Solar Thermal Heating

Final Report

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EXECUTIVE SUMMARY

The NAU Solar Thermal Capstone team has been tasked with designing a solar thermal heating system for the engineering building on campus. This design must be capable of offsetting all, or a large quantity, of the load used to heat the engineering building year round. This design must pay itself off against costs of carbon emissions and energy usage within 5 years. Assuming the design meets the standards and offsets reasonable carbon emissions, the design may be replicated on similarly heated buildings on NAU's south campus. The current system in place for all buildings' heating on NAU's south campus utilizes a central boiler plant which distributes high temperature hot water (HTHW) to each building's internal hydronic loop; thus providing hot air through a heat exchanger. To offset this, the team initially must consider whether their design will be integrated as a preheater for the current system or in parallel with the current system. Should this design be integrated as a preheater, it will only offset the building's load without rendering the centralized boiler units unnecessary. This system is beneficial in case the designed solar system does provide satisfactory energy and heating. Running the solar system in parallel will allow the designed system to take over all hot water for the internal hydronic loop and completely covers the offset of the central boiler unit.

The team utilized multiple references to approximate the potential returns of the design. The team used the Solar Redbook irradiance data to get a rough estimate of the heating we could expect. The numbers appeared to be too high, so the team moved on to other resources. The System Advisor Model, which simulates the net returns of a solar thermal heating system using collected irradiance data from NREL, and factors in heating losses. The results from this simulation showed a much lower return than the team was hoping for. This prompted the team to develop an experiment to determine the real returns that the team can use in the proposal. The team acquired an out of use Solar Thermal panel from a previous project to use in the test. The experiment consisted of pumping water through the Solar Thermal panel and measuring the temperature and pressure change through the panel and extrapolating that data to a larger system.

After testing the panel on multiple days, the data showed that the team would need 518 panels in order to meet the heating and flow rate requirements. This is problematic as there is only space for at maximum 180 panels. On top of that, the current cost of heating the building was found to be just under $111,000 annually using natural gas and implementing the 180 panel maximum was estimated to cost upwards of $1,000,000. With this in mind, the team saw fit to propose this data for a future project when the financial and economic returns are more fruitful. The entirety of the team's research and effort is outlined in this final proposal.

ACKNOWLEDGEMENTS

The NAU Solar team would like to acknowledge Dr. Jennifer Wade, Dr. David Trevas, Dr. Sarah Oman, David Willy, and Jon Heitzinger for their dedication to this project and their willingness to work with the team to help develop a successful solar thermal system while ensuring the team had the necessary resources to accomplish their goals.

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1 BACKGROUND

1.1 Introduction

Our team has been tasked with developing a solar thermal heater of a hydronic loop running through the engineering building on NAU's campus. The solar panels will be utilized alongside a boiler's HTHW line to provide heating to the engineering building. Upon completion, the carbon footprint of NAU's campus will be reduced, working in accordance with the goals of the project's sponsor: NAU's Green Fund. These solar panels have the potential to not only reduce the carbon footprint of the campus, but also lower the cost required to run the natural gas boilers, thus lowering the long-term costs of natural gas. Assuming this solar system works to our anticipated standards, similar systems will be implemented on multiple other buildings on campus, overall reducing the carbon footprint significantly, aiding in the prevention of the current global warming crisis.

1.2 Project Description

As designated by the sponsors of this project, the team is tasked with the following.

> "NAU is committed to lowering our impact on the local and global environment. The University community is currently undergoing a process to create an updated Climate Action Plan, with the primary goal of becoming carbon neutral while remaining financially sustainable as an institution. While our electricity loads could be met with renewable grid electricity, renewable heating is a bigger challenge. Most campus operations use centralized natural gas boilers to generate steam (North Campus) or high temperature hot water (South Campus). This high thermal energy fluid is then pumped to different buildings around campus where it passes through heat exchangers to transfer the thermal energy to secondary building hot water loops (hydronic loops)."

In summary, in accordance with NAU's goal of becoming carbon neutral and initiating their Climate Action Plan, the team must attempt to solve renewable heating, in this case through solar panels to offset the load to the central boilers.

2 REQUIREMENTS

2.1 Customer Requirements (CRs)

The requirements denoted in the project statement include lowering the overall carbon emissions by the university, cost effectiveness, current-system integration, and self-sustainability. NAU's GreenFund and Climate Action Plan strive to lower the university's effect on global carbon emissions, and as such our team has been tasked with aiding this goal. We must design a solar thermal heating system to reduce the demand for the boiler systems currently in place without completely redesigning the hydronic loop of the building. Finally, the solar panels must offset enough of the building's energy demand to run throughout the day using only heat generated by the solar panels.

2.2 Engineering Requirements (ERs)

In order to offset the demand by the central boiler system, our team had to analyze the current demand and consumption trends. Throughout the daytime of the year's lowest solar irradiance, an average of 1.4 MMBTUs/hr is required, and as such this is the target for the solar system being designed. Similarly, in accordance with the current pumps and hydronic loop, a temperature change of 40℉ must be designed for with a return of 100℉ and a supply of 140℉. The pumps operate at 150 GPM which must be matched and achieved through the solar panels to be designed for without reducing the head by the pumps in place.

2.3 Functional Decomposition

The primary function of the installed design is demonstrated below in figure 1. It needs to be able to heat the water to the necessary output from a necessary input all while maintaining the flow rate dictated on the functional decomposition below. In completing the design and testing phases, we have determined the functions of the project have not changed. Our goal is to match the 150 GPM flow rate denoted in the functional decomposition below, however we have determined that the selected panels may not reach this. In lieu of this, a percentage of the flow may be diverted through our panels to compensate for the lower flow rate.

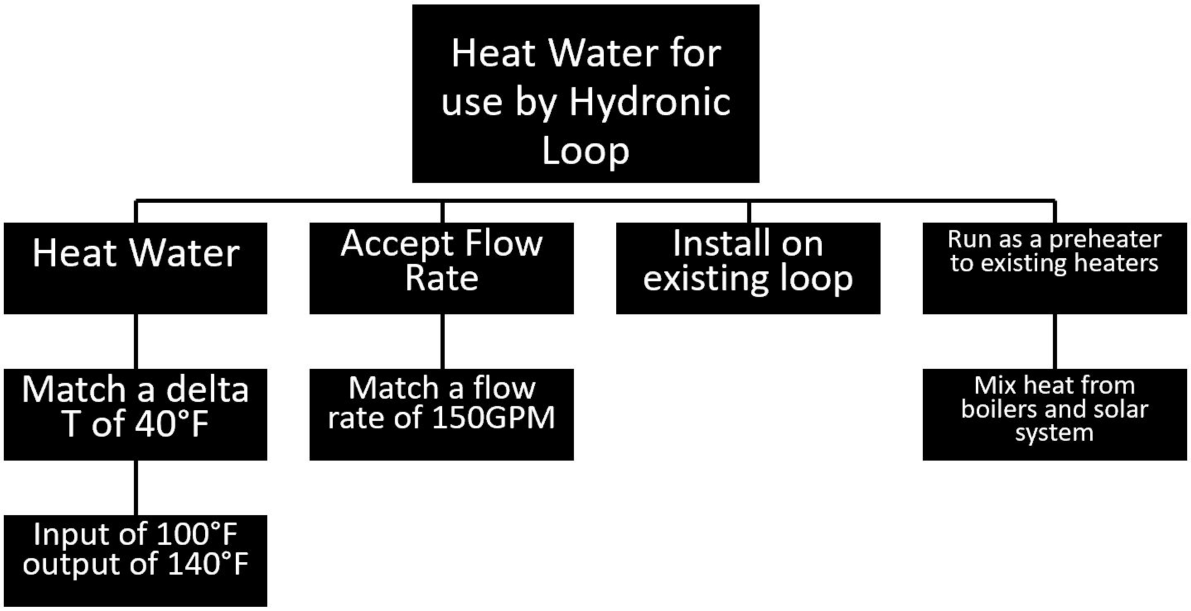


Figure 1. Functional Decomposition

2.3.1 Black Box Model

The Black Box Model in figure 2 depicts the primary function of the system, heating water, along with the ingoing and outgoing signals, materials, and energies. The only material entering the system is a water/glycol mix as there is no human interaction here. The energies going in come in the form of thermal (heat) energy and radiant energy from the sun. Going out of the system, however, is only thermal energy in the form of heat transfer. Finally, the only signals the system requires to run are electrical signals for the pumps.

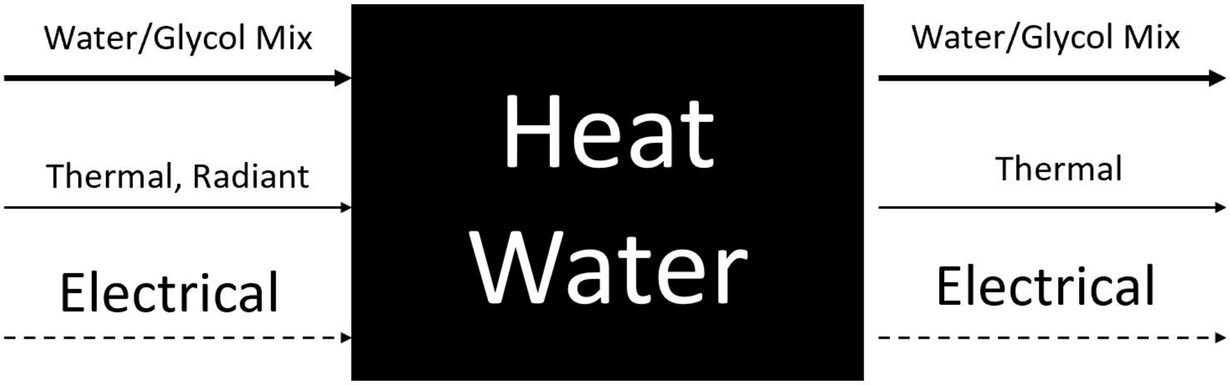


Figure 2. Black Box Model

2.3.2 Functional Model

Figure 3 below depicts the functional model created for this solar system. It details how the various signals, energies, and materials dictated in the black box model are used in every step of the system. This allows the team to more closely analyze each step of the design process to determine feasibility and functionality of different components. Upon final testing and design, this model depicts all relevant processes through the designed system.

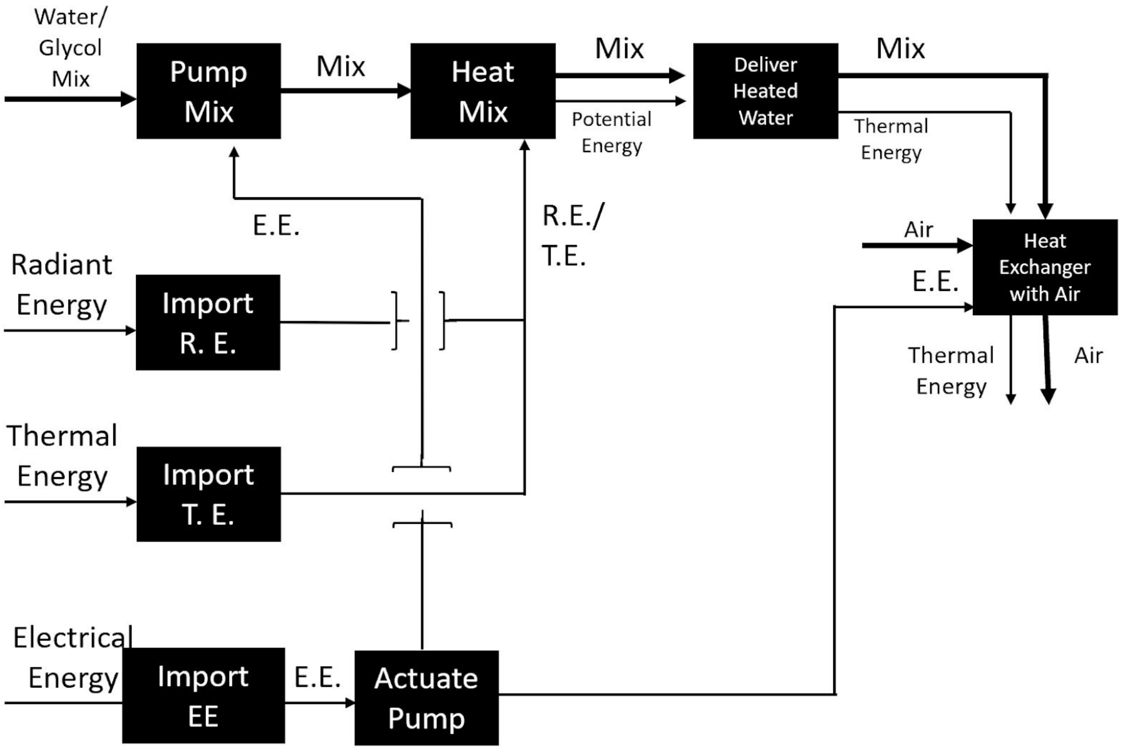
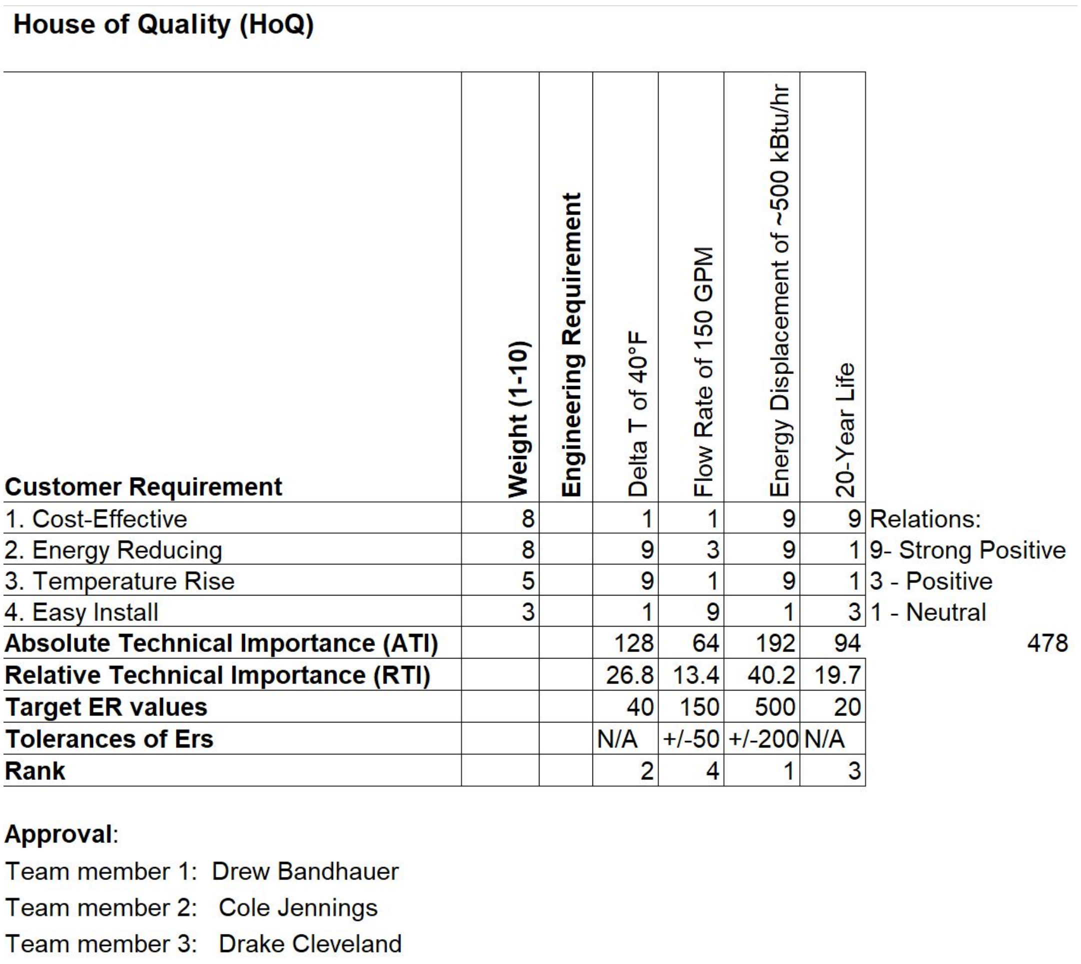


Figure 3. Functional Model

2.4 House of Quality (HoQ)

Figure 4 below demonstrates the house of quality for this project. The only requirements set out for this project include temperature change and flow rate requirements, energy displacement for the boiler, and a lifespan of 20 years. All of these requirements contain a large tolerance except the temperature change as this is the only requirement needed to ensure the engineering building operates as normal. To test these, the team acquired a panel consistent with those being used on the building itself, and ran water through the panel over a 7 hour period. Thermocouples were used to attain inlet and outlet temperatures.



House of Quality (HoQ)

Customer Requirement	Weight (1-10)	Engineering Requirement	Delta T of 40°F	Flow Rate of 150 GPM	Energy Displacement of ~500 kBtu/hr	20-Year Life	
1. Cost-Effective	8		1	1	9	9	Relations:
2. Energy Reducing	8		9	3	9	1	9- Strong Positive
3. Temperature Rise	5		9	1	9	1	3 - Positive
4. Easy Install	3		1	9	1	3	1 - Neutral
Absolute Technical Importance (ATI)			128	64	192	94	478
Relative Technical Importance (RTI)			26.8	13.4	40.2	19.7	
Target ER values			40	150	500	20	
Tolerances of Ers			N/A	+/-50	+/-200	N/A	
Rank			2	4	1	3	

Approval:

Team member 1: Drew Bandhauer
Team member 2: Cole Jennings
Team member 3: Drake Cleveland

Figure 5: House of Quality

2.5 Standards, Codes, and Regulations

The team has done extensive work with heat transfer calculations to determine the necessary production of solar panels to ensure the building will be properly heated. Because of the importance of these calculations, the team utilized multiple ASTM standards regarding heat transfer and solar energy to properly understand the background of the calculations and their accuracy. The first standard described in Table 1 below outlines specific terminology used in solar energy and their definitions. The team previously had an understanding of solar energy and heat transfer concepts, but this standard allowed the team to improve on their prior knowledge of the subjects.

Additionally, the team found a guide to analyzing heat transfer fluids in terms of its movement through a pump. This will be useful when the team tests the solar panels for their production. The majority of the team’s work revolved around understanding heat transfer in solar thermal applications, and this standard could potentially be a useful guide to understanding how liquid may react through the tube while it is being heated.

Table 1: Standards of Practice as Applied to this Project [1]

Standard Number or Code	**Title of Standard**	**How it applies to Project**
ASTM E772-15	Standard Terminology of Solar Energy Conversion	Helps when the team is researching solar energy and developing an understanding of its different factors.
ASTM D8046-16a	Standard Guide for Pumpability of Heat Transfer Fluids	Useful tips for analyzing the fluid in the panel system

3 DESIGN SPACE RESEARCH

The following section describes the research conducted by the team throughout the duration of the project to develop a solar thermal system.

3.1 Literature Review

The most useful piece of literature used by the team in the first semester of the project was a design guide used by the U.S. Army for solar hot water systems [2]. This detailed guide walked through the process of designing a hot water system similar to the one that the team was assigned to create for the capstone project. To better understand the process of using solar energy for heating in a building, the team reviewed the guide thoroughly. The team was able to gain an understanding of how the time of year, placement of the array of collectors, and solar radiation can affect the efficiency and production of a solar system at any given time.

Additionally, the same guide described different types of solar systems and their specific functions, from which the team could determine which particular system was most fitting for the project. From this document, the team concluded and confirmed that the use of evacuated tube collectors would prove effective with the Flagstaff climate, the cost effectiveness of the collectors, and the overall requirements given to the team. This allowed the team to continue with the evacuated tube panel that was used in a previous project at NAU to work with and focus the design on.

Once it was determined that the panels being used were the SunMaxx VHP30 solar collectors, the team researched the specifications of the panel and heavily utilized the SunMaxx Solar Thermal Collectors Technical Reference [3]. This manual provided specifications for many types of their products along with descriptions of their functions and production rates. These specifications for the collector were used as a base for testing to understand how the Flagstaff climate would affect the panel with respect to its anticipated production.

For this project, the types of literature found to be most useful were technical guides that could describe the inner workings of solar heating as well as specific production that could be expected from the system. The team utilized the researched literature to fully develop the solar system that could fit the project's needs while being able to understand details of the system that needed to be accounted for.

3.2 Benchmarking

The team has built on the research of past and current solar thermal projects in order to propose a competent design. Using this information to the team's advantage is called benchmarking, and is a tool commonly used by practicing engineers and researchers in general. Benchmarking for the scope of this project will require an entire system analysis, as well as subsystem analysis. The system analysis will consist of an analysis of a design as a whole in order to get a better idea of what to expect from the team's proposed design and what it should accomplish. A subsystem analysis looks at the components of the system and the roles each component plays. The results from the benchmarking was that the ideal design will include a non-concentrating solar panel, piping that is in series with the heat exchanger, and a control valve to be used to regulate the amount of hot water that flows to each level's heat exchanger.

3.2.1 System Level Benchmarking

For the benchmarking analysis, the team looked at multiple examples of existing water heating designs in the real world. The first system analyzed took place on NAU's own campus and has already been a huge point of reference for the project thus far: the HLC Solar Thermal System. While the project was unsuccessful, the team still has plenty to take away from it, especially where the project went wrong. Using the stepping stones and data collected from this system has been crucial to the team's success thus far and will continue to be going forward. Another point of reference the team looked at is the current production and cost of NAU's Natural Gas Heating Plant. The information gathered from this analysis was crucial to determining the viability of the project as a whole.

3.2.1.1 Existing Design #1: NAU HLC Solar Thermal System

The NAU HLC Solar Thermal system has been the biggest point of reference so far, as the design was implemented less than a mile away from the engineering building. