amount of energy it absorbs, but it does not help to reduce losses at all [8].

- **Evacuated tube collectors**

Evacuated tube collectors consist of parallel glass tubes, which are glued to one or two central tubes, where heat exchange is performed. The pipes are under some vacuum, which achieves better insulation and reduces losses as heat is transmitted only by radiation and not by convection. Each tube consists of a glass airtight tube, containing a bronze heater, inside which the heating medium is located.

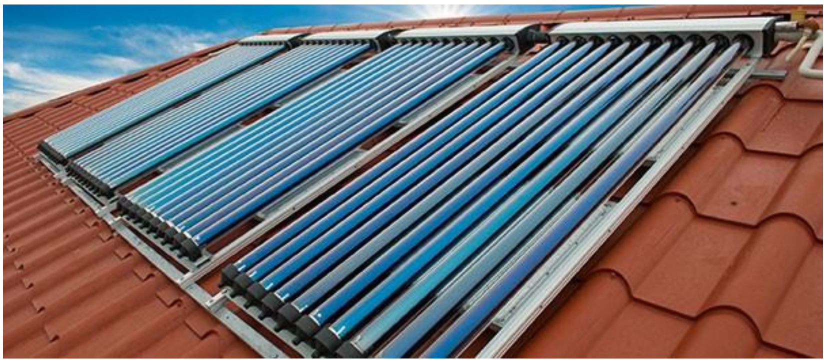


Figure 1.15: Evacuated tube collectors

During operation, the collected heat is transferred through aluminum foil to a copper tube containing an inorganic non-toxic volatile liquid (evaporated at 25 °C). When the tube starts and heats, this fluid is converted to overheated steam, rises upstream of the tube located inside the heat exchanger and warms the water used. Then, after the fluid has transferred heat to the use water, it is concentrated and lowered to the bottom of the tube and the process is repeated.

Heat pipe evacuated tube collectors are offered in two versions, one with a dry and one with a wet connection. For the **dry connection**, the condenser surrounds the collector, and provides a good heat-conducting link to a double tube heat exchanger. This permits defective tubes to be exchanged without emptying the solar circuit. For the **wet connection** the condenser is immersed in the heat transfer medium. If tubes have to be exchanged, it is necessary to empty the collection device at the top [1].

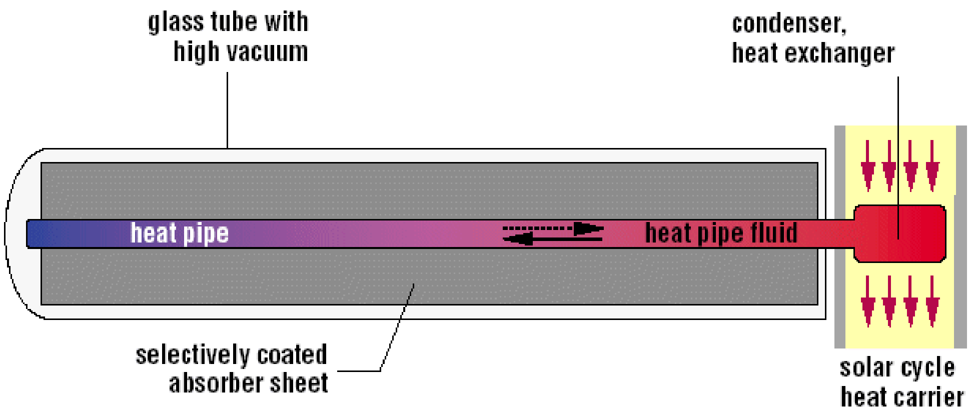


Figure 1.16: Principle of an evacuated tube collector with heat pipe, view from top [10]

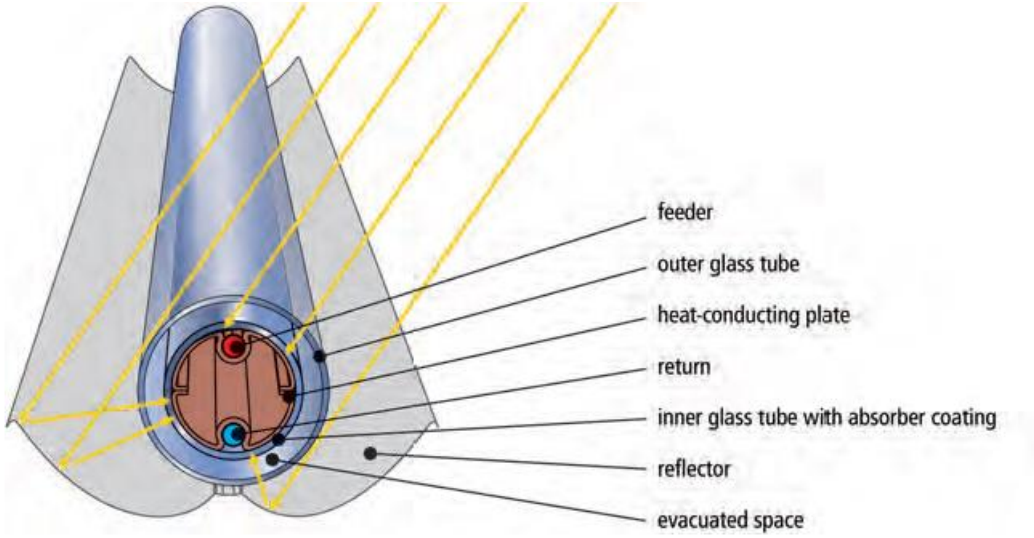


Figure 1.17: Schematic diagrams of a heat pipe absorber evacuated tube solar collector [1]

The advantage of evacuated solar collectors over flat plate collectors is that they have a higher efficiency and reduced heat loss due to optimum thermal insulation. They also overcome a smaller installation area due to their high performance. But they also have disadvantages such as the high cost of installation and the high operating temperature they develop, which makes them unsuitable for housing considering that in summer the temperature inside them exceeds 300°C. For this reason, they are mainly used in cold climates and in applications requiring water temperatures above 80°C (solar air conditioning, industry) [22].

In short, the advantages and disadvantages of an evacuated tube collector are:

Advantages

- It achieves a high efficiency even with large temperature differences between absorber and surroundings.
- It achieves a high efficiency with low radiation.
- It supports space heating applications more effectively than do glazed flat-plate collectors.
- It achieves high temperatures, for example for steam generation or air-conditioning.

- It can be easily transported to any installation location because of its low weight, sometimes the collector is assembled at the installation site.
- By turning the absorber strips (in the factory or during assembly) it can be aligned towards the sun (only relevant for certain products).
- In the form of direct through-flow tubes it can be mounted horizontally on a flat roof, hence providing less wind load and lower installation costs. In this way penetration of the roof skin is avoided.

Disadvantages:

- It is more expensive than a glazed flat-plate collector.
- It cannot be used for in-roof installation.
- It cannot be used for horizontal installation for heat pipe systems (inclination must be at least 25°C) [1] [23].

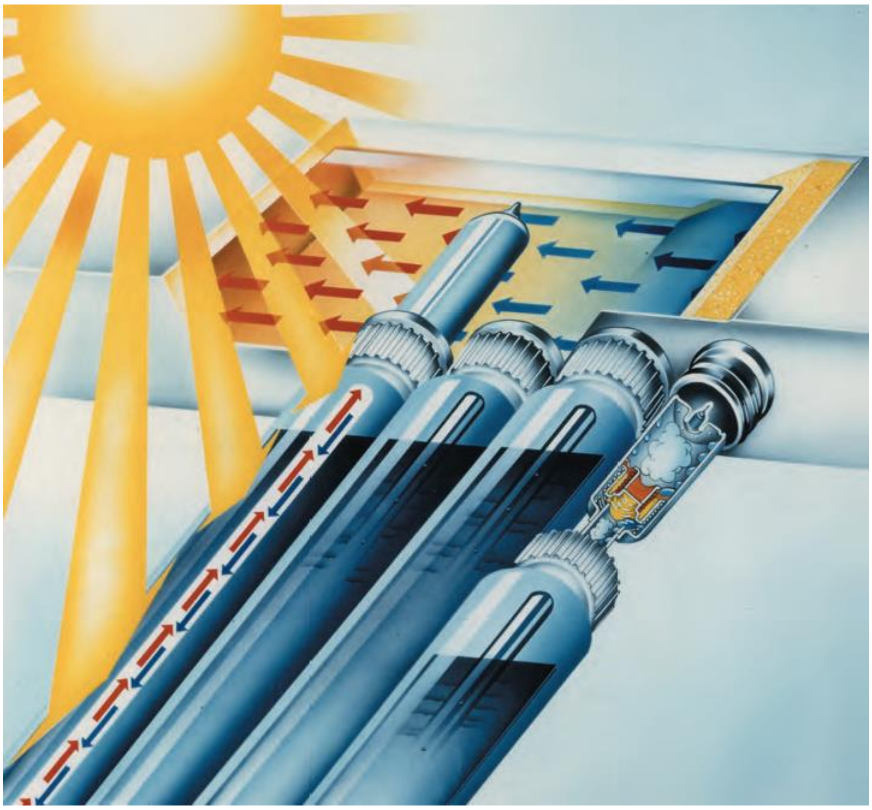


Figure 1.18: Cross-section of a heat-pipe evacuated tube collector [1]

- **Concentrated Collectors**

The concentrated collectors are used to collect solar radiation and convert it to medium or high temperature heat. Sunlight is concentrated using optical systems, which allows temperatures much higher than flat plate collectors.

A concentrated solar collector consists of the optical system or concentrator and the receiver. The concentrator receives the sun's radiation, concentrates it and directs it to the receiver, which in turn absorbs it. The concentrator can be a lens and diffract the sunlight or it can be a mirror and reflect it. There are still many types of concentrators, such as flat, parabolic, or consisting of a series of moving flat mirrors, which, with appropriate mechanisms, monitor the course of the sun. Also, the receiver can be a flat, convex or concave surface.

There are many types of collectors such as, parabolic troughs, solar towers in heliostat field, linear Fresnel reflectors, and parabolic dishes. These are the main technologies used in the concentrating solar thermal power plants. Each of these types of collectors has its own peculiarities and its own operating principles.

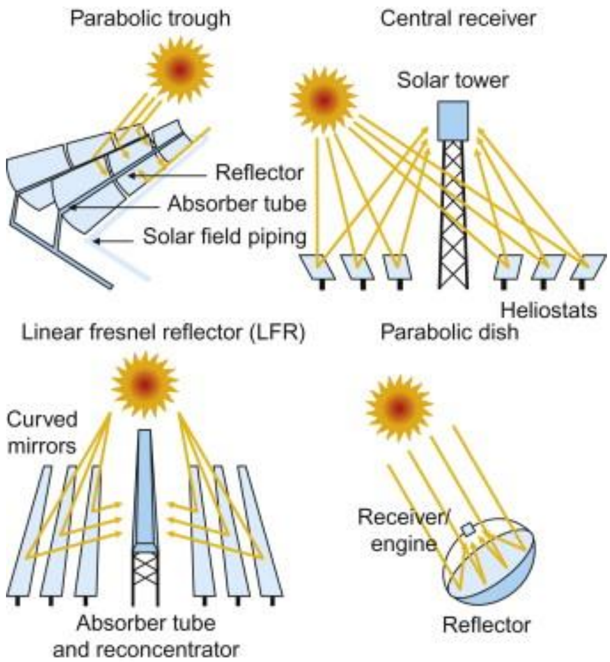


Figure 1.19: Typical solar concentrators: parabolic trough concentrator, parabolic dish concentrator, linear Fresnel reflector, and heliostat field concentrator [24]

Dish concentrating solar power (CSP) systems use paraboloidal mirrors which track the sun and focus solar energy into a receiver where it is absorbed and transferred to a heat engine/generator or else into a heat transfer fluid that is transported to a ground-based plant. The bulk of commercial CSP activity with dish concentrators involves the use of receiver integrated Stirling engines for direct production of electricity.

The Stirling engine is a closed gas engine, which produces work by heating and cooling the same gas mass and does not exchange gas with either the cold or the hot source, but only heat. It has two pistons, the power piston, which is hermetically closed and the separation piston, which is porous and partially permits gas flow through it.

Dish concentrators have the highest optical efficiencies, the highest concentration ratios and the highest overall conversion efficiencies of all the CSP technologies. Some prototype dish/Stirling systems have been erected and operated in Saudi Arabia, Spain and the USA. The levelized electricity costs are still relatively high in comparison with those of solar tower or parabolic trough plants. However, a dramatic cost reduction is thought to be possible when such systems are produced in large numbers and in volume production [25][1].

Figure 1.20: Dish concentrating solar power park

Figure 1.21: Dish/Stirling demonstration systems [1]

Parabolic trough systems use curved, parabola-shaped reflectors that use mirror coating to concentrate sunlight on a tube filled with liquid. This tube, frequently called a Dewar tube, is usually filled with oil and carries the heated fluid to an engine like a traditional power plant. To reach its maximum thermal efficiency of 60–80%, parabolic reflectors are mounted on tracking systems to follow the sun. The intensity of the concentrated solar rays heats the liquid medium to approximately 400°C [26].

Figure 1.22: Parabolic trough collectors systems [1]

Fresnel reflectors are like parabolic troughs in that solar radiation heats a receiver pipe, which contains the heat transfer. Fresnel reflectors are long and narrow, have little to no curvature, and several receivers are connected to form a module. Inside the pipes flow water or a mixture of water and about 70% quality steam, and the operating temperature is about 260°C.

At the exit of the tubes, water and steam are separated, and saturated steam is produced to generate electricity using a conventional Rankine cycle power block. The heat can also be used to preheat feedwater [27].

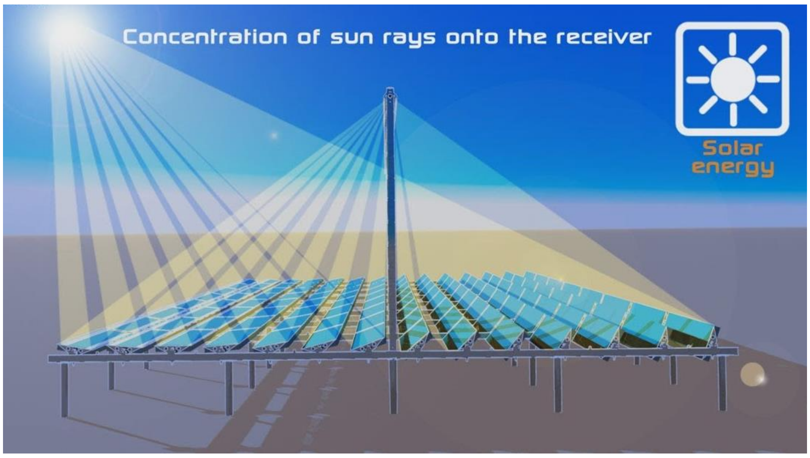


Figure 1.23: A Fresnel reflector concentrating system

A solar power tower is a system that converts energy from the Sun – in the form of sunlight – into electricity that can be used by people by using a large scale solar setup. The setup includes an array of large, sun-tracking mirrors known as heliostats that focus sunlight on a receiver at the top of a tower. In this receiver, a fluid is heated and used to generate steam. This steam then powers a conventional turbine generator to generate electricity. Potential downsides of using towers such as this is that they involve large facilities that require large amounts of initial investment. As well, the large field of mirrors and tower that can range from 50 to more than 100 meters can be seen as an eyesore and can impact that local landscape.

Figure 1.24: A solar power tower as shown from the ground (left) and from height (right) [28]

The most important advantage of these collectors is, to achieve very high operating temperatures (up to 550°C), which makes them useful for industrial use and in electricity generation. However, one major disadvantage is that they only use direct radiation, which results in the energy of diffuse radiation being lost. Nonetheless, collectors are new technology with great prospects for the industry [28].

1.6.2. Solar collector performance

The amount of heat collected from a solar collector system can be predicted from the solar collector efficiency (η_c):

$$\eta_c = \eta_o - \frac{a_1(T_C - T_a) + a_2(T_C - T_a)^2}{G}$$

Solar collector efficiency varies significantly with changes in the quantity of solar radiation (G), ambient air temperature (T_a), and average collector internal fluid temperature (T_c).

For a first order analysis the average collector internal fluid temperature is assumed to be the linear average of the inlet (T_{in}) and outlet temperatures (T_{out}) of the collector:

$$T_c = \frac{T_{in} + T_{out}}{2}$$

The optical efficiency (η_o) and thermal loss coefficients (a_1, a_2) are generally determined experimentally. Optical and thermal losses both have an impact on the collector efficiency, and their relative contributions depend mainly on the physical design of the collector.

Nomenclature

a_1, a_2	:collector thermal loss coefficients (W/m^2 °C)
A_c	:total solar collector area (m^2)
c_p	:specific heat capacity (kJ/kg°C)
G	:solar radiation (W/m^2)
m	:mass flow rate (kg/s)
mc_p	:heat flow rate (kW/°C)
Q_S	:solar collector duty (kW)
T_a	:ambient temperature (°C)
T_c	:solar collector temperature (°C)
T_{in}	:solar collector inlet fluid temperature (°C)
T_{out}	:solar collector outlet fluid temperature (°C)
η_c	:solar collector efficiency
η_o	:solar collector optical efficiency

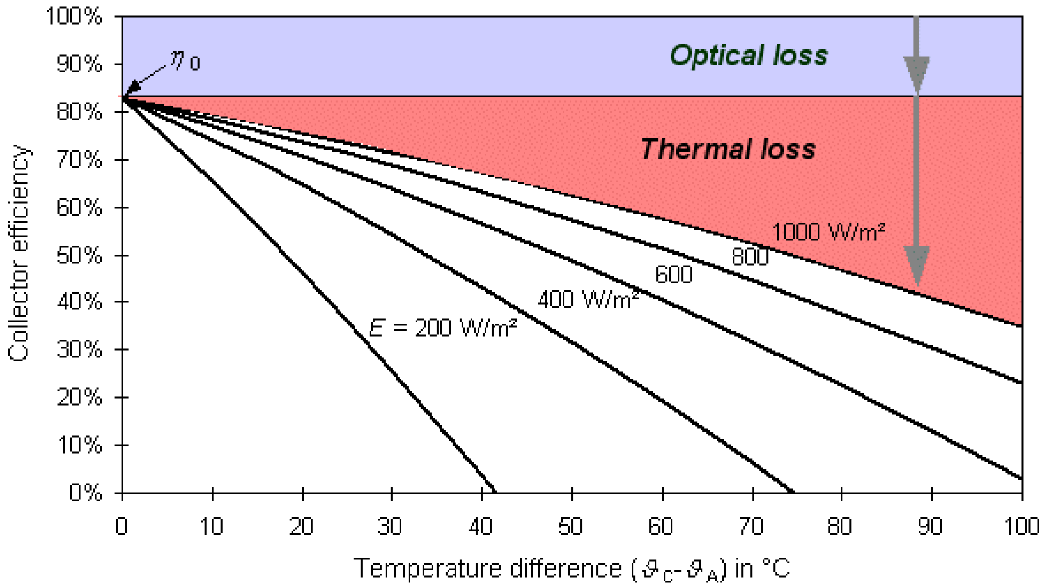


Figure 1.25: Collector efficiency for a typical evacuated tube collector at several solar radiation levels [10]

Once the optical efficiency and thermal loss coefficients are known the total solar collector outlet or solar duty (Q_S) can be determined using:

$$Q_S = \eta_c G A_c = \eta_o G A_c - A_c a_1 (T_c - T_a) - A_c a_2 (T_c - T_a)^2$$

where A_c represents the total solar collector area.

The collector temperature (T_c) is affected not only by the level of solar radiation but also by the mass flow rate of the fluid through the collector (m). Intuitively, as the mass flow rate is lowered, the outlet temperature from the solar collector will rise. This will lead to an increase in the solar collector temperature, which will in turn lower the collector efficiency. The mass flow rate as a function of temperature rise (ΔT) can be calculated using:

$$m = \frac{Q_s}{c_p \Delta T} = A_c \left(\frac{\eta_0 G - a_1 (T_c - T_a) - a_2 (T_c - T_a)^2}{c_p \Delta T} \right)$$

and $\Delta T = T_{out} - T_{in}$

where c_p is the specific heat capacity of the fluid [29].

