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<< **Eco-Energy Engineering** >>

Improvements and experimental assessment of a flat plate solar collector

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ABSTRACT

Motivation: Using renewable energy systems instead of fossil fuels and nuclear energy has become an important aspect in modern engineering. In accordance with this focus, the University of Portland designed a Capstone project centered on generating sustainable energy. Since 2015, senior Mechanical Engineering students have been doing research on the use of the Organic Rankine Cycle to convert solar energy to electrical energy. To improve the energy output of the system, it became essential to design the solar collector to work as efficiently as possible.

Results: It was determined that the solar cycle on the roof of Shiley Hall was functioning properly. Prior results indicated a maximum temperature difference of 12.7ºC in December. The efficiency ratio of the collectors has been improved to 40% in December by adjusting the angle to the given conditions. The collector now can be connected to a measurement system that collects temperature data permanently and stores it on a SD card that can be read manually.

1 INTRODUCTION

Solar energy is an unlimited form of energy that can be used with minimal pollution to the environment. Harnessing the energy of the sun could easily produce the global consumption of energy, given that it was used in a utilitarian fashion.

Sunlight can provide energy in different ways. It is the foundation of every energy source we use on Earth.

To make effective use of the sunlight, engineers have invented solar thermal panels that directly use thermal energy to heat water and other mediums. Furthermore, the heat that is transported and stored by these mediums can be utilized to heat a house or provide warm water. Another way to produce energy from sunlight is to employ the use of photovoltaic cells. These cells can generate electric energy simply by harnessing the light emissions from the sun.

There are many implications to using solar energy, one of which includes its lack of availability. If the sun is not shining, it is simply not possible to produce energy. In addition, it is difficult to store thermal energy for long periods of time because there are high losses associated with high temperatures.

The idea behind this project is to combine a hybrid solar collector with an Organic Rankine Cycle to store the power of the solar energy when it is available in huge loads. It converts the solar energy into electric energy, providing the highest quality of all different energy forms and has several applications. Another advantage of electric energy is its ability to be stored without any great loss.

The University of Portland is interested in this form of generating energy and started its initial capstone project in 2015.

The purpose of the project was to design and construct an Organic Rankine Cycle to generate power using the solar collectors on the green roof of Shiley Hall at the University of Portland.

2 SOLAR ORGANIC RANKINE CYCLE

The Organic Rankine Cycle (ORC) is a technology to generate electric power out of heat. It is named after the organic fluid which is used to run the cycle. The operating fluid and the connected lower temperatures to vaporize the fluid are the main differences to a usual Rankine Cycle, which uses water and steam for the process of converting heat to electric energy. Some examples for common fluids used in an Organic Rankine Cycle are ammonia, ethanol and some refrigerants like R134a.

Due to the low temperatures needed for vaporizing the fluid, the ORC is very interesting for renewable energy research fields like solar power, biomass or industrial waste heat usage.

2.1 History

The principal of the cycle can be attributed to William John Macquorn Rankine who published a manual about it in 1859. He was a Scottish mechanical engineer who lived in the 19th century. [1, p.4]

Another important person in the evolution of the ORC process was Thomas Howard who built the first running ORC in the year 1826. He used alcohol and ether as working fluids and ran an engine designed for 24hp for a brief period of time. [2, p.119]

The evolution of ORC systems stagnated after fossil fuels became popular because they could supply higher temperature levels. Therefore, mostly Rankine Cycles with water and steam were used due to the higher effectiveness and less strict safety requirements.

In modern times, where renewable energy systems are becoming more popular all over the world, Organic Rankine Cycles are gaining engineers' interest again. This is due to the low temperature levels that can be provided by renewable energy sources, such as solar energy or the heat of biomass and waste heat of industrial processes.

2.2 Function principle

An Organic Rankine Cycle (ORC) works like a conventional steam Rankine Cycle, but uses a working fluid that is not water.

The organic medium is pressurized and flows through a heat exchanger where it is vaporized by the higher temperature from the heat source. Next, the hot, pressurized vapor releases its energy by streaming through a turbine that generates electrical power. After that, the vapor condenses in another heat exchanger and the process starts from the beginning. [1, p.1]

The problem with a conventional steam Rankine Cycle is that water is used as the thermal medium, which has disadvantages when compared with organic materials.

For example, water has a high amount of latent heat, so high temperature and pressure is needed to vaporize water. These high temperature levels are commonly supplied by nuclear power or fossil fuels.

Another disadvantage is that the turbine blades and other components must be built robustly due to the high temperature and velocities compared to the Organic Rankine Cycle. It is also important to design the system in a way that no condensation occurs during the stream phase in the turbine to protect the turbine blades from erosion.

2.3 Designed system

Due to sealing problems and other design criteria like the mobility and the safety for future lab appliance, the team decided to redesign the whole Organic Rankine Cycle, except for the solar collectors. Figure 1 shows a schematic drawing of the entire system.

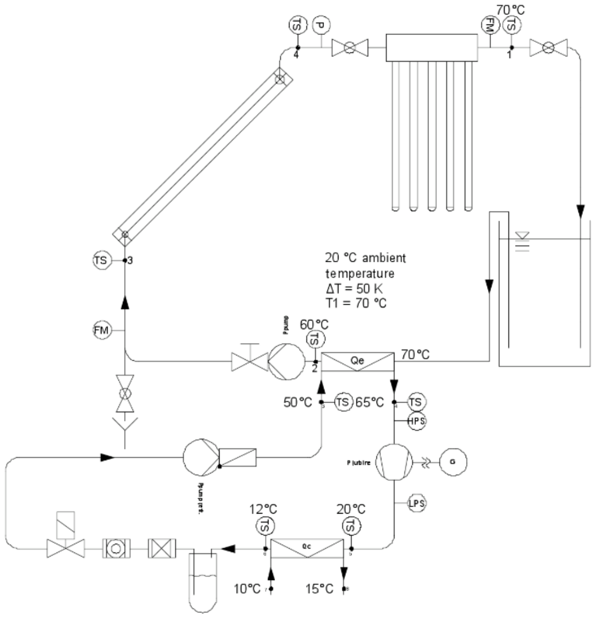

Figure 1. Schematic drawing of designed ORC [3, p.1].

On one side, the schematic drawing shows the order in which the components of the refrigerant cycle are to be assembled and under which temperatures they will operate.

The refrigerant cycle, with all its components, is designed for the refrigerant R134a. R134a is also known as 1,1,1,2-Tetrafluoroethane and is a high-temperature refrigerant which is also used for domestic refrigeration and automobile air conditioners.

The medium was chosen due to its thermophysical properties and its easy availability. Another significant advantage of R134a is its low global warming potential (1430) [12] in comparison to other comparable refrigerants.

The other side of the drawing depicts the existing hot water system on the roof. It shows the flat plate solar collector and the evacuated tubes in the top part of the figure. The water running through the cycle is stored in a 15 gallon (57 l) plastic tank, which is shown on the right side of the schematic. It can be refilled with a tap on the roof. Due to simpler construction and the possibility of easy modification, the system was designed to run as an open system by the Senior Design Team 2015. The same reasons also led to the decision of using water as operating fluid. To prevent damages through freezing water in the pipes, the solar cycle has to be emptied and shut down during winter.

Pictures and more detailed descriptions of the current solar cycle can be found in chapter 3.3.

3 SOLAR COLLECTOR

The solar collector is the heat source of the entire system and should provide the cycle with the amount of heat needed to vaporize the medium in the refrigerant cycle.

In the following chapters, different types of solar collectors will be described and at the end, the systems will be compared in a table. Each collector will have a small section where their properties will be described according to the climate of Portland.

3.1 Flat plate Solar collector

The flat plate solar collector is the most common form of solar collectors. One of the main reasons for this is the easy concept of the design which is shown in the following figure and described in chapter 3.1.1.

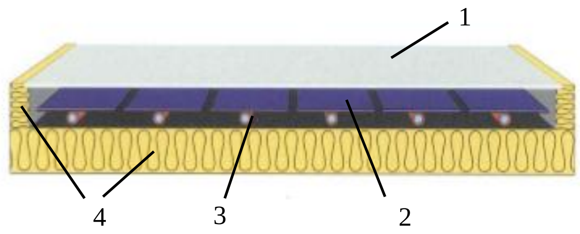

Figure 2. Schematic of a typical flat plate solar collector [13, p10].

3.1.1 *Design and material*

The purpose of the *transparent cover panel* (1) is to let through as much light radiation as possible. Good cover panels let through about 95% of the radiation [13]. The short-waved light radiation passes through the transparent layer and is absorbed by the absorber plate. The long-waved heating radiation cannot escape through the cover panel and so the heat is trapped inside the collector. In the next layer is the *absorber plate* (2). Its main function is to absorb the highest amount of potential heat and transmit it with high efficiency to the *absorbing tubes* (3). Reaching high temperature levels entails higher thermal losses, which should be minimized by the *insulation* (4) of the collector panel.

Due to its frequent use, the materials of flat plate solar collectors must be highly resistant to seasonal temperature extremes. Therefore, it is common to use a water anti-freeze emulsion to prevent the working fluid from freezing. For the other described parts of the construction, it is possible to use a wide range of materials. The most common material for the housing is aluminum, even if there are, for example, collectors made out of wood or even plastic [13].

3.1.2 *Stagnation*

Conventional flat plate collectors generate temperatures of about 100-150°C [13]. If the closed circuit of the heating medium stops because the buffer tank is already at its maximum temperature, the collector cannot drain the absorbed heat of the collector field. The consequence is a stagnation of the system because the water emulsion vaporizes in the overheated collectors. The whole cycle cannot proceed until the collector cools itself down and the heating medium becomes liquid again.

Therefore, it is important to have an extension vessel that can take the volume of the expanding hot fluid and gas for as long as the emulsion needs to cool down and condense again [13].

3.1.3 *Efficiency*

Flat plate solar collectors usually have an efficiency ratio of about 80% [13]. This means that they have an energy output of approximately 700W/m^2 when we assume a clear summer day like the 21st of July 2017. The following figure shows the solar radiation and the ambient temperature over daytime.

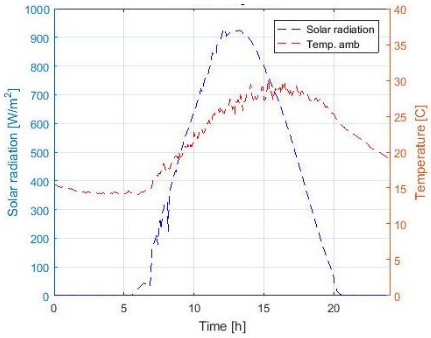

Figure 3. MATLAB Plot of solar radiation and temperature over time.

The figure shows data from Dr. Eckmann's weather station [9] which was computed with MATLAB (described in detail in chapter *4.3 MATLAB)*

The plot shows a slight stagnation in radiation and temperature between 7 and 8. This may have been caused by a cloud covering the sun for a short time. In addition to this, a little delay of the temperature to the solar radiation can clearly be seen. This is due to the time that the surfaces need to be heated up by the sunlight.

The efficiency of flat plate collectors is strongly depended on the angle of the incoming radiation. The ideal angle would be 90 degrees. The lower the angle is, the more the radiation is reflected from the transparent panel and the absorber. Therefore, the efficiency can be increased by adjusting the angle to different periods of the year. During summer, when the sun is high, it would be better to have them adjusted flat. During winter, when the sun is low, it is better to have them adjusted steep.

3.1.4 *Advantages and disadvantages in Portland Climate*

- The plot also shows a high amount of direct solar radiation during summer times in the Portland area. This is a big advantage for using flat plate solar collectors because they perform well under these conditions.
- A disadvantage of using flat plate collectors in Portland is their poor performance for diffuse radiation. On average, the winter season in Portland counts 17 official sunny days [14].

3.2 Evacuated tubes

Evacuated tubes work similarly to flat plate solar collectors. The sunlight enters the collectors through the transparent cover and heats the absorber. The absorber transfers the heat with high efficiency to the working fluid. Even if it is the same principle to generate heat, there are two different designs for evacuated tubes. They will be described in the following chapters.

3.2.1 *Design*

The first design described is the **direct flow design**. This design works like a flat plate collector. The fluid runs through the absorber tube and is heated by the radiation of the sun. Figure 4 shows the typical U-shape of the absorber tube in the evacuated tube.

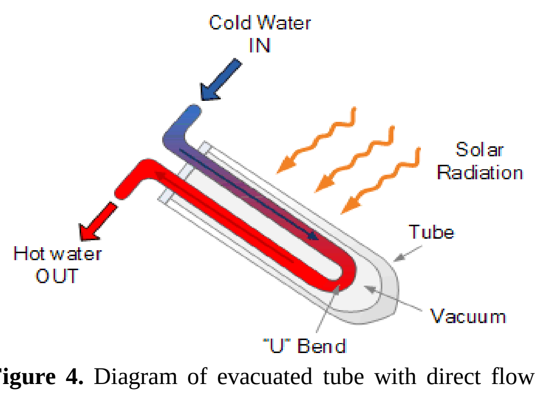

Figure 4. Diagram of evacuated tube with direct flow design [15].

The second common design is the **heat pipe design**. A special feature of this design is that the heated fluid is separated in the heat pipe. It transmits the heat to the working fluid of the cycle in an extra heat exchanger. Figure 5 will help to understand how the design works.

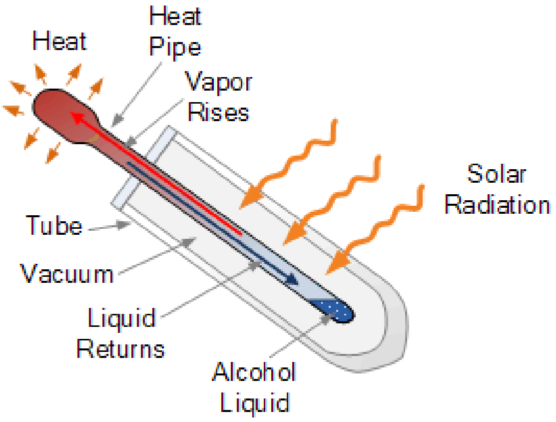

Figure 5. Diagram of evacuated tube with heat pipe design [15].

The liquid heats and vaporizes due to the low pressure in the tubes. The hot vapor rises to the heat bulb and transmits the heat to the actual working fluid of the solar cycle. For proper function of the system, it is recommended to have the tubes at a minimum tilt of 30° [15]. This design allows the user to change tubes in an easier manner than with the direct flow design. In case of a broken glass cover, the whole tube can be removed and replaced with a new one without affecting the other tubes.
Another common design of evacuated tubes is the **Compound Parabolic Concentrator** (CPC) design. Here, parabolic mirrors are placed under the tubes to get even more solar radiation to the absorber tube.

3.2.2 *Efficiency*
When it comes to the efficiency of evacuated tubes, a diagram, which compares these to other collector types, can help to understand the issue. The diagram in Figure 6 shows how flat plate collectors and evacuated tubes are connected in terms of efficiency and temperatures ranges.

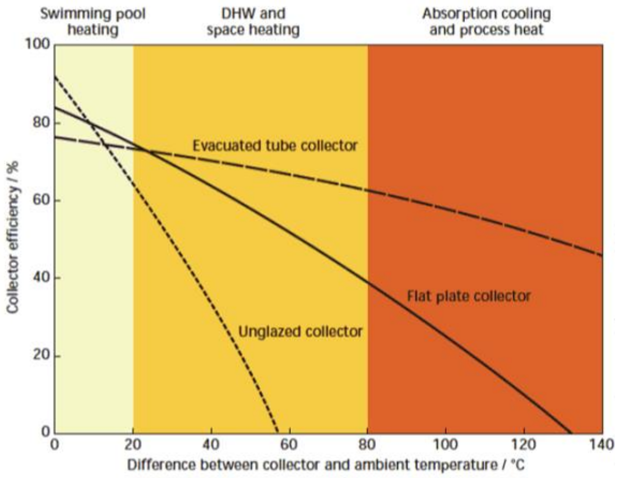

Figure 6. Efficiency diagram solar collectors [16].

As shown in the diagram, the efficiency of the evacuated tubes starts lower than the efficiency of the flat plate collectors, but stays on a high level when it comes to high temperatures.
The advantages it brings to combine different collector types are described in Chapter 3.3 Hybrid collectors.

3.2.3 *Advantages and disadvantages in Portland Climate*

- Due to the round design, the tubes can collect more sunlight throughout the day. The adjustment to the angle of the sun is not as important as it is for flat plate solar collectors.
- Evacuated tubes have a great performance with diffuse radiation and cold weather, which is the case in winter times in the Portland area.

3.3 Hybrid collector & Current system

"The current solar collector was designed to optimize the system for the Portland area, while facilitating a longer-term goal of energy generation with a small Rankine cycle. The design team examined parabolic trough, flat plate collectors, and evacuated tube collectors. The collector concepts were evaluated for maintenance, tracking systems, location, and solar radiation availability." [4]
The former senior design project team aimed to build a system that is easy to handle and modify for research purposes. The team built all components of the system on their own. The only major parts that were purchased were the evacuated tubes. For assembling the entire system, the technical advisors of the faculty were happy to help.
"To increase the efficiency of the individual flat plate and evacuated tube solar collectors for this system, the two designs were combined into one small hybrid prototype collector utilizing both forms of solar energy collection." [4]

The following section shows a picture of the hybrid collector describes the old system.

Figure7. Hybrid solar collector on green roof [4].

The old system had a total aperture area of 2.8m^2 (1.2m^2 flat plate and 1.6 m^2 evacuated tubes) [4]. The system worked well but had some issues, and due to freezing pipes in the winter time it had to be dissembled, repaired, and rebuilt.
Now, the system exists out of a flat plate solar collector, which is in a series with the evacuated tubes. These are now located differently and attached to a metal construction that will not have problems with erosion. The aperture area of the collectors is still the same.

Figure 8. Flat plate solar collector on green roof.

The first figure shows the self-manufactured flat plate collector on the green roof. It consists of a copper pipe which is attached on a black absorber plate. The housing of the collector is made of aluminum and the construction of painted steel, so no corrosion will occur.

Figure 9. Evacuated tubes on green roof.

The figure above shows the relocated evacuated tubes on the construction of aluminum. As read in Chapter 3.2, the angle for heat pipe evacuated tubes should be at least 30 degrees, which could not be realized in the current setting.
The main properties, advantages and disadvantages of different types of solar collectors will be summarized in Table 1.

Table 1. Displays properties of different collectors.

Type of collector	Temp. range	Efficiency	Advantages	Disadvantages
Flat plate	Aound 100°C	>80% for direct radiation	Good performance for direct radiation, Cheap, Easy to build or modify	Bad performance for diffuse radiation
Evacuated tubes	>150°C possible	<80% for direct radiation but stays high	Lighter, Adjustment is not that importat, Better insulation, Higher temperatures possibler	Expensive, Fragile glass cover
Hybrid	Around 100°C	Depends	Combines advantages	complexer system, expensive

4 MEASUREMENT SYSTEM

To improve a solar system, it is largely important to collect as much data as possible. Due to strict regulations for roof access, the collection of the data was a big challenge at the beginning of the semester. To get work done on the roof it was necessary to make regular appointments with the technical advisors of the faculty. Another big issue of the former measurement system was that it was not possible to collect data permanently. The former measurement system required the manual connection and operation of a laptop for reading the thermocouples of the solar collectors and the pyranometer. To work around this issue, the system was modified to store data using a standard SD card that could be read offline. The current data collecting system consists of:

- **Four type K Thermocouples** which are placed in key locations as shown in Figure 1 modified.
- The **data acquisition box** (DAQ) which was programmed with **Arduino**.
- **SD card** which is placed in the DAQ box (see Figure 13) and can be read with a laptop.

The listed components will be described in detail in the following sections. In addition to this the program MATLAB which was used to compute the data will be described.

4.1 Thermocouples

For measuring the temperature of the water in the cycle, type K thermocouples (Figure 10) were used. They were placed in key locations by the senior design team 2016. As seen in Figure 11, they measure the in - and outlet temperature of the flat plate solar collector, the outlet temperature of the evacuated tubes and the ambient temperature right under the flat plate solar collector. They are connected to the DAQ box and send their information in voltage to the processing Arduino hardware. The software converts the signal into for human readable temperature data in degrees Celsius.

Figure 10. Type K thermocouple used for ambient temperature measurement

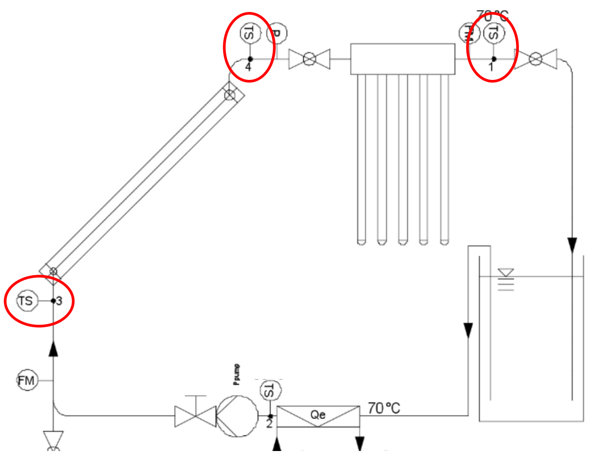

Figure 11. Modified schematic drawing of solar cycle with thermocouples [3].

