Final Report

4GA50, Solar Heat System - DBL

Group 10

Full Name	Student ID
Tobias Wejbora	[redacted]
[redacted]	

Tutor: Luc Beerten

Eindhoven, April 2, 2026

Contents

List of symbols

Table 0.1: List of symbols

Symbol	Quantity	Unit	Unit abbreviation
L	Length	Meter	m
D	Diameter	Meter	m
V	Volume	Cubic meter	m^3
v	Velocity	Meters per second	m/s
T	Temperature	Degrees Celsius	$°C$
t	Time	Minutes, seconds	min, s
ϕ	Flow rate	Liters per minute	L/min
$\dot{m}$	Mass flow	Kilogram per second	kg/s
k	Thermal conductivity	Watt per meter-Kelvin	W/mK
h	Heat transfer coefficient	Watt per square meter-Kelvin	$W/(m^2K)$
c	Specific heat	Joule per kilogram Kelvin	J/kgK
R_{conv}	Thermal resistance (convection)	Degrees Celsius per watt	$°C/W$
R_{cond}	Thermal resistance (conduction)	Degrees Celsius per watt	$°C/W$
μ	Dynamic viscosity	Kilogram per meter-second	kg/ms
ρ	Density	Kilogram per cubic meter	kg/m^3
Nu	Nusselt number	-	-
Re	Reynolds number	-	-
Pr	Prandtl number	-	-
Kb	Boltzmann constant	-	-
D_{inner}	Diameter of the inner side of a curved media	Meter	m
D_{outer}	Diameter of the outer side of a curved media	Meter	m
R	Thermal resistance	Kelvin second per Joule	Ks/J
A	Area	square meter	m^2
f	Darcy friction factor	-	-
q	Heat flux	Watt per square meter	W/m^2
Q	Energy	Joule	J
$\dot{Q}$	Heat flow	Joule per second	J/s

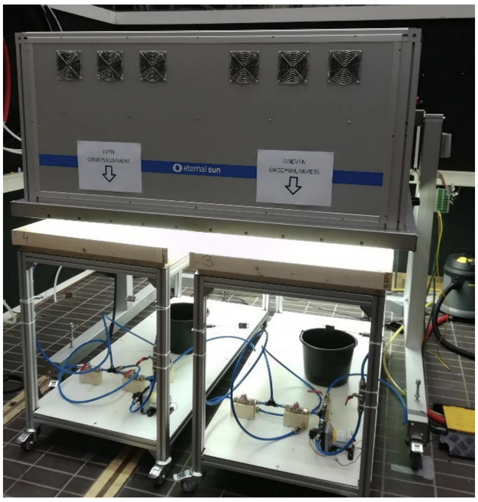
1 | Introduction

1.1 | Stating the Problem

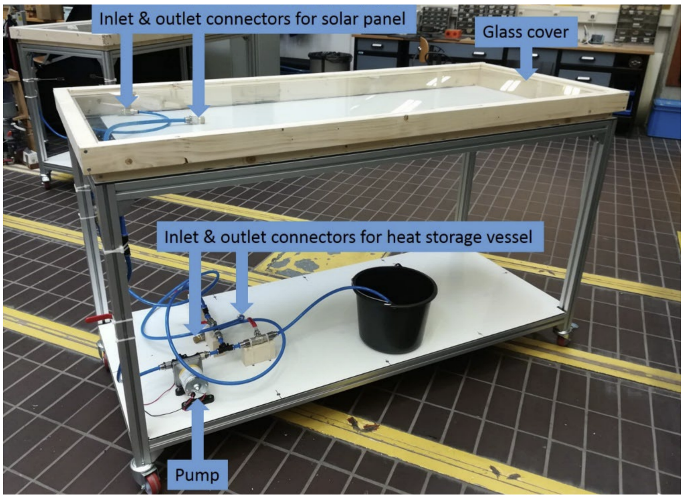
Earth is currently confronted with significant global warming and climate change challenges. The adverse effects of these phenomena are increasingly evident, as people worldwide are forced to abandon their homes due to water scarcity, wildfires, rising sea levels and devastating floods. Recognizing the urgent need for action, 195 countries came together to sign the Paris Climate Agreement in 2015 [24]. The primary objective of this international accord is to limit the global temperature increase in the current century to below two degrees Celsius. To achieve this ambitious goal and reduce CO_2 emissions, the development and implementation of sustainable energy solutions are of paramount importance.
Though on a small scale, this project aims to address such pressing concerns by focusing on the development and testing of a self-made solar heat system (SHS), designed according to the sustainable principles of Cradle-to-Cradle (C2C).

1.2 | General Overview

The SHS referred to in this project is a device specifically designed to harness the energy from sunlight and convert it into heat to warm water. It comprises two main components: a solar collector and a heat storage vessel. The SHS seamlessly integrates into an existing general setup, as depicted in Figure B.1b. The primary objective of this project is to achieve optimal water heating efficiency while adhering to the C2C principle, ensuring the complete re-usability of materials without compromising their value. To simulate sunlight, an artificial 'sun' is utilized, as illustrated in Figure B.1a. The performance evaluation of the SHS involves drawing one litre of water from the storage tank at the conclusion of a 20-minute test cycle and measuring the resulting temperature increase. Subsequently, the solar collector is dismantled within a span of 15 minutes, showcasing the application of C2C. Emphasizing the importance of recyclability, the project minimizes the overall quantity of materials required for constructing a complete solar heat system.



(a) Light source



(b) Wooden cart

Figure 1.1: Testing facilities

The project followed 7 design phases, which are reflected in the structure of this report. Chapter 2 presents the conceptual designs and a brief analysis of the features desired in the final design. Chapter 3 shows the final design and all of its details. Chapter 4 covers the realization phase where the physical design is built. Chapter 5 discusses the building and testing of the design and the results obtained. Chapter 6 describes and explains the Matlab model that was used to simulate the heat transfers that took place within the final design. Finally, Chapter 7 draws a conclusion based on the results and contains various suggestions and further possible improvements of the SHS.

1.3 | RPC List

The inherently vague SHS must satisfy the following solution boundaries in terms of requirements, preferences, and constraints:

Requirements:

- The design needs to follow the Cradle-to-Cradle (C2C) principle which means that it must be fully recyclable after it accomplished its purpose.
- The system cannot have any type of leakages.
- The design must be efficient, meaning that as much heat must be absorbed, and heat losses should be minimized.
- The temperature of the water must reach at least 50 °C.

Preferences:

- The design is easy to build, therefore not many modifications need to be made to the parts provided.
- Use only a small amount of parts.
- The design is creative and out of the box.
- The design is as efficient as possible.
- All the parts are fully reusable.

Constraints:

- The collector part of the system must fit in a space of 670mm x 1640mm x 65mm.
- The vessel must fit in a space of 600mm x 1400mm x 600mm.
- The surface of the artificial sun is 2mm x 1.3m and it produces a constant power density of 1000 W/m2. The collector is at a vertical distance of 10cm from the artificial sun.
- The surface temperature of the solar simulator is approximately 60 °C during operation.
- The inlet and outlet ports should be copper pipes of at least 10cm.
- The flow range of the pump is 0.1-3 L/minute.
- The connecting tubes of the solar collector and the heat storage vessel are polyurethane and have a wall thickness of 2mm and an outer diameter of 12mm.
- The cost of the entire system must not exceed 25 TU/e coins.
- The design needs to be built only using the provided materials.
- There is only a 15-minute window to set up and dissemble the system after it was left to run for 20 minutes.

2 | Conceptual Designs

The project's main goal is to heat up at least 1 litre of water as much as possible in a time frame of 5 minutes under the artificial sun and 20 minutes rest. Therefore, it is desired to have as much heat transfer as possible in the solar collector and as little heat loss as possible in the rest of the system. To initiate the still rather open-ended design process, individual research was conducted on existing models to gain inspiration for creative, efficient and unique ideas. While considering the technical and financial requirements, preferences and constraints, sketches were made to show different concepts that were subsequently combined into one design.
For the solar collector (SC), common principles were maximizing light-absorption efficiency by using thin, heat-conducting copper pipes, reducing leakage likelihood by minimizing sharp bends, maximizing the tube lengths, and incorporating glass to create a closed space where light rays are reflected to create a greenhouse effect. The differences in designs are described in the three sections below. The design commonalities and differences of the storage vessel are described in Section 2.5.

2.1 | SC Concept 1

The first design involves black-painted copper tubes, aluminium tape, Kingspan Therma insulation and centralizing the copper pipes. The basic principle behind it is to maximize the copper tubing which goes into the centre of the SC. The idea is to expose as much water to the artificial sun and keep it as far as possible from the edge of the solar collector because that is the place where the heat leaks into the environment the most. Furthermore, to minimize heat losses to the surroundings, a sheet of Kingspan Therma insulation would be placed under the aluminium foil. The copper tubes are to be painted black in order to increase the emissivity in the radiation heat transfer. The 3D model of the design can be seen in Figure 2.1. The main problem with this design, however, is that the copper is too expensive and relying solely on radiation from the artificial sun as the primary way of energy input into the system is not advisable.

2.2 | SC Concept 2

The second concept is designed without the use of copper piping. Instead, the design makes use of polyurethane tubing, which is a much cheaper material. Consequently, a larger length of tubing can be used. However, polyurethane tubing has a lower thermal conductivity compared to copper. If 15 coins are spent on purchasing the tubing, 125m can be bought. However, the pump that will push the water through the collector can only supply a maximum pressure of 3.1 bar, limiting the maximum pipe length that can be used. This length can be determined using Equation (E.14). Since there is insufficient information provided about the polyurethane tube, a few assumptions are made, and the effect of the bends in the tube is neglected. Solving this equation yields the following result: to utilize the entirety of the 125m, the flow speed of the water can only reach 0.6 L/min. This flow speed forces the water to circulate the system circa 8.5 times in 20 minutes. Due to the facts mentioned above, this design was not visualization in a drawing, however, the general concept can be seen in Figure 2.2.

2.3 | SC Concept 3

The third concept(Figure 2.3)incorporates a custom-fitted bitumen sheet, which reflects and concentrates the majority of heat back onto the copper tubing or back onto the glass pane. This arrangement maximizes heat conduction. The sheet serves the purpose of preventing heat that does not reach the pipes from being lost. To enhance the reflection concept and minimize heat loss, the aluminium tape is placed underneath the SC and the bitumen sheet. The SC tubes need to be held in place since they are elevated a bit. To do this, 3D-printed stands are used at the round parts of the tubes, keeping them separate from the bitumen sheet. The 3D-print file consists of eight stands connected to each other with thin rods because it is only allowed to print one component. The 3D model can be seen in Figure A.1 from Appendix A.

2.4 | SC Concept 4

The fourth concept, seen in Figure 2.4, utilizes the bitumen sheet, copper piping and PVC piping. The design focuses on a parallel piping concept where all copper pipes are arranged in parallel. Water enters through the inlet PVC pipe and then flows through all copper pipes simultaneously before exiting through the outlet PVC pipe. This configuration allows the flow rate to divide among the different tubes, reducing the water's velocity. Ultimately, this facilitates more convective heat transfer from the copper pipes to the water within the 5-minute time slot. However, the design prioritizes using as many copper pipes as possible within the budget, sacrificing the inclusion of insulation materials. Additionally, only 40% of the SC area is covered by copper piping, which is not efficient. The design also presents practical challenges, such as connecting the PVC pipes and the copper pipes, as no connectors are provided in the material list. The concern of potential leakages, along with the need for additional PVC materials like end caps, makes this design unfavourable.