As can be seen from the performance characteristics of solar collectors, there is no universally best solar collector. For example, in low temperature applications in areas with high insolation, an unglazed collector with a plastic absorber resistant to ultra-violet radiation may be the optimum choice. On the other hand, under high insolation conditions, solar thermal electricity generation requires the use of evacuated tubes located at the focus of line-axis tracking parabolic reflectors [22].

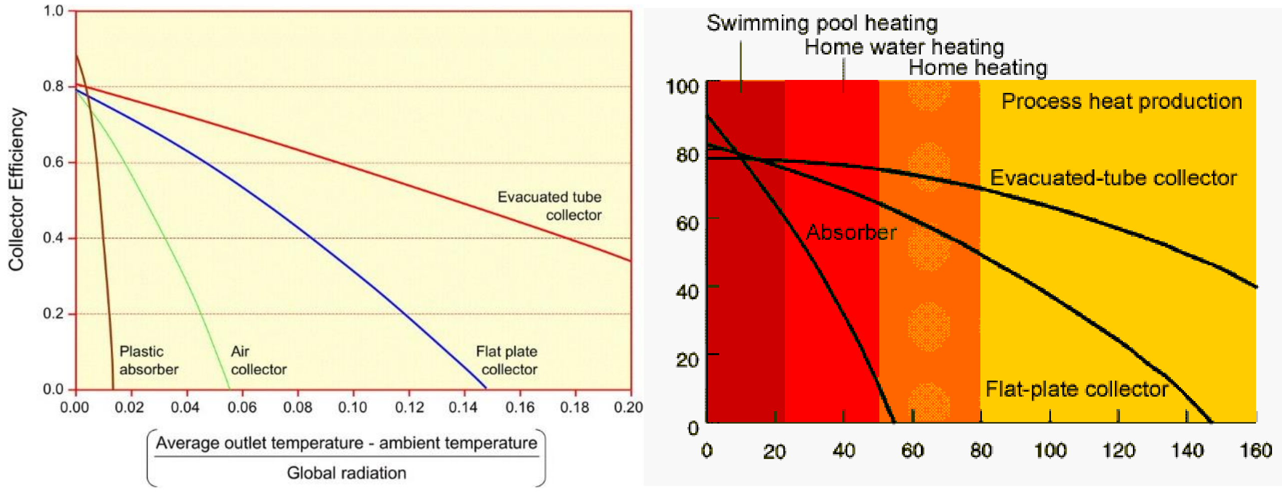


Figure 1.26: Graph of efficiency and temperature ranges of various types of collectors [22]

1.6.3. Orientation and Tilt of Solar Collectors

In order to maximize the thermal efficiency of solar panels, is essential to optimize the incident solar radiation.

Generally, a solar collector gives off more heat as the sun's rays fall on it vertically. In most solar systems, steady orientation is chosen to achieve an average annual incidence angle of solar radiation as close as possible to 90°. The best orientation for the placement of solar water heaters and solar collectors in Greece is the south, so that collectors can take advantage of as much sunshine as possible.

Also, the inclination of the solar collector should be around 20-50 degrees, depending on latitude. Higher or lower inclination in the solar collector reduces efficiency. For Greece and in general for all the northern hemisphere countries, the collector's inclination should be approximately equal to the latitude of the region.

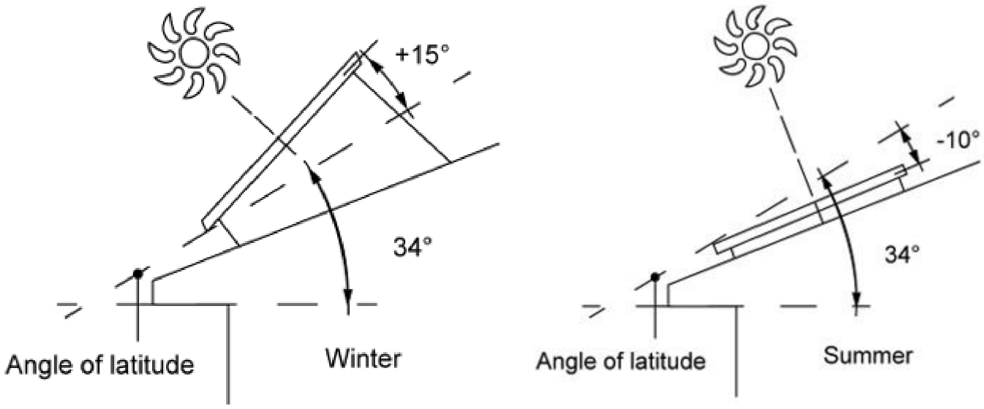


Figure 1.27: Change of inclination depending on the season [30]

This gradient can be varied to maximize the utilization of solar energy depending on the season and use, but with a slight decrease in annual solar coverage. Thus, by increasing the slope relative to the horizontal plane (10° - 15° greater than the latitude), it is possible to maximize energy profits during the winter period while decreasing the slope (10° -15° below the slope). latitude), maximizing energy profits during the summer [31].

CHAPTER 2

DESIGN AND CONSTRUCTION OF EXPERIMENTAL SOLAR SYSTEM

2.1. Introduction

The development, design and construction of an experimental solar system is at the forefront of the diploma thesis. This experimental device is a forced circulation system that fulfills the conditions to produce hot water for domestic use and space heating.

The main purpose is to complete Life Cycle Assessment and energy - economic - environmental evaluation of vacuum solar panels with advanced design.

Initially, the experimental device is designed in three-dimensional and two-dimensional with the help of which the final solar thermal system is constructed and assembled. The 3D design was made using Siemens NX12 while the 2D design was made using Microsoft Excel10.

Afterwards, it presents-analyzes the designs and presents the operating principles of the device. In the next step, reference is made to the methodology and assembly work for the design and manufacture of the solar thermal system. Finally, we analyze and illustrate the components and measuring instruments that make up our system.

2.2. Solar system design

As can be seen from the device below, the system consists of an evacuated tube solar collector and a storage tank with a mantle type heat exchanger. The storage tank is placed below the highest point of the solar collector and thus a forced circulation system is formed.

For the proper operation of the forced system, it is necessary to use a circulation pump that moves the liquid for heating conversion from the tank to the collector through the pipes. Immediately after the circulation pump, an electromagnetic flowmeter was installed to control and measure the flow.

Afterwards, the operation of the closed-circuit tank-collector is presented: Initially the antifreeze fluid which is mixture of propylene glycol and water (45% glycol, 55% water) with the help of the circulator pump flows through the pipes to the upper point of the solar collector. Through the evacuated tube solar collector, the liquid for heating conversion is heated and came down the tank, then enters the mantle and as it moves towards the outlet it transfers heat to the domestic water. Finally, the flow rate of the liquid for heating conversion is accurately measured through the electromagnetic flowmeter, while changing the operating speed of the fluid pump achieves the maximum temperature of the liquid for heating conversion at the collector outlet and therefore different maximum operating water temperatures.

Also, describing the open circuit of the device, the use water enters the storage tank, is heated by alternating heat with the liquid for heating conversion and then exits the tank. For economy in the amount of water supply and to zero the waiting time for the arrival of hot water, a hot water recirculation system was installed. By opening and closing the appropriate switches, the pump is switched on and the water used in the tank is re-circulated, achieving a constant temperature inside.

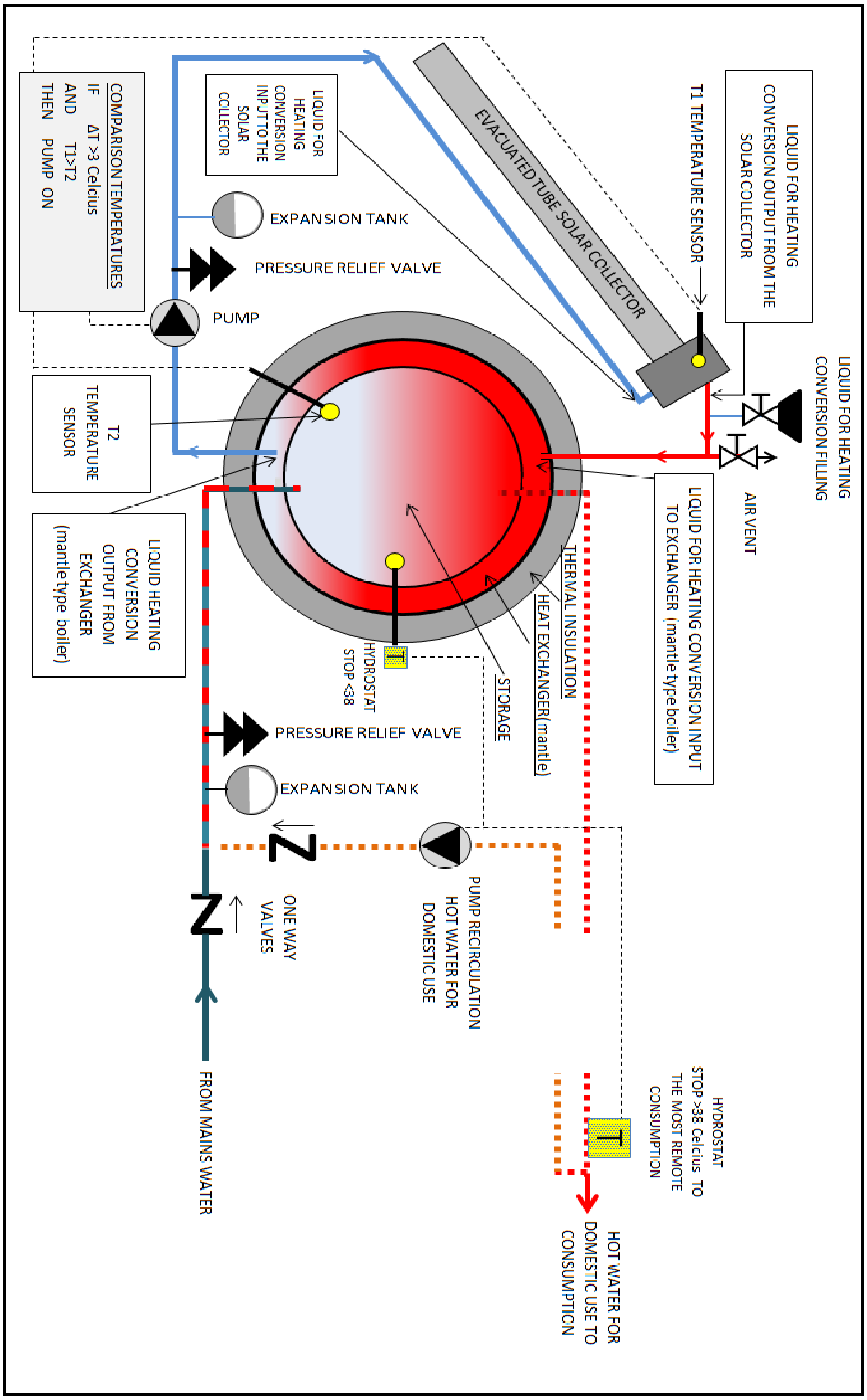


Figure 2.28: Diagram of the solar system of liquid for heating conversion accelerated circulation which shows hydraulic and electrical connections in section

As detailed below, the three-dimensional design of the experimental device is displayed of different angles:

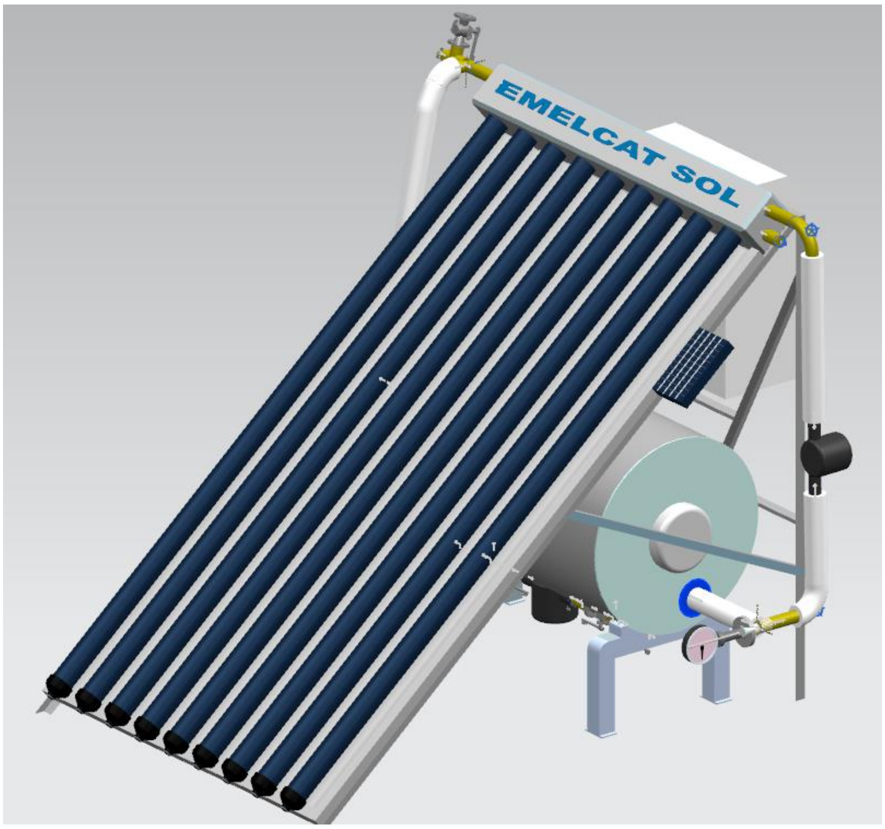


Figure 2.29: 3D experimental device design

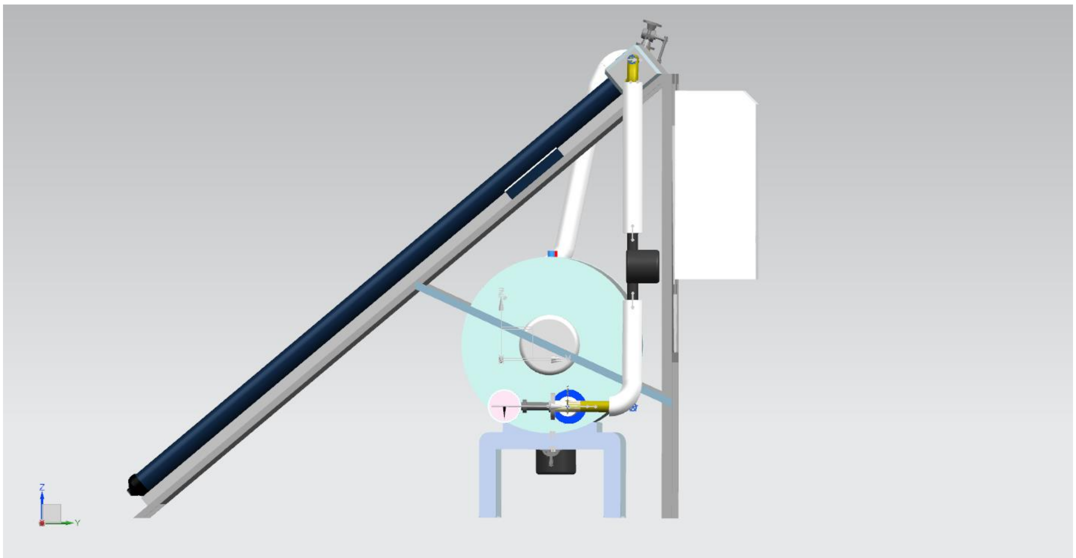


Figure 2.30: Right side view

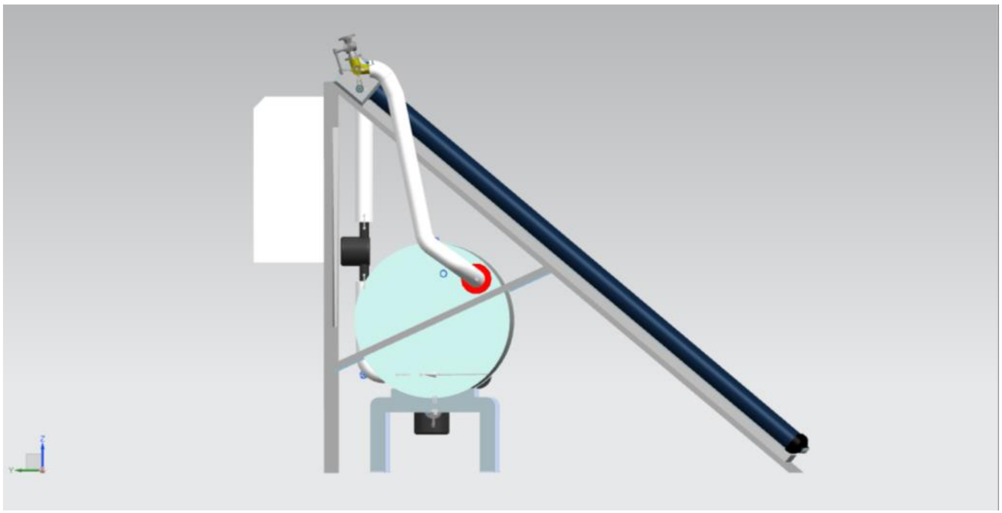


Figure 2.31: Left side view

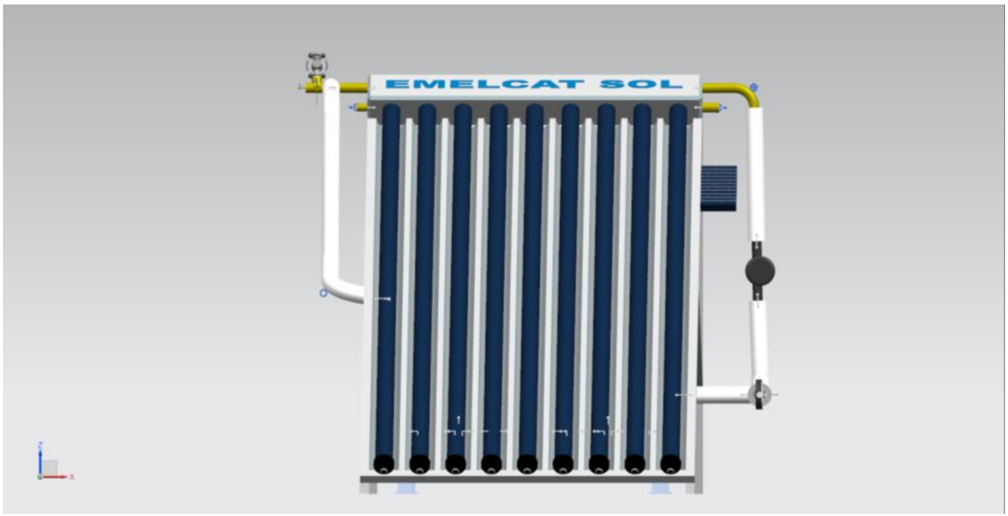


Figure 2.32: Front view

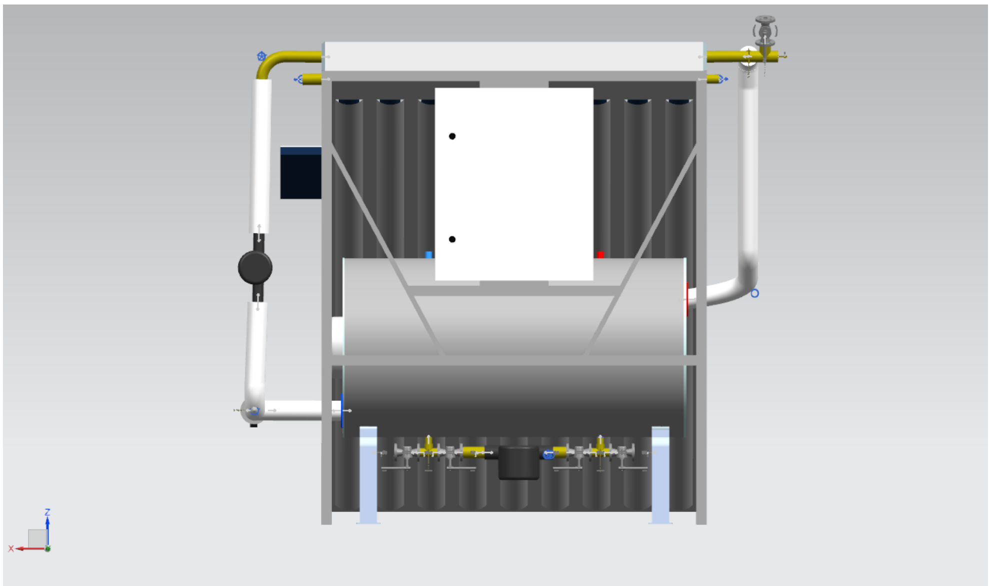


Figure 2.33: Back view

2.3. Procedure for assembly and construction of the experimental device

In this section it conducts the gradual assembly of the experimental device which includes: an evacuated solar collector and a hot water storage tank, 210lt of the company EmelcatSol, the appropriate piping, 2 different pumps, a pressure gauge, an electromagnetic flowmeter, a pyranometer, an anemometer, a few thermocouples and a data logger. All of the above parts will be studied in detail in the next section.