4.2 Data acquisition box

The data acquisition box was originally built by students from George Fox University to collect pressure and temperature data from turbines or other technical components. As seen in Figure 12, it has a small display which shows the current data. It can be switched to the next screen by pressing the metal button in the middle of the box. The box has several sensors and a cable with power adapters for power supply. The data collection starts as soon as the black start switch is turned on. The hardware can be programmed with the Arduino software which will be explained in the *4.2.1 Arduino* section. For further information also see Appendix A which contains the electric schematic of the box.

Figure 12. Picture of DAQ box closed.

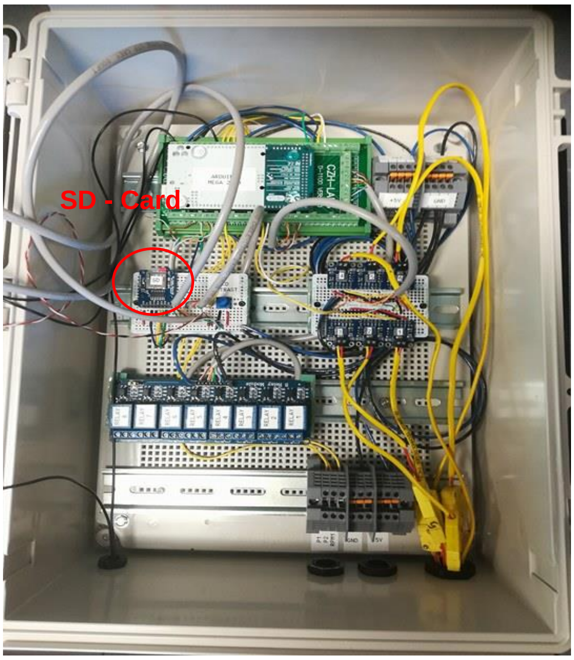

Figure 13. Picture of DAQ box inside.

Due to the high value of the box and its components, it was carefully wrapped up in two layers of plastic to guarantee that the system was weather proof. Additionally, the box was strapped to the construction under the flat plate collector to prevent mechanical damage.

4.2.1 *Arduino*

To extract useable data out of the DAQ box, a soft – and hardware which converts the electrical signals into readable data and stores it on a SD – card is needed. Due to the easy operation and its inexpensiveness, the Arduino is the ideal system for research projects like this. The homepage describes Arduino with the following words "Thanks to its simple and accessible user experience, Arduino has been used in thousands of different projects and applications. The Arduino software is easy-to-use for beginners, yet flexible enough for advanced users. It runs on Mac, Windows, and Linux. Teachers and students use it to build low cost scientific instruments, to prove chemistry and physics principles, or to get started with programming and robotics. Designers and architects build interactive prototypes, musicians and artists use it for installations and to experiment with new musical instruments. Makers, of course, use it to build many of the projects exhibited at the Maker Faire, for example. Arduino is a key tool to learn new things. Anyone - children, hobbyists, artists, programmers - can start tinkering just following the step by step instructions of a kit, or sharing ideas online with other members of the Arduino community." [5].

Arduino was programmed to create a text file on the SD-card and write the collected data on it in an interval of one minute. The interval can be changed in the code by modifying the refresh rate. The code can be seen in the Appendix B.

4.3 MATLAB

To analyze data in a proper way, it is important to pick out the most relevant details and visualize them. To make this happen, the software MATLAB was used for computing and analyzing the collected temperature data and the available solar data from Dr. Eckmann's weather station on Christie Hall.

For the analyzing of data points, engineers and scientists often need a mathematical connection to the trend of the data points. In some cases, it is important to find equations that can represent the data. Therefore, MATLAB has some special tools which were also used in this project.

- "**Curve fitting** is a procedure in which a mathematical formula (equation) is used to best fit a given set of data points. The objective is to find a function that fits the data points overall. This means that the function does not have to give the exact value at any single point, but fits the data well overall" [6, p.194].

  Essentially, the method of curve fitting can be used to describe data point with mathematical equations. In the project, it was used to represent the solar radiation and the ambient temperature changing over day time. The commands used and the resulting findings are described in the following sections.
- "Interpolation is a procedure for estimating a value between known values of data points. It is done by first determining a polynomial that gives the exact value at the data points, and then using the polynomial for calculating values between the points" [6, p.194].

  This method can be used when, for example, a sensor has an issue and cannot collect a data point at a certain time but works again the points afterwards. Therefore, the missing data value can be estimated with the method of interpolation. If the estimation is at the end of the data set and should predict following data points, it is called extrapolation.

In this paragraph the numerical methods which were used to transfer the data from the excel sheet into the software and visualize it in plots are described.

- The first and most important command which was used is *xlsread*. The command can read data from excel sheets into MATLAB. The data can be used as a matrix or vector then.
- The next described code was used to get the length of the solar radiation data (collected in five minute intervals) on the same length than the temperature data of the collector which was collected in one minute intervals. The used code line was "*kroon(SR_nov18x, ones(5,1))*" [7]. The combination of the two comments creates a vector which uses the same value five times before the next value comes up. Basically, the same solar radiation was used for five temperature points.
- Another key expression was the following one: "*deltaTD(isnan(deltaTD)) = 8*" [8]. It overwrites the occurring NAN values with the chosen number (8). The mentioned line of code was necessary to get rid of the NAN values which occurred at some points because of failure of the thermocouples. The *polyfit* and *polyval* command can't deal with these data points.

More details about the used methods and commands can be found in the MATLAB code in the Appendix C.

5 CALCULATIONS

To scale the improvements of a system, it is essential to calculate numerous aspects of it. Due to the huge amount of work, it is common to use programs like Polysun for calculations of entire systems. For this research paper a program like this was not available. Therefore, the calculations were done by hand and Excel. Another aspect to consider is, that there a several values of the used materials needed to get valuable results.
To get reasonable values to compare, the simplified versions of equations were used.

5.1 Efficiency

The performance of the system was based on the first law of thermodynamics. The enthalpy of the water exiting the system and the enthalpy of the water entering the system. Since the water does not change phase the approximation may be used that the change of the enthalpy is approximately the specific heat multiplied by the change in temperature as shown in Equation 1.

$$Q_u = mc_p(T_o - T_i) \qquad (1)$$

The equation used calculates the useful energy output Q_u of the collector in the unit [J]. To get the power in [W] out of the equation, it is necessary to make the first derivative. Now Q and m are energy flow [J/s] = [W] and mass flow [kg/s]. Therefore, the values for mass flow and the difference in temperature [K] have to be known from the collector. For the specific heat c_p, the value for water is 4190 J/kgK.

To calculate the efficiency of the collector, the energy output of the collector has to be divided through the energy input of the sun I in [W/m^2] over the area of the collector A in [m^2].

$$\eta = \frac{Q_u}{AI} \qquad (2)$$

The shown equation is used to calculate the momentarily performance of the collector. To get the overall performance, it is necessary to calculate it over the whole day. Therefore, an integral is used for the changing variables delta T and the solar radiation.

$$\eta = \frac{\int Q_u dt}{A\int I dt} \quad (3)$$

5.2 Losses

Like every other system, to generate energy solar collectors have several components which transfer energy. This is connected to different kinds of energy losses. The different types of losses and how they are calculated are explained in this chapter.
For a better understanding, Figure 14 shows a sketch of the different types of optical losses.

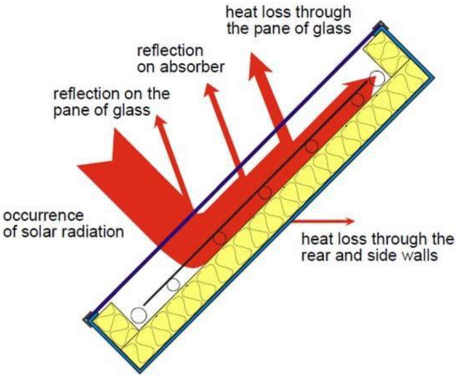

Figure 14. Different losses of flat plate collector [17].

The different kinds of losses are basically the same in evacuated tubes. The different shape of the transparent cover and the higher insulation value for vacuum should be considered.

5.2.1 Optical losses

Optical losses occur when the solar radiation enters the transparent cover of the solar collector. At this component, a part of the radiation is reflected by the medium. Thus, only a reduced amount of radiation can enter the collector. There is a small amount of the already reduced radiation that gets reflected again by the absorber plate. To keep this reflected long-waved radiation in the collector, there are some special coatings for the inside of the transparent plate which reflect the heat radiation, in the collector and use it to heat the absorber plate. To calculate the optical losses, some coefficients which describe the amount of lost radiation were developed.

$$Q_i = I(\tau\alpha)\cdot A \quad (4)$$

Equation 4 describes the Energy input Q_i of the sun which was already calculated in equation 2 for the efficiency. In this equation, the radiation I gets multiplied with the dimensionless factors τ and α. The letter τ stands for the percentage of transmitted solar radiation of the transparent cover panel and α for the absorbed percentage of radiation of the absorber plate. Therefore, it is better when the values of both coefficients are as big as possible. Common numbers for good transparent panels are around 0.95. For the absorptions coefficient, common values range from 0.15 (black paint) to 0.95 (TiNOx coating) [13].

5.2.2 Thermal losses

As be seen in Figure 14, there are two types of heat losses in a flat plate solar collector. On one side the reflected radiation of the absorber plate, and on the other side the heat transmission through the insulation.
The heat which gets lost through the transparent panel can be minimized through special coatings as mentioned in 5.2.1. The heat loss through the insulation can be minimized with thicker or higher quality insulation.
The lost energy Q_o is described by the following equation.

$$Q_o = U_L A(T_c - T_a) \quad (5)$$

The energy is calculated by multiplying the heat transfer coefficient U_L in [W/m^{2}K] with the total area A [m^2] of the insulation and the temperature difference of the collector temperature T_c in [K] and the ambient temperature T_a in [K].
The same equation can be used for calculating the heat losses for hot water storage tanks and piping.
Another thing that should be considered when designing a solar collector is that the distance between absorber plate and transparent cover panel should be as small as possible to prevent convection heat losses.

6 IMPROVEMENTS AND RESUTS

The goal of the project was to improve the performance of the solar system and its components. To archive this goal, it was important to collect data and compare it to each other, to get more valuable results out of the changes that were made.
The following paragraphs will describe the former system and its performance, the tests and changes which were done, and some recommendations for next project teams working with the collectors.

6.1 Former system

When the former system was set up, there were multiple aspects that needed to be taken care of immediately. Before the system could be put in operation, it had to be cleaned up and refilled with new water. Due to the open design of the solar cycle, the working fluid was clearly soiled after the long time in which it was not used. Another thing that needed to be fixed was the leaking sealings of some tubes of the system.
When the first steps to get the system running were done, it was time to analyze the components and see where improvements could be made.