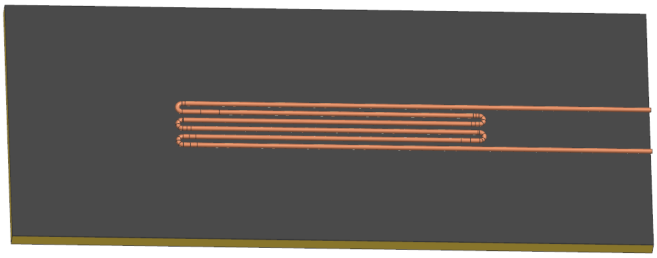


Figure 2.1: Black copper tubing centred in the middle of the solar collector

Figure 2.2: Polyethylene tube arrangement

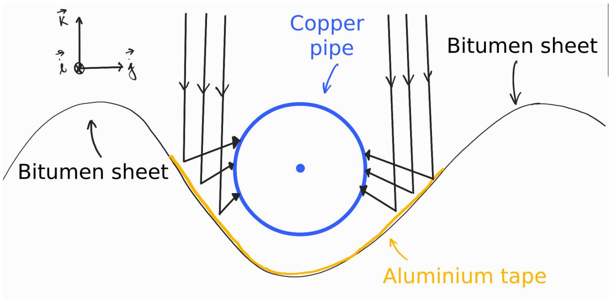


Figure 2.3: The bitumen sheet effect

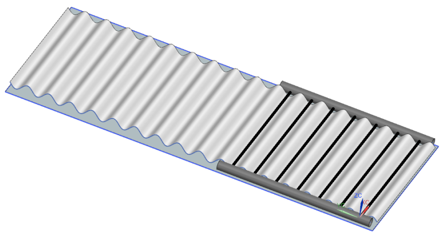


Figure 2.4: PVC copper piping design

2.5 | Storage Vessel Commonalities and Differences

For the storage vessel, all designs consider the concept of temperature stratification to facilitate the sinking of cold water and prevent re-circulation. The inlet is placed higher than the outlet and the most ideal tank-aspect ratio is used. In this case, this ratio is 3, so the vessel's height is 3 times bigger than the diameter. [19] Different options for certain aspects were explored, such as identifying the best insulation materials with low thermal conductivity, like Kingspan Therma, polystyrene, or polyurethane foam foil. The potential water absorption and rotting of plywood were compared to the benefits of thick PVC piping. The concept of using a pipe with the largest diameter was duelled with creating an air gap for better insulation by adding a smaller cylinder inside. For this, pipes with diameters of 110mm and 50mm prove to be the most suitable. However, to accommodate a volume of 1 litre, the length of the small pipe must be at least 670mm, which requires a height adjustment of around 400%, which is not practical. Moreover, even without the insulation material, the total costs would be too expensive (3.88 TU/e coins). A sketch of the initial storage vessel concept can be seen in Figure A.2.

3 | Detailing the Final Design

This chapter describes the detailing phase, during which a lot of calculations were made and a Matlab model was created to determine the optimal parameters and eliminate ideas that were not feasible (see Section 4).

3.1 | Solar Collector

The final design optimises and combines the features of the designs discussed in Section 2. Each final component will be explained in its own section and the final assembly of the design will be presented at the end.

3.1.1 | Copper Piping

Copper piping is exclusively used to directly heat the water. Copper piping of diameter 12mm was chosen, because it has the smallest wall thickness of 1mm, allowing for faster heat transfer through the pipe. Furthermore, the 12mm pipe costs the least, meaning that more piping can be allocated in the budget. A total of 6.5 meters of copper piping is used, of which one meter of copper piping is provided for free. 0.2 meters are designated for the inlet and outlet piping for the heat collector and the rest 0.8 meters are used for the copper piping in the solar collector. Hence, in the material list, only 5.7 meters of copper piping had to be purchased using TU/e coins. A CAD model of the copper piping is visualized in Figure B.3a.

3.1.2 | Bitumen Corrugated Sheet

The troughs of the bitumen sheet can be configured in two directions, by either having the direction of the waves parallel or perpendicular to the long side of the aluminium plate. For the chosen design, having the direction of the waves perpendicular to the long side of the aluminium plate allows for a copper pipe configuration with minimal bending. This not only makes it easier to manufacture but also minimises frictional pressure drop in the pipes. The copper piping runs through every second trough in the bitumen sheet which gives no thermal benefit but spreads the piping evenly through the bitumen sheet. The bitumen sheet is a good absorber of radiation due to the fact that it is black. The purpose of the sheet, however, is to reflect radiation onto the copper pipes. Hence, the sheet is covered with aluminium tape to stop the radiation absorption. For the design, the bitumen sheet(Figure B.3b) is cut down to 1300mm lengthwise instead of the initial 1640mm.

3.1.3 | Aluminium Tape

As mentioned in Section 3.1.2, the aluminium tape is used to reflect the solar radiation off the bitumen sheet. Since no emissivity values are given for aluminium tape, we can assume that it has an average emissivity value for aluminium, which is around 0.15[26]. The surface area of the bitumen sheet is $1.1m^2$ which translates to 22.19 meters of aluminium tape with a fixed width of 0.05 meters.

3.1.4 | Black Paint

The copper pipes should absorb as much radiation as possible. The given copper pipes have an emissivity of around 0.65[17] which means they reflect 35% of the incoming radiation. We increase the emissivity of the copper pipes by coating the copper pipes with black paint, which has an emissivity value of around 0.95[17]. A thin coating of black paint is added so that there are minimal thermal resistances through the black paint.

3.1.5 | Standoffs

Another feature implemented is the elevation of the copper pipes. Instead of resting the copper pipes on the bottom of the bitumen sheet, 3D printed stand-offs are used to rest the copper pipes 19mm in height; the height of the X axis of the wave-like shape of the bitumen sheet. This aims most reflected radiation from the bitumen sheet towards the copper pipes. Lastly, in order to create a closed system, a glass pane is used to create the greenhouse effect, and Kingspan Therma insulation foam is used to cover up the feed-through gap of the given solar collector encasing.

3.1.6 | Final Assembly

The final assembly of all components can be found in Figure 3.1. The bitumen sheet and copper piping were placed on the provided aluminium plate. The copper piping was elevated by the standoffs and threaded through the troughs of the bitumen sheet. Another figure which shows the exploded version of the final design can be found in Figure B.2).

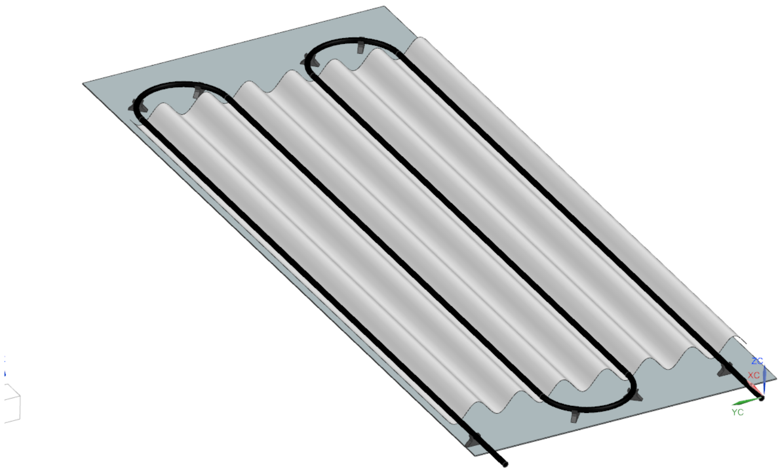


Figure 3.1: Final CAD Drawing of Solar Collector

3.2 | Storage Vessel

For the heat storage vessel, the main focus lies on good insulation to prevent heat loss, while still keeping a cheap design because of the budget. Figure B.1 from Appendix B shows a detailed version of the storage vessel.

3.2.1 | Storage Shape

A cylinder-shaped storage vessel is used since it is the cheapest and easiest to build and disassemble. It also has the smallest surface area, which also minimizes heat loss. On top of that, the smallest diameter pipes as in- and outlets are chosen, to lose as little heat as possible.

3.2.2 | Insulation Material Choice

To isolate the storage vessel, three different materials are available. These are Kinspan Therma plates, Tempex Polystyrene plates and Polyethylene foam foil. The only option to surround the cylinder with insulation material is Polyethylene foam foil because the other two materials can not be bent. Also, using foam foil reduces the convectional air gap and therefore prevents the most heat loss. Polyurethane foam foil has a thermal conductivity of 0.04 [W/(m K)], which is great for its price.

3.2.3 | Dimensions and Calculations

The vessel should be able to hold 1L, which is the same as $0.001m^3$. With the inside of the PVC pipe having a diameter of $0.110 - 2 \times 0.032 = 0.1036mm$, the area of the inside is $(\pi/4) \times 0.1036^2 = 0.008429m^2$. Therefore the minimum height of our PVC pipe should be $0.001/0.008429 = 0.1186m$ or 119mm. Leaving a bit of air, the PVC pipe is 130mm high.
The circumference of the PVC pipe is equal to 0.346 meters. The circumference of the PVC end caps is 0.3594 meters. Just to be certain, a circumference of 0.36 meters is taken. It was calculated that by cutting 1 meter of foam foil in strips of 13 centimetres, it can be wrapped around the PVC pipe 16 times, making the thickness of the foil layer 0.048mm or 4.8cm. That is almost 5cm of insulation material, which prevents a lot of heat loss.

3.2.4 | Insulation for the top and bottom

Finally, the top and bottom of the storage vessel needed to be isolated, since that is the main place where heat loss occurs when we have foam foil around the pipe. For this, using Tempex Polystyrene or Kingspan

Therma is an option, because the end caps have flat surfaces.

If the insulation plates would only cover up the cylinder itself, there would be spots on the edge of the end caps where the most heat loss would occur. Therefore, the whole top and bottom, including the foam foil, are covered in insulation material, making the total area of the top and bottom 20.6cm by 20.6cm each. Since Kinspan Therma is costly and the majority of TU/e coins are needed for the solar collector, plates of Tempex Polystyrene are used. 1 plate is more than enough to cover up the top and bottom, with a thickness of 5cm. The thick Tempex plate underneath the storage vessel also serves as a stand to keep it upright, which gets rid of the task to design some kind of stand for it.

3.2.5 | Final Design and Costs

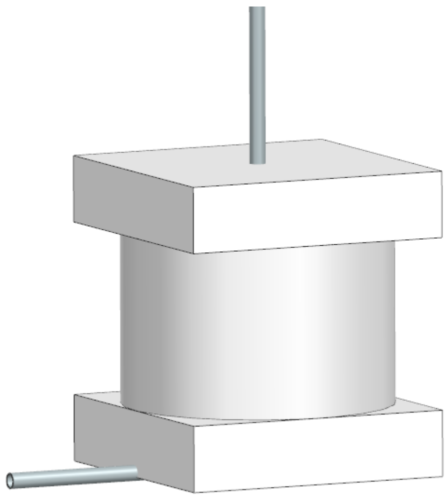


Figure 3.2: Final CAD design with foam foil and Tempex plates

Calculations show that this design costs 2.92 TU/e coins, which is quite cheap and therefore meets the requirements, preferences and constraints.

3.3 | Material List

The following comprehensive material list seen in Table 3.1 combines the materials for both the solar collector and heat vessel.

Table 3.1: Material List

Material Name	Quantity	Price	Cost (TU/e Coins)
Bitumen corrugated sheet	1	2.48	2.48
Aluminium tape	22.19m	0.19	4.2161
Glass cover	1	2.5	2.5
Copper pipes	5.7m	1.99	11.343
Black paint	1	1.2	1.2
Polyethylene foam foil	3	0.12	0.36
Straight screw on coupling	2	0.4	0.8
PVC end cap 110mm	2	0.43	0.86
PVC pipe 110mm	0.13m	2.37	0.3081
Tempex polystyrene plate	1	0.83	0.83
Duct tape	1m	0.1	0.1
Total Cost			**24.997**

3.4 | C2C Acknowledgment

The implementation of C2C principles goes hand in hand with conducting a Life Cycle Assessment (LCA); a systematic evaluation method that assesses the environmental performance of a product throughout its entire life cycle, from its 'cradle' (material extraction), through production and usage to its 'grave' (the disposal). C2C eliminates the concept of the grave, and 'old' material is viewed as an (improved) resource. The following sections describe a short LCA of the materials. Section 6 discusses the final C2C assessment of the system, based on the disassembly.