The assembly stages are presented below:

- **1st stage:** Creating a support base, installation of a solar collector and the storage tank.

Initially, it was created the base on which the solar collector was placed, while the storage tank was placed below the highest point of the collector. To make it easier to move the system, we create a body by Dexion, on which the whole system was connected. In this properly designed body, 4 wheels were placed.

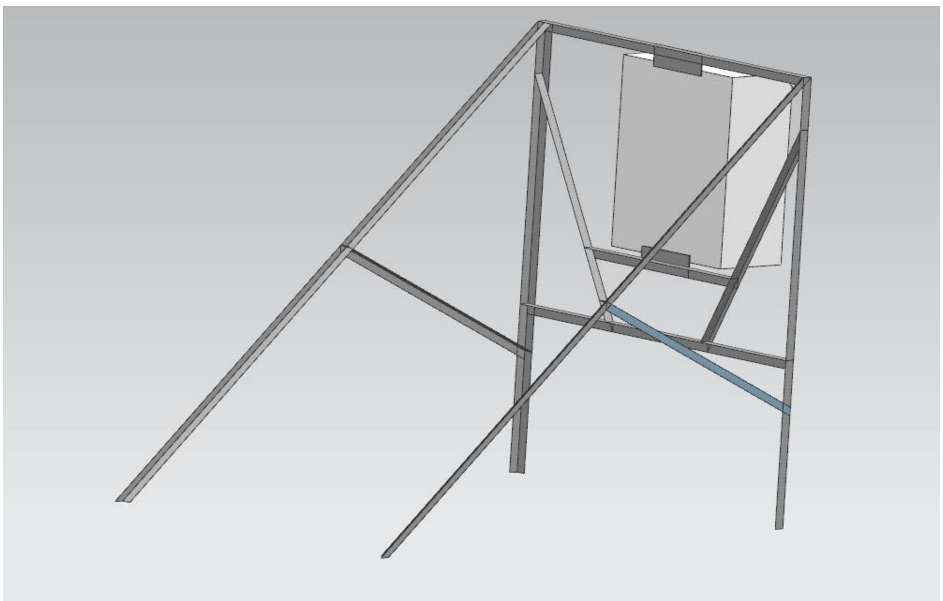


Figure 2.34: 3D support base display

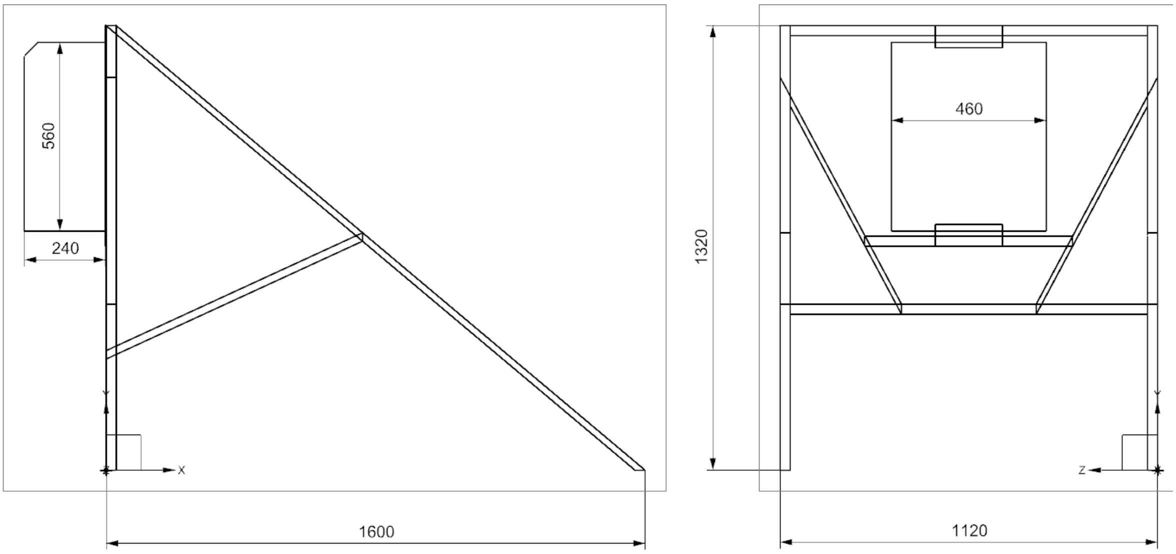


Figure 2.35: Support base dimensions (mm)

Figure 2.36: Support base

Figure 2.37: Backview of support base

- **2nd stage:** Hydraulic system connection, installation of measuring instruments and pumps, installation of thermal insulation.

At this stage of assembly, the closed circuit of the system was formed, through which the liquid for heating conversion will flow. The flow of fluid starts from the inside of the storage tank, flows through the collector pipes and ends up inside the tank, with the help of the circulator. Also, above the circulator, a small frame was placed in which there is a photovoltaic, which has the role of the switch for the circulator.

Furthermore, the collector open circuit was connected to the water supply network, with the aim of achieving the maximum temperature difference that develops between its inlet and outlet, as well as the flow rate of the liquid for heating conversion. The recirculation pump was then placed in the open circuit of the storage tank, which connects the hot water outlet to its inlet to the tank.

Pipes with a diameter of 18 * 2 mm as well as brass hydraulic components, dimensions 1/2 and 3/4 of an inch, were used for the connection of the above. Also, at the inputs and outputs of the closed and open circuit, manometers were connected to measure the pressure of the liquid for heating conversion. Also, temperature sensors were installed together with immersion tubes to measure the temperature at each inlet - outlet of the solar collector and the storage tank. Finally, an electromagnetic flowmeter was used in the closed circuit of the collector to control and measure the fluid flow.

After the completion of the hydraulic connection of the system, thermal insulation was installed in all the pipes and connections. Then all the points were covered with aluminum tape.

Figure 2.38: Creation of a closed circuit with the installation of a circulator and a flowmeter

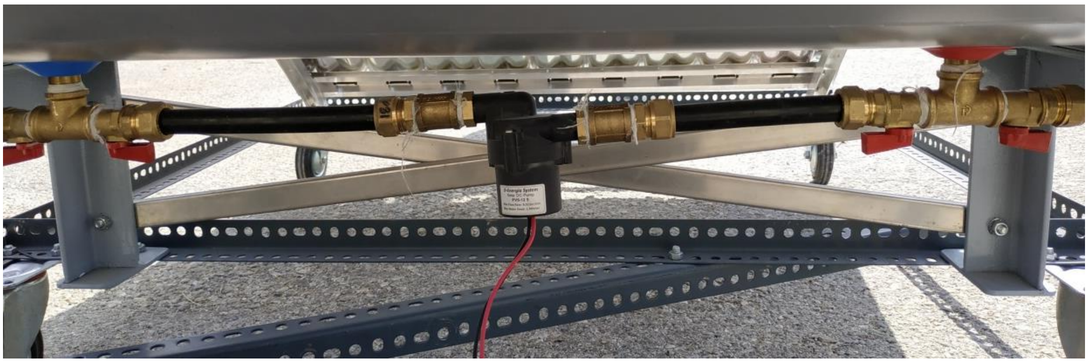


Figure 2.39: Creation of a closed circuit using a recirculation pump

3rd stage: Electrical wiring Data Logger, circulators, and electromagnetic flowmeter

The last part of the construction concerned the electrical connection of the system with a data unit (Data Logger), so that the measurements taken by the measuring sensors were recorded and stored in a file, with the help of a computer. With the recording of the data, it becomes possible to carry out the experiments for the certification of the solar thermal system. The Data Logger device is located on the back of the support base.

A CMP 3 pyranometer was also connected to the Data Logger to estimate the intensity of solar radiation during the export of experiments and an anemometer to record air velocity.

Figure 2.40: Connection of pyranometer (left) and anemometer (right) to the data logger

Figure 2.41: The data logger, the thermocouples, the power supply of the flowmeter and the dimmer

The integrated system is presented below:

Figure 2.42: Front view of experimental Solar system

Figure 2.43: Left side view

2.4. Display parts and experimental device equipment

Below is an analysis of the measuring instruments and equipment that constitute the experimental device.

2.4.1. Evacuated Solar Collector EMELCATSOL

The ESOL-U collector, which is used in the experimental device, is ideal for the production of hot water, covering up to 80% of the annual needs, as well as for space heating, providing up to 60% fuel economy.

The vacuum tubes are made of BOROSILICATE 3.3 GLASS, an extremely durable material in abrupt temperature differences, but also in external factors (weather conditions, etc.). The selective coating of the pipes is three layers of Cu / SS-Aln, in order to achieve the maximum possible absorption of solar radiation. Also, ESOL-U collectors have the ability to be installed in a slope range of 0-90, which is a perfect choice covering all needs for each requirement. Finally, the CPC-type reflector, made of specially processed aluminum, offers the maximum possible use of incident radiation, even on days with low sunlight. It also offers long life as well as special resistance to all environmental conditions [32] .

The features given by the manufacturer are:

Model: 9 ESOL-U

Serial Number: U09-100133

Date of manufacture: 07/2019

Frame area: 2.3 m^2

Absorber area: 2.1 m^2

Maximum operating pressure: 1MPa

Capacity of liquid for heating conversion: 4lt

Maximum instantaneous collector performance: 0.57

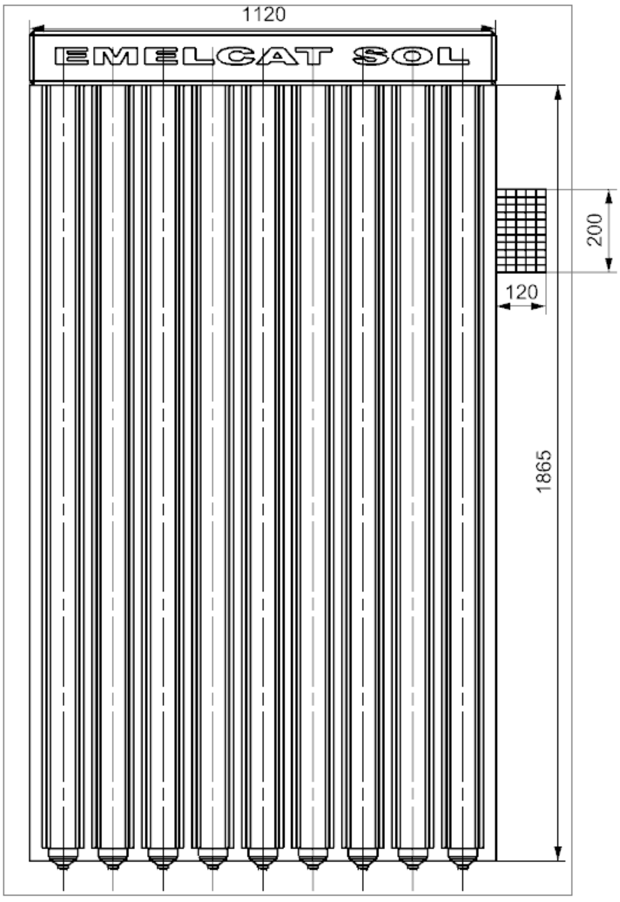


Figure 2.44: Solar collector frame dimensions (mm)

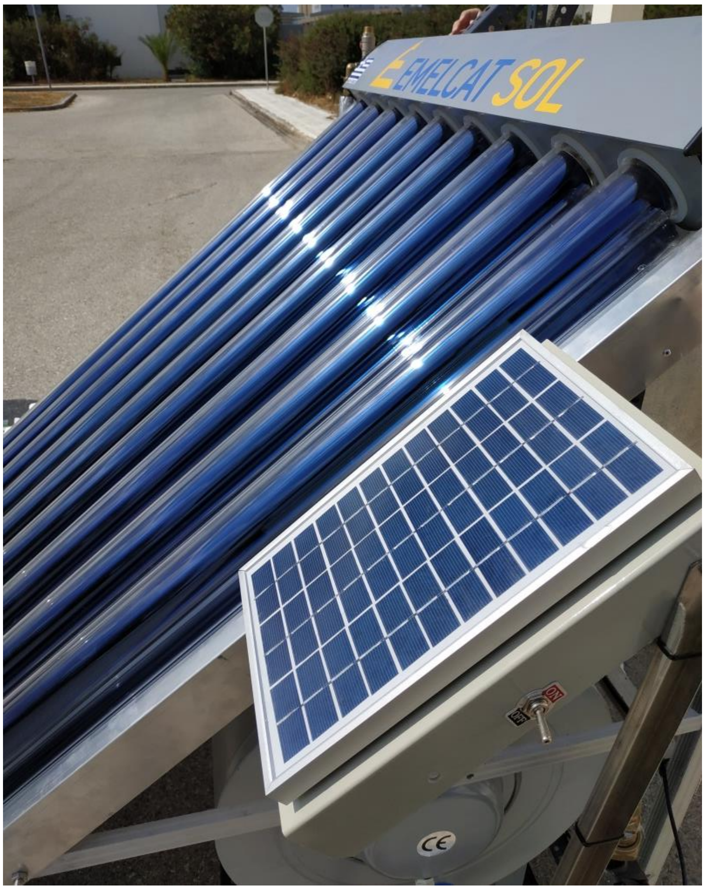


Figure 2.45: Evacuated Solar Collector

2.4.2. Storage Tank EMELCATSOL

The hot water storage tank is a mantle type. Its facilities allow the operation of a dual-energy system for heating hot water. The system operates entirely through solar radiation. The capacity of the tank is 210 lt.

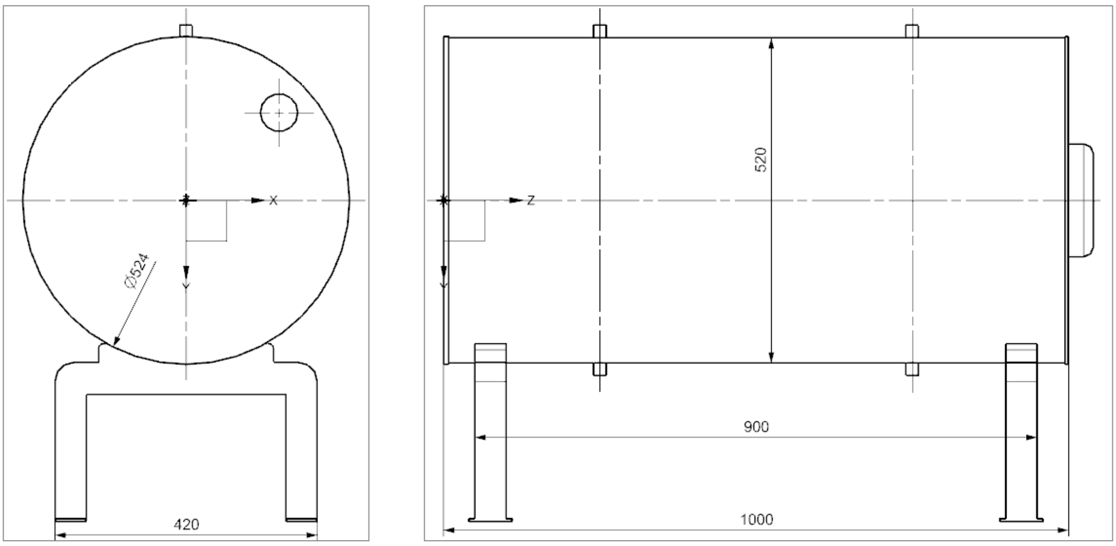


Figure 2.46: Storage tank dimensions (mm)

Figure 2.47: Storage tank

2.4.3. Circulator GRUNDFOS ALPHA SOLAR 25-75 180

The circulator is designed to be integrated in all kinds of thermal solar systems with either variable (matched-flow) or constant flow rate. The speed can be controlled by a low-voltage PWM (Pulse Width Modulation) signal from a solar controller to optimize the solar harvesting and temperature of the system. As a result, the power consumption of the pump will be reduced considerably.

The advantages and features of this circulator are:

- Constant speed.
- PWM A profile. The PWM signal is a method for generating an analog signal using a digital source.
- Low Energy Efficiency Index
- Maintenance-free
- Low noise level
- Very simple installation [33]

Figure 2.48: Circulator Grundfos

The specifications are the following:

Technical

Head max: 7.5m

TF class: 110

Materials

Pump housing: Cast iron

Installation

Range of ambient temperature: 2-70 ^{o}C

Maximum operating pressure: 10 bar

Pipe connection: G 1 ½

Pressure rating: PN 10

Port to port length: 180mm

Liquid

Pumped liquid: Water

Liquid temperature range: 2-110 ^{o}C

Selected liquid temperature: 60 ^{o}C

Density: 983.2 kg/m^3

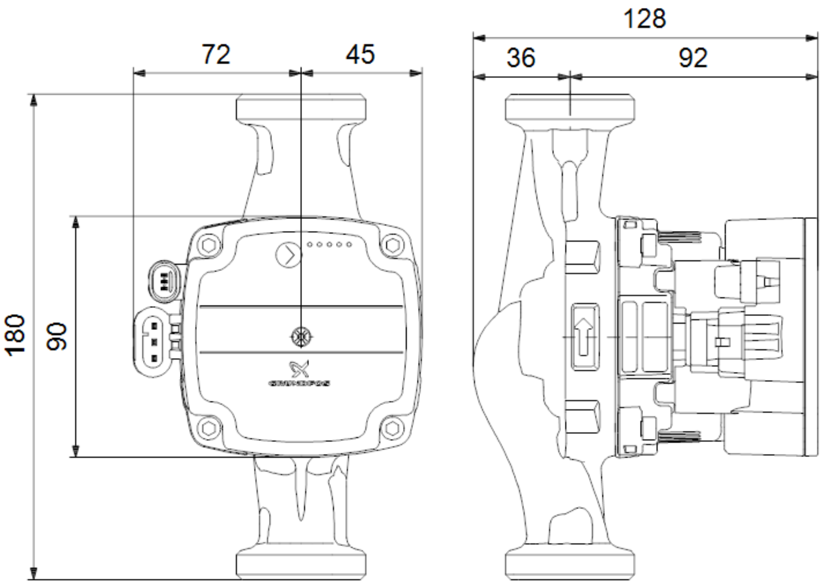


Figure 2.49: Alpha Solar circulator dimensions (mm) [33]

2.4.4. Solar DC pump D-Energia System PV5-12 5

In large buildings (hotels, hospitals) nowadays for the heating of water use in central installation, in addition to oil use solar systems or heat pumps are used or even the discarded heat of the central cooling system of the building. However, due to the long distances of the hot water storage tank from the taps, the hot water when a tap is opened is slow to come, resulting in water being discharged and waiting time required.

For these reasons we use the hot water recirculation system. This includes a small cross-section pipe (Φ16 or 1/2¨) from the farthest tap to the hot water tank. Before this pipe enters the hot water storage tank, a small hot water pump (hot water circulating pump) is installed. This pump circulates water from the farthest tap to the tank so that the hot water pipe from the tank to the tap always has hot water. In some cases, time and temperature limits are used. All hot water pipes are thermally insulated.