6.1.1 *Orientation*

The analyses started with the orientation of the two solar collectors. The flat plate collector was orientated in direction southeast (approximately 140° azimuth) and the evacuated tubes were faced northeast (approximately 50° azimuth). For better understanding, Figure 15 shows the location of the green roof and the solar collectors.

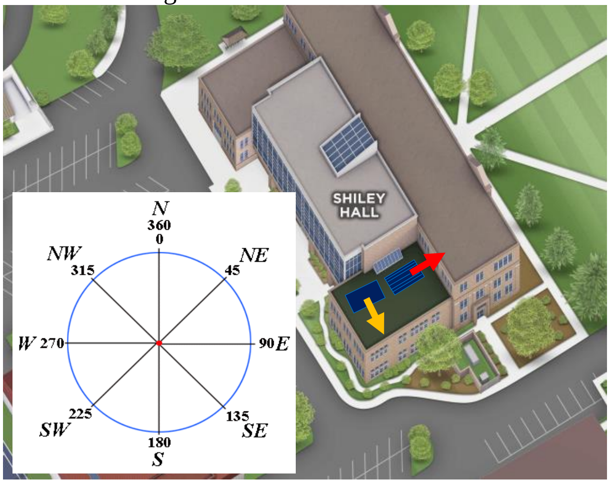

Figure 15. Top view of green roof with azimuth [10,11].

The yellow arrow shows the orientation of the flat plate solar collector and the red one the orientation of the evacuated tubes.

6.1.2 Angle

Also, the angles of both collectors were not adjusted for the time of the year. The flat plate collector was at about 20 degrees which is too flat for September. The angle of the evacuated tubes was even lower (approximately 5°). The following figure shows the optimal orientation of solar collectors for different times of the year.

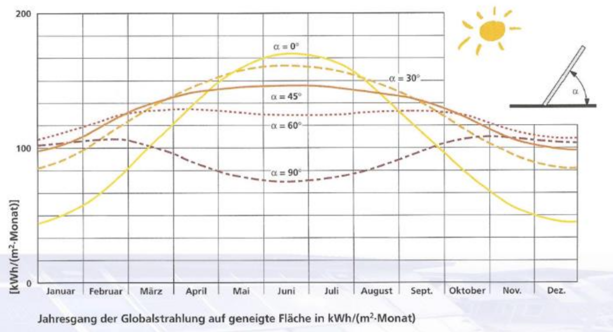

Figure 16. Diagram of energy output for different tilt angles over the year [13].

As shown in Figure 16 (bigger version in Appendix F), it makes a significant difference to tilt the collectors in different times of the year. For example, the ideal angle for September would be about 30°-45° to get the most energy output of the collectors.

6.1.3 Insulation

As described in chapter 5.2 Losses, it is very important to have a well-insulated system for maximal efficiency.

Except for the flat plate collector and the vacuum insulation of the tubes themselves, no insulation was used for the whole cycle. The next picture shows the heat exchanger where the evacuated tubes transmit their heat to the working fluid of the cycle. The aluminum box and the small copper pipes which go into it are major parts with high temperature losses.

Figure 17. Heat exchanger evacuated tubes.

As it can be seen in Figure 18, the tubes and the tank only consist of a thin layer of plastic and are sources of enormous heat loss when the water inside is heated up.

Figure 18. Plastic tank and connection tubes of the system.

The open tank also leads to other issues like pollution of the working fluid which can be harmful for the pump. Additionally, an open system is always connected to evaporation losses. Through leaks and evaporation, the system lost about three gallons of water during the tested time from the 14th of November to the shutdown at the 6th of December.

6.1.4 Data collection

The main issue of the former system was the way the data was generated. To collect temperature data of the collectors, it was necessary to make appointments with a technical advisor of the faculty to gain roof access. These appointments were possible for a maximum of 1 hour. In this hour, the whole cycle had to be started, a laptop had to be connected to the Arduino program and then the data could be measured for the rest of the time. At the end of the appointment the system had to be shut down again. One time, measuring was halted due to rainy weather conditions.

6.2 Tested changes

Due to the late completion of the data collecting system, there was not much time left to actually test physical improvements of the system. The next few paragraphs describe the work done and the tested improvements of the system.

- At the beginning of the semester some appointments on the roof were made to fix the issues and analyze the current status of the system.
- The next weeks were spent to build and program a system to collect data permanently.
- On the 6th of November, it was planned to place the DAQ on the roof to collect data permanently and without manual operators.
  The installation was canceled because of concerns of the technical advisor about the weather resistance of the box. The next possible appointment was booked for the 14th of November.
- On the 14th of November 2017, the box finally got installed weather proof.
- On the 17th of November 2017, the first temperature data was read out of the SD-card to see if everything worked as it should. As this was confirmed, the angle and the orientation of the flat plate collector was adjusted.
  The flat plate collector was faced south (180° azimuth) and has been adjusted to an angle of approximately 70° which is ideal for November as seen in Figure 16.
  For adjusting of the evacuated tubes, it would have been necessary to build a construction which was not possible due to a short window of time.
- On the 5th of December 2017, the angle has been adjusted to about 80 degrees.
- Additionally, a flat mirror was placed under the evacuated tubes to reflect more sunlight onto the absorbing area (see Figure 20)
- On the 6th of December, the system was shut down due to the low temperatures at night to prevent any damage of the system

The following figures document the done work with some pictures of the system.

Figure 19. Flat plate solar collector with adjusted angle for November conditions.

Figure 20. Upgraded evacuated tubes with mirrors underneath and the tilted flat plate collector in the background.

Figure 21. Emptied evacuated tubes, tank and the disconnected tubes.

6.2.1 Analysis of collected data

In this chapter the collected data gets analyzed and discussed.

The first figure shows the output temperature of the collectors for the whole time data was generated.

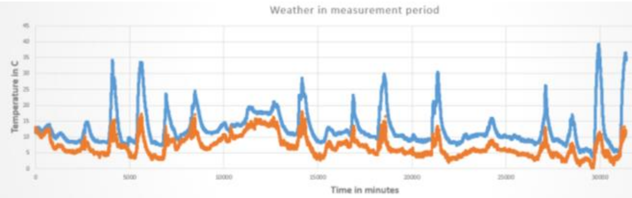

Figure 22. Excel plot of temperature data over time.

The plot shows that there were only 8 days with significant energy output of the collector (>25°C). The most valuable ones were analyzed in MATLAB and are described in the following paragraphs. A bigger version of the plots described in this chapter ar Ae inppendix E.

The next two figures show the performance of the collector and the weather on the 18th of November (2nd significant peak in Figure 22).

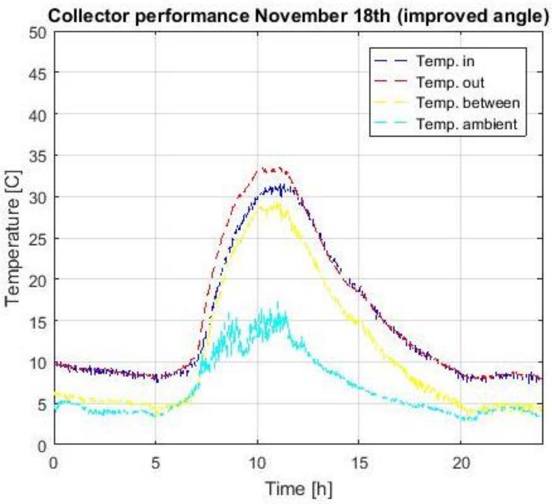

Figure 23. MATLAB plot collector performance 18th of November.

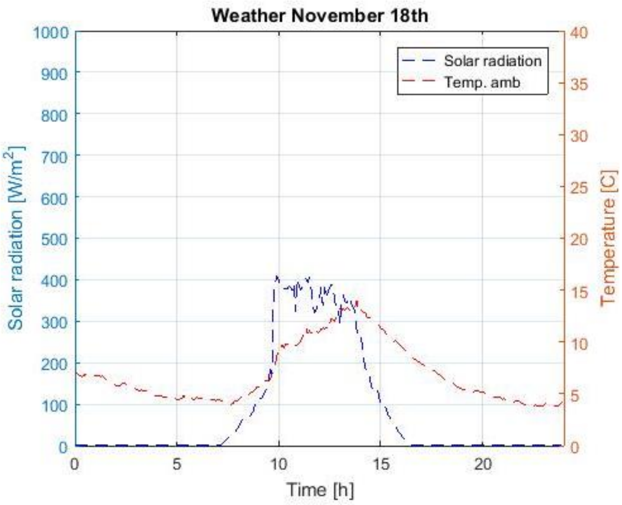

Figure 24. MATLAB plot solar radiation and ambient temperature 18th of November.

The first plot shows the temperature of the flat plate collector inlet, outlet, outlet of evacuated tubes and the ambient temperature. The temperature differences between the sensors do not make sense because the outlet temperature (yellow) of the flat plate collector during the day is lower than the output of the whole system (red). This is maybe due to a wet thermocouple which delivered wrong values.

The next two figures show the performance of the collector at the 5th of December. This plot seems to be more reasonable according to the temperature levels.

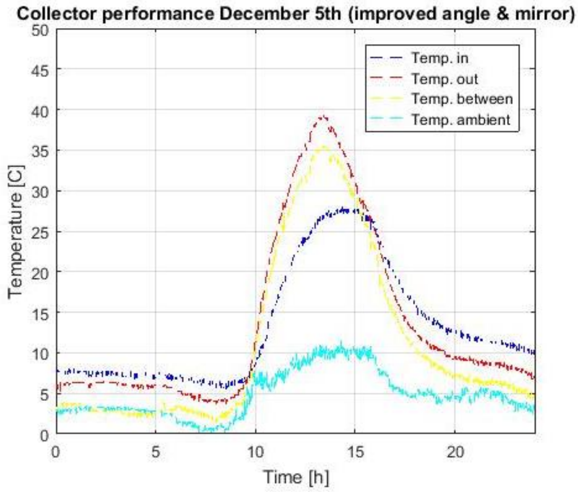

Figure 25. MATLAB plot collector performance 5th of December.

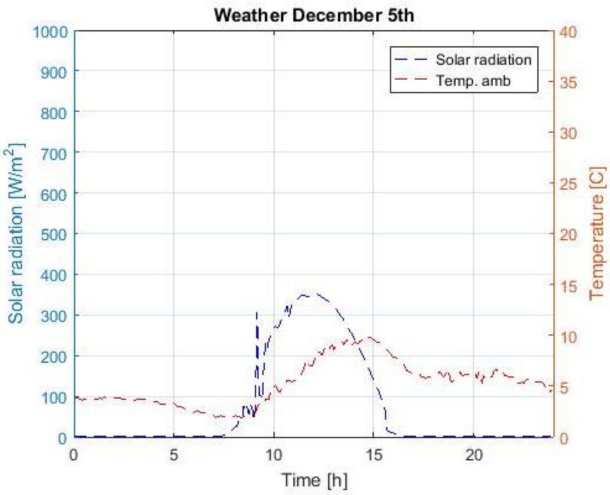

Figure 26. MATLAB plot solar radiation and ambient temperature 5th of December.

Figure 26 shows a more constant curve of the solar radiation than the Figure 24 which means that there is more direct radiation than it was on the 18th of November.

The plot in Figure 23 shows a delta T of 12.7°. This lead to an efficiency calculation of 40%.

The usage of the mirror which was placed under the evacuated tubes can be seen in the delta T of 5° only through the evacuated tubes.

The calculation was done with the listed equations in chapter 5. The value for the flow rate was 7gph (0.0074kg/s). The incoming radiation at this point was 351W/m^2. Compared to the efficiency calculation of the former project team who got their delta T of nearly 50°C and an efficiency of 40-45% with an even lower flowrate of 0,0063kg/s [4], this is definitely not a bad result.

6.2.2 Summer performance

The performance of the modified collector in Summer times was estimated and visualized with MATLAB which is shown in the following figure.

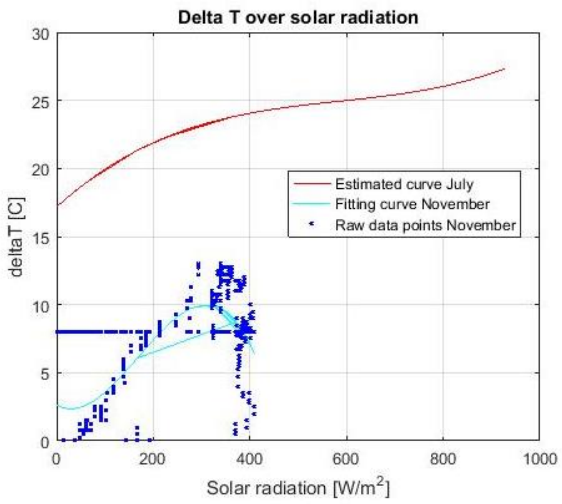

Figure 27. MATLAB plot temperature difference over solar radiation.

The plot in Figure 27 shows the blue data points which visualize the temperature difference of the solar collector input and output temperature. Due to the bad data of the November day, only the data of the December day was used. To approximate the performance of the collector at the 21st of July 2017, the Solar radiation and the ambient temperature shown in Figure 3 was used. For further detailed information, take a look at the MATLAB code shown in Appendix C.

As conclusion of the performance estimation it has to be said, that the mirror would have an even bigger impact on the system than shown with the red line in the plot. Due to the high amount of direct radiation on the day in July, the mirror would probably work very well and reflect the radiation in a better angle to the tubes than in Winter times.

6.2.3 Integration in ORC

Due to the reason, that the collectors should supply the at the beginning of the report described Organic Rankine Cycle in future, some calculations according to this have been made.

The energy output of the collector was calculated with equation 1. With the values of the former project team, an energy output of 1320W is calculated.

For the designed ORC of the project team an energy output of approximately 13000W would be necessary to run the turbine. This is about 10 times the amount of generated heat from the collectors. To reach this high level of energy, it would be necessary, to place 9 more solar systems like they are now on the roof. This would conform an area of 28m^2 on the roof only for the collectors. To make the project more feasible, it would be better to increase the performance of the collectors, so the area can be minimized. For example, if the efficiency would be doubled, the area would only be like 10m^2. When all the other components also could be improved, the area could be even smaller.

6.3 Recommended changes

Due to the strict policy for roof access and the late finalization of the data collecting system, it was unfortunately not possible to do a lot of tests with the collectors. For the faculty members and students working on the project in the future, this chapter shows and describes recommendations to make the system more efficient. To make things clearer, the recommended points are described in detail after the following list.

6.3.1 Summarized recommendations

- Relocate evacuated tubes (azimuth 180°, angle at least 30°)
- Build user for warm water
- Maybe consider lab to make indoor tests of collectors possible
- Use anti-freeze to make testing in winter possible
- Insulation heat exchanger (see Figure 17)
- Insulation tubes
- Insulate tank
- Use coating for flat plate collector cover panel to minimize heat losses
- Reduce distance of cover panel and absorber plate
- Calibrate thermocouples to get more valuable data
- New flow meters to make adjusting of the flow rate easier.

6.3.2 Detailed recommendations

Relocation

As mentioned in Chapter 6.1.1, the evacuated tubes and the flat plate solar collector were placed suboptimal. To get the highest amount of solar radiation during daytime, both collectors should be faced south (azimuth 180°).

In Addition to the adjusting of the azimuth, it is important to adapt the angle of the collectors to the given conditions. As it can be seen in Figure 16 (also Appendix F) there is a big difference in which time of the year the collectors are performing only according to the high of the sun. Another reason for adjusting the evacuated tubes, is that they perform better when the angle is at least 30° due to their working principle. For nearer information see Chapter 3.2.1.

Temperature difference

As it can be seen in Equation 1, the energy output of the system strongly depends on the difference of the inlet and outlet temperature of the collector. With the small plastic container which is currently used for the system, the water in the tank gets heated up in a short amount of time. This leads to a higher inlet temperature of the collector and so the temperature difference gets smaller and so does the energy delivered by the collector. To solve this problem, it is necessary to use a bigger tank or build some kind of user for the hot water. If the hot water from the tank can be used to heat another fluid through a heat exchanger, like it is planned when the solar cycle gets combined with the ORC, the inlet temperature of the collectors will be lower. Another method to get rid of the hot water in the tank could be to supply some heating for the thermodynamics lab.

Time period for testing

Another idea to improve the project would be to build a solar collector which can perform inside of a lab. It would be possible to simulate the radiation of the sun with certain electric lights. With lab conditions it would be way easier to get access to the collector and it would be possible to test different things all over the year. This solution could even lead to a lab for renewable energy where different methods of generating energy could be tested and compared.
To make tests of the collector possible over the whole year, it would be necessary to use anti-freeze for the water in the system. If tests in the winter are not required, it would at least save time and work for emptying the collector before low temperatures occur and for refilling the system when the tests are continued in spring.

Heat losses

Another problem of the current system is the lack of insulation. Especially when cold ambient temperatures occur, it is essential to have a well-insulated system. This also includes the tubes, heat exchanger of the evacuated tubes collector and even the tank. In Chapter 5.2.2 the background of thermal losses is described.
Heat losses also could be minimized by applying a special anti-reflection layer on the cover panel of the flat plate collector. The principle of heat loss due to reflection is described in Chapter 5.2.1 Equation 4.
In Addition to that change it would also be good to reduce the distance between the cover panel and the absorber plate. If the distance is to high, convection occurs. This also leads to heat losses.

Sensors

All the tests won't bring any progress if the used sensors can't be trusted. To prevent problems like they occurred when creating the plot shown in Figure 23, it would be necessary to calibrate the thermocouples before using them for the experiments. This would also provide more valuable calculations of the collector performance.
Also, the flow meters were pretty hard to adjust accurate. The meters sometimes changes their flowrate without being adjusted. This can also be caused by the polluted water which is due to the open system. For exact calculations of performance, it would be important to repair and maintain the old flow meters or incorporate new ones.

7 ACKNOWLEDGEMENTS

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At the very least, I want to thank my American friends Rachel Punzalan and Annie Turner for investing their time to help me with my grammar and supplied me with banana bread to stay strong through the whole process of writing this paper.

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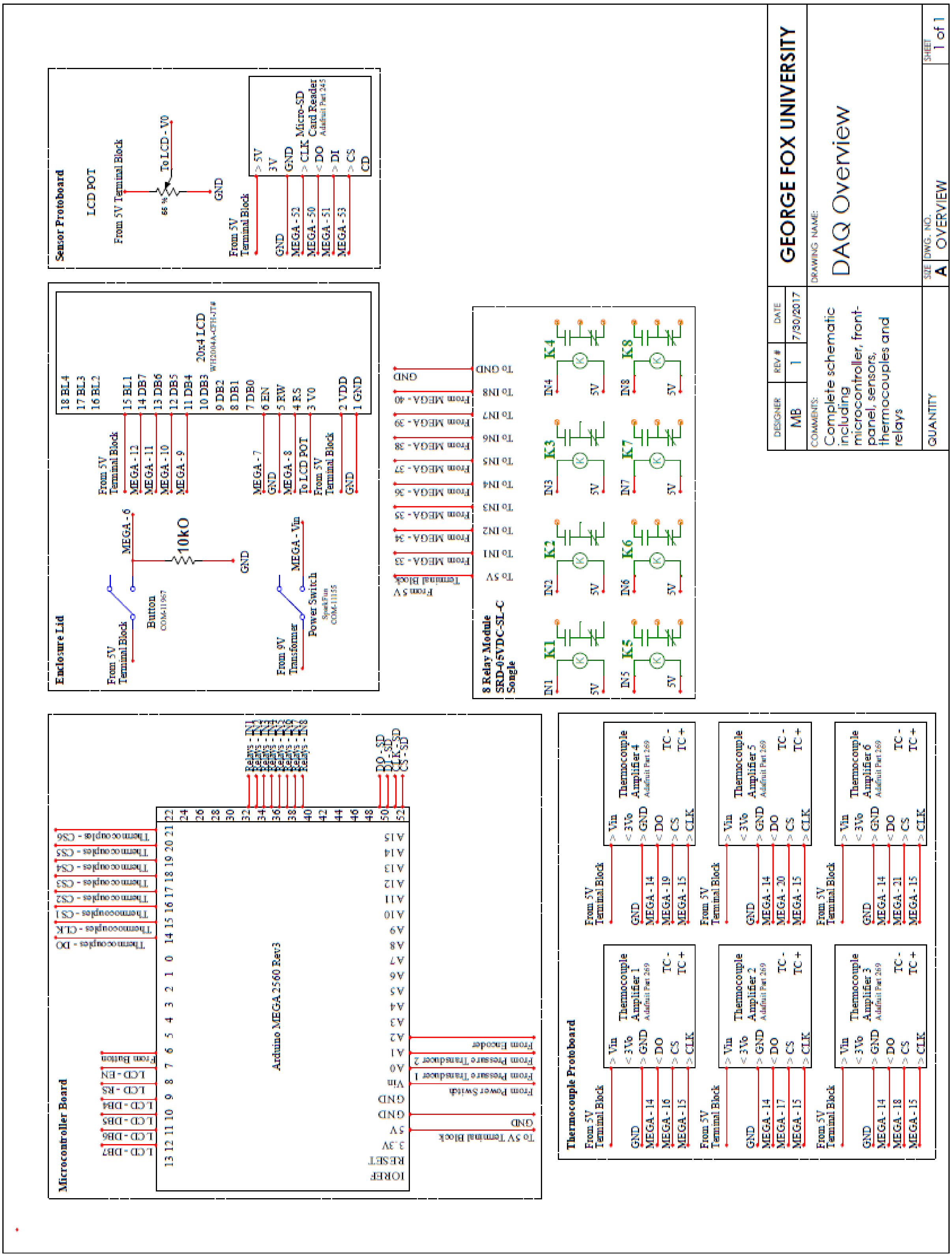
APPENDIX A / ELECTRIC SCHEMATIC DAQ