3.4.1 | Material Assessment

There are 5 main C2C requirements that are generally agreed upon by academics; 1) material health (toxicity rate regarding people and the environment); 2) product circularity (encourages the recyclability of materials for future uses); 3) renewable energy and carbon management (incl. minimized emission production); 4) water and soil stewardship; 5) social fairness (manufacturers must respect people's and nature's health, safety and rights). In the LCA, the first three requirements can be evaluated best. An assessment follows:

- The thermoplastic PVC can be reused, regrind, melted, and extruded indefinitely.[25]
- The glass cover is fully recyclable, although this process does require a lot of energy. [20]
- Cutting the bitumen corrugated sheet to the constrained dimensions leaves rectangular and L-shaped pieces, which are not useful for the sheets' primary use; roofing. This can be fixed by glueing them together with an overlap of the first wave (strength and no leakage) or recycling the bitumen (whose virgin resource, petroleum, is not sustainable). [16]
- The SC pipes are bent such that they will not fit directly in another system, which can be solved by fully melting the copper and moulding it into a new shape. In case the copper is purified correctly, it can be used for electrical purposes too. [14]
- The pipes are sprayed black outside, which poisons the air. This black paint will not interfere with copper during melting since it vaporizes before the copper melts. The vaporized paint does contain harmful and poisonous gasses. It can be removed with paint-remover, but this can release pollutants. Still, it is included, because it results in a higher temperature.
- Polyethylene foam foil and Tempex polystyrene plates have similar material properties and are both completely recyclable. This can be done by compressing pieces together, shredding and melting all material and using them as raw ingredients for plastic materials, or heating them extremely with the absence of oxygen, to decompose the material into different chemicals.[21]
- Duct tape, which mainly consists of adhesive, scrim and polyethylene, does not meet the criteria of product circularity, because it is impossible to isolate once combined with other components. This is also the case for PVC glue (materials with the glue are probably lost as well), and for aluminium tape (the presence of non-aluminium materials like the sticky side can affect the recyclability).[18]

3.4.2 | Emission Score

In total, the embodied carbon of the materials in the system totals 58.81 kg of CO_2 equivalency (CO_2eq) C.3.1. Since this does not account for the distribution, usage and disposal of materials, the true amount probably lies much higher. To heat 1 litre of water from room temperature to 50 °C, approximately 125.4 kilojoules (kJ) of energy are needed C.3.2. This requires combusting approximately 0.0023 cubic meters of methane gas C.3.3, which would emit approximately 4.25 grams of CO_2eq emissions. We assume this is also the resulting emission quantity of a gas boiler. Here we do not account for its production carbon emissions, because we assume that all houses still have a gas boiler. From the calculated numbers, we derive the total amount of water that needs to be heated by the (newly installed) solar collector before its emission-free heating compensates for its LC emissions to be 13837.6 litres of water C.3.4. This equals around 275 hot showers. In a complete LCA, weights should be attached to the materials and all criteria, to create a score for the C2C of the system.

4 | Matlab Numerical Model

This chapter describes the Matlab model, which modelled the temperature the system would reach and helped gain ideas by identifying improvable design aspects.

4.1 | Numerical Model

The modelling of the solar heat system was essential. Modelling is a way of simplifying reality by making a series of assumptions and creating a representation of the system. With the help of such a model, predictions can be made about how different conditions influence the temperature of the water. These can then be analyzed and manipulated to gain insights into its behaviour. With this numerical model, calculations could be done to support certain decisions and predict the system's overall performance.

The numerical model was made in Matlab. To keep things organized, two scripts were developed, constants.m and numeric.m. The constants.m script contains all the needed constants and the numeric.m script contains all the calculations needed to calculate the temperature increase of the water over time. For more information, see Appendix E.2. In order to calculate the temperature increase over time, the net heat transfer to the water had to be known. In the model, the thermal resistances of the in-going heat flow at the collector and the out-going heat flow at the heat storage vessel are summed up for each time increment dt. All these calculations are done in a for loop, so all the calculations are done for each increment dt. Since the heat flux is assumed to remain constant, the in-going and outgoing heat flow can be computed. The difference between the in-going heat flow and the out-going heat flow is the total effective heat that is supplied to the water. The temperature increase of that time increment can be computed when multiplied with dt and substituted into:

$$\Delta T = \frac{Q}{\rho \cdot V \cdot c_p} \tag{4.1}$$

This temperature increase is then added to the old temperature to obtain the new temperature. This process is repeated a total of 1200 times since dt is chosen to be one second.
The temperature of the water was plotted over time. According to the model, the water would reach a maximum temperature of 49.3°C, see Figure 4.1. The efficiency of the solar heat system according to the model is 9.4%. So 9.4% of the heat supplied by the artificial sun is effectively supplied to the water in the storage vessel.

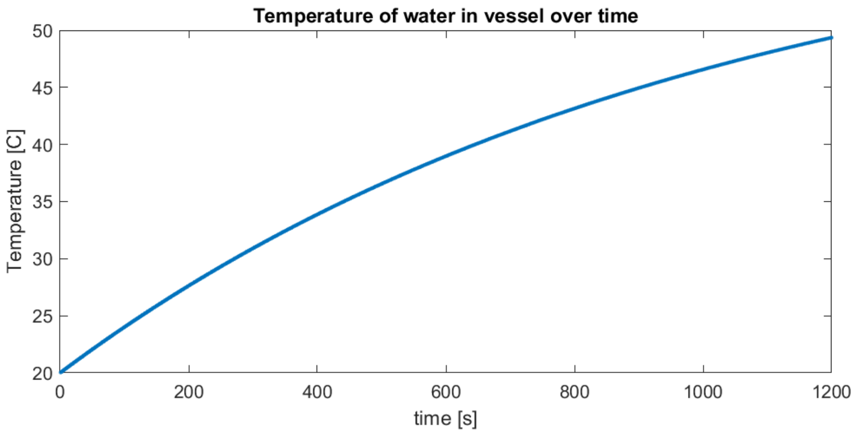


Figure 4.1: Temperature of the water over time

4.2 | Assumptions

In order to describe the system, the model makes some assumptions. Assuming certain conditions or factors makes the model easier to understand and analyze. These assumptions are either variables that are negligible or variables that cannot be computed with the available information.

First, the model assumes that everything starts at room temperature, set at 20 °C. The flow of the pump can be adjusted, but in the model, the pump has a constant flow of $3.0 \cdot 10^{-5} m^3/s$, which is the highest value the pump can deliver. Another assumption is the fact that the tubing of the collector is perfect, meaning that there are no dents or curves in the tubes. Moreover, all mediums are assumed to have a constant density, and all materials are 100 percent pure, meaning that the material properties are given and constant everywhere in the material. Some bigger assumptions are that the heat flux through all mediums is constant. This way the thermal resistances are in series. These thermal resistances can then be summed up to one total resistance.

Lastly, it is assumed that 75% of the reflected rays by the aluminium tape are reflected towards the copper tube. This assumption is backed up by measurements made with the help of an online ray optics simulator. The aluminium tape acts as a mirror when a beam of rays is radiated on the aluminium tape. The following is obtained, see Figure 4.2.

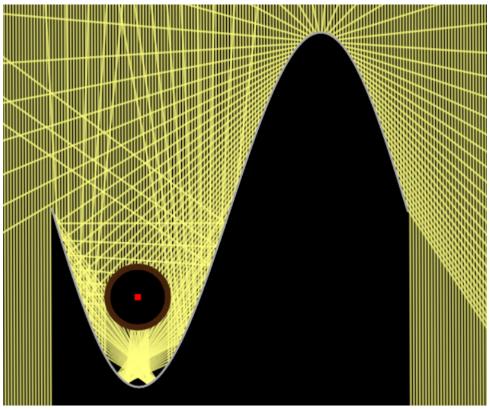


Figure 4.2: Reflection of aluminium tape

The circle represents the copper pipe at the height of the stand-offs. It can be deduced that the ray density at the bottom is higher than higher up. The number of rays reflected by the mirror and the number of rays hitting the pipe are counted for increasing ray densities. This introduces a high measurement uncertainty, so the outcome must be considered carefully. From the measurements, it follows that 76.2% of the reflected rays by the aluminium are reflected towards the copper pipe, see Table E.1. However, here it is assumed that every ray is perfectly reflected. To take into account the unevenness of the aluminium tape, the 76.2% is rounded off to 75%.

4.3 | Flowchart

The flowchart in Figure 4.3 depicts all relevant processes and how they interact. It starts with the artificial sun which delivers a constant heat flux to the system. The heat flows and the interactions between them are described between the artificial sun and the temperature of the water in the vessel. The red processes lead to a decrease in the water temperature but an increase in the temperature of the surroundings, whilst all the green processes lead to an increase in the water temperature. All the processes have a number at the end, which corresponds to their relevant equations enlisted in Appendix E.1.

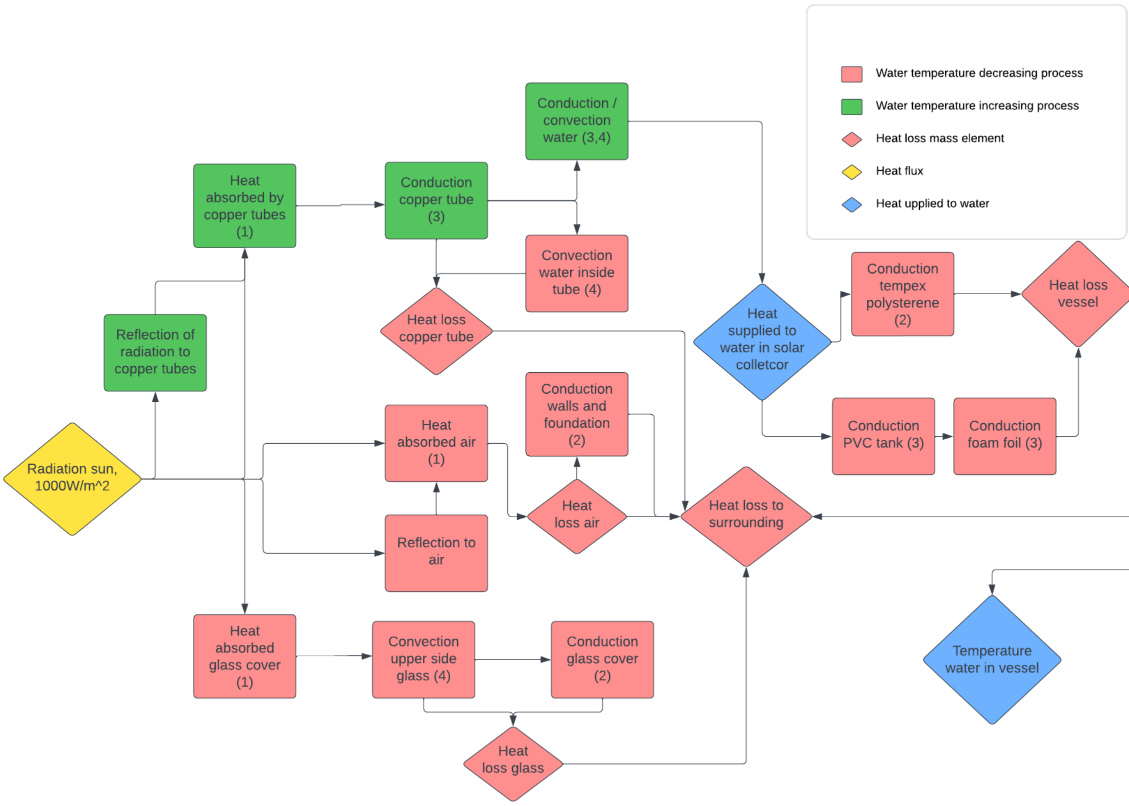


Figure 4.3: Flowchart

4.4 | Parameter Optimization

It is really important that the most optimal set of adjustable parameters is chosen for the design. To find out if this has been achieved, a parameter test was conducted. Some parameters like the Stefan Boltzmann constant and the heat flux of the artificial sun are not design-dependent; they are the same for each design. The only parameters that have been adjusted were the diameter of the copper pipes and the length because these have the biggest effects on the outcome of the temperature. Multiple iterations were done and the following results were found. For the chosen design with an amount of 5.5 meters of copper pipes with an outer diameter of 12 millimetres, the final end temperature will be 49.3 °C. After the computations for the design with copper pipes with an outer diameter of 15 were made, the outcome was as follows: the maximum length was 4.40 meters and the final end temperature was 48.1 °C. Then the final end temperature was computed for the copper pipe with the largest outer diameter of 22 millimetres. The maximum length of these pipes will be 2.74 meters and the final end temperature would be 43.9 °C. In Table 4.1, the three different outcomes for the three different design options can be seen. It can be seen that the final end temperature of copper design 3 is the highest. Based on this the conclusion has been made that the design with the copper pipes of an outer diameter of 12 millimetres is the best option, and that is why this design has been chosen.

Table 4.1: Parameter optimization table

Different design options	**Copper 1**	**Copper 2**	**Copper 3**
Length	2.7m	4.4m	5.5m
Outer diameter	22mm	15mm	12mm
Wall thickness	1.1mm	1.0mm	1.0mm
Final end temperature(°C)	**43.9**	**48.1**	**49.3**

5 | Realization

This chapter describes the building process and the problems that were encountered. The assembly sequence of the design can be found in Appendix C.2.