Figure 2.50: Solar DC pump

In this particular experimental device, a recirculation pump is used, the characteristics of which are as follows:

Max Flow Rate: 8.5 lt/min

Max Static Lift: 1.4m

Inlet/Outlet: NPT/BSP ½

Liquid Temperature: 0-110 ^{o}C

Range of Ambient Temperature: -40-70 ^{o}C

Power Supply: DC power supply, battery, solar powered

Motor Type: brushless DC motor

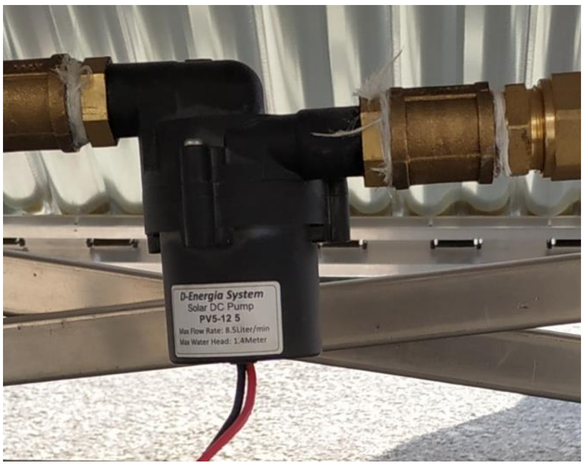


Figure 2.51: recirculation pump

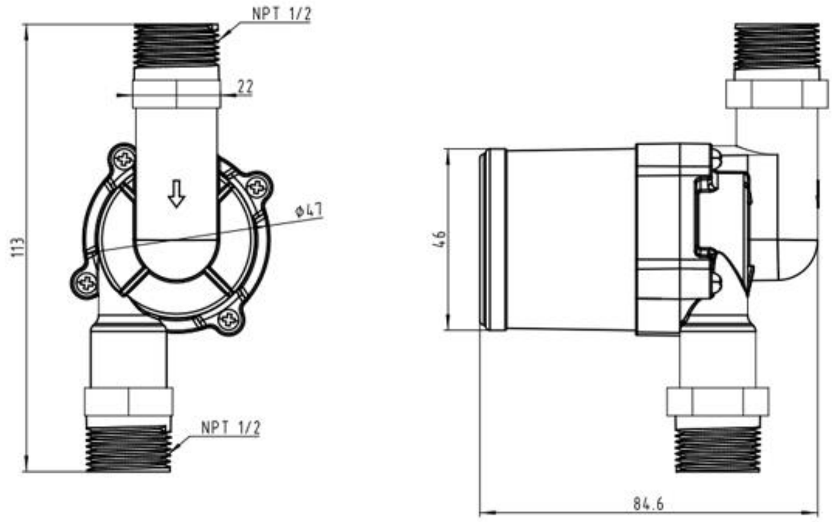


Figure 2.52: Solar DC pump dimensions (mm) [34]

2.4.5. Photovoltaic panel

Figure 2.53: photovoltaic panel

In the experimental device there is a photovoltaic panel which is located in a frame next to the solar collector. Its dimensions are 120mm width and 200mm length.

The role of the photovoltaic panel is to supply the circulator which provides the possibility of remote placement of the container. Essentially, it has the role of a switch, as when it is sunny, it immediately gives electricity to the circulator, which in turn moves the entire thermal system. Conversely, when there is no sunshine and no hot water production is needed, the photovoltaic panel gives the circulator limited or no electricity, thus saving energy. In this way the system becomes autonomous.

2.4.6. Electromagnetic flowmeter

After the GRUNDFOS circulator, a high-precision electromagnetic flowmeter, of the company ifm model SM6000 was installed. With this specific flowmeter it is possible to take two measurements. The first refers to the flow of fluid flowing through the collector pipes and the second refers to its temperature.

The flow sensor is based on the Faraday induction principle. Conductive fluid, flowing in a conductor with a magnetic field, produces voltage, which is proportional to the velocity or flow rate.

The voltage is detected by electrodes and converted into evaluation electronics. Various processing data processing capabilities are available: analog, binary and pulse outputs. Due to the flexible programming via buttons, the flow sensor can be adapted to different operating conditions. The sensor is mounted via an adapter. The high degree of protection and the robust compact housing set the sensor apart in the field.

Figure 2.54: Electromagnetic flowmeter

The main specifications are presented below [35] :

Technical specifications	
Measuring range	0.1….25l/min
Medium temperature [^{o}C]	-10…70
Pressure rating [MPa]	1.6
Operating voltage [V]	18…30 DC
Current consumption [mA]	95; (24V)
Process connection	threaded connection G 1/2 DN15 flat seal

2.4.7. Pyranometer Kipp & Zonen CMP 3

The CMP 3 pyranometer uses a 64-junction thermopile sensing element with a highly absorptive and spectrally flat black coating to capture incoming radiation and covert it to an electrical signal. This detector is protected by a high quality 4mm thick glass dome. The electrical output is provided as an mV signal and is expressed in Watts per meter square. The CMP 3 is designed for continuous indoor and outdoor use.

Figure 2.55: CMP 3 pyranometer

The CMP 3 is fully compliant with all ISO-9060 Second Class pyranometer performance specification criteria. It is intended for shortwave global solar radiation measurements in the spectral range from 310 to 2800nm. Units are supplied with a comprehensive, traceable calibration certificate

An Adjustable Tilt CMP Mounting Kit is available to allow the CMP 3 to be mounted at any angle from 0° to 90° to provide an accurate reading for the position and angle of fixed photovoltaic panels. The position and angle of solar panels make a big difference to the performance and return on investment of a solar energy power plant. A horizontally mounted pyranometer measures the global short-wave radiation from the sun and sky in a way that is easily comparable with other sites and with solar energy database information. However, for fixed angle (non-tracking) PV panels it is important to know the energy available within the 'view' of the panel [36] [37].

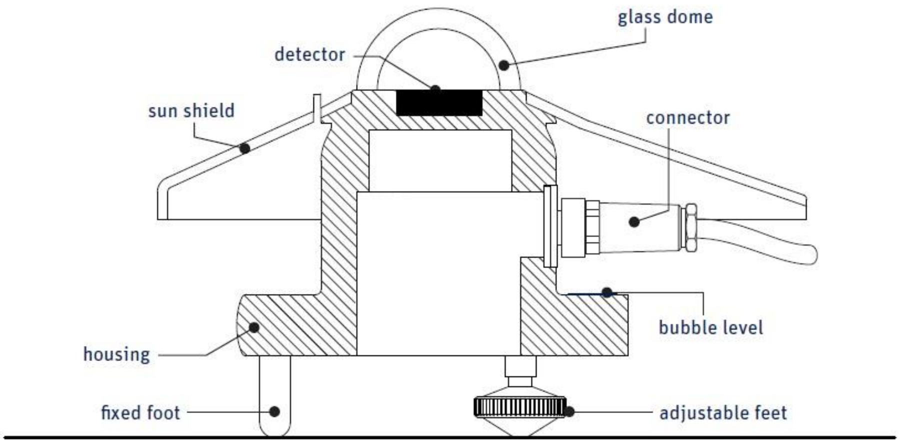


Figure 2.56: Pyranometer diagram [36]

2.4.8. Anemometer Windspeed A100K

Anemometer A100K that is used, are robustly constructed using weather resisting plastics, anodized aluminum and stainless steels enabling them to withstand continuous exposure to the weather, including marine environments, making them suitable for a wide range of applications where accuracy and sensitivity are very important. The A100 series anemometers all share the same basic construction and use the same R30 series 3-cup Rotors. Different internal modules and components are used to provide various output signals. The use of a precision ball-race mounted shaft ensures the essential low threshold speed and good repeatability. The outline and mechanical design, common to all the A100 series, remains largely unchanged since the introduction of the original Porton™ Anemometer in 1972, the electronics modules being continuously developed during this time to provide a well tried, durable and reliable product [38].

Figure 2.57: Anemometer Windspeed A100K

Basic specifications:

Maximum Windspeed: over 75m/s

Temperature Range: -50 to 70^{o}C

Accuracy: 1% of reading between 10 and 55m/s, 2% above 55m/s

2.4.9. Thermocouples – Immersion Tubes

A thermocouple is a sensor for measuring temperature. This sensor consists of two dissimilar metal wires, joined at one end, and connected to a thermocouple thermometer or other thermocouple-capable device at the other end. When properly configured, thermocouples can provide temperature measurements over wide range of temperatures.

Thermocouples are known for their versatility as temperature sensors therefore commonly used on a wide range of applications - from an industrial usage thermocouple to a regular thermocouple found on utilities and regular appliances. Thermocouples are placed in immersion tubes in cases that are immersed in the pipes and come in contact with the liquid obtained and the water used.

A standard T-type thermocouple is used in this experimental device: The Type T is a very stable and is often used in extremely low temperature applications and the temperature range is from (-270^{o}C to 370^{o}C).

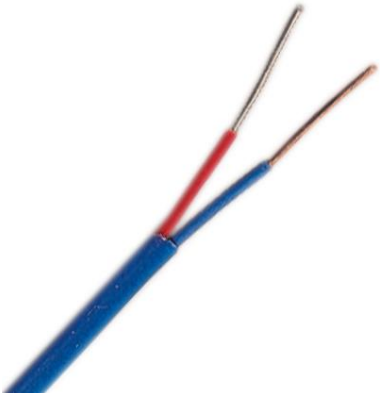


Figure 2.58: A thermocouple type T

Figure 2.59: Immersion tube

2.4.10. Main plumbing equipment

- **Bourdon Pressure Gauge**

Bourdon tube pressure gauges are used for the measurement of relative pressures from 0.6 ... 7,000 bar. They are classified as mechanical pressure measuring instruments, and thus operate without any electrical power.

Bourdon tubes are radially formed tubes with an oval cross-section. The pressure of the measuring medium acts on the inside of the tube and produces a motion in the non-clamped end of the tube. This motion is the measure of the pressure and is indicated via the movement.

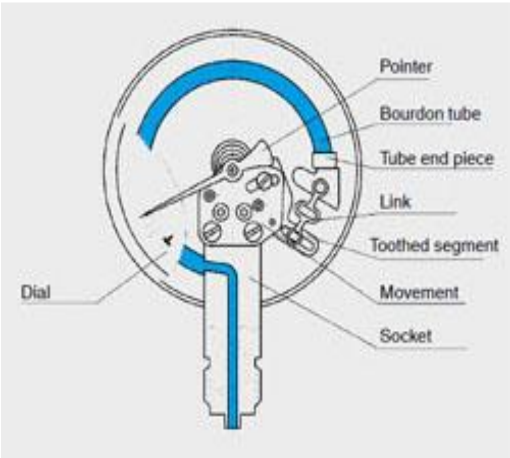


Figure 2.60: Cross section diagram of Bourdon tube pressure gauge

The C-shaped Bourdon tubes, formed into an angle of approx. 250°, can be used for pressures up to 60 bar. For higher pressures, Bourdon tubes with several superimposed windings of the same angular diameter (helical tubes) or with a spiral coil in the one plane(spiral tubes) are used.

A standard Bourdon tube pressure gauge are suitable for liquid or gaseous media, which are not highly viscous or crystallising, so long as they do not attack copper alloy parts. The measuring range covers 0.6 ... 1,000 bar [39].

Figure 2.61: Standard Bourdon tube pressure gauge

- **Expansion Tank**

A water heater expansion tank is another small tank that is attached to the water supply pipe of the water heater. The expansion tank is designed to handle the thermal expansion of water as it heats up in the water heater, preventing excessive water pressure. If water pressure gets to high it can damage valves in plumbing fixtures, joints in supply pipes and the water heater itself. Expanding water from the water heater flows into the expansion tank, relieving water pressure in the system. The tank is partially filled with air, whose compressibility cushions shock caused by water hammer and absorbs excess water pressure caused by thermal expansion.

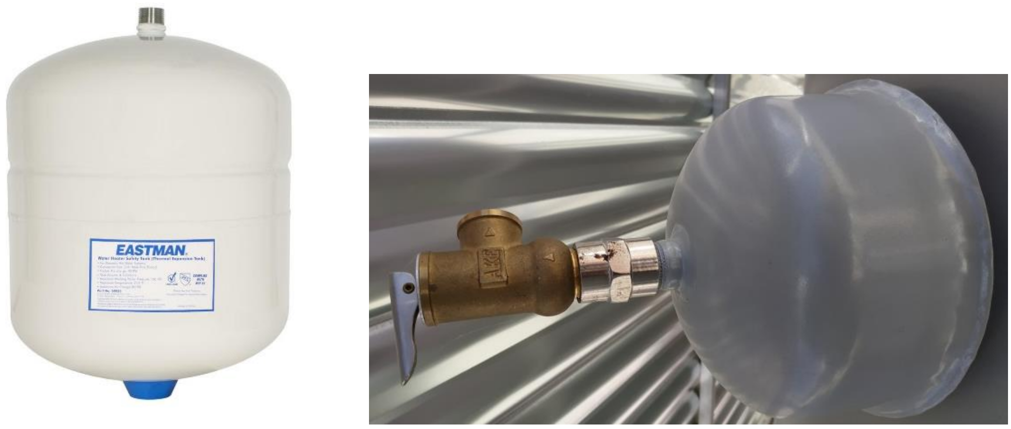


Figure 2.62: Expansion tank

- **Check Valves - non-return valve**

The check valve prevents wastewater from inside the house returning to the water supply where it can contaminate the supply of fresh water.

Check valves are two-port valves, meaning they have two openings in the body, one for fluid to enter and the other for fluid to leave. There are various types of check valves used in a wide variety of applications. Check valves are often part of common household items. Although they are available in a wide range of sizes and costs, check valves generally are very small, simple, or inexpensive. Check valves work automatically, and most are not controlled by a person or any external control; accordingly, most do not have any valve handle or stem. The bodies (external shells) of most check valves are made of plastic or metal.

An important concept in check valves is the cracking pressure which is the minimum differential upstream pressure between inlet and outlet at which the valve will operate. Typically, the check valve is designed for and can therefore be specified for a specific cracking pressure.

Spring-type check valves are recommended to prevent forward or reverse flow at night. However, swing-type check valves are recommended for use with PV powered DC pumps, which may not generate enough force to open a spring-loaded check valve [14] .

Figure 2.63: Check valve

- **Pressure Relief Valves**

The primary purpose of a pressure relief valve is to open to relieve excess pressure, reclose and prevent further flow of fluid after normal conditions have been restored. A secondary purpose is to minimize damage to other system components through operation of the pressure relief valve itself [40] .

Figure 2.64: Pressure relief valve

- **Air vent valve**

When liquid is pumped through the system at startup, the initial air inside the piping is pushed into the air vent by the pressure of the flow. The float remains in the lower part of the air vent, allowing the valve to remain open and continuously discharge air.

After the initial air venting, liquid flows into the air vent. The float rises with the rising liquid and closes the valve.

If air enters the air vent while it is closed, the liquid level drops and the float lowers, allowing the valve to open and discharge air once more.

Figure 2.65: Air vent valve

2.4.11. Data recording system (Data Logger)

A data logger is a device used to record and store the output of one or more sensors. In some cases, the data logger interprets the electrical signal from the sensor and converts it to units. In cases where a smart sensor provides digital output, the data logger simply records the data. Early data loggers were strip chart recorders that recorded measurement data onto paper. Over time, data loggers evolved to store data digitally on various types of media. Today, data is typically stored on modern flash memory and often transmitted via a variety of telemetry methods.

Most modern, general-purpose data loggers are microprocessor-controlled electronic devices that can interface directly with a variety of sensors to do the following:

- Provide measurements at specific time intervals
- Process statistical and mathematical data
- Store data
- Initiate a variety of telecommunications
- Transmit measurement data and calculated values

A data acquisition system consists of multiple electronic devices that act together to serve the primary purpose of collecting measured data. The general-purpose data logger is often considered the brain of a data acquisition system, but it is only one of the interfaced components used in the process of acquiring, recording, transmitting, and analyzing measurements [41] .

A general-purpose data logger consists of the following parts and ports:

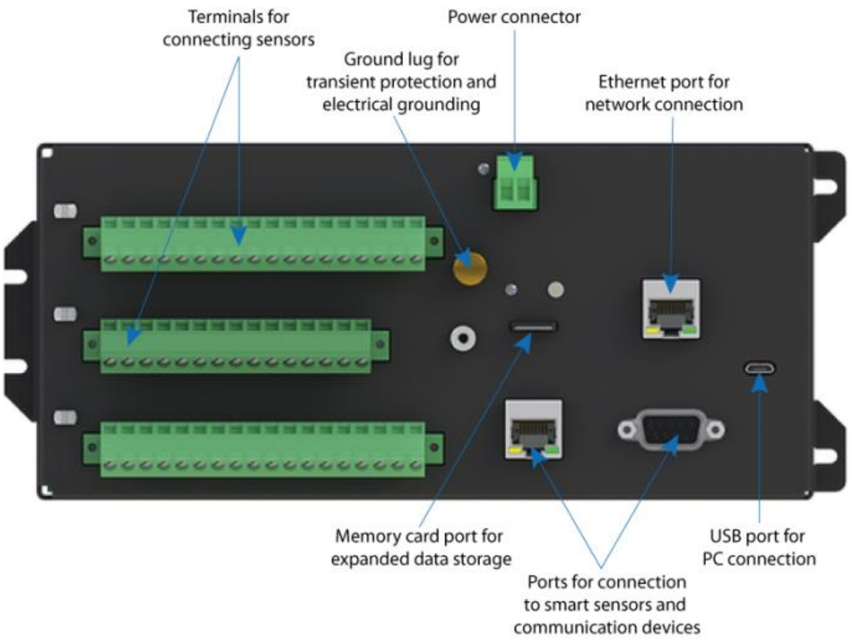


Figure 2.66: Data Logger Parts[41]

Data Loggers can be connected to a variety of instruments to measure the intensity of the total density of solar radiation, its spectral distribution (spectral instruments), the speed and direction of the wind, humidity (absolute and relative), the weight pressure, ambient temperature, etc. At the same time, they have the ability to receive inputs (signals) for measuring pulses, difference in potential of current intensity, temperature (spaces, surfaces, fluids), pressure, etc. The common feature of all possible types of Data Loggers is the limitation of the signal input voltage, which varies depending on the application. In addition, all of these electronic systems have the ability to support appropriate software both for reading measurements and for storing and processing them. Finally, an important advantage of Data Loggers can be considered the ability to program the download of the type and frequency of measurements in real time.

An electronic data recording system from Campbell Scientific was selected for the implementation of the experiment. The specific model is CR1000X. This data logger is for external use and does not require a continuous connection to a computer because it has a separate data collection and storage unit. It also offers the ability to connect the measuring

instruments used in the system. Finally, there is the possibility of remote connection of the user to the computer connected to the Data Logger. The CR1000X model as well as the computer connection and communication peripherals is presented in detail below.

- **Data Logger CR1000X**

The CR1000X is a data logger that provides measurement and control for a wide variety of applications. Its reliability and ruggedness make it an excellent choice for remote environmental applications, including weather stations, mesonet systems, wind profiling, air quality monitoring, hydrological systems, water quality monitoring, and hydrometeorological stations.

The CR1000X is a low-powered device that measures sensors, drives direct communication and telecommunications, analyzes data, controls external devices, and stores data and programs in onboard, nonvolatile storage. The electronics are RF-shielded by a unique sealed, stainless-steel canister. A battery-backed clock assures accurate timekeeping. The onboard, BASIC-like programming language, common to all contemporary Campbell Scientific data loggers, supports data processing and analysis routines [41] .

Figure 2.67: CR1000X data logger[41]

The specifications are the following:

Operating Temperature Range: -40° to +70°C (standard)

-55° to +85°C (extended)

Analog Inputs: 16 single-ended or 8 differential (individually configured)

Pulse Counters: 10 (P1 to P2 and C1 to C8)

Voltage Excitation Terminals: 4 (VX1 to VX4)

Communications Ports: Ethernet, USB Micro B, CS I/O, RS-232, RS-422, CPI, RS-485

Data Storage Ports: microSD

Switched 12 Volt: 2 terminals

Battery-backed SRAM for CPU Usage & Final Storage: 4 MB

Data Storage 4: MB SRAM + 72 MB flash (Storage expansion of up to 16 GB with removable microSD flash memory card.)