APPENDIX B / CODE DAQ

```
/*
* DAQ_Code
 *
 * Code to collect data on Univeristy of Portland's
 *  Organic Rankine Cycle. The DAQ includes
 *  6 thermocouples, 2 pressure transducers, and an
 *  encoder to measure RPM. An LCD screen displays
 *  real-time data, with all sensor inputs saved
 *  to an SD card for additional anlaysis.
 *
 * Created on 7/28/2017 by Michael Boller
 *  George Fox University
 */


//===================================================================
//     Declare Global Variables & Header Files.
//===================================================================
// Include the LCD library code:
#include <LiquidCrystal.h>
// Include SPI & Adafruit Thermocouple library
#include <SPI.h>
#include "Adafruit_MAX31855.h"
// Include SD Card library
#include <SD.h>

// USE THIS PARAMETER TO DETERMINE HOW FAST THE DAQ READS DATA!
// The number is in milliseconds
#define REFRESH_RATE 500

// Pin declarations for LCD display
#define LCD_RS 8
#define LCD_EN 7
#define LCD_D4 9
#define LCD_D5 10
#define LCD_D6 11
#define LCD_D7 12

// Pin declarations for relays
#define RELAY1 33
#define RELAY2 34
#define RELAY3 35
#define RELAY4 36
#define RELAY5 37
#define RELAY6 38
#define RELAY7 39
#define RELAY8 40

// Pin declarations for additional sensor inputs
#define PRESSURE_SENSOR_1 A0
#define PRESSURE_SENSOR_2 A1
#define RPM_SENSOR_1 A2

//Pin declarations for pushbutton input
#define BUTTON_PIN 6

// Pin delcarations for software SPI with the six thermocouples.
#define DO 14
#define CLK 15
#define CS1 16
#define CS2 17
#define CS3 18
#define CS4 19
#define CS5 20
#define CS6 21

//Pin declarations for the SD card
#define CS_SD 53
#define DO_SD 50
#define DI_SD 51
#define CLK_SD 52

// LCD attribute delcarations
#define LCD_COLUMNS 20
#define LCD_ROWS 4
#define LCD_SCREENS 4

// Message types for lcd_handler function
#define LCD_TEMP_1 0
#define LCD_TEMP_2 1
#define LCD_PRESSURE_RPM 2
#define SD_CARD_STATUS 3

// Relay control
#define RELAY_CLOSED 0
#define RELAY_OPEN 1

// Debounce time
#define DEBOUNCE_DELAY 200

// Variables for sensor inputs
float temp1 = 0;
float temp2 = 0;
float temp3 = 0;
float temp4 = 0;
float temp5 = 0;
float temp6 = 0;
float pressure1 = 0;
float pressure2 = 0;
float rpm1 = 0;

// Variables used in the pushbutton operation
int lastDebounce = 0;

// Variable used in determining the refresh of the LCD
int lastUpdate = 0;
int screen = 0;

// Variables used for SD card data
long messages = 0;
bool cardError = 0;

// Initialize the LCD with the numbers of the interface pins
LiquidCrystal lcd(LCD_RS, LCD_EN, LCD_D4, LCD_D5, LCD_D6, LCD_D7);

// Initialize the Thermocouples
Adafruit_MAX31855 thermocouple1(CLK, CS1, DO);
Adafruit_MAX31855 thermocouple2(CLK, CS2, DO);
Adafruit_MAX31855 thermocouple3(CLK, CS3, DO);
Adafruit_MAX31855 thermocouple4(CLK, CS4, DO);
```

```
Adafruit_MAX31855 thermocouple5(CLK, CS5, DO);
Adafruit_MAX31855 thermocouple6(CLK, CS6, DO);

//Initialize the data file from the SD card
File data;


//=============================================
     =====================
//   The Setup Function which initializes the program
//=============================================
     =====================
void setup()
{
 // Set up the LCD's number of columns and rows:
 lcd.begin(LCD_COLUMNS, LCD_ROWS);
 // Printing a welcome message:
 lcd.print(" Welcome to the DAQ ");

 // Setting the hardware SS pin as an output
 pinMode(CS_SD, OUTPUT);

 //Initializing the SD card
 if (!SD.begin(CS_SD)) {
  // If the SD card did not initialize, throw error flag
  cardError = 1;
  return;
 }

 // Setting relay pins as outputs
 pinMode(RELAY1, OUTPUT);
 pinMode(RELAY2, OUTPUT);
 pinMode(RELAY3, OUTPUT);
 pinMode(RELAY4, OUTPUT);
 pinMode(RELAY5, OUTPUT);
 pinMode(RELAY6, OUTPUT);

 // Turning relays off
 relay_handler(RELAY1, RELAY_OPEN);
 relay_handler(RELAY2, RELAY_OPEN);
 relay_handler(RELAY3, RELAY_OPEN);
 relay_handler(RELAY4, RELAY_OPEN);
 relay_handler(RELAY5, RELAY_OPEN);
 relay_handler(RELAY6, RELAY_OPEN);

 // Opening the data file to store data to SD card:
 data = SD.open("daq_data.txt", FILE_WRITE);

 // If file was opened sucessfully, write opening lines of CSV
    file
 if (data)
 {
  // Write opening headers:
  data.println("TC1,TC2,TC3,TC4,TC5,TC6,P1,P2,RPM1");
  // Close the file to save the information
  data.close();
  // Increase the message count for display
  messages++;
 }
 else
 {
  // Throw error flag if file did not open
  cardError = 1;
 }

 // Pause to allow opening mesage to be seen
 delay(500);
}


//=============================================
     =====================
//    This is The Main Loop, it contains the program's main
    code.
//=============================================
     =====================
void loop()
{
 // Reading temperatures from the thermocouples
 temp1 = thermocouple1.readCelsius();
 temp2 = thermocouple2.readCelsius();
 temp3 = thermocouple3.readCelsius();
 temp4 = thermocouple4.readCelsius();
 temp5 = thermocouple5.readCelsius();
 temp6 = thermocouple6.readCelsius();

 // Reading pressure from pressure transducers
 // Input the sensor location and the maximum pressure reading
 pressure1 = pressure_handler(PRESSURE_SENSOR_1, 200);
 pressure2 = pressure_handler(PRESSURE_SENSOR_2, 200);

 // Reading RPM from encoder (Uncomment when function is
    complete)
 //rpm1 = encoder_handler(RPM_SENSOR_1);

 // Changing the LCD screen every time a button is pressed
 if (digitalRead(BUTTON_PIN) && ((millis() - lastDebounce)
    > DEBOUNCE_DELAY))
 {
  // Incrementing to the next screen
  screen++;
  // Looping back to the first screen
  if (screen >= LCD_SCREENS)
  {
   screen = 0;
  }
  // Updating the text on the LCD screen
  lcd_handler(screen);
  // Saving the last screen refresh time
  lastDebounce = millis();
  // Saving last debounce time
  lastUpdate = millis();
 }

 // Refreshing the LCD screen and printing to the SD card
 //  every 500 milliseconds
 if ((millis() - lastUpdate) > REFRESH_RATE)
 {
  // Opening the data file to store data to SD card:
  data = SD.open("daq_data.txt", FILE_WRITE);

  // If file was opened sucessfully, writing sensor data in
  //  CSV format
  if (data)
  {
   data.print(temp1);
```

```
      data.print(",");
      data.print(temp2);
      data.print(",");
      data.print(temp3);
      data.print(",");
      data.print(temp4);
      data.print(",");
      data.print(temp5);
      data.print(",");
      data.print(temp6);
      data.print(",");
      data.print(pressure1);
      data.print(",");
      data.print(pressure2);
      data.print(",");
      data.println(rpm1);
      // Closing the file to save the data
      data.close();
      // Increase the message count for display
      messages++;
    }
    else
    {
      // Throw error flag if file did not open
      cardError = 1;
    }
    // Updating the text on the LCD screen
    lcd_handler(screen);
    // Saving last screen refresh time
    lastUpdate = millis();
  }

  // Sample Relay Open & Close Command:
  //relay_handler(RELAY1, RELAY_OPEN); // Relay OPEN
  //relay_handler(RELAY1, RELAY_CLOSED); // Relay CLOSED
}


//===========================================================================================
//    This section contains functions called by the Main Loop.
//===========================================================================================

/*
 * This funtion reads the pressure transducer
 * Arguments: pin - the pin the sensor is wired to
 *          maxPressure - the upper range of the pressure sensor
 * Returns: the pressure in psi
 */
float pressure_handler(int pin, int maxPressure)
{
  float pressure;
  // Reading the sensor and converting to PSI (5V/1024Counts*"maxPressure"psi/5V)
  pressure = analogRead(pin)*maxPressure/1024;
  return pressure;
}

/*
 * This funtion controls the encoder
 * Arguments: pin - the pin the sensor is wired to
 * Returns: rotations per minuite (rpm)
 */
float encoder_handler(int pin)
{
  // Code needs to be implemented...
}

/*
 * This funtion controls the relays
 * Arguments: pin - the pin the relay is wired to
 *          relayStatus - RELAY_OPEN or RELAY_CLOSED
 * Returns: none
 */
void relay_handler(int pin, int relayStatus)
{
    if (relayStatus)
    {
      digitalWrite(pin, HIGH);
    }
    else
    {
      digitalWrite(pin, LOW);
    }
}


/*
 * This funtion writes new screens to the LCD screen
 * Arguments: messageType - the type of message to display:
 *                      LCD_TEMP_1 - Thermocouples 1-3
 *                      LCD_TEMP_2 - Thermocouples 4-6
 *                      LCD_PRESSURE_RPM - Pressure & RPM
 *                      SD_CARD_STATUS - SD Card Status
 * Returns: none
 */
void lcd_handler(int messageType)
{
  switch (messageType) {
    case LCD_TEMP_1:
      {
        lcd.clear();
        lcd.print(" Thermocouples 1-3 ");
        lcd.setCursor(0, 1);
        lcd.print("TC 1: ");
        lcd.print(temp1);
        lcd.print(" C");
        lcd.setCursor(0, 2);
        lcd.print("TC 2: ");
        lcd.print(temp2);
        lcd.print(" C");
        lcd.setCursor(0, 3);
        lcd.print("TC 3: ");
        lcd.print(temp3);
        lcd.print(" C");
        break;
      }
    case LCD_TEMP_2:
      {
        lcd.clear();
        lcd.print(" Thermocouples 4-6 ");
        lcd.setCursor(0, 1);
        lcd.print("TC 4: ");
        lcd.print(temp4);
```

```
      lcd.print(" C");
      lcd.setCursor(0, 2);
      lcd.print("TC 5: ");
      lcd.print(temp5);
      lcd.print(" C");
      lcd.setCursor(0, 3);
      lcd.print("TC 6: ");
      lcd.print(temp6);
      lcd.print(" C");
      break;
     }
    case LCD_PRESSURE_RPM:
     {
      lcd.clear();
      lcd.print("   Pressure & RPM   ");
      lcd.setCursor(0, 1);
      lcd.print("P 1: ");
      lcd.print(pressure1);
      lcd.print(" psi");
      lcd.setCursor(0, 2);
      lcd.print("P 2: ");
      lcd.print(pressure2);
      lcd.print(" psi");
      lcd.setCursor(0, 3);
      lcd.print("RPM: ");
      lcd.print(rpm1);
      lcd.print(" rpm");
      break;
     }
    case SD_CARD_STATUS:
     {
      lcd.clear();
      lcd.print("   SD Card Status   ");
      lcd.setCursor(0, 1);
      if (cardError)
      {
       lcd.print("Status: SDCard ERROR");
      }
      else
      {
       lcd.print("Status: SD Card OK");
      }
      lcd.setCursor(0, 2);
      lcd.print("New Recordings: ");
      lcd.print(messages);
      break;
     }
  }
}
```