5.1 | Session 1

In the first building session, there were unexpected issues with the delivery of materials. The end caps for the vessel did not come with pre-drilled holes, and the copper pipe was not provided in a straight form. This posed a significant problem since the rolled-up copper pipe needed to be straightened before bending it into the required turns. Unfortunately, during the straightening process, an error occurred that resulted in a kink in the pipe Figure C.1a. Due to the high risk of breaking the pipe and the non-existent possibility of removing the kink, it could not be used in a straight part of the assembly. Consequently, the endpoints of the copper pipes were misaligned with each other. This caused the endpoints of the copper pipes to be not aligned with each other.
Furthermore, the tool used for bending the pipes had a fixed radius that was considerably smaller than the radius specified in the design. To address this issue, a small straight piece had to be inserted between two turns as a workaround. As a result of these challenges, the final outcome was as shown in Figure C.2b. Although the pipe fits over the sheet, it is not perfectly aligned as intended.
Assembling the storage vessel, on the other hand, was relatively trouble-free. Firstly, the contact points between the vessel and the caps were sanded to ensure better adhesive attachment. This is shown in Figure C.1b. The TA drilled holes in the end caps and also added threads to accommodate the compression fittings. To prevent leakages, several layers of Teflon tape were applied during the mounting process. Then, the caps were successfully attached to the pipe.
While the project manual mentioned the provision of a small amount of free copper for mounting on the storage vessel, this was not the case initially. However, after requesting assistance from the TA, 20cm of additional pipe was provided.

5.2 | Session 2

In the second building session, there were still a few tasks remaining, including adding aluminium tape to the bitumen sheet, insulating the storage vessel, and straightening out the copper pipe that had slight bends in certain places.
To enhance reflection and create a greenhouse effect, the aluminium tape was applied to the bitumen sheet. The kinks and misplaced bends in the copper pipe were corrected using a vice, resulting in a much better fit of the solar collector on the bitumen sheet. The result is shown in Figure C.2c.
For the storage vessel, the sides of the PVC pipe were insulated according to the theoretical design. Strips of foam foil were cut and wrapped around the pipe. The strips were slightly wider than stated in Section 3.2.3 to account for the protruding end caps and to prevent any air gaps when adding the Tempex plates. The total thickness of the insulation layer was approximately 6cm. It should be noted that the actual insulation layer was slightly thicker than calculated due to the presence of small air gaps between each layer in practice.
Furthermore, the Tempex plates were cut to fit on the top and bottom of the storage vessel. However, there was a slight air gap between the foil and the Tempex plate. To close this convectional air gap, a gentle force had to be applied to press the plates down. Since rubber bands were not available and using tape was not ideal due to the C2C concept, two thin strips of foam foil were wrapped around to close the gap effectively. The insulated storage vessel is shown in Figure C.2d.

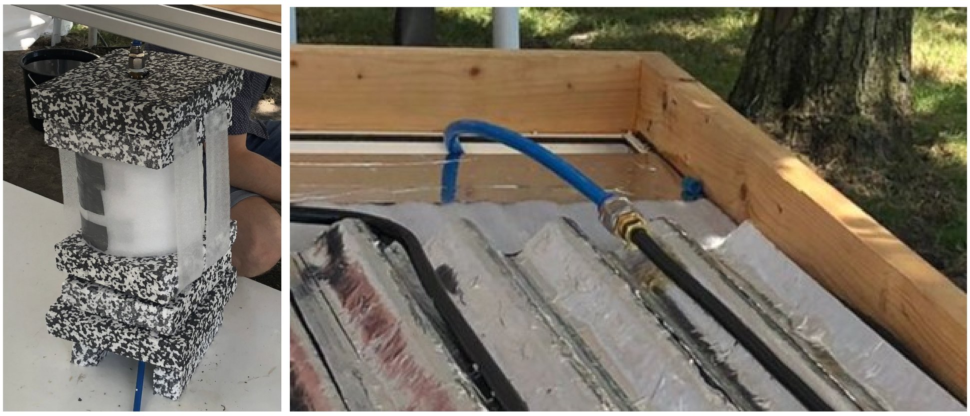
5.3 | Session 3

In the third and final building session, the aluminium tape cover was improved by adding tape on the parts where the bitumen sheet was still visible. Additionally, the copper tubing was painted black outside with black spray paint, and straight screw-on couplings were attached to the pipes. A piece of Tempex was cut for the gap in the SC setup, and an extra layer of leftover polyurethane foam foil was placed below the bitumen sheet (same width and length). Lastly, it was also checked if such foil could be wrapped around the blue tubing during the testing, but this proved to be too difficult and would require too much tape, which is unsustainable.

6 | Testing and Evaluation

6.1 | Preparation

The testing commenced with a 15-minute preparation phase, during which the SC was placed onto the cart. The storage vessel was connected to the inlet and outlet connection points by using water-sealed connectors as can be seen in the left picture of Figure 6.1. Also, the copper tube had the same connectors attached to its ends which were then screwed to the blue water pipe (see the right image) that was already connected to the pump. A short test was done to make sure that the system was completely water sealed and to fill it with water. The system was then filled with water, and the pump's mass flow rate was set to the desired 3 litres/min. The system had a leakage in the lower part of the storage vessel, but it was a minor issue as the heater was anyway loaded with more water than needed. A picture of the leak can be found in Figure D.1a.



(a) Storage vessel set up **(b)** Solar collector connected to water pipes

Figure 6.1: Preparation phase

6.2 | Testing and Outcomes

The testing phase involved getting the cart to the testing room where it had 2 thermal sensors connected to both ends of the copper tubing which were monitoring the inlet and outlet flows of the water that are highlighted in figure D.2. The system was put under the solar system (see D.4) and the sensors started registering the temperatures which were then shown on the computer as can be seen in figure D.3. Also, the flow rate was constantly displayed on the screen and it was fluctuating between 2.7 and 2.9 L/min even though the pump was set to 3 L/min. This was followed by a 20-minute heating period. The disconnection phase, lasting 5 minutes, involved extracting 1 litre of water from the heat storage vessel and measuring its temperature. Subsequently, the system was emptied, and all inlet and outlet connection points were disconnected. After 20 minutes the temperature reached 43.5 °C as it can be seen in Figure D.1b. It was a bit below the goal but it is, overall, a satisfying result. There are many reasons why the final temperature is smaller than the one predicted by the MATLAB model, but only the most important of them will be mentioned here.

Firstly, the copper pipes were not completely placed in the centre of the bitumen sheet trough, so not all the light rays were reflected towards the copper tubing. Also, the aluminium tape was not perfectly laid on the bitumen sheet, so it had many imperfections which did not reflect the light to the same extent. Another explanation is that the model did not consider all the possible heat losses to the environment. There are many holes in the upper part of the cart which let the hot air escape the system. Also, the blue pipes that connected both sections of the cart and the water pump were not insulated, thus it was not taken into consideration in the numerical model. The storage vessel also had some big issues as it had a leakage which was an important source of heat loss as it was not completely insulated. Again, as mentioned in the numerical model chapter one of the assumptions was that the heat flux is the same in the whole system, but in reality, that is not the case as the temperatures differ for each element of the design which leads to a difference in the amount of energy transferred from part to part for every single heat transfer that takes place. The parts used for building the solar heat system had imperfections (impurities), so their material constants are not exactly the same as the ones used in the MATLAB model.

Unfortunately, the temperature evolution of the system that was recorded during the testing session was lost, so there is no data which would describe how our design performed over time. The assistants provided the results of a similar design from the previous years and it can be seen in figure 6.2, so this graph is going to be further explained.

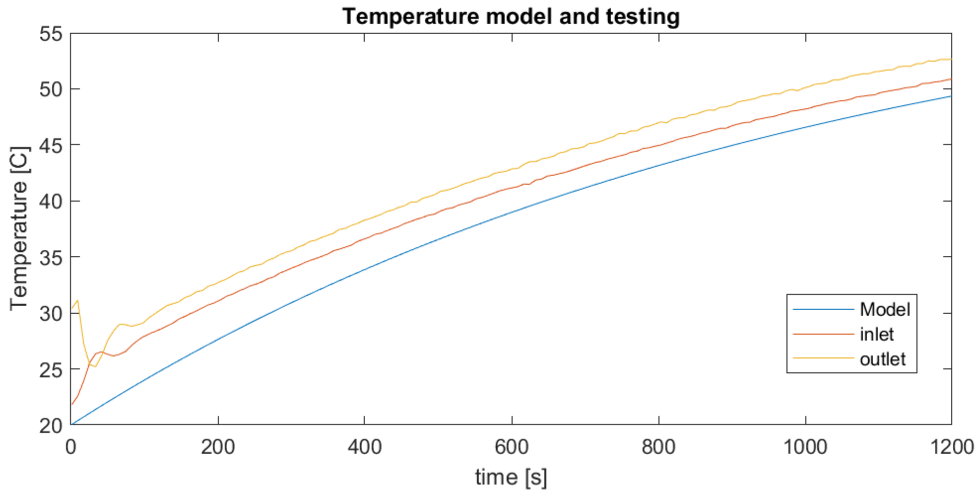


Figure 6.2: Testing results

First of all, the graph contains two plots: the blue one represents the temperature recorded by the sensor attached to the inlet flow of water and the orange one the outlet flow. In the beginning, the difference between the sensors is considerable, but after some time it stabilizes to a difference of 1 - 2 °C. Both plots have a curved shape as shown in the MATLAB model prediction graph, and this shows that it still stands as an accurate enough representation of reality.

6.3 | Disassembling Phase and C2C Evaluation

Lastly, the whole system had to be disassembled within 15 minutes. The largest problems were removing the aluminium tape from the plate and bitumen sheet, taking the duct tape off the foam foil, removing the screw-on couplings, and preventing small Styrofoam grains from blowing into the environment. We suggest that the disassembly should have taken place inside, to ease this. After dismantling, all the parts were thrown away in the right recycle bin.
Even though it is the long-term intention to manufacture solar panels in Europe designed to be circular (Net Zero Industry Act and the Critical Raw Materials Act), a market study shows that many current solar panels and collectors still find their way into landfills or incinerators. The biggest complexity lies in the difficult assembly of professional systems, which makes disassembly tedious. Given this, the recyclability of our system was relatively good.

7 | Conclusion

In summary, the project embarked on a comprehensive exploration of various conceptual designs during the brainstorming phase. These initial designs were subsequently refined and consolidated into a final design. Throughout the process, four distinct designs were conceived, each offering unique features and advantages.

The first designs all introduced their concepts, which could later be combined to create an optimized final design.
The first design involved positioning the copper pipes in direct contact with an aluminium plate, which was coated with black paint. To enhance efficiency, insulation material was incorporated beneath the aluminium plate. The second design experimented with polyurethane tubes. After doing length and pressure calculations, this design did not outweigh the others.
The third design incorporated a bitumen sheet coated in aluminium tape, serving as a mirror to reflect radiation onto the copper pipes. To optimize the reflection, the copper pipes were elevated using 3D printed standoffs, ensuring that the pipe would be located at the focal point of the reflected rays. Furthermore, insulation was utilized to cover the feed-through hole in the solar collector box, preventing heat loss.
Finally, the fourth design also employed a bitumen sheet coated with aluminium tape, but the configuration of the copper pipes was parallel. This arrangement aimed to enhance heat distribution and overall system performance.
In terms of the heat storage vessel, the primary principles focused on minimizing the volume of the vessel while also maximizing insulation thickness around the vessel. Having less water in the heat vessel allows for a higher temperature due to there being less water. On the other hand, having a smaller container means that heat losses will be greater since the surface area to volume of water ratio is more excellent. To mitigate this, insulation was maximized on the outside of the vessel. Overall, these principles helped improve the effectiveness of the system.

The final design is mainly based on Conceptual Design 3 with further detailing done to finalize the concept. With a budget of 25 TU/e coins, a maximum of 6.5 meters of copper piping was able to be purchased. The rest of the budget was needed for the other materials. This design was chosen due to many factors: the system can be easily disassembled, radiation absorption is maximized with the reflective mirror concept, insulation is incorporated and the C2C concept is met in some parts. In total, the solar collector costs 22.08 TU/e coins and the heat storage vessel costs 2.92 TU/e coins. The assembly of the design was simple except for the bending of the copper pipes. This proved to be the most challenging part since with the given tools, a perfect circular 180° bend was difficult to make.
With regard to the RPCs, the final design met some of the major requirements. The design adhered to the C2C principle except for the black spray paint, duct tape, and aluminium tape since it was hard to remove on some surfaces. The heat storage vessel also suffered minor leakages. During the testing, a temperature of 50 °C was not reached. However, the whole design is easily assembled since the dimensions were designed well. Overall, some C2C choices could have been avoided but some of these choices, like the PVC glue, were sacrifices that had to be taken in order to have a feasible and functioning design.
Lastly, there are possibilities for improvement. First of all, not putting aluminium tape on the aluminium plate will drastically decrease the disassembly time and material usage, and better the C2C performance. Secondly, bending the copper pipe more accurately will in practice bring the results closer to the theoretical values, since the bitumen sheet reflection works optimally when the copper is right in the middle. With the copper tubes being even slightly off-centred, the focal point of the light rays will not hit the copper and the system will therefore miss out on potentially higher temperatures. Furthermore, with more resources, the design can be made more sustainable. For instance, putting reusable elastic bands around the storage vessel instead of foam foil would spare materials. This is again a good option with regard to C2C, but also for convenience. Having access to more different materials will allow more creativity when designing and make realization easier.