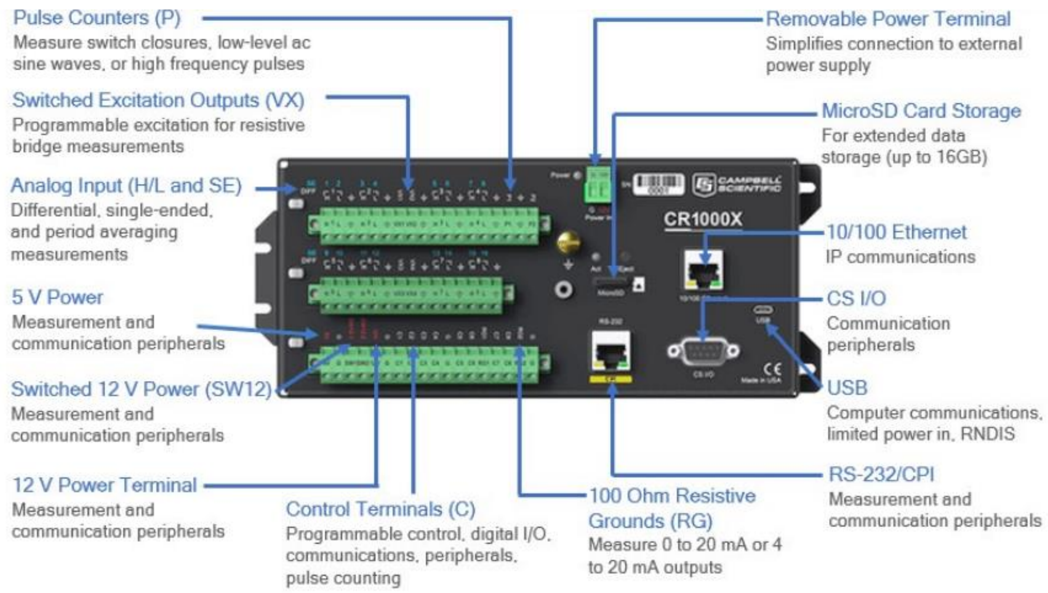


Figure 2.68: CR1000X ports

- **Measurement and Control Peripherals - Communications**

The CR1000X is compatible with all our CDMs, multiplexers, vibrating-wire interfaces, terminal input modules, and relays.

The CR1000X communicates with a PC via direct USB port, 10/100baseT Ethernet port, multidrop modems, short-haul modems, phone modems (land line, digital cellular, and voice-synthesized), RF telemetry, and satellite transmitters (HDR GOES, Argos, Meteosat, Iridium, and Inmarsat).

Data can be viewed on the CR1000KD Keyboard Display, the CD100 Mountable Display with Keyboard, an iOS or Android device (requires our free Logger Link app), CD295 Data View II Display, or other third-party devices[41].

- **The Loggernet Software**

The programming of the operation of the electronic data recording system was carried out through appropriate software. A computer was installed indoors on which Campbell's Loggernet 4.6 program was installed. Loggernet is a software program that is fully compatible with CR1000X and all peripherals used. The purpose of this software is initially to provide step-by-step guidance on the electronic installation of the system with the ultimate goal of taking measurements and recording data. These steps determine the order in which the instruments are connected as well as the way in which each of the instruments must be connected to the Data Logger in order to be recognized by the program. The time interval between successive measurements, their units of measurement and in the case of potentiometers and voltage dividers how degraded the output value will be from the actual.

The software which was used has the ability to monitor the results in real time either through tables or through time change diagrams of the quantities obtained from our installation. Finally, the data received by the Loggernet software from the Data Logger and the multiplex card can be saved in a .dat or .csv file and then further processed through Microsoft Excel software [41] .

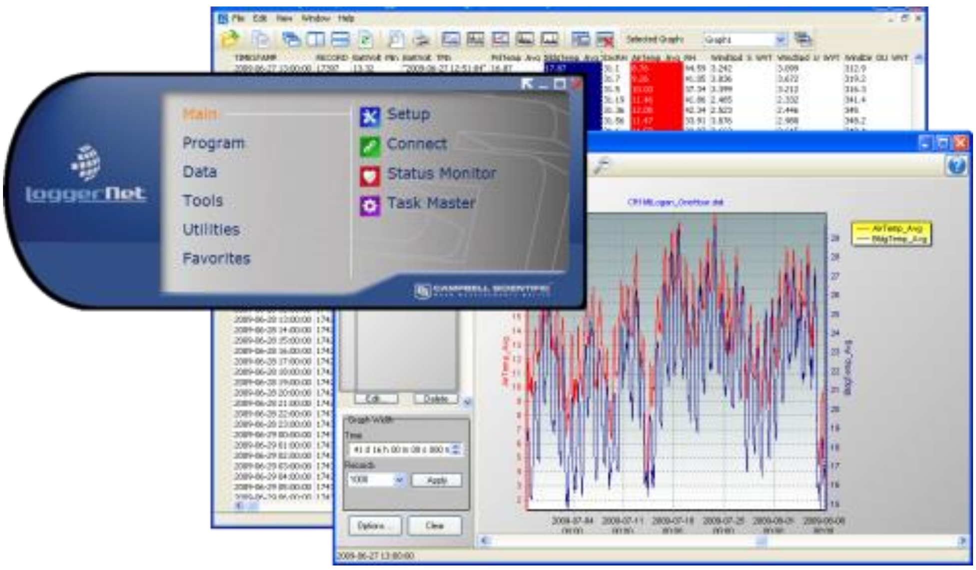


Figure 2.69: The Loggernet Software program

CHAPTER 3

LIFE CYCLE ASSESSMENT

3.1. Introduction

Our generation is facing formidable challenges of a changing climate and an overall increasing pressure on the environment, challenges that are under the influence of human-made activities. Life cycle assessment (LCA) is a methodology for assessing environmental impacts associated with all the stages of the life-cycle of a commercial product, process, or service. For example, in the case of a manufactured product, environmental impacts are assessed from raw material extraction and processing, through the product's manufacture, distribution and use, to the recycling or final disposal of the materials composing it. An LCA study involves an analytic inventory of the energy and materials that are required across the industry value chain of the product, process or service, and calculates the corresponding emissions to the environment. By this way LCA study assesses growing potential environmental impacts. The aim is to document and improve the overall environmental profile of the product.

Figure 3.70: LCA main stages

3.2. Historical and methodological background

Life-cycle-oriented methods that were forerunners of today's LCA were developed in the 1960s in cooperation between universities and industry. They were known as Resource and Environmental Profile Analysis (REPA) or Eco Balances until the term LCA became the norm in the 1990s. The method development initiated in the US and mainly took place there and in Northern Europe. Early methods could be characterized as material and energy accounting and were inspired by material flow accounting, as they were focused on inventorying energy and resource use (crude oil, steel), emissions and generation of solid waste, from each industrial process in the life cycle of product systems.

As inventories got more complex, the primary focus on accounting the physical flows in a product life cycle was gradually extended with a translation of the inventory results into environmental impact potentials. In other words, from a list of resource uses and emissions a set of indicator scores for an assessed product was calculated, representing contributions to a number of impacts categories, such as climate change, eutrophication and resource scarcity.

In the early years of the LCA history, environmental concerns addressed by the methods tended to shift with public concerns, and there was no consistency of the applied methods. In some years, the focus was on the generation of solid waste, which was considered problematic, especially in the US, where landfilling was the dominant waste management practice. In other years, when the price on oil was fluctuating or high, energy use was the focus of early studies. Public concerns also shifted with respect to emissions, which in some periods were deemed to be sufficiently controlled by regulation and voluntary measures by industry, but at other times considered very problematic. Early impact assessment methods tended to represent impacts from emissions in the form of dilution volumes of air or water needed to dilute the emissions to safe levels, or below regulatory limits.

During the 1990s many impact assessment methods evolved, and the ambition has since then been to quantify all relevant environmental impacts, independent of shifting public concerns, with the goal of avoiding burden shifting. The first impact assessment methodology to cover a comprehensive set of midpoint impact categories, as we know them today, was CML92 (Centrum voor Milieukunde Leiden). It was released in 1992 by the Institute of Environmental Sciences at Leiden University in the Netherlands. The Swedish EPS (Environmental Priority Strategies) method looking at the damages caused took a different approach focusing on the damages to ecosystems and human health, rather than midpoint impacts, an approach that was followed by the Dutch Eco-indicator 99 methodology released in 1999 with a more science-based approach to the damage modelling. The early 1990s also saw the birth of a number of life cycle inventory databases managed by different institutes and organizations and covering different industrial sectors. Due to differences in data standards and quality, the resource uses and emissions of a single industrial process could, however, differ substantially in the different databases, but at this point in the development, the focus was on expanding the coverage and for many processes, where there were no data at all. This situation was improved in 2003 with the release of the first ecoinvent database (v 1.01) covering all industrial sectors and aiming for consistent data standards and quality. Alongside with this development in process-based LCA, a "top-down" approach was developed based on the work of the economist Leontief on input-output analysis of economies. This "top-down" approach to constructing an inventory is based on combining the national statistics of the trade between sectors with information on sector-specific environmental loads to arrive at an environmentally extended input/output analysis.

Inherent in the discussion of LCI data was also a more fundamental difference in the perception of the product life cycle and LCA and its potential application. The attributional perspective aims to quantify the environmental impacts that can be attributed to the product system based on a mapping of the emission and resource flows that accompany the product as it moves through its life cycle, applying representative average data for all processes involved in the life cycle in a book keeping approach. The consequential perspective is concerned with the potential consequences of the decision based on the results of the LCA, and involves modelling of the broader economic system that the decision affects.

The modelling of increasingly complex product systems and the proliferation of LCI data and impact assessment methodologies created a need for dedicated LCA software and the first versions of both SimaPro and GaBi, two widely used software were released around 1990.

In the twenty-first century, impact assessment methods have consecutively been refined and several methodologies have emerged and are frequently being updated. The first impact assessment methods took into account the often large differences in the environmental hazards of the individual emissions. The realization that there can be very large differences also in the sensitivity of the environment receiving the impacts lead to the release of the EDIP2003 (Environmental Design of Industrial Products) method with spatially differentiated impact assessment methods covering global impacts like eutrophication and acidification. With the globalization of production and an increased focus on bio based products in LCA, methods for impact assessment of extraction-related impacts like water use and land use have seen a lot of activity in the 2000s and 2010s. Hybrid LCA has emerged to reap the benefits of process-based and input/output based inventory analysis. Acknowledging that sustainability also has a social dimension a growing activity has attempted to develop methods for Social LCA to quantify social impacts of product life cycles. A framework for life cycle sustainability assessment (LCSA) has emerged for performing assessments and aims to take into account an environmental, social and economic dimension of sustainability [42] [43] .

3.3. International Harmonization and Definitions

Various Life Cycle Assessments which performed from time to time by different scholars led to different and sometimes conflicting conclusions.

Historically, the first attempt to reach agreement on international level began within the Society for Environmental Toxicology and Chemistry (SETAC) in 1990. The harmonization process soon led to the writing and issuance of the SETAC Code of Conduct for the LCA (SETAC 1993).

Subsequently, a second LCA standardization effort was launched within the International Organization for Standardization (ISO). The international standards developed and adopted in the late 1990s provided recommendations for various methodological issues not covered by the SETAC Code. However, many methodological problems remain unresolved in ISO texts.

SETAC definition:

"Life Cycle Assessment is an objective method of evaluating environmental charges associated with a product, an activity by identifying and calculating the energy and materials used and their emissions into the environment and finally evaluating and exploiting opportunities to achieve environmental improvements. The assessment covers the entire life cycle of the product, process or activity, including the receipt and processing of raw materials, processing, transport and distribution, use or reuse, maintenance, recycling and recycling deposition ".

Figure 3.71: Society for Environmental Toxicology and Chemistry logo

ISO(14040:2006) principles framework:

“LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave)”.

There are four phases in an LCA study:

a) The goal and scope definition phase,

b) The inventory analysis phase,

c) The impact assessment phase, and

d) The interpretation phase.

The scope, including the system boundary and level of detail, of an LCA depends on the subject and the intended use of the study. The depth and the breadth of LCA can differ considerably depending on the goal of a particular LCA.

The life cycle inventory analysis phase (LCI phase) is the second phase of LCA. It is an inventory of input/output data with regard to the system being studied. It involves collection of the data necessary to meet the goals of the defined study.

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system's LCI results so as to better understand their environmental significance.

Life cycle interpretation is the final phase of the LCA procedure, in which the results of an LCI or an LCIA, or both, are summarized and discussed as a basis for conclusions, recommendations and decision-making in accordance with the goal and scope definition [44] [45].

Further analysis is presented in the next subchapters.

Figure 3.72: International Organization for Standardization logo

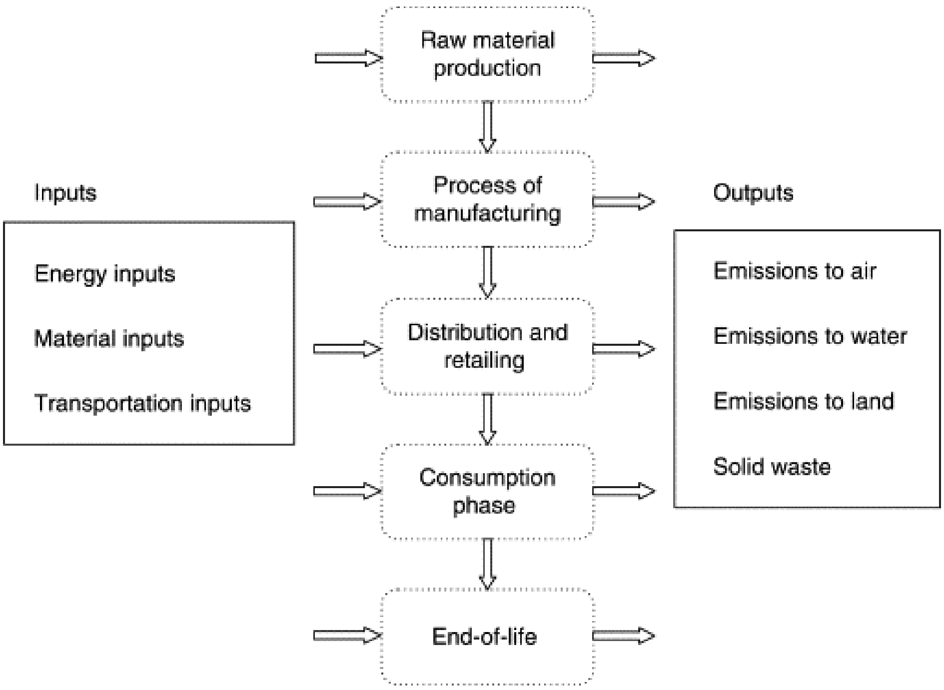


Figure 3.73: Example of a product system for LCA

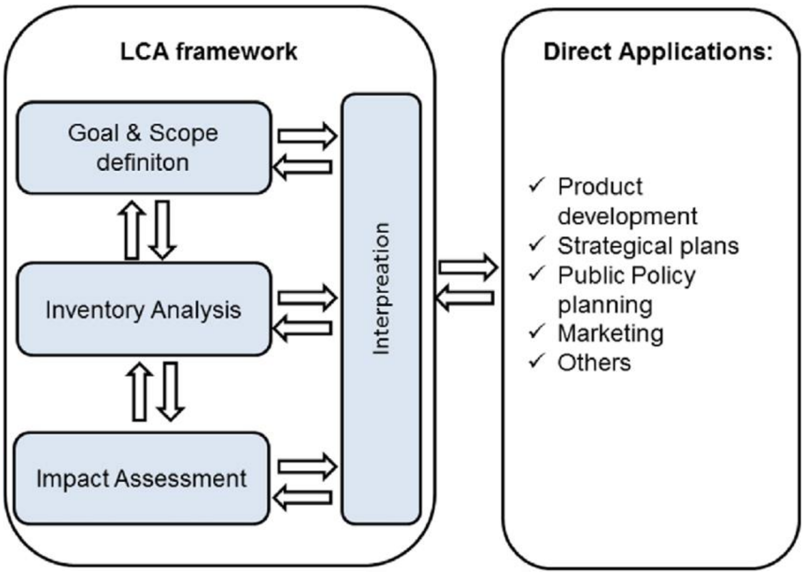


Figure 3.74: Framework of LCA

3.4. Benefits and Restrictions

A main strength of LCA is its completeness in terms of its life cycle perspective and coverage of environmental issues. This allows the comparison of environmental impacts of product systems that are made up of hundreds of processes, accounting for thousands of resource uses and emissions that are taking place in different places at different times. However, the comprehensiveness is also a limitation, as it requires simplifications and prevalence in the modelling of the product system and the environmental impacts that prevent LCA from calculating actual environmental impacts. Considering the uncertainties in mapping of resource uses and emissions and in modelling their impacts and the fact that calculated impacts are aggregated over time and space it is more accurate to say that LCA calculates impact potentials.

Another strength in the context of comparative assessments is that LCA follows the "best estimate" principle. This generally allows for unbiased comparisons because it means that the same level of precaution is applied throughout the impact assessment modelling. A restriction related to following the "best estimate" principle is, however, that LCA models are based on the average performance of the processes and do not supports the consideration of risks of rare but very problematic events like marine oil spills or accidents at industrial sites. As a consequence, nuclear power, for example, appears quite environmentally friendly in LCA because the small risk of a devastating disaster, like the ones that happened in Chernobyl or Fukushima is not considered.

A final limitation worth keeping in mind is that, while LCA can tell you what (product system) is better for the environment, it cannot tell you if better is "good enough". It is therefore wrong to conclude that a product is environmentally sustainable, in absolute terms, with reference to an LCA showing that the product has a lower environmental impact than another product [42]

3.5. Goal and Scope Definition

An LCA starts with a studious and calculated definition of the goal of the study. Why is this study produced? Which question(s) is it intended to answer and for whom is it performed? The goal definition sets the context of the LCA study and is the basis of the scope definition where the assessment is framed and outlined in accordance with the goal definition, primarily in terms of

- Defining the functional unit: a quantitative description of the function or service for which the assessment is performed, and the basis of determining the reference flow of product that scales the data collection in the next LCA phase, the inventory analysis.

- Scoping the product system, deciding which activities and processes belong to the life cycle of the product that is investigated.
- Selecting the assessment parameters, for example the impacts that should be assessed in the study.
- Selecting the geographical and temporal boundaries and settings of the study and the level of technology that is relevant for the processes in the product system.
- Deciding the relevant perspective to apply in the study: should it be a consequential study assessing the impacts that can be expected as a consequence of choosing one alternative over another, or should it be an attributional study assessing the impacts that are associated with the studied activity?

The goal definition and the ensuing scope definition are very important to consider because they have a strong influence on the validity of the conclusions and recommendations that are based on the results of the LCA.

3.6. Life Cycle Inventory (LCI)

The second stage of the LCA is the collection and processing of data. Data collection still represents in most studies that step which requires the most thorough work and is of course the most time consuming. The data refers to the functional unit while the designer has at his disposal some computer programs for their processing.

In LCI each product must be presented as a system which is defined by a set of processes that are materially or energetically related. Each system contains all the stages of the product life cycle while in the system environment belong all the mass and energy flows that enter the system as well as flows from it. At this stage, all values of material and energy flows from cradle-to-grave are measured and recorded, as quantities in physical units. It is useful to distinguish between two types of data:

1. *Foreground data*, which refers to specific data you need to acquire for modeling your system. Typically, it is data that describes a particular product system or a specialized production system.
2. *Background data*, which is data for the production of generic materials, energy, transport and waste management. This
data you can find in SimaPro databases and from literature.

3.6.1. Foreground Data

In foreground data you will have to collect information from specific companies. Most frequently, one or more questionnaires need to be made to collect such data. It is important to establish good contacts with the people who are asked to fill in the questionnaire and to understand what these people know, in what way data is available, and what terminology and units are used.

Collecting data from other parties is not always easy. It is useful to carefully consider the following points:

• The willingness to supply data depends on the kind of relationship you have with the data owners. Some parties will be interested as they may have similar goals; some will see your LCA activities as a threat. In some cases, most of the data collection effort is in establishing a good relationship in which people trust each other. At the very least you will have to be
open about why you need the data, what will be done with it, and how it will be presented.