APPENDIX C / CODE MATLAB

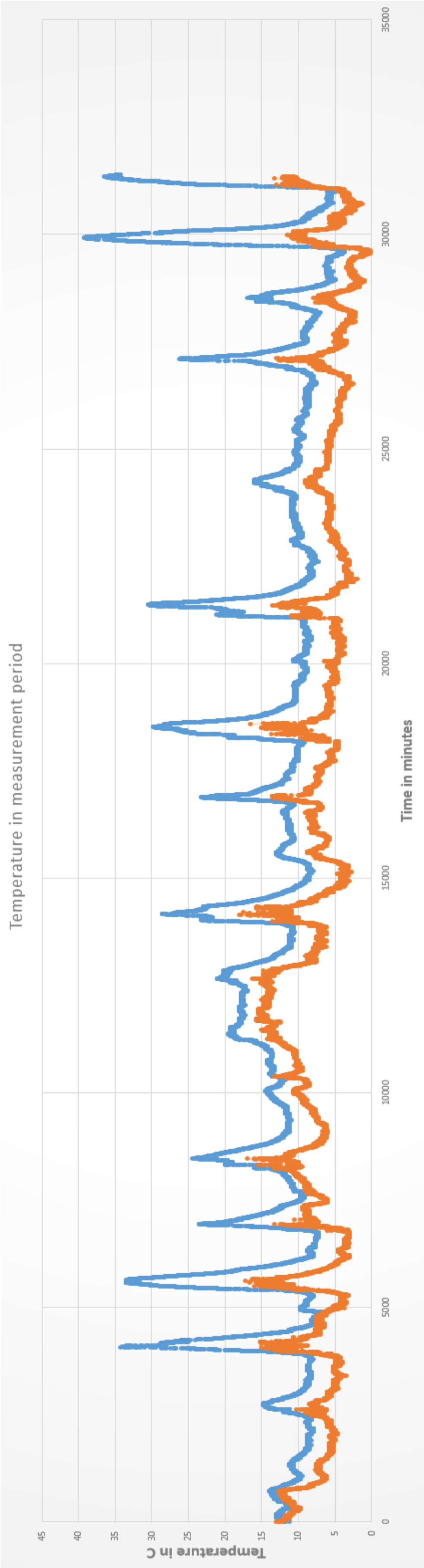
```
%Christoph Oberhuber
MatLab Final Project
%--------------------------------------
--------------------------------------
%Computing and visualising Solar Radi-
ation Data
%--------------------------------------
--------------------------------------
%The used data was collected by Dr.
Eckmann's weather station on the roof
%of Christie Hall.
%File
name:"ChristiePyranometer_FromOct16-
2016toOct16-2017-in_PDT.xlsx"

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

clear all
close all

%The first step of the project is to
read out the data of the excel sheet.

%Files named SRx_... contain solar ra-
diation data and temperature data from
%Dr. Eckamnn's weather station, files
with data_... contains temperature
%data which was collected by the sen-
ior design team from the solar
%collector.

%Using readxls command to import data
from excel sheet "SRx_07_21_17.xlsx"
%which only contains data from the
21st of July 2017 (00:00 to 24:00)
SRx_jul21=xlsread('SRx_07_21_17.xlsx',
'Sheet1','B2:D289');

%Using readxls command to import data
from excel sheet "SRx_11_18_17.xlsx"
%which only contains data from the
18th of November 2017 (00:00 to 24:00)
SRx_nov18=xlsread('SRx_11_18_17','Shee
t1','A2:D289');


%Using readxls command to import data
from excel sheet "SRx_12_05_17.xlsx"
%which only contains data from the
05th of December 2017 (00:00 to 24:00)
SRx_dec05=xlsread('SRx_12_05_17','Shee
t1','A2:D289');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Using readxls command to import data
from excel sheet "data_11_18_17.xlsx"
%which only contains data from the
18th of November 2017 (00:00 to 24:00)
da-
ta_nov18=xlsread('data_11_18_17','Shee
t1','A1:F1441');

%Using readxls command to import data
from excel sheet "data_12_05_17.xlsx"
%which only contains data from the 5th
of December 2017 (00:00 to 24:00)
da-
ta_dec05=xlsread('data_12_05_17','Shee
t1','A1:F1441');

%To make reading out and scaling the
time easier, the Excel sheets were
%modified. A column which contains the
time in houres was added, so the
%time of the day can be seen easily in
the plot.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%The second step of the project is to
plot the raw data points to compare
%temperature and solarradiation on a
day in July, November and (December).

%July 21st
time=SRx_jul21(:,3);             %de-
fining time to values of 3rd column
SR_jul21=SRx_jul21(:,1);         %de-
fining solar radiation to values of
1st
                                 %col-
umn
subplot(2,3,3)                   %de-
fining place in plot with subplot
yyaxis left                      %de-
fine primary yaxis
plot(time,SR_jul21,'--b')        %plot
solar radiation over time
axis ([0 24 0 1000])             %de-
fine axis range
xlabel('Time [h]')               %label
xaxis
ylabel('Solar radiation [W/m^2]') %la-
bel 1st yaxis
Temp_jul21=SRx_jul21(:,2);       %de-
fining temperature to values of 2nd
                                 %col-
umn
yyaxis right                     %add
second yaxis for temperature
plot(time,Temp_jul21,'--r')      %plot
temperature over time
```

```
ylabel('Temperature [C]')        %label
2nd yaxis
legend('Solar radiation','Temp. amb')
%add legend
axis ([0 24 0 40])               %de-
fine axis range
title('Weather July 21st')       %add
title
grid on                          %add
grid

%Analysis of summerday:
%When you take a look at the plot, you
see a little stagnation in
%radiation and temperature between 7
and 8. This may have been caused by
%a cloud covering the sun for some
time.
%Also a little delay of the tempera-
ture to the solar radiation can be
%clearly seen in the first plot. This
is due to the time, that the surfaces
%need to get heated up by the sun-
light.

%November 18th
SR_nov18=SRx_nov18(:,3);         %de-
fining solar radiation to values of
3rd
                                 %col-
umn
subplot(2,3,1)                   %de-
fining place in plot with subplot
time=SRx_nov18(:,1);             %de-
fining time as 1st column
yyaxis left                      %de-
fine primary yaxis
plot(time,SR_nov18,'--b')        %plot
solar radiation over time
axis ([0 24 0 1000])             %de-
fine axis
xlabel('Time [h]')               %label
xaxis
ylabel('Solar radiation [W/m^2]') %la-
bel 1st yaxis
Temp_nov18=SRx_nov18(:,4);       %de-
fining temperature to values of 4th
                                 %col-
umn
yyaxis right                     %add
second yaxis for temperature
plot(time,Temp_nov18,'--r')      %plot
temperature over time
ylabel('Temperature [C]')        %label
2nd yaxis
legend('Solar radiation','Temp. amb')
%add legend
axis ([0 24 0 40])               %de-
fine axis
title('Weather November 18th')   %add
title
grid on                          %add
grid

%Analysis of November day:
%When you take a look at the plot, you
can see that the solar radiation and
%the ambient temperature are way lower
than in July. Also the time range
%where the sun is actually available
is signifficant shorter than in summer
%time.


%December 5th
time=SRx_dec05(:,1);             %de-
fining time as 1st column
SR_dec05=SRx_dec05(:,3);         %defin-
ing solar radiation to values of 1st
column
subplot(2,3,2)
yyaxis left                      %de-
fine primary yaxis
plot(time,SR_dec05,'--b')        %plot
solar radiation over time
axis ([0 24 0 1000])             %de-
fine axis
xlabel('Time [h]')               %label
xaxis
ylabel('Solar radiation [W/m^2]') %la-
bel 1st yaxis
Temp_dec05=SRx_dec05(:,4);       %defin-
ing temperature to values of 2nd col-
umn
yyaxis right                     %add
second yaxis for temperature
plot(time,Temp_dec05,'--r')      %plot
temperature over time
ylabel('Temperature [C]')        %label
2nd yaxis
legend('Solar radiation','Temp. amb')
%add legend
axis ([0 24 0 40])               %define
axis
title('Weather December 5th')    %add
title
grid on                          %add
grid

%!!!!!!!!!Analysis of December day:
%Data couldn't be delivered from Dr.
Eckmann till the due date.

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%The next step is to visualize the
collector performance for the shown
%dates.
```

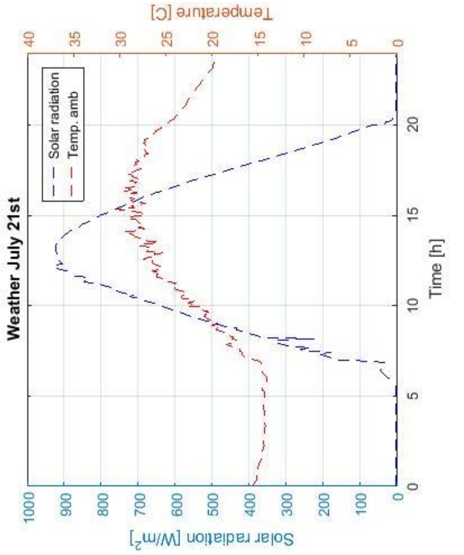
```
%Visualizing 18th of November (im-
proved angle)
time_o=data_nov18(:,1);          %de-
fining time to values of 1st column
Temp_inN=data_nov18(:,3);        %de-
fining inlet temperature to values of
3rd column
Temp_betweenN=data_nov18(:,4);   %de-
fining temperature output of flatplate
collector to values of 4th column
Temp_outN=data_nov18(:,5);       %de-
fining outlet temperature to values of
5th column
Temp_ambN=data_nov18(:,6);       %de-
fining ambient temperature to values
of 6th column
subplot(2,3,4)                   %place
subplot in 2nd position
plot(time_o,Temp_inN,'--
b',time_o,Temp_outN,'--
r',time_o,Temp_betweenN,'--
y',time_o,Temp_ambN,'--c') %plot tem-
peratures over time
xlabel('Time [h]')               %label
xaxis
ylabel('Temperature [C]')        %label
yaxis
legend('Temp. in','Temp. out','Temp.
between','Temp. ambient') %add legend
axis ([0 24 0 50])               %set
axis limit for better plot
title('Collector performance November
18th (improved angle)') %add title
grid on                          %add
grid

%Visualizing 5th of December (improved
angle & mirror)
time_o=data_dec05(:,1);          %de-
fining time to values of 1st column
Temp_inD=data_dec05(:,3);        %de-
fining inlet temperature to values of
3rd column
Temp_betweenD=data_dec05(:,4);   %de-
fining temperature output of flatplate
collector to values of 4th column
Temp_outD=data_dec05(:,5);       %de-
fining outlet temperature to values of
5th column
Temp_ambD=data_dec05(:,6);       %de-
fining ambient temperature to values
of 6th column
subplot(2,3,5)                   %place
subplot in 3rd position
plot(time_o,Temp_inD,'--
b',time_o,Temp_outD,'--
r',time_o,Temp_betweenD,'--
y',time_o,Temp_ambD,'--c') %plot tem-
peratures over time
xlabel('Time [h]')               %label
xaxis
ylabel('Temperature [C]')        %label
yaxis
legend('Temp. in','Temp. out','Temp.
between','Temp. ambient') %add legend
axis ([0 24 0 50])               %set
axis limit for better plot
title('Collector performance December
5th (improved angle & mirror)') %add
title
grid on                          %add
grid

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%The next step is to lay a curve into
the plot, to get a mathematical
%context for the datapoints. This will
happen by using polyfit and
%polyval.
%The purpose is to get a mathematical
context out of the curve fitting from
%the Noveber and December collector
data over the solarradiation. With
%these numbers it should be possible
to estimate the summer performance of
%the collector.

%defining deltaTs
deltaTN = Temp_outN - Temp_inN; %due
to bad quality of the temperature
%points of the November day (maybe wet
thermocouple) the more valuable data
%from the December day was used for
the curvefitting.
%December data was computed with the
compareable November day radiation.
deltaTD = Temp_outD - Temp_inD;
%deltaTD(~any(~isnan(deltaTD),
2),:)=[]; polyfit only showed nans so
I
%tried this command but it removed da-
ta points so the X and Y vectors
%(needed for polyfit and polyval)
weren't the same size anymore.
%https://www.mathworks.com/matlabcentr
al/answers/68510-remove-rows-or-cols-
whose-elements-are-all-nan
%so the code from the cited source was
used.

%The following code line overwrites
nan values with a choosen value (8).
Tried
%to use a function of the squareroot
to make a better estimation on the
%given data points but that didn't
work.
deltaTD(isnan(deltaTD)) = 8; %value 8
was choosen because it brings the most
valuable curvfitting plot
```

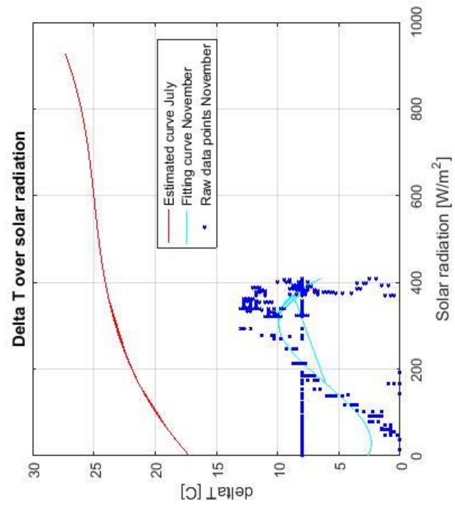
```
%To make plotting and comparing of
deltaT and solar radiation possible it
%is necessary to bring the solar radi-
ation vectors on the same size than
the
%temperature vector which is 5 times
larger because data gets collected
%every minute. Solar radiation only
every 5 minutes.
SR_nov18x=SR_nov18(:);
SR_nov18reshaped=kron(SR_nov18x, o-
nes(5,1));
SR_jul21x=SR_jul21(:);
SR_jul21reshaped=kron(SR_jul21x, o-
nes(5,1));
%preparing T July for plotting it over
solar radiation.
Temp_jul21x=Temp_jul21(:);
Temp_jul21reshaped=kron(Temp_jul21x,
ones(5,1));
%Code line was copied from following
source
%https://www.mathworks.com/matlabcentr
al/answers/131660-extend-a-vector-by-
extending-its-elements

n=3;      %defining degree of polynom,
3 was chosen experimentally (lowest
possible number for fitting curve)
pN=polyfit(SR_nov18reshaped,deltaTD,n)
;   %using polyfit command to return
the coefficients for the radiation da-
ta in November
pyN=polyval(pN,SR_nov18reshaped);
%using polyval command to return the
value of a polynomial of degree n
evaluated at x values
%To estimate the summer performance,
the delta T was assumed with the
%available data points of the ambient
temperature from Dr. Eckmann.
pJ=polyfit(SR_jul21reshaped,Temp_jul21
reshaped,n); %using polyfit command to
return the coefficients for the radia-
tion data in July
pyJ=polyval(pJ,SR_jul21reshaped);
%using polyval command to return the
value of a polynomial of degree n
evaluated at x values
subplot(2,3,6)
%place subplot in 5th position
plot(SR_jul21reshaped,pyJ,'r',SR_nov18
re-
shaped,pyN,'c',SR_nov18reshaped,deltaT
D,'b*','MarkerSize',2) %plot data-
pooints of solar radiation over time
ylabel('deltaT [C]')
%label yaxis
xlabel('Solar radiation [W/m^2]')
%label xaxis
legend('Estimated curve July','Fitting
curve November','Raw data points No-
vember') %add legend
axis ([0 1000 0 30])
%set axis limit for better plot
title('Delta T over solar radiation')
%add title
grid on
%add grid

%free space in subplot could be used
for diagrams of efficiencies or simi-
lar
%Will maybe be considered for other
reports and research.
%Momentan efficiency of collector was
calculated in Excel sheets in appen-
dix.
```

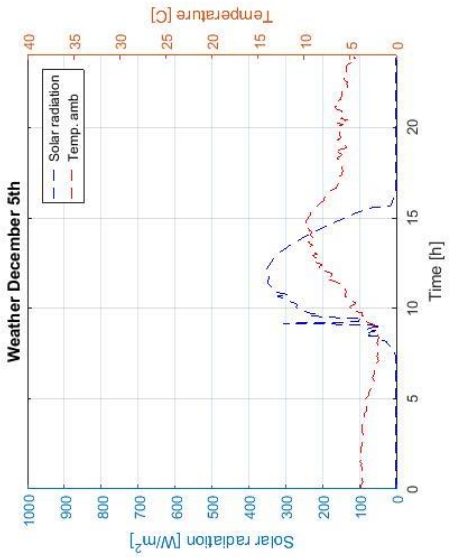
APPENDIX D / PLOT TEMPERATURE DATA

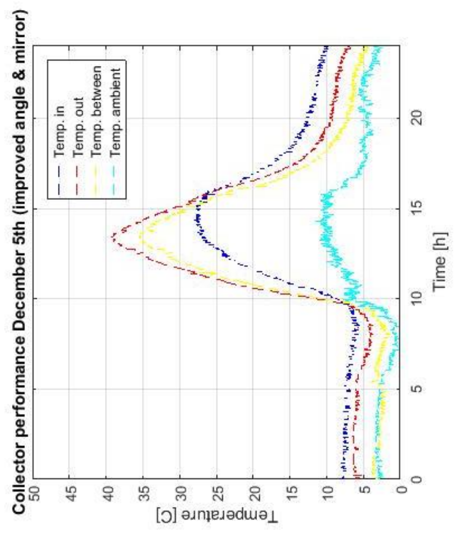


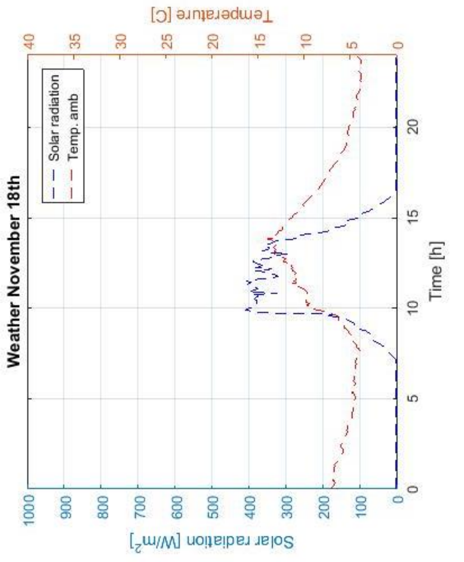
APPENDIX E / PLOT SOLAR AND TEMPERATURE DATA

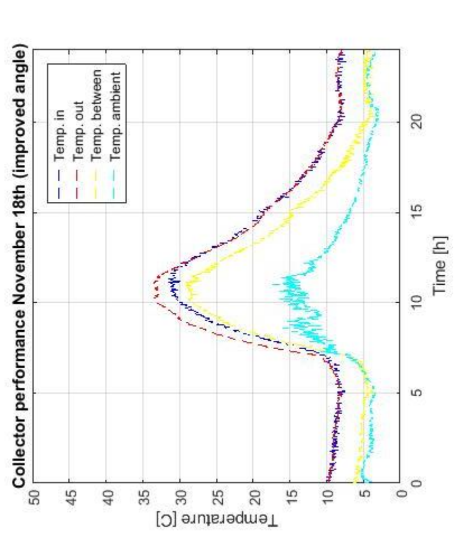












APPENDIX F / DIAGRAM ANGLE ADJUSTMENT