8 | References

[1] Aluminum Tape — AMERICAN ELEMENTS xAE; — americanelements.com. https://www.americanelements.com/aluminum-tape-7429-90-5. [Accessed 21-Jun-2023].

[2] Bitumen technology: crude moves and carbon savings for the industry — worldhighways.com. https://www.worldhighways.com/wh6/feature/bitumen-technology-crude-moves-and-carbon-savings-industry#. [Accessed 21-Jun-2023].

[3] CARBON FOOTPRINT OF ALUMINIUM - Alupro — alupro.org.uk. https://alupro.org.uk/sustainability/fact-sheets/carbon-footprint/. [Accessed 21-Jun-2023].

[4] Carbon footprint of polyethylene produced from CO2 and renewable H2 via MTO route - LUTPub — lutpub.lut.fi. https://lutpub.lut.fi/handle/10024/163642. [Accessed 21-Jun-2023].

[5] Duct Tape – A Preliminary Analysis — nicolemoes.com. https://nicolemoes.com/2017/04/03/week-11-duct-tape-a-preliminary-analysis/#. [Accessed 21-Jun-2023].

[6] How Much CO2 Is Saved When an Aluminum Automobile Frame Is Used Instead of a Steel One? — sustamize.com. https://www.sustamize.com/blog/how-much-co2-is-saved-when-an-aluminum-automobile-frame-is-used-instead-of-a-steel-one#. [Accessed 21-Jun-2023].

[7] Physical properties of glass — Saint Gobain Building Glass UK — saint-gobain-glass.co.uk. https://www.saint-gobain-glass.co.uk/en-gb/architects/physical-properties#. [Accessed 21-Jun-2023].

[8] Polystyrene - Wikipedia — en.wikipedia.org. https://en.wikipedia.org/wiki/Polystyrene#. [Accessed 21-Jun-2023].

[9] Sustainability - Adapa - adaptive moulds — adapamoulds.com. https://adapamoulds.com/sustainability/#. [Accessed 21-Jun-2023].

[10] The Paint Foundation — thepaintfoundation.com. https://thepaintfoundation.com/the-new-normal.php. [Accessed 21-Jun-2023].

[11] Understand your copper emissions — carbonchain.com. https://www.carbonchain.com/blog/understand-your-copper-emissions#. [Accessed 21-Jun-2023].

[12] Admin. What is the typical coverage of a 400ml Spray Paint Aerosol? — yourspraypaints.com. https://www.yourspraypaints.com/faq-items/what-is-the-typical-coverage-of-a-400ml-spray-paint-aerosol/#. [Accessed 21-Jun-2023].

[13] Jiahui An, Fan Wu, Dali Wang, and Jing You. Estimated material metabolism and life cycle greenhouse gas emission of major plastics in china: A commercial sector-scale perspective. *Resources, Conservation and Recycling*, 180:106161, 2022.

[14] Copper Development Association. Recycling of Copper — copper.org. https://www.copper.org/environment/lifecycle/ukrecyc.html, 2022. [Accessed 07-Jun-2023].

[15] Kortpack BV. You can order foam foil on a roll of 125 cm wide, 2 mm thick here — Directly available — kortpack.nl. https://www.kortpack.nl/en/moving-materials/protective-films/foam-wrap-125cm-x-250m-2mm-thick-1-roll. [Accessed 21-Jun-2023].

[16] Centexbel. Recycling process for bituminous waste products — Centexbel - VKC — centexbel.be. https://www.centexbel.be/en/news/recycling-process-bituminous-waste-products, 17 August 2021. [Accessed 07-Jun-2023].

[17] Fluke Corperation. Fluke: Emissivity values of common materials. https://www.bergeng.com/mm5/downloads/fluke/Emissivity-Values-of-Common-Materials-Chart.pdf. [Accessed 07-Jun-2023].

[18] Katherine Gallagher. Is Tape Recyclable? — treehugger.com. https://www.treehugger.com/is-tape-recyclable-5083466#, June 4, 2021. [Accessed 07-Jun-2023].

[19] Simon Ievers and Wenxian Lin. Numerical simulation of three-dimensional flow dynamics in a hot water storage tank. *Applied Energy*, 86(12):2604–2614, 2009.

[20] Guardian Industries. Cradle to Cradle — guardianglass.com. https://www.guardianglass.com/eu/en/who-we-are/our-expertise-and-commitments/sustainability/cradle-to-cradle. [Accessed 07-Jun-2023].

[21] Intcorecycling. Is polyethylene foam recyclable -INTCO Recycling. https://www.intcorecycling.com/Do-You-Know-Whether-Polyethylene-Foam-Could-be-Recycled.html#. (Accessed on 06-14-2023).

[22] Ali Jamali. *Unconsolidated Oil Sands: Vertical Single Well SAGD Optimization*. PhD thesis, 05 2014.

[23] M. Liu, S. Zhu, and W. Li. Co2 emission of building glass production. *Energy Education Science and Technology Part A: Energy Science and Research*, 32:1203–1212, 03 2014.

[24] United Nations. The Paris Agreement — UNFCCC. https://unfccc.int/process-and-meetings/the-paris-agreement. (Accessed on 06-14-2023).

[25] OEPEA. Onze Positie — epea.com. https://epea.com/nl/over-ons/onze-positie, 2020. [Accessed 07-Jun-2023].

[26] Thermoworks. Infrared Emissivity Table — thermoworks.com. https://www.thermoworks.com/emissivity-table/. [Accessed 07-Jun-2023].

A | Appendix - Conceptual Designs

A.1 | Conceptual designs

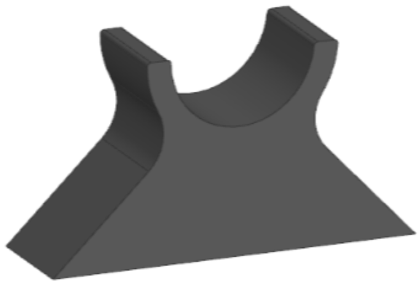


Figure A.1: 3D-printed stand

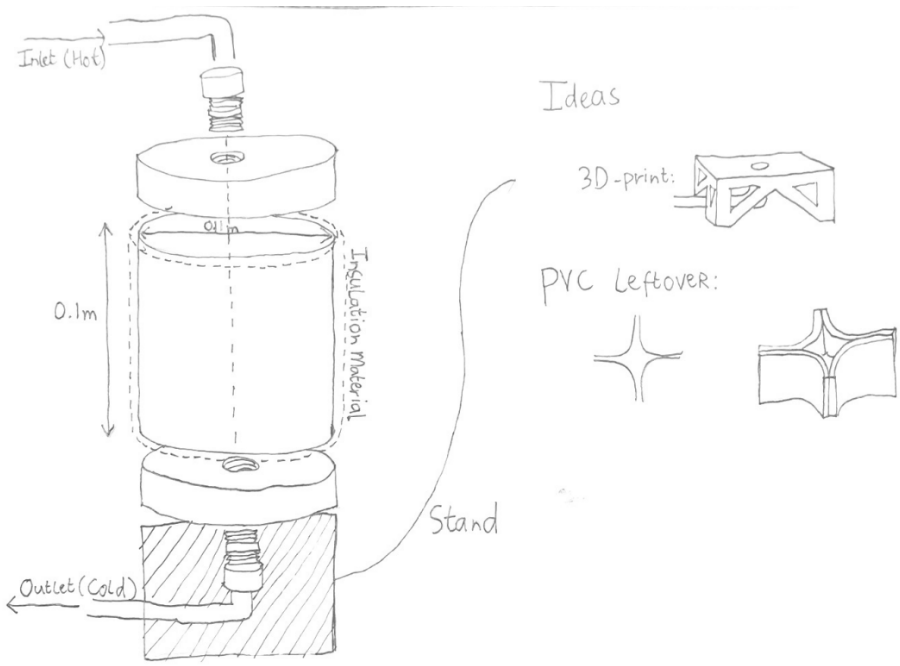
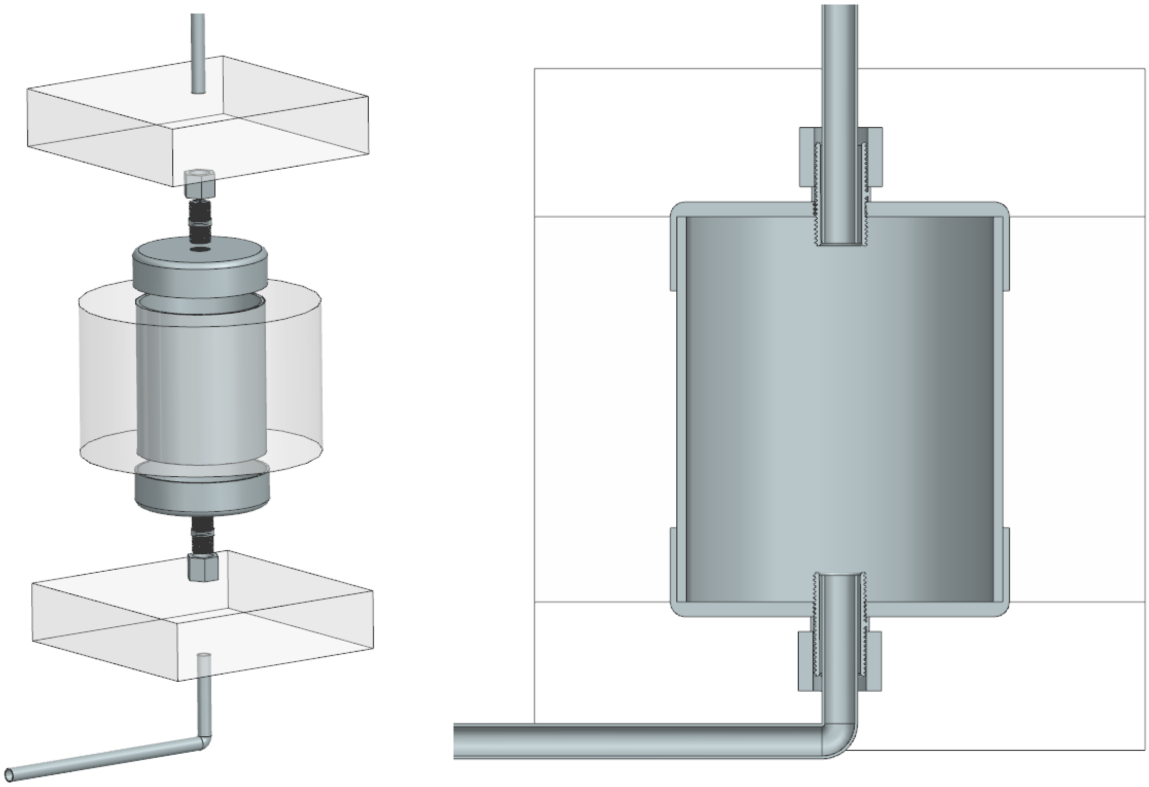


Figure A.2: Initial Heat Storage Vessel Sketch

B | Appendix - Detailing Final Design

B.1 | Detailed Pictures of the Final Design



(a) Exploded picture (b) Side profile

Figure B.1: Storage vessel

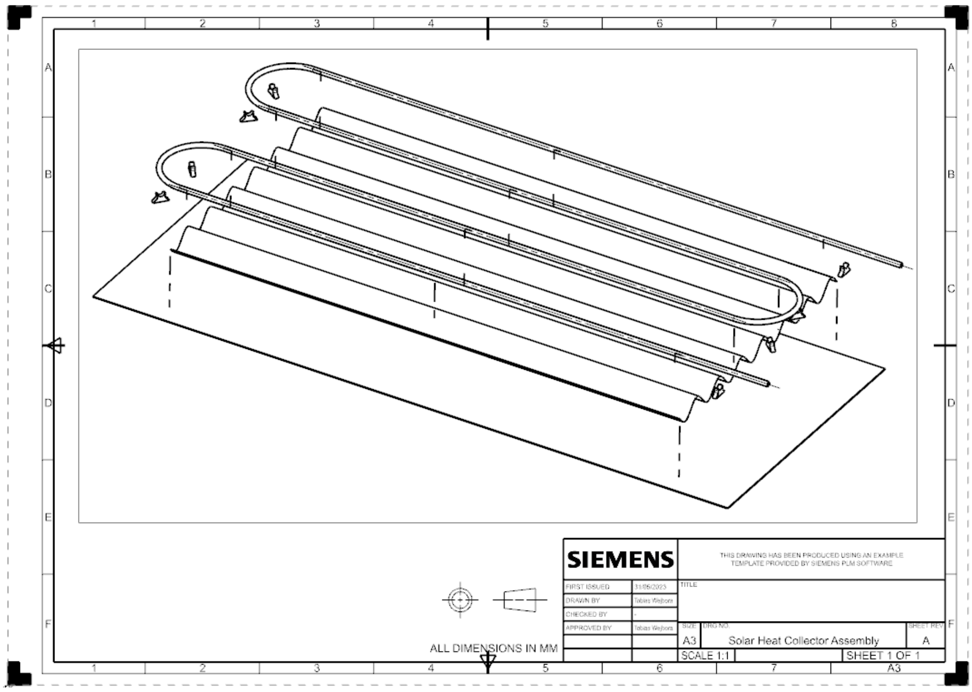
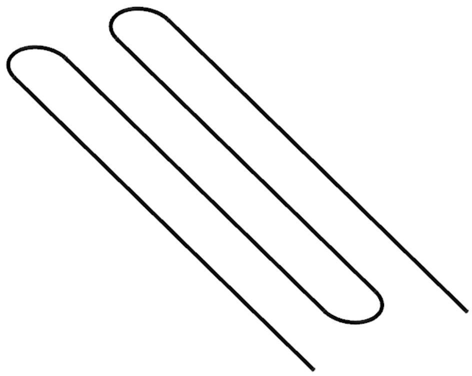
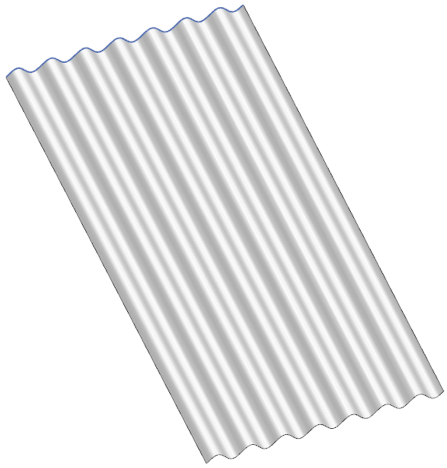


Figure B.2: Exploded picture of the solar collector



(a) CAD of copper piping



(b) CAD of Bitumen corrugated sheet

C | Appendix - Realization

C.1 | Building Preparation

The preparation before the building is divided into two parts; the solar collector preparations and the storage vessel preparations.

- Solar collector preparations
  - The copper will be bent into the desired shape using the bitumen sheet as a reference.
  - The corrugated sheet itself will be cut in the correct dimensions.
  - The 3D-printed stands will be broken apart, leaving 8 identical pieces to place underneath the copper pipe.
  - The copper pipe will be hammered flat to a certain extent, to increase the surface area.
- Storage vessel preparations
  - The Polyethylene foam foil will be cut into 7 strips of 13 cm in height, leaving some leftover material.
  - The Tempex Polyurethane plates will be cut into two pieces of .. by .. cm, leaving quite some leftover material.
  - A hole will be made in the Tempex Polyurethane plate for the in and outlet to fit in.

C.2 | Assembly Sequence

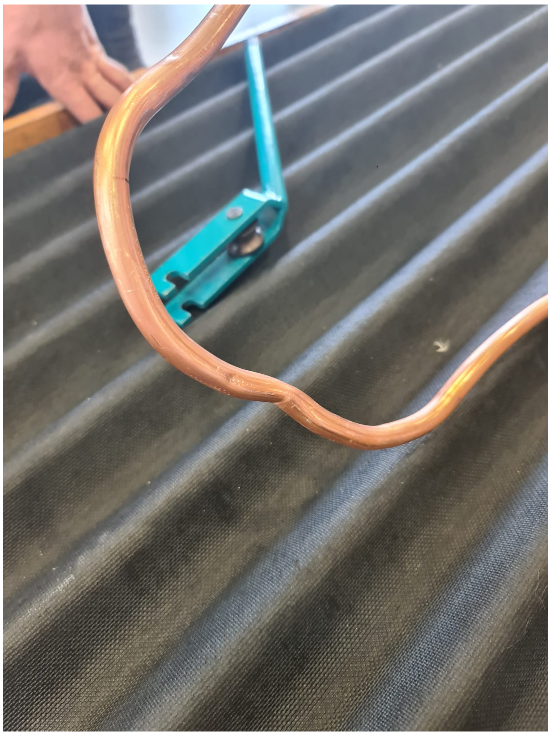
After the preparations, the design can be assembled.

- Solar collector assembly
  - The aluminium tape will be placed on the table surface
  - The bitumen sheet will be put on top of the aluminium tape
  - The copper pipe will be placed on the bitumen sheet, on top of the 3D-printed stands.
  - The in and outlet of the solar collector will be attached to the blue tubes using compression fittings.
- Storage vessel assembly
  - The PVC end caps will be glued onto the PVC pipe to prevent water leakage.
  - The first layer of foam foil will be taped to the vessel to prevent it from falling off.
  - The rest of the foam foil will be winded up.
  - The Tempex plates will be placed on top and on the bottom
  - The in and outlet of the solar collector will be attached to the blue tubes using compression fittings.

After the assembly, leftover isolation materials can be and will be used to insulate the parts of the system that would be major heat loss places otherwise, like the blue tubes and the in and outlet copper pipes of the storage vessel. Finally, the glass pane will be placed on top of the solar collector.

C.2.1 | Disassembling

The disassembling of the system was very similar to the assembling, with a few key considerations. Before initiating the disassembly, it was important to ensure that all the water had been completely drained from the collector. Once confirmed, the blue tubes could be safely disconnected from the collector, causing each part to become loose and easily removable. Additionally, the insulation around the storage vessel could effortlessly be taken off if we only use a small amount of glue.



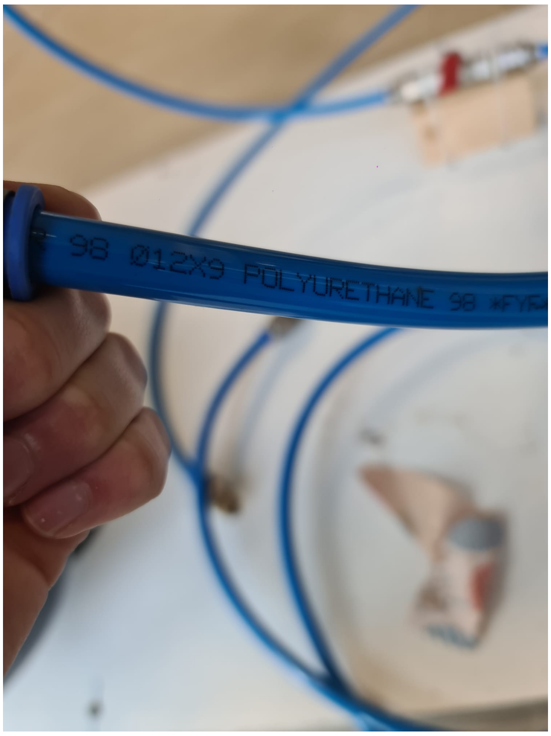
(a) Kink in pipe

(b) PVC pipe

(c) Storage vessel

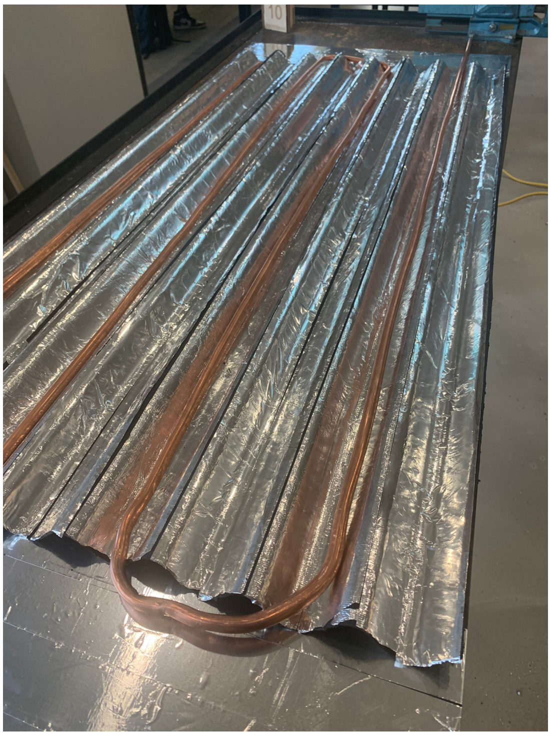
(d) Finished storage vessel without insulation

Figure C.1: Realization Phase Images



(a) Polyurethane pipe

(b) Bitumen sheet and pipe



(c) Finished solar collector

(d) Finished storage vessel

Figure C.2: Realization Phase Images Continued

C.3 | Solar Heating System Life-Cycle (LC) Carbon Emissions

C.3.1 | Calculation A

Bitumen corrugated sheet

- Dimensions: 200 cm x 86 cm x 0.3 cm = 5,160cm^3
- Mass = density x volume = 1.01 (g/cm^3) [22] x 5,160 = 5,211.6 g = 5.2116 kg
- Emission bitumen: 700 kg carbon / 1,000 kg bitumen [2]
- Carbon footprint: 3.65 kg CO_2

Aluminium tape

- Dimensions: 22.19 m x 50 mm x 0,18 mm = 0.00019971 m^3
- Mass = density x volume = 2700 (kg / m^3) [1] x 0.00019971 = 0.539 kg tape
- Emissions Aluminium: 7kg / kg [3]
- Carbon footprint: 3.773 kg CO_2

Glass cover

- Dimensions: 4 mm x 670 mm x 1720 mm = 4609.6 cm^3 = 0.0046096 m^3
- Mass = density x volume = 2500 (kg per m^3) [7] x 0.0046096 = 11.524 kg
- Emissions Glass: 3.08 kg / kg [23]
- Carbon footprint: 35.49 kg CO_2

Copper pipes

- Dimensions:
  - Length: 5.7 m
  - Outer diameter: 12 mm
  - Wall thickness: 1 mm
  - Inner diameter: 10 mm
- Area:
  - 1: Pir2 = 113,1 mm^2
  - 2: = 78,5 mm^2
  - Total: 34,6 mm^2 = 0,0000346 m^2
- Volume = area x length = 0.0000346 x 5.7 = 0.00019722 m^3
- Density = 8,830 (kg / m^3) x 0.00019722 = 1.74 kg
- Emissions Copper: 4.1 kg / 1 kg [11]
- Carbon footprint: 7.14 kg CO_2

Can of black paint

- Dimensions: 0.2 m^2 of copper painted
- Volume = coverage per ml x area covered = 1 m^2 / 200 ml [12] x 0.2 = 40 ml
- Emissions paint: 13.58 kg CO_2eq / 5 L paint [10]
- Carbon footprint: 0.543 kg CO_2

Polyethylene foam foil

- Dimensions: 1 m x 3 mm x 3 m = 0.009 m^3
- Density: 125 cm x 250 m x 2 mm = 13 kg 0.625 m^3 = 13 kg 1 m^3 = 20.8 kg [15]
- Mass = density x volume = 20.8 x 0.009 = 0.187 kg
- Emissions (high-density polyurethane): 3.11 kg / 1 kg [4]
- Carbon footprint = 0.58 kg CO_2 Straight screw on coupling (steel)
- Amount: 2
- Mass = 0.05 kg 0.1 kg for 2
- Emissions: 2.75 kg / 1 kg [6]
- Carbon footprint: 0.275 kg CO_2

PVC end caps

- Quantity: 2
- Outer diameter: 110 mm , Wall thickness 2.2 mm
- Total volume = 8,3629 mm^3
- Mass: 1,380 (kg / m^3) https://www.bpf.co.uk/plastipedia/polymers/PVC.aspx x 0.000083629 = 0.115 kg
- Emissions: 3.43 kg / 1 kg [13]
- Carbon footprint: 0.396 kg CO_2

PVC pipe

- Dimensions
  - Length: 0.13 m
  - Diameter: 110 mm
  - Wall thickness 3.2 mm
- Total volume: 139,577 mm^3
- Mass = 0.193 kg
- Carbon footprint: 0.661 kg CO_2

Tempex polystyrene plate

- Dimensions: 100 cm x 50 cm x 5 cm = 25.000 cm^3
- Mass: 20 (kg / m^3) [8]
- Emissions: 210 kg / m^3 [9]
- Carbon footprint: 5.25 kg CO_2

Duct tape

- Dimensions: 1 m x 50 mm x 0.5 mm = 0.000025 m^3
- Emissions: 1.75 kg / roll of 0.00004366 m^3 [5]
- Carbon footprint: 1.05 kg CO_2

Total: 58.81 kg CO_2

C.3.2 | Calculation B

To calculate the energy required to heat 1 litre of water from room temperature to 50 degrees Celsius, we multiply the mass by the Specific Heat Capacity and the Temperature Difference, which results in approximately 125.4 kilojoules (kJ) of energy being needed to heat 1 litre of water from room temperature to 50 degrees Celsius. The calorific value of methane, which is the primary component of natural gas, is typically around 55 megajoules per cubic meter (MJ/m^3). To determine the volume of methane gas (in cubic meters, m^3) required to produce 125.4 kilojoules (kJ) of energy, we can use the following calculation: Volume of methane gas (m^3) = Energy (kJ) / Calorific value (kJ/m^3). Through this equation, we see that approximately 0.0023 cubic meters (or 2.3 litres) of methane gas would be needed to produce 125.4 kilojoules of energy.

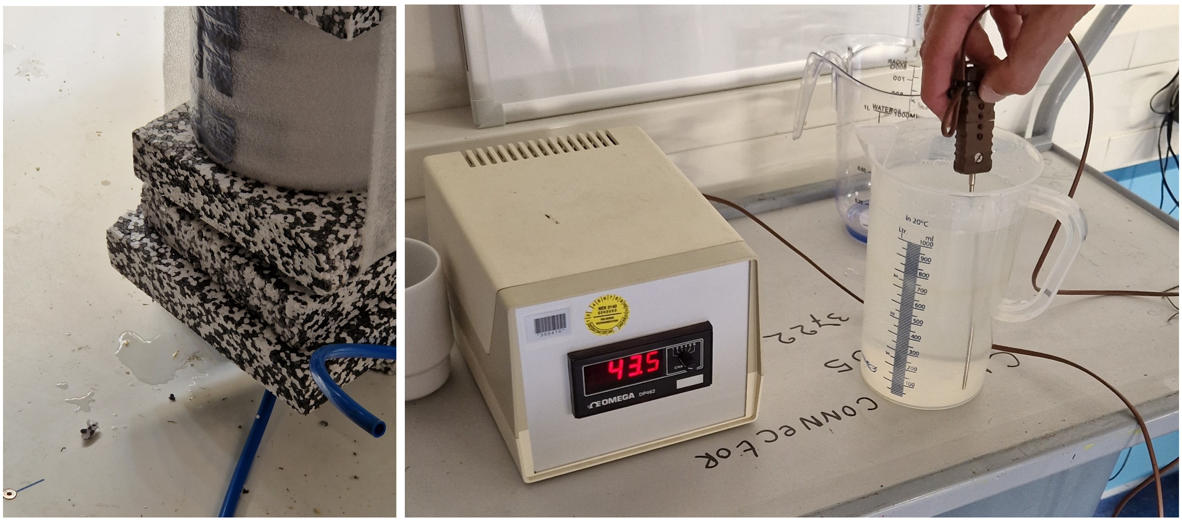
C.3.3 | Calculation C

To determine the CO_2eq emissions emitted by combusting 0.0023 cubic meters of methane we need to consider the carbon content of methane and its combustion process. The carbon content in methane is one carbon atom (C) per molecule. The chemical equation for the combustion of methane is: $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. To calculate the CO_2eq emissions, we need to convert the volume of methane to mass using its density at standard temperature and pressure (STP). Assuming a density of 0.6685 kg/m^3, we can calculate the mass of methane to be 0.00154 kilograms. Next, we can calculate the amount of CO_2eq emissions produced by using the following formula: CO_2eq emissions = Mass of methane (kg) * (Molecular weight of CO_2 / Molecular weight of CH4). This gives us CO_2eq emissions 0.00425 kilograms. Therefore, combusting 0.0023 cubic meters of methane to produce energy for heating 1L of water from room temperature to 50 degrees would emit approximately 4.25 grams of CO_2eq emissions. We assume this is also the resulting emission quantity of a gas boiler. Here we do not account for its production carbon emissions, because we assume that all houses still have a gas boiler.

C.3.4 | Calculation D

From the calculated numbers, we derive the total amount of water that needs to be heated by the (newly installed) solar collector before its emission-free heating compensates for its LC emissions: 58.81 kg / 0.00425 = 13837.6 litres of water. This equals around 275 hot showers.
In theory, the C2C score of the Material List could have been improved by using other materials, like **Still have to check/write this** Acrylate transparent tube Polyurethane tube Plywood Gaffer tape Double-sided adhesive tape

D | Appendix - Testing and Evaluation



(a) Leakage (b) Final result

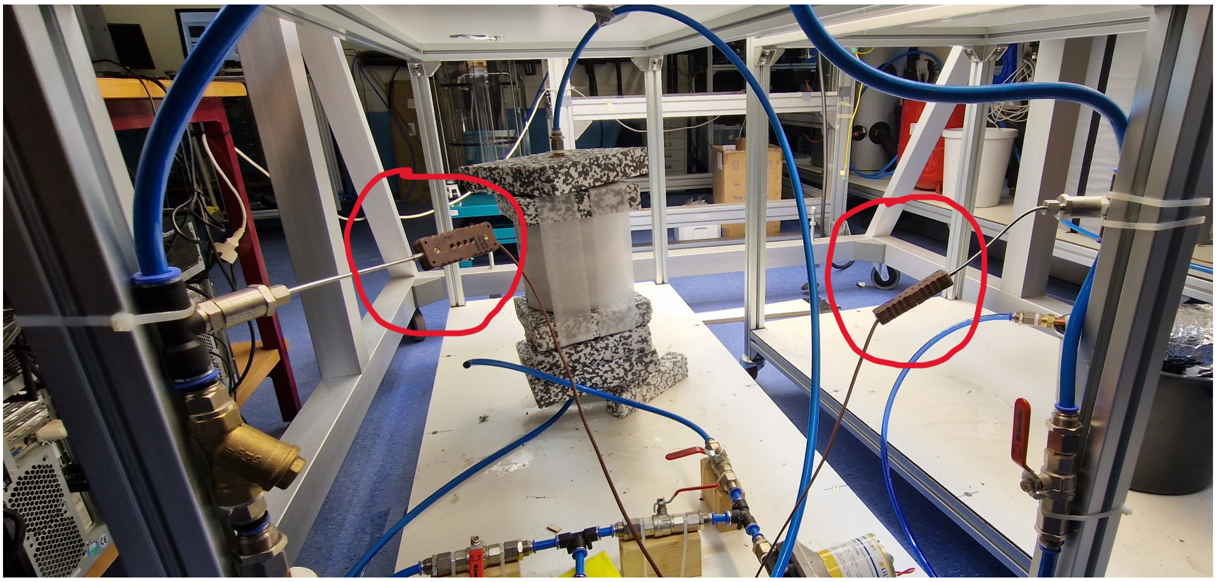
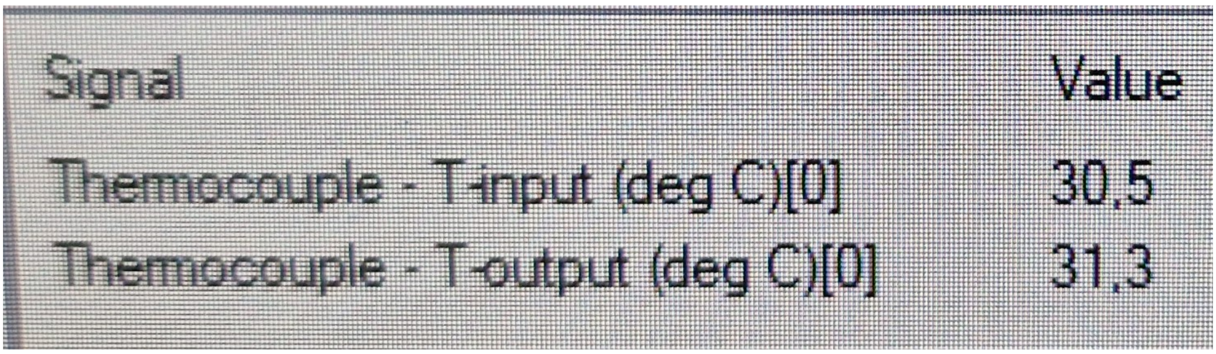


Figure D.2: Temperature sensors



Signal	Value
Themocouple - T-input (deg C)[0]	30,5
Themocouple - T-output (deg C)[0]	31,3

Figure D.3: Example temperatures

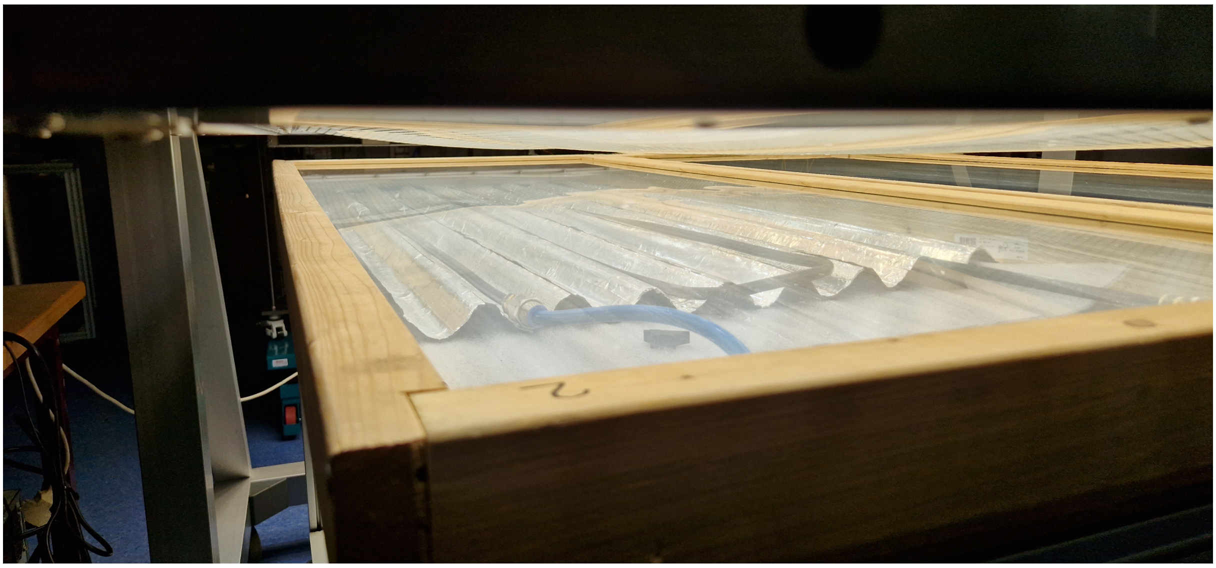


Figure D.4: Artificial light

E | Appendix - Matlab Numerical Model

E.1 | Relevant Equations

Required heat

$$Q = mc_p \Delta T \tag{E.1}$$

Efficiency

$$\mu = \frac{q_{sun}}{Q_W} \cdot 100 \tag{E.2}$$

Thermal resistance

$$\frac{dQ}{dt} = \frac{\Delta T}{R} \tag{E.3}$$

Radiation absorbed

$$\frac{dQ}{dt} = eAScos(\theta) \tag{E.4}$$

Conduction through straight media

$$R_{cond} = \frac{dx}{kA} \tag{E.5}$$

Conduction through radial media;

$$R_{cond} = \frac{ln(\frac{D_{outer}}{D_{inner}})}{2\pi Lk} \tag{E.6}$$

Convection

$$R_{conv} = \frac{1}{hA} \tag{E.7}$$

Heat transfer coefficient upper surface glass cover

$$h = 1.32 \cdot (\frac{p(T_{air} - T_{glass})}{4A})^{0.25} \tag{E.8}$$

Heat transfer coefficient inside pipes

$$h = \frac{Nuk}{D} \tag{E.9}$$

Nusselt number according to empirical correlations

$$Nu_D = \frac{(f/8)\,(\mathrm{Re}_D - 1000)\,\mathrm{Pr}}{1 + 12.7(f/8)^{1/2}\left(\mathrm{Pr}^{2/3} - 1\right)} \tag{E.10}$$

Darcy friction factor

$$f = (0.79 \ln(\mathrm{Re}_D) - 1.64)^{-2} \tag{E.11}$$

Reynolds number

$$Re = \frac{\rho v D}{\mu} \tag{E.12}$$

Prandtl number

$$Pr = \frac{c_p \mu}{k} \tag{E.13}$$

Hazen-Williams equation

$$S = \frac{h_f}{L} = \frac{10.67\ Q^{1.852}}{C^{1.852}\ d^{4.8704}} \tag{E.14}$$

Flow rate

$$\phi = Av \tag{E.15}$$

Mass flow

$$\dot{m} = \rho \phi \tag{E.16}$$

E.2 | Constant.m script

```
%%%Material Properties
%C=specific heat in J/kg.K
%k=thermal conductivity coefficient in W/mK
%P=density in kg/m^3
%E = emissivity

Cair = 1005; %J/kg.K
kair = 0.0263; %W/m.K
Pair = 1.161; %kg/m^3
Eair = 0.8;

Cwater = 4184; %J/kg.K
kwater = 0.609; %W/m.K
Pwater = 997; %kg/m^3
Ewater = 0.96;
fw = 1.0*10^-3; %Dynamic viscocity
Re = 6437; %Reynolds number

Ccopper = 385; %J/kg.K
kcopper = 400; %W/m.K
Pcopper = 8960; %kg/m^3
Ecopper = 0.93;

kpvc = 0.19; %W/m.K
kpoly = 0.04; %W/m.K
kglass = 0.96; %W/m.K
ktempex = 0.030; %W/m.K
kwood = 0.12; %W/m.K
ktrespa = 0.30; %W/m.K
kblue = 0.13;

%%% Additional constants
sb = 5.6703*10^-8; %Stefan-Boltzmann constant (W/m^2.K^4)
qsun = 1000; %Heat flux of artificial sun (W/m^2)

%%% Dimensions in m
D1copper = 19.8*10^-3; %inner diameter copper tubing
D2copper = 22*10^-3; %outer diameter copper tubing
D1pvc = 10.36*10^-2; %inner diameter pvc tube
D2pvc = 11*10^-2; %outer diameter pvc tube
D1ins = 11*10^-2; %inner diameter foam foil
D2ins = 15.8*10^-2; %outer diameter foam foil
D2blue = 12*10^-3; %outer diameter blue flexible tubing
D1blue = 9*10^-3; %inner diameter blue flexible tubing
Dtempex = 5*10^-2; %thickness tempex polystyrene insulation
tglass = 4*10^-3; %thickness glass
twood = 50*10^-3; %thickness of Pinewood at the sides
ttrespa = 6*10^-3; %thickness of the trespa at the bottom
hvessel = 13*10^-2; %height storage vessel
Lcopper = 2.743; %length of copper tubing inside the collector
hcover = 0.067; %height of space with glass cover
hempt = 0.171; %height without glass cover
Lcoptank = 0.2; %length of copper tubing outside storage vessel
Lblue = 6.15;

%%% Starting temperatures
```

```
Twater = 293.15; %Temperature water, Kelvin
Tcopper = 293.15; %Temperature copper, Kelvin
Twatervessel = 293.15; %Temperature water in storage vessel, Kelvin
Tair = 293.15; %Temperature air underneath glass, Kelvin
Tout = 293.15; %Temperature ambient outside vessel, Kelvin, constant
Tsolar = 333.15; %Temperature surface artificial sun, Kelvin, constant

%%% Area's in m^2
Acout = pi*D2copper*Lcopper; %outer surface area copper piping system
Acin = pi*D1copper*Lcopper; %inner surface area copper piping system
Atot = 0.67 * 1.72; %Total area that is subjected to radiation
Accros = (pi/4)*D2copper^2; %cross-sectional area copper tubes
Atvessel = (pi/4)*D2pvc^2; %surface area top and bottom vessel
Ablue = (pi/4)*D1blue^2;
Ahit = pi*D2copper*Lcopper; %Area of light that hits outer surface
    copper
Awood = 0.67*hcover+1.72*hcover; %Inner surface area pinewood
pglass = 2*0.67+2*1.72; %Perimeter of the glass
pvessel = pi * D2pvc; %Perimeter Vessel
%%% Volume's in m^3
Vwater = pi*(D1copper^2 / 4)*Lcopper; %Total amount of water in the
    collector
Vwatervessel = Atvessel*hvessel;
Vcopper = pi*(D2copper^2 / 4) * Lcopper - Vwater; % Volume copper
Vair = (hcover * Atot) - Vcopper - Vwater; % Volume air in collector
Vblue = Lblue*Ablue;
Aalu = 1.1095; %Area of aluminum
Ealu = 0.05; %Emissivity aluminum

%%% Additional computations
Lh = 4*Atot/pglass; % Used in the calculation for convection coefficient
Qpump = 0.1; %Flow rate of pump in l/min
mflow = Pwater * Qpump; %mass flow rate
Pr = (Cwater*fw) / kwater; %Prandtl number
f = (0.79*log(Re)-1.64)^-2; %Darcy friction factor
Nu = (f/8)*(Re-1000)*Pr / (1+12.7*(f/8)^(0.5)*(Pr^(2/3)-1)); %Nusselt
    number
houter = 1.32*(abs(Tsolar-Tair)/Lh)^0.25; %convection coefficient air
hinner = (Nu*kwater) / D1copper; %convection coefficient water


%%% Graphing arrays
times = [];
tempQin = [];
tempQout = [];
tempwv = []; % water vessel
efficiency = [];
```

E.3 | Numeric.m script

```
%%% Get all constants
constantsfinal

t = 1200; %total time duration
delta_t = 1; %time increment
%%% for loop
for time = 1:delta_t:t
    %%% Calculate all thermal resistances
    % Qin, Calculate thermal resistances between sun and water
    % Calculate thermal resistance convection air between sun and glass
    R1 = 1 / (houter * Atot);
    % Calculate thermal resistance conduction glass
    R2 = tglass / (kglass * Atot);
    % Calculate thermal resistance conduction air
    R3 = hcover / (kair * Atot);
    %Calculate thermal resistance conduction copper pipe
    R4 = log(D2copper/D1copper) / (2*pi*Lcopper * kcopper);
    %Calculate thermal resistance convection inside pipe
    R5 = 1 / (hinner * Acin);
    %Calculate total thermal resistance between sun and water
    Rin = R1 + R2 + R3 + R4 + R5;

    % Qout, Calculate thermal resistances between water and environment
    % Calculate resistance conduction copper pipe outside storage vessel
    R6 = log(D2copper / D1copper) / 2*pi*Lcoptank *kcopper;
    %  Calculate resistance conduction pvc of tank
    R7 = log(D2pvc / D1pvc) / 2*pi*hvessel *kpvc;
    % Calculate resistance polyethelyne foam foil around perimeter tank
    R8 = log(D2ins / D1ins) / 2*pi*hvessel*kpoly;
    % Calculate resistance Tempex polystyrene top and bottom tank
    R9 = 2*Dtempex / ktempex*(Atvessel-Accros);
    % Calulate resistance wooden walls
    R10 = 2*twood / kwood*Awood;
    % Calculate resistance trespa at the bottom
    R11 = ttrespa / ktrespa*Atot;
    %Calculate resistance blue flexible tubing
    R12 = log(D2blue/D1blue)/(2*pi*Lblue*kblue);
    % Calculate total thermal resistance between water and environment
    Rout = R6+R7+R8+R9+R10+R11+R12;

    %Calculate the amount of radiation the copper tubing absorbs
    Qabs = (0.75*(1-Ealu)*Aalu*Ecopper*Ahit + Ecopper*Ahit)*qsun;
    %Calculate Qin
    Qin= Qabs + (Tsolar - Twater) / Rin + (Tout-Twater)/(R10+R11);
    %Calculate Qout
    Qout = (Twater-Tout) / Rout;
    %Calculate dQw, the net heat flow to the water
    dQw = Qin-Qout;
    %Compute temperature increase over time increment dt
    dTw = dQw*delta_t/((Vwater+Vwatervessel+Vblue)*Pwater*Cwater);
    %Compute the new water temperature and append to array
    Twater = Twater + dTw;
    %Compute the efficiency of the system over time
    ef = (dQw*100)/(qsun*Atot);
    times(end+1) = time;
    tempwv(end+1) = Twater;
```

```
    tempQin(end+1) = Qin;
    tempQout(end+1) = Qout;
    efficiency(end+1) = ef;
end
%Graph Temperature of water in vessel over time
tiledlayout(2,2)
nexttile
plot(times, tempwv -273.15, '.');
title('Temperature of water in vessel over time');
xlabel('time [s]');
ylabel('Temperature [C]');
%Graph Qin over time
nexttile
plot(times, tempQin, '.');
title('Qin overtime');
xlabel('Time [ s ]');
ylabel('Q [ W ]');
%Graph Qout over time
nexttile
plot(times, tempQout, '.');
title('Qout overtime');
xlabel('Time [ s ]');
ylabel('Q [ W ]');
%Graph the efficiency of the system overtime
nexttile
plot(times, ef, '.');
title('Efficiency of the system')
xlabel('Time [s]');
ylabel('Efficiency [%]');
```

E.4 | Graphs numerical model

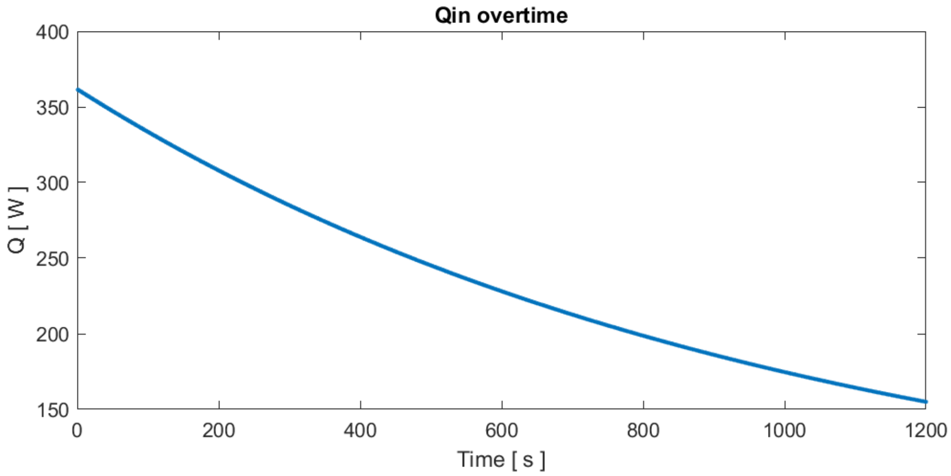


Figure E.1: Qin over time

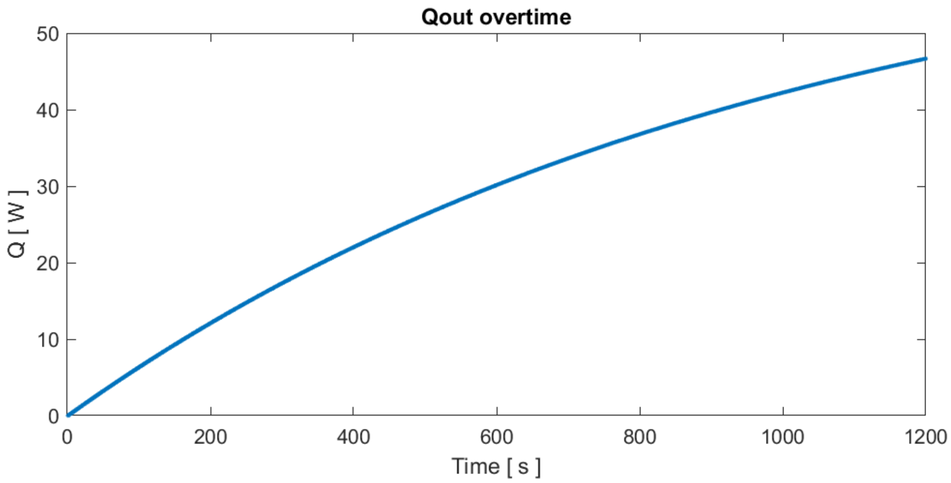


Figure E.2: Qout over time

E.5 | Reflection determination

Table E.1: Reflection measurements

Ray Density	Reflected rays by aluminium	Reflected rays towards the tube	%
-3	4	4	100%
-2.87	5	3	60%
-2.706	6	5	83.33%
-2.5785	7	6	85.7%
-2.4086	7	5	71.4%
-2.2812	9	6	66.6%
-2.1962	10	7	70%
-2.1113	11	9	81.8%
-2.0688	11	8	72.7%
-2.0263	12	9	75%
-1.9838	13	10	76.9%
-1.8139	14	11	78.57%
Total	**109**	**83**	**76.2%**