• Confidentiality issues can be important. Sometimes environmental input and output data can reveal certain technical or commercial secrets. One way of dealing with this is to involve an independent consultant that averages the data from different suppliers. Sometimes a branch or industry association can play this role.

• Terminology issues. For each industry sector, there are different ways of measuring and expressing inputs and outputs. When you develop a questionnaire, you should try to use the terms and units that are applicable within this sector. In order to do so you should first discuss the issues you are interested in and then produce a questionnaire [46].

3.6.2. Background Data

Depending on the goal and scope of your study, a large part of the data you will need will be background data, which you do not need to collect via a questionnaire. Background data is usually available in databases or can be found in literature. Using background data requires great care. You need to investigate how well the data found in databases fits with the requirements defined in the goal and scope. Below it is described the two most important data sources available to the LCA community: the ecoinvent database and the input-output databases.

SimaPro comes with the ecoinvent database, covering over 10,000 processes. This database is the result of a joint effort by different Swiss institutions to update and integrate several life cycle inventory databases.

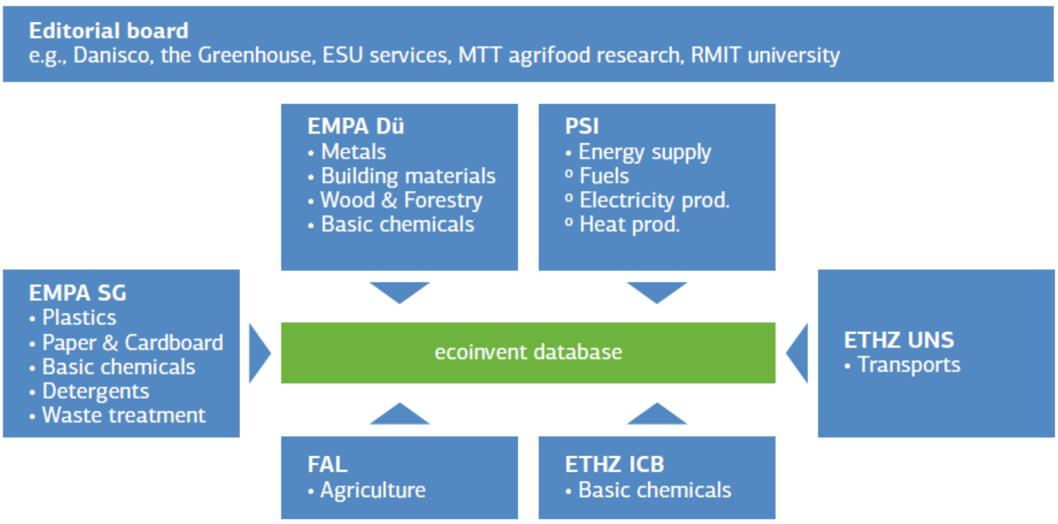


Figure 3.75: The Swiss organizations that have joined forces to create the ecoinvent database.

ETH Zurich, PSI, EMPA, EPF Lausanne and ART provide data for the ecoinvent database. A group of LCI experts from these institutions are responsible for the data collection. Additionally there is an "Editorial board" which is responsible for quality control. They perform the review, validation, and editing of all new datasets before their inclusion in the ecoinvent LCI database under the supervision of the LCI experts.

Ecoinvent key characteristics:

- Covers a broad range of data.
- Consistent application of system boundaries and allocation.
- Well documented
- Consistent specification of uncertainty data, usually as a lognormal distribution with standard deviation.
- Emissions are specified with sub-compartments, for example an emission to air can be specified as an emission in a high
or low density population area or stratosphere. Impact assessment methods can differentiate between these specifications.
- Includes capital goods as a default, which is important for energy systems such as wind and hydropower, but also for transportation systems.
- Comes in the EcoSpold 2 format which has become a de-facto standard that is very in line with the ISO 14048 standard.
- Is updated regularly by the ecoinvent Centre [47].

Input output databases contain data per economic sector rather than per process as seen in conventional databases. For example, there is data in input-output databases on the agricultural sector, the banking sector, the transport and the consultancy sectors. The advantage of using this type of data is that you have an assessment for an entire economy. The disadvantage is that the result may not be specific enough for the research questions. For instance, you cannot compare two building materials if they both come from the same building materials sector. [48]

3.6.3. Key Steps in LCI

1. **Develop a flow diagram**

A flow diagram is a tool to map the inputs and outputs to a process or system. The "system" or "system boundary" varies for every LCA project. The goal definition and scoping phase establishes initial boundaries that define what is to be included in a particular LCA; these are used as the system boundary for the flow diagram. Unit processes inside of the system boundary link together to form a complete life cycle picture of the required inputs and outputs (material and energy) to the system. Flow diagrams are used to model all alternatives under consideration. For a comparative study, it is important that both the baseline and alternatives use the same system boundary and are modeled to the same level of detail. If not, the accuracy of the results may be skewed.

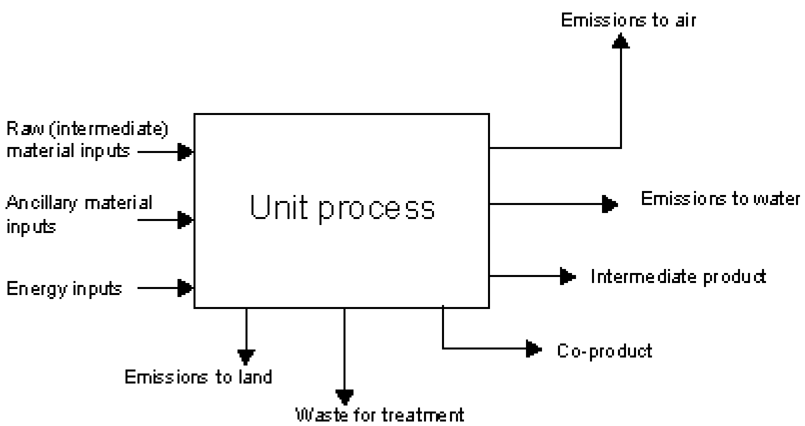


Figure 3.76: Generic unit process

2. **Develop an LCI data collection plan**

As part of the goal definition and scoping phase, the required accuracy of data was determined. When selecting sources for data to complete the life cycle inventory, an LCI data collection plan ensures that the quality and accuracy of data meet the expectations of the decision-makers. Key elements of a data collection plan include the following:

1. Defining data quality goals
2. Identifying data quality indicators
3. Identifying data sources and types
4. Developing a data collection worksheet and checklist.

3. Collect data

Data collection efforts involve a combination of research, site-visits and direct contact with experts, which generates large quantities of data. As an alternative, it may be more cost effective to buy a commercially available LCA software package. Prior to purchasing an LCA software package the decision-makers or LCA practitioner should insure that it will provide the level of data analysis required.

4. Evaluate and document the LCI results

When writing a report to present the final results of the life-cycle inventory, it is important to thoroughly describe the methodology used in the analysis. The report should explicitly define the systems analyzed and the boundaries that were set. All assumptions made in performing the inventory should be clearly explained. The basis for comparison among systems should be given, and any equivalent usage ratios that were used should be explained.[49]

3.6.4. Sensitivity analysis and results

The sensitivity analysis is performed in the context of the LCA inventory analysis and is a means of determining the diversity and uncertainty of the data as well as the data gaps that affect the final conclusions of the study. It is part of the stage of improving the life cycle assessment process while additionally helping both in dealing with future legislation and in planning the company's priorities.

The LCI results are a list that contains the amounts of pollutants released into the environment and the amounts of energy and materials consumed. Information can be disaggregated based on the stage of the life cycle, the medium in which the pollutants are released (air, water, soil), a specific process or any combination of them.

3.7 Life Cycle Impact Assessment (LCIA)

The third stage of the LCA, Impact Assessment, is a tool that links the results of detailed data inventory to environmental problems. of LCI. Various committees are still working on creating a method. A first global consensus is reflected in ISO DIN 14044, which follows the SETAC recommendations.

The ISO 14040/14044 standards distinguish mandatory and
optional steps for the LCIA phase, which will all be explained further in this chapter:

Mandatory steps:

1) Selection of impact categories, category indicators and characterization models. (In practice typically done by choosing an already existing LCIA method).

"Which impacts do I need to assess?"

2) Classification (assigning LCI results to impact categories according to their known potential effects, i.e. in practice typically done automatically by LCI databases and LCA software).

"Which impact(s) does each LCI result contribute to?"

3) Characterization (calculating category indicator results quantifying contributions from the inventory flows to the different impact categories, i.e. typically done automatically by LCA software).

"How much does each LCI result contribute?"

Optional steps:

4) Normalization (expressing LCIA results relative to those of a reference system).

"Is that much?"

5) Weighting (prioritizing or assigning weights to the each impact category)

"Is it important?"

6) Grouping (aggregating several impact indicator results into a group).

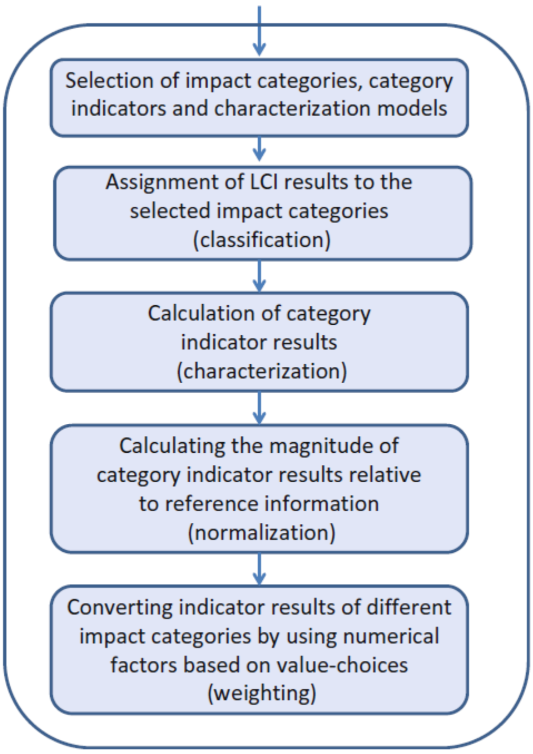


Figure 3.77: The main steps of life cycle impact assessment[50]

3.7.1. Selection of impact categories

The impact categories are several and the analysis we will do depends mainly on two factors: the first one is the point of view of studying the object, that is, if we are more interested in effects on humans or the ecosystem and the second is the quantity and quality of the data we have at our disposal for analysis. The objective of selecting impact categories, category indicators and characterization models is to find the most useful and needed ones for a given goal.

3.7.2. Classification

In this step, the elementary flows of the LCI are assigned to the impact categories to which they contribute; for example an emission of CO_2 into air is assigned to climate change or the consumption of water to the water use impact category. This is not without difficulty because some of the emitted substances can have multiple impacts in two modes:

- In parallel: a substance has several simultaneous impacts, such as SO_2 which causes acidification and is toxic to humans when inhaled.
- In series: a substance has an adverse effect which itself becomes the cause of something else, such as SO_2 which causes acidification, which then may mobilize heavy metals in soil which are toxic to humans and ecosystems.

This step requires considerable understanding and expert knowledge of environmental impacts and is therefore typically being handled automatically by LCA software (using expert-based, pre-programmed classification tables) and not a task that the LCA practitioner needs to undertake.[42]

When the impact assessment is based on **midpoint impact indicators**, the classification gathers the inventory results into groups of substance flows that have the ability to contribute to the same environmental effect in preparation for a more detailed assessment of potential impacts of the environmental interventions, applying the characterization factors that have been developed for the concerned impact category.

Some key impact midpoint categories are listed below:

- The Abiotic Depletion Potential (ADP) is measured in relation to global stocks.
- The Energy Depletion Potential (EDP) is measured in Mj / kg or in Mj / m^3.
- The greenhouse effect or otherwise Global Warming Potential (GWP), is measured in relation to the effect of 1kg CO_2.
- Photochemical cloud or otherwise Photochemical Oxidant Formation (POCP) is measured in relation to the effect of 1 kg of ethylene.
- Acidification (AP) is measured in relation to the effect that 1kg SO_2 has.
- Human Toxicity (HT) is measured in relation to the amount of weight of the human body that can be exposed to the permissible toxic limit of one kg of the substance.
- Aquatic Ecotoxicity (ECA) refers to the amount of water that will be contaminated as a critical level of 1kg of substance.
- Terrestrial Ecotoxicity (ECT) refers to the soil load that will be contaminated as a critical level of 1kg of substance.
- Nutrifiication (NP), measured in relation to the effect of 1kg of phosphorus.
- The ozone depletion (ODP) is measured in relation to the effect of 1 kg CFC-11. [17]

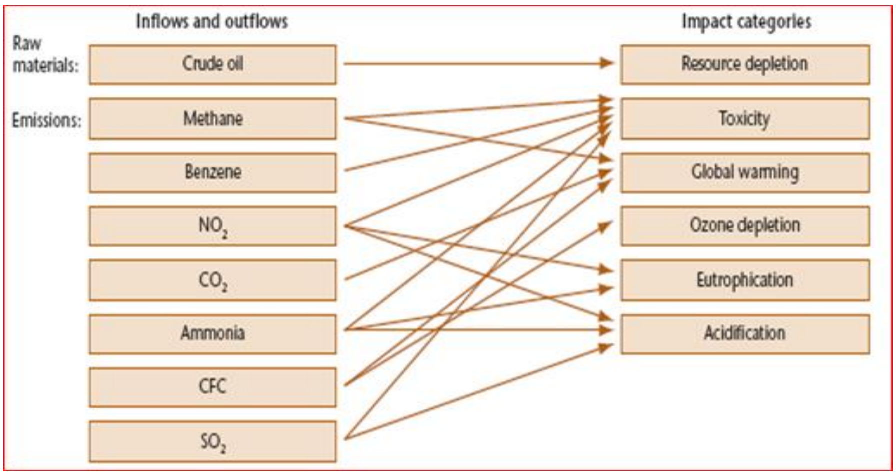


Figure 3.78: Relations between emissions and impact categories [51]

Additional modelling elements are used to expand or link midpoint indicators to one or more **endpoint indicator** (sometimes also referred to as damage or severity). These endpoint indicators are representative of different topics or "Areas of Protection" (AoP) that "defend" our interests as a society with regards to human health, ecosystems or planetary life support functions including ecosystem services and resources, for example. As discussed, endpoint indicators are chosen further down the cause–effect chain of the environmental mechanism closer to or at the very endpoint of the chains—the Areas of Protection. The numerous different midpoint indicators therefore all contribute to a relatively small set of endpoint indicators as can be observed in figure below. Although, different distinctions are possible and exist, typical endpoint indicators are:

- Human health
- Ecosystem quality or natural environment
- Natural resources and ecosystem services

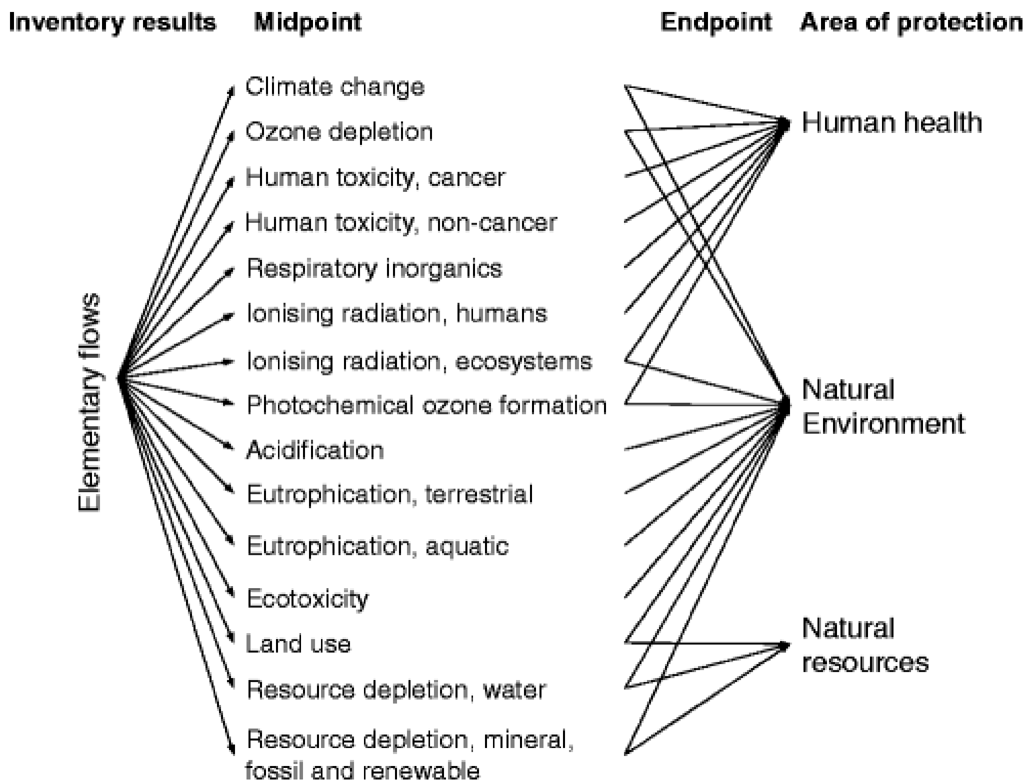


Figure 3.79: Impact categories and pathways [52]

3.7.3. Characterization

Characterization factors are calculated using characterization models and relate or translate the elementary flow into its impact on the chosen indicator for the impact category. Udo de Haes et al. (2002) proposed a framework for calculation of characterization factors (CF) according to which the CF is expressed as the product of a fate factor (FF), an exposure factor (XF) for the exposure of sensitive targets in the receiving environment and an effect factor (EF) expressing the effects of the exposure on the targets for the impact category.

$$CF = FF * XF * EF$$

This generic framework has since been applied with some modifications in most of the emission-related impact categories, with contents, metrics and meanings of the three factors that vary according to the impact category.

Substance	Amount (kg)	GWP Equivalence factor	CO_2 (kg)
Methane	0.001	11	0.011
CO_2	25	1	25
N_2O	5	270	1350
CH_2Cl_2	0.0005	15	0.0075
$CFCl_3$	0.00001	13000	0.13
$C0_2$ - equivalents			1375.1485

Figure 3.80: Impact category index (GWP) given in kg CO_2 equivalent.

The final result of characterization step is a list of potential environmental impacts. This list of effect scores, one for each category, is called the environmental profile of the product or service.

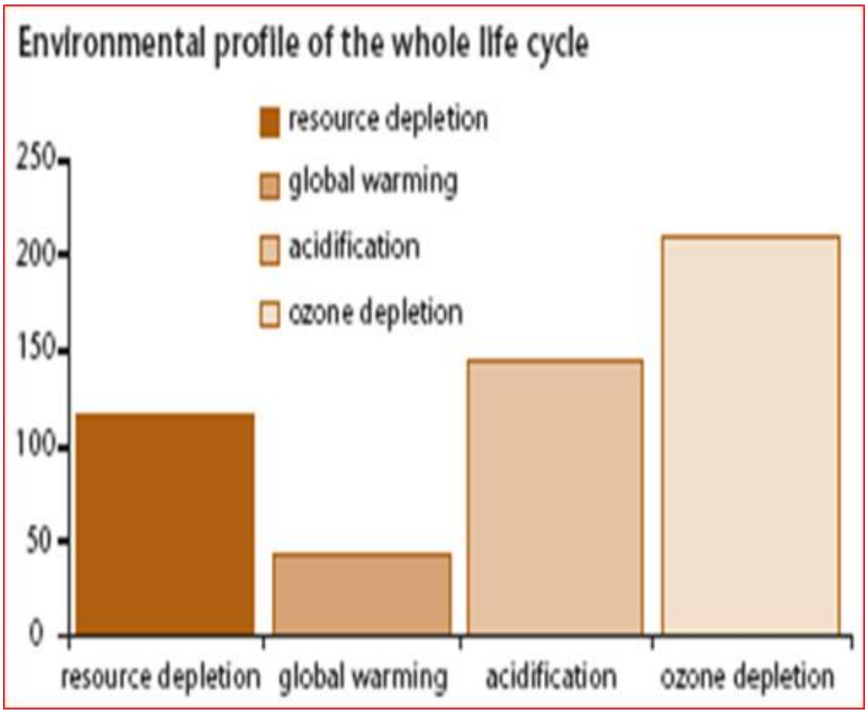


Figure 3.81: The impact of a cycle expressed as the sum of each kind of impact summed over the entire life cycle.[51]

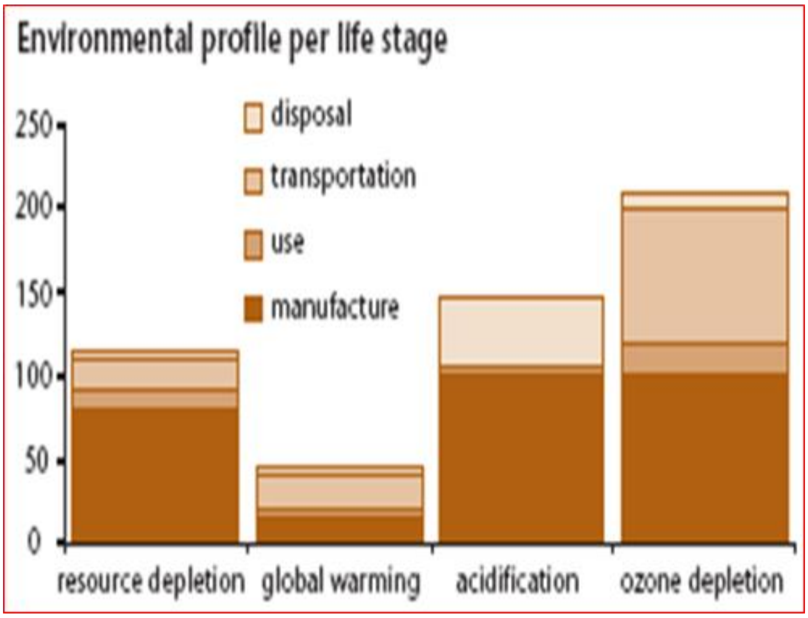


Figure 3.82: The impact expressed separately for each life stage.

3.7.4. LCIA Evaluation

With the classification and characterization, an environmental profile is given to the product, while with the evaluation the researcher converts the environmental profile into a data table. This makes it easier to compare and evaluate the reliability of the result.

The valuation is carried out in 4 stages:

1. Determining the burden of environmental problems
2. Conversion of the environmental profile into an environmental table
3. Check the correctness of the result
4. Overview of the LCA by external scholars

3.8. Interpretation

Interpretation is the final step of an LCA and is a systematic technique for identification, quantification, control and evaluation of the results of the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA).

At this stage all the results are linked to each other and decisions are made that will improve processes and situations concerning the industry and the environment.

According to the standard ISO 14044 the steps for interpreting the results are as follows:

A. The significant issues (key processes and assumptions, most important elementary flows) from the other phases of the LCA are identified.
B. These issues are evaluated with regard to their influence on overall results of the LCA and the completeness and consistency with which they have been handled in the study.
C. The results of the evaluation are used in the formulation of conclusions and recommendations from the study.

CHAPTER 4

DETAILED RESULTS AND ENVIRONMENTAL ANALYSIS OF THE SOLAR SYSTEM VIA THE SIMAPRO 8 SOFTWARE

4.1. Introduction

In order to evaluate the environmental performance of solar system, Simapro software and the Ecoinvent 3.1 database have been used. SimaPro is the leading LCA software package, with a 25-year reputation in industry and academia in more than 80 countries. It is an accurate and science-based tool that provides the highest level of transparency of all LCA packages currently available. SimaPro allows the control of entire supply networks and provides total insight into databases and unit processes, giving the user full ownership of their choices and assumptions. It is essential for high quality research and it is also necessary for educating LCA practitioners who understand the conceptual basis of what they are doing. SimaPro allows the effective application of LCA expertise, empower solid decision-making, change products life cycles for the better, and improve company's positive impact. SimaPro has been designed to be a source of science-based information, providing full transparency and avoiding black-box processes.

SimaPro is a professional tool to collect, analyze and monitor the sustainability performance data of products and services. The software can be used for a variety of applications, such as sustainability reporting, carbon and water footprinting, product design, generating environmental product declarations and determining key performance indicators. With SimaPro, the you can: 1. easily model and analyse complex life cycles in a systematic and transparent way, 2. measure the environmental impact of the products and services across all life cycle stages, 3. identify the hotspots in every link of the supply chain, from extraction of raw materials to manufacturing, distribution, use, and disposal.

The Swiss Centre for Life Cycle Inventories (the Ecoinvent Centre) has the mission to promote the use and good practice of life cycle inventory analysis through supplying life cycle inventory (LCI) data to support assessment of the environmental and socio-economic impact of decisions. The strategic objective is to provide the most relevant, reliable, transparent and accessible LCI data for users worldwide.

The ecoinvent database comprises LCI data covering all economic activities. Each activity dataset describes an activity at a unit process level. The complete list of all names of datasets, elementary exchanges, and of all regional codes is available at www.ecoinvent.org. Consistent and coherent LCI datasets for different human activities make it easier to perform LCA studies, and increase the credibility and acceptance of the LCA results. The assured quality of the life cycle data and the user-friendly access to the database are prerequisites to establish LCA as a reliable tool for environmental assessment that will support an integrated product policy. Data quality is maintained by a rigorous validation and review system.

The ecoinvent LCI datasets are intended as background data for LCA studies where problem- and case-specific foreground data are supplied by the LCA practitioner. The LCI and life cycle impact assessment (LCIA) results of ecoinvent datasets, may be used for comparative assessments with the aim to identify environmentally preferable goods or services, but should not be used without considering the relevance and completeness of the data for the specific assessment. The ecoinvent datasets may also be useful as background datasets for studies in material flow accounting and general equilibrium modelling [53][54].

4.2. ReCiPe method

General Principles

Intended purpose of the methodology:	Combining midpoint and endpoint methodologies in a consistent way
Midpoint/endpoint:	Midpoint and endpoint characterisation factors are calculated on the basis of a consistent environmental cause-effect chain, except for land-use and resources
Time horizon	20 years, 100 years or indefinite, depending on the cultural perspective
How is consistency ensured in the treatment of different impacts in characterization in normalization and weighting?	For all emission based categories similar principles and choices are used. All impacts are marginal. All impact categories of the same area of protection have the same indicator unit. Same environmental mechanism for midpoint and endpoint calculations is used.
Midpoint impacts covered	climate change; ozone depletion; terrestrial acidification; freshwater eutrophication; marine eutrophication; human toxicity; photochemical oxidant formation; particulate matter formation; terrestrial, marine, freshwater ecotoxicity; ionizing radiation; agricultural land occupation; natural land transformation; depletion of fossil fuel resources; depletion of mineral resources;
Endpoint impacts covered:	Human health (DALY); ecosystem quality (biodiversity, PDF.m2.yr); resources (surplus cost)
How is normalization preformed?	Normalization data are available for Europe and the world in year 2000, for 16 midpoint categories and for the three endpoint categories. Normalization data on land transformation and fresh water depletion are not included
	In a separate project, three methods are

How is weighting performed?	developed: - For endpoints a manual for panel weighting is available, but no operational generic weighting set have been developed - For the midpoints a monetization method on the basis of prevention costs is provided. - For endpoints a monetization on the basis of damage costs is provided. - The weighting triangle can be used at the endpoint level.

ReCiPe is a follow up of Eco-indicator 99 and CML 2002 methods. It integrates and harmonizes midpoint and endpoint approach in a consistent framework. The method which was chosen to evaluate the results is Europe ReCiPe Endpoint Hierarchist. The unit of measurement used for the overall results is 1 Pt, which is equal to 1/1000 of the annual environmental load of one average European resident.

4.3. Network of the Solar System

The software generates a network in which all the processes are presented. Each box represents a process. Arrows show the flows between processes. The red column to the right of each box indicates the environmental load generated in each process and its upstream processes. This is a useful feature as it is easy to see which process is considered important and which is less.

The single score was selected for the presentation of the network. As the network of the system consists of 2022 nodes, a contribution threshold of 1% was set for its display. According to the above restriction, the network shown below consists of nodes that have a contribution of more than 1 percentage points. Also below is the network with a 10% contribution threshold to make it easier to visualize the most significant parts.

It is observed that the maximum environmental load is caused by the node corresponding to the vacuum collector level with a load rate of 63.6%. Next is the storage tank with a contribution rate of 31.3%. Finally is the support system of the collector(framework) with a contribution rate of a 3.9%. The indications are clarified by the use of more intense red flow lines.

Aluminium palette with parabolic reflectors CPC(5)	kg
Copper grid(4)	kg
Evacuated tube collector(2)	p
Evacuated tubes(5)	kg
Hot water tank 210l(2)	p
Insulation - Inner instrunments(4)	kg
Interstice(4)	kg
Packaging - Storing the collector(3)	m2
Packaging - Storing the tank(3)	p
Solar plate(4)	kg
Solar system evacuated tube CPC Collector, one family house(1)	p
Support system of the collector(2)	p
Water tank (buttom)(4)	kg
Water tank inner(4)	kg

Figure 4.83: Table of all processes

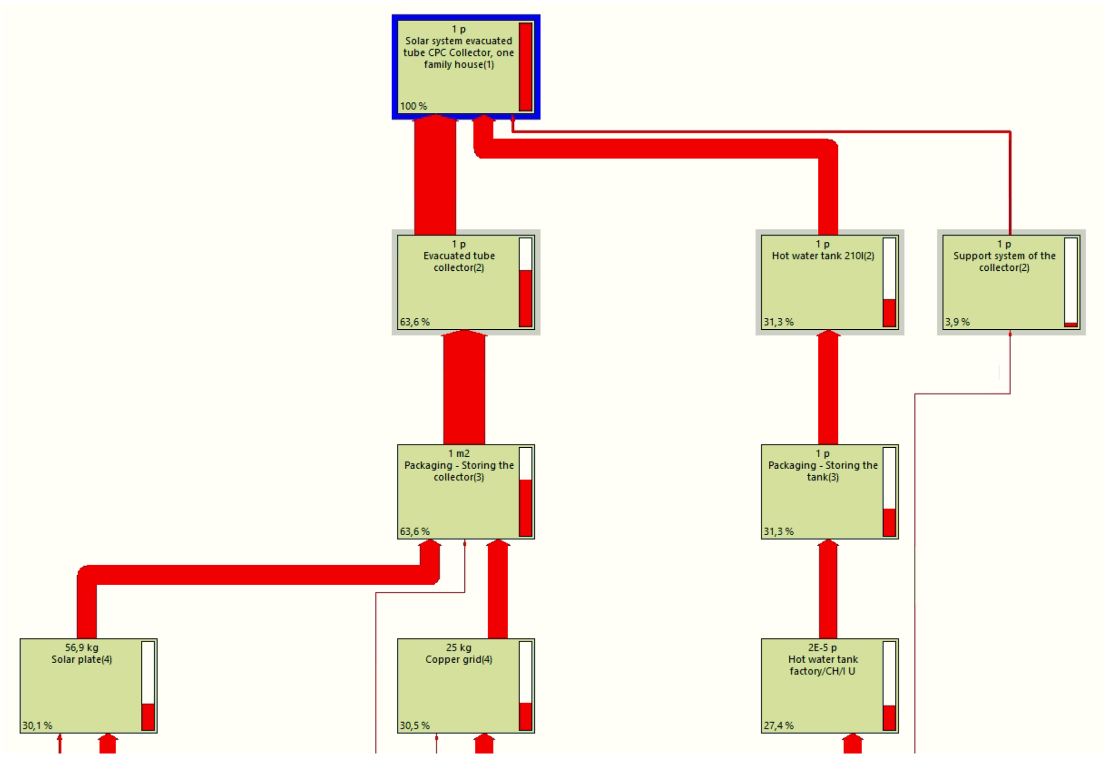


Figure 4.84: Main network processes

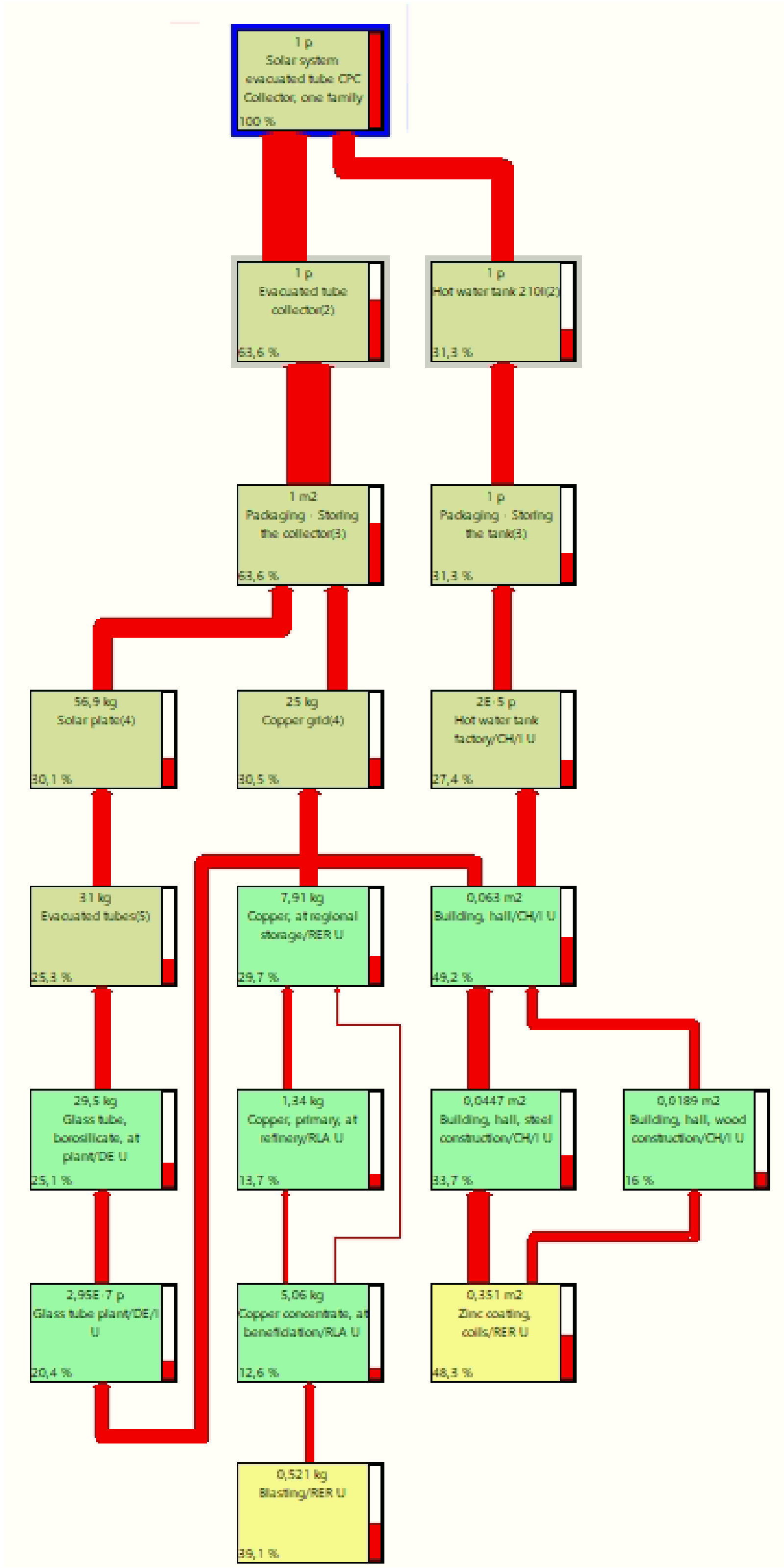


Figure 4.85: Process network for the Solar system evacuated tube CPC Collector. Cut-off threshold: 10%, visible nodes: 19 total nodes: 2022.

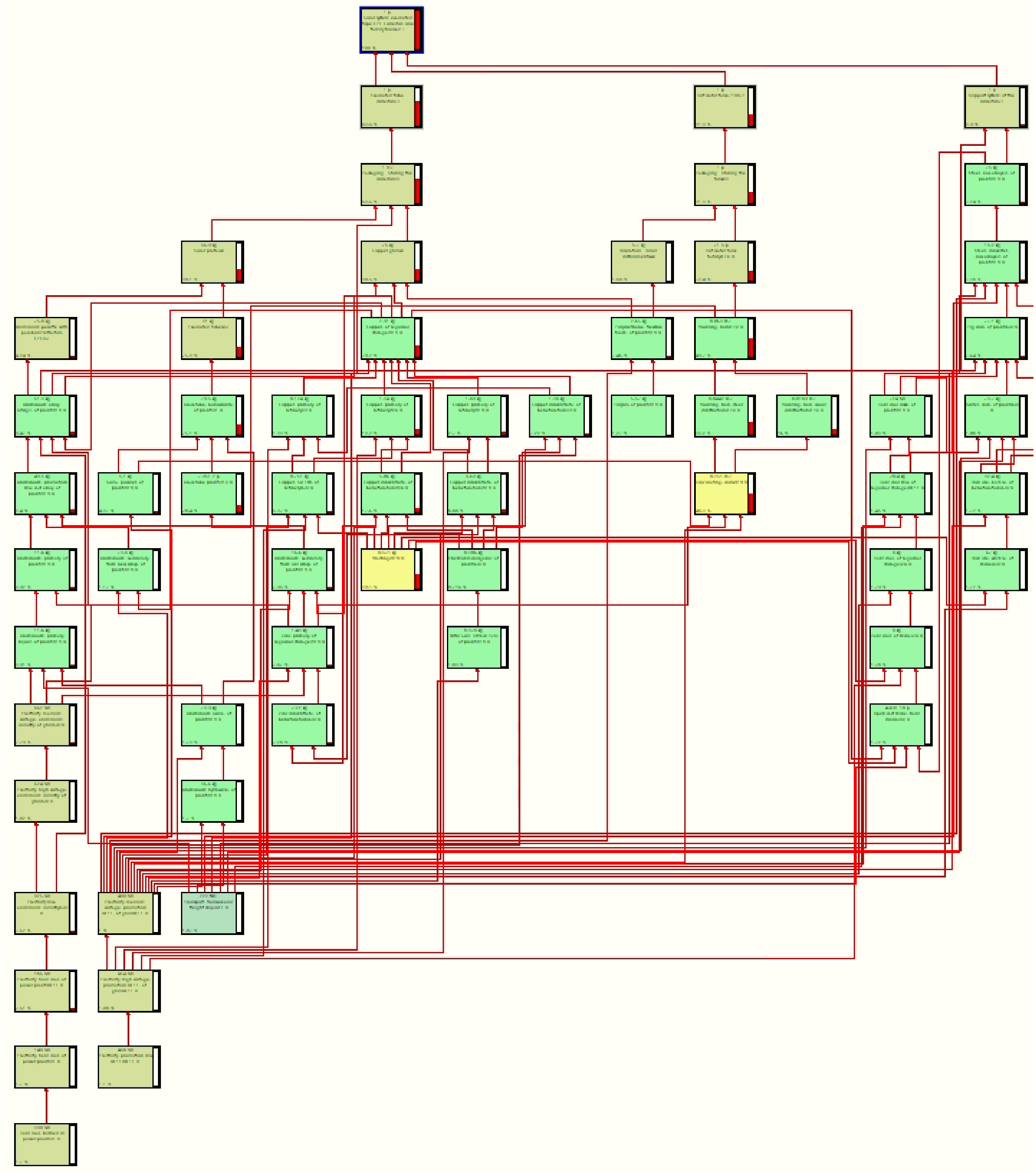


Figure 4.86: Process network for the Solar system evacuated tube CPC Collector. Cut-off threshold: 1%, visible nodes: 63 total nodes: 2022.

4.4. Impact assessment and interpretation of Solar system evacuated tube CPC collector

The diagram below shows that the greatest environmental burden is caused by the collector level. The areas of impact considered are human health, ecosystem quality and resources. Analytically:

- Human health: The results are expressed as the number of years of life lost and number of years of disability life. From the combination of these results the corresponding unit of measurement is called DALY (Disability Adjusted Life Years).
  In this category of damage the maximum load is caused by the collector level. Next is the storage tank and finally the support system.
- Ecosystem quality: An approach to describing ecosystem quality is in terms of energy, matter and information flow. The results are expressed as number of species that disappeared in a designated area for a specified time (species.yr).
  As like as the previous category, the maximum environmental load is caused by the collector. Next are the storage tank and then the support system.
- Resources: Here the method we use has chosen to base this model on the geological distribution of fossil fuels and fuels and evaluate how their use causes changes in effort extraction of future resources. The results are expressed as surplus energy required for future export of fossil fuels ($).
  Here the maximum environmental load is caused by the collector but next is the support system because of the high usage of steel.

The above findings are presented in the table and diagram below:

Damage Category	Evacuated tube collector	Hot water tank 210lt	Support system of the collector	Total
Human Health	29.17063	5.803513	4.470075	41.95648
Ecosystem	8.257831	4.961451	1.709646	16.2266
Resources	0.040896	0.009849	0.021005	0.074833
Total	37.46936	10.77481	6.200726	58.25791

Figure 4.87: Method: ReCiPe Endpoint (H) V1.11 / Europe ReCiPe H/A Indicator: Single score per end point category.

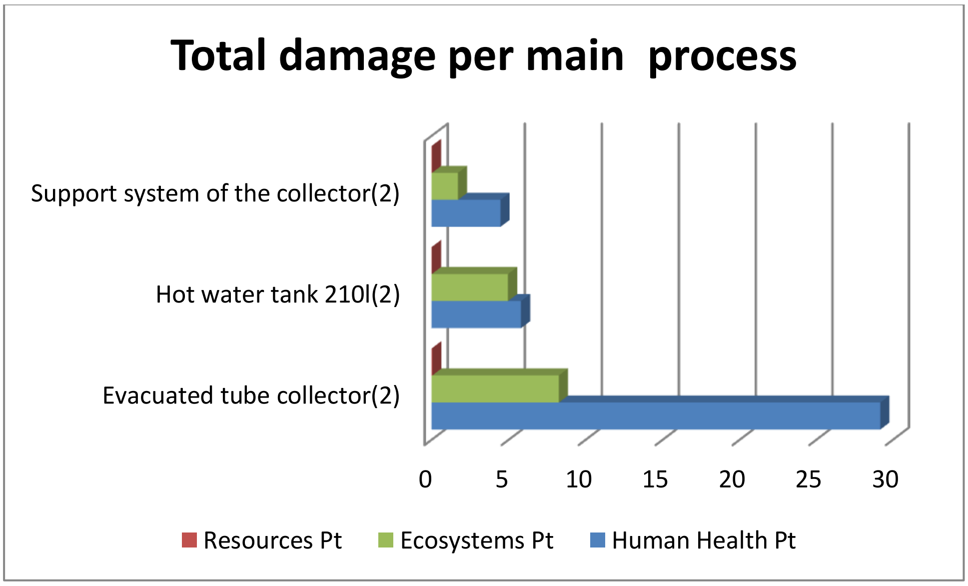


Figure 4.88: Total damage per main process

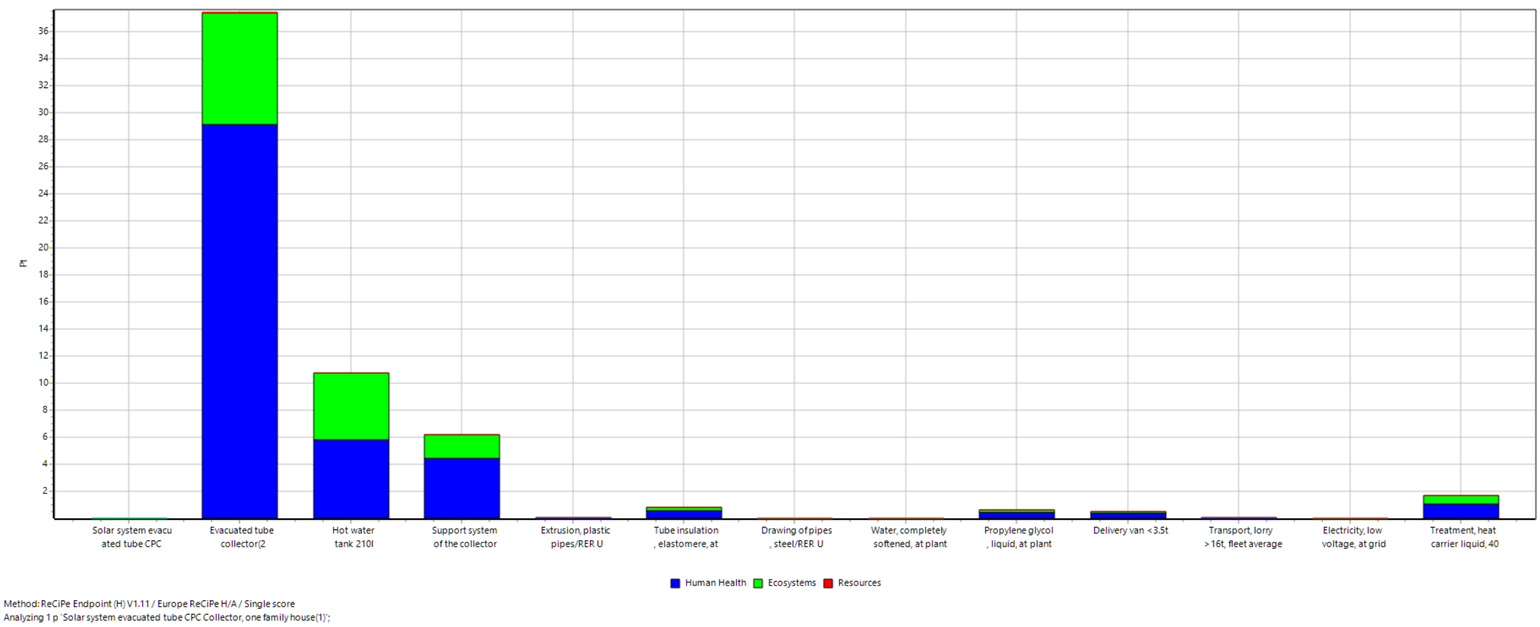


Figure 4.89: Total damage per process SimaPro program view

The final result that we distinguish from the environmental burden of the liquid wastewater treatment, the propylene glycol nodes and the transport via delivery van is important but is overshadowed by the particularly higher values found in the three cases mentioned above.

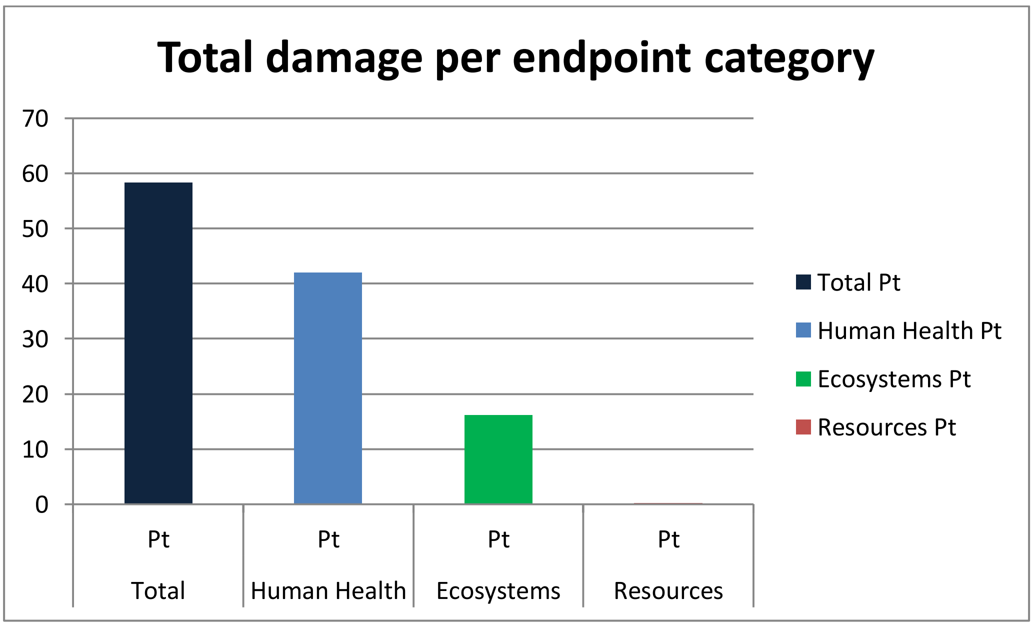


Figure 4.90: Total damage per endpoint category

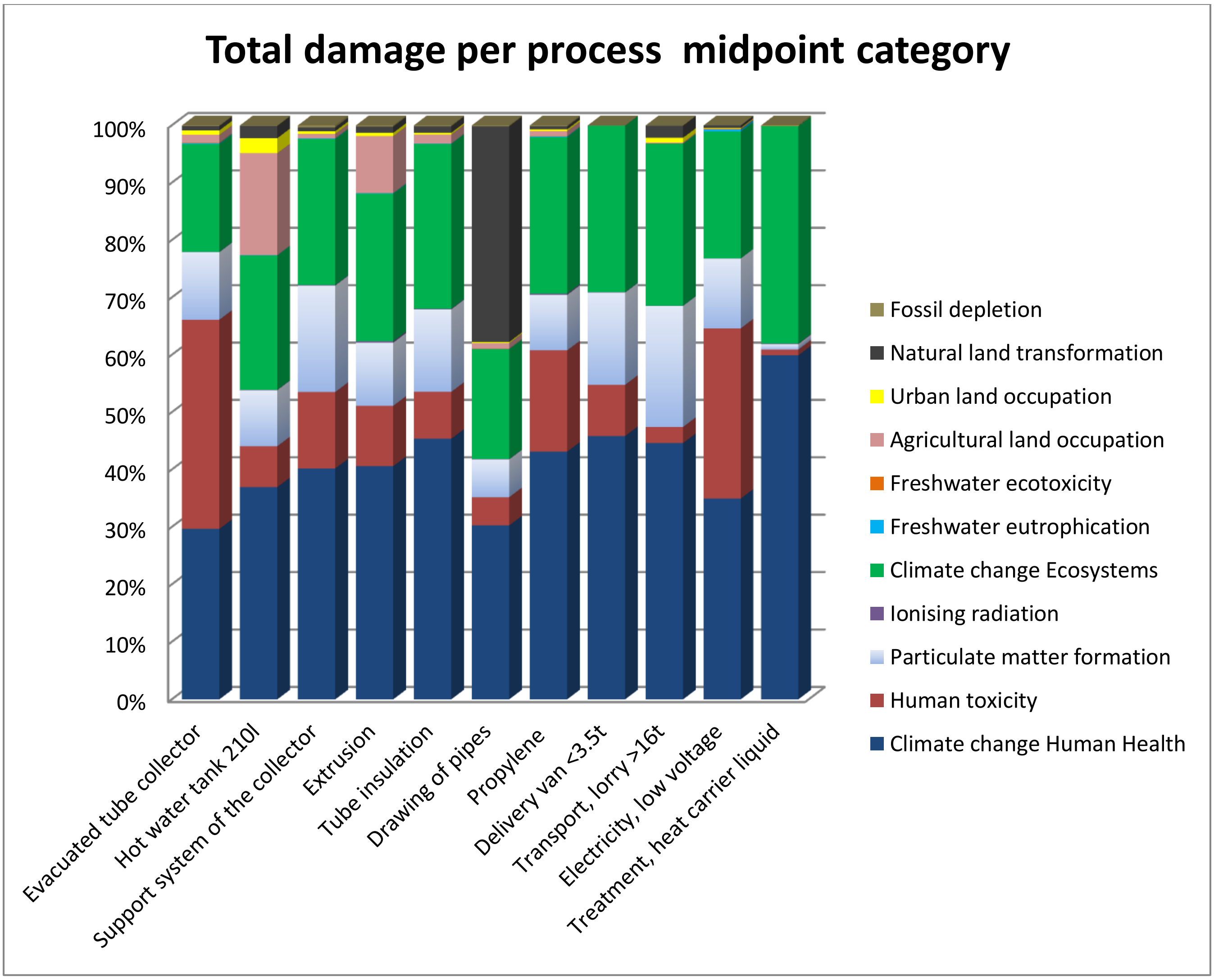


Figure 4.91: Total damage per process midpoint category

we observe that the greatest effect per process has the climate change human health category (34%), followed by the human toxicity (27%) and the third most important is the climate change ecosystems (21%).

Below is described the most important midpoint impact categories and the unit processes with the highest Pt.

Climate change Human Health
magnesium 3.6 Pt
hard coal burned in power plant 2 Pt
natural gas burned 1.9 Pt
lignite burned in power plant 1.5 Pt
aluminum primary liquid 1.2 Pt

Human Toxicity
disposal, sulfidic tailings 9.8 Pt
copper primary 2.1 Pt
disposal, spoil from lignite mining 1.6 Pt
disposal, spoil from coal mining 0.65 Pt
disposal, redmud from bauxite digestion 0.16 Pt

Climate change ecosystems
magnesium 2.3 Pt
lignite burned in power plant 1.4 Pt
natural gas burned 1.2 Pt
aluminum 0.75 Pt
heat carrier liquid 0.68 Pt

PARTICULATE MATTER FORMATION
copper 1.3 Pt
iron ore 0.45 Pt
bauxite at mine 0.43 Pt
blasting 0.26 Pt
glass tube borosilicate 0.24 Pt

Figure 4. 92: main midpoint impacts and main unit processes environmental load

Midpoint Category	Unit (Pt)
Climate change Human Health	**19.51945035**
Human toxicity	**15.49013564**
Particulate matter formation	**6.898603763**
Ionising radiation	**0.043778284**
Climate change Ecosystems	**12.35646877**
Freshwater eutrophication	**0.068326243**
Freshwater ecotoxicity	**0.040797786**
Agricultural land occupation	**2.497508949**
Urban land occupation	**0.603903978**
Natural land transformation	**0.584452802**
Fossil depletion	**0.074833305**

Figure 4.93: Total damage per midpoint category

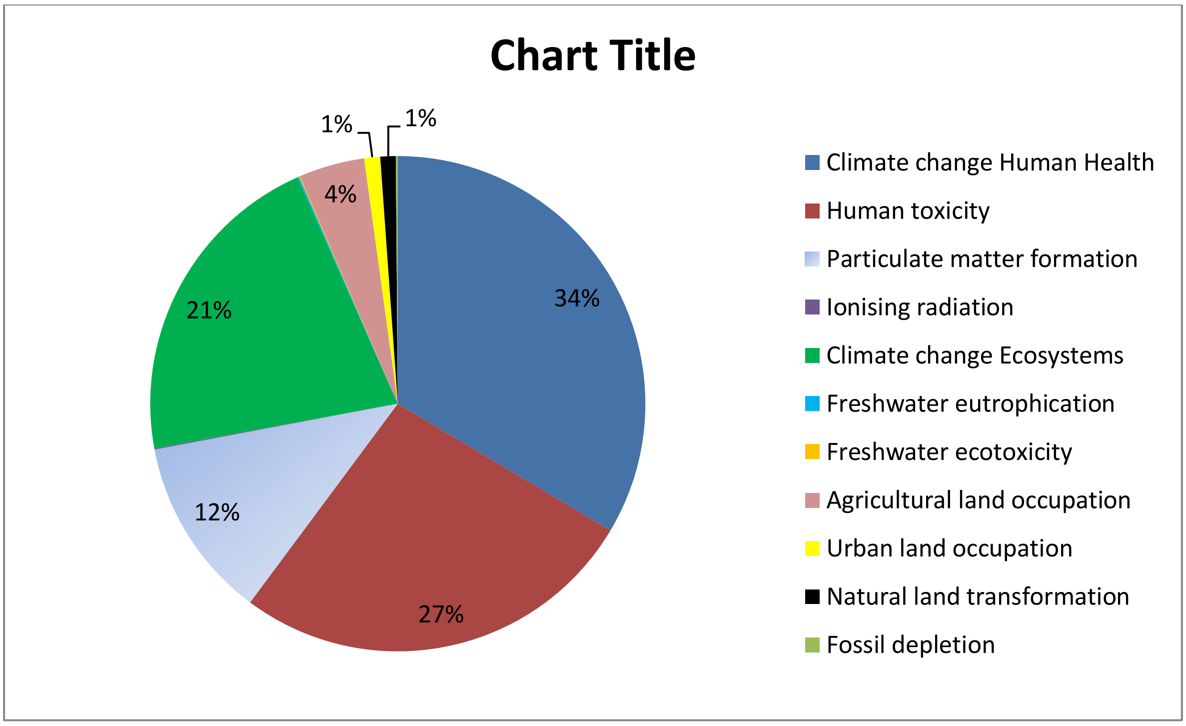


Figure 4.94: Pie chart of total midpoint category

4.5. Uncertainty analysis

SimaPro software enables the reporting of uncertainty analysis under conditions of absolute uncertainty. The confidence interval is set at 95%

Damage category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
Single score	Pt	58.98	56.23	22.71	38.49%	44.74	84.05	0.72
Confidence interval 95%								

Figure 4.95: Uncertainty analysis results table

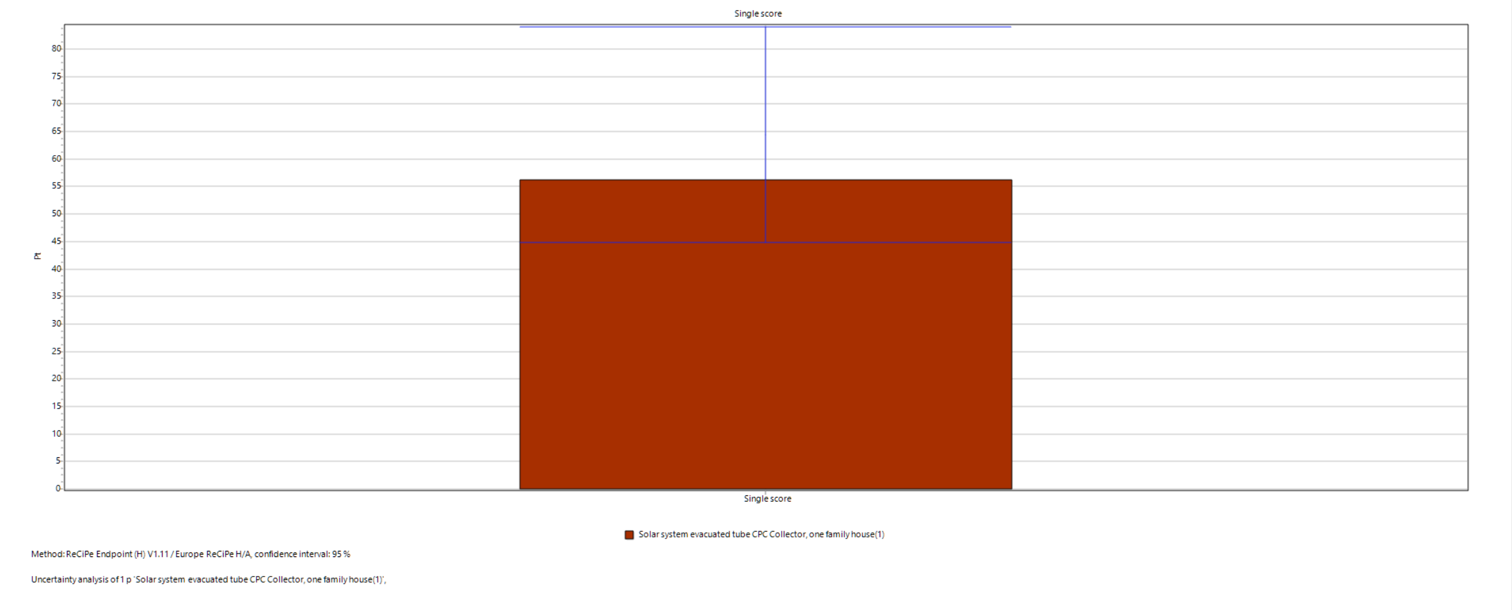


Figure 4.96: Uncertainty analysis diagram

The results showed that while there is 95% confidence, the value of the final result, of the system as a whole, ranges between 45Pt and 87Pt with mean 59Pt a standard deviation of 22.7 and coefficient of variation 38.49%.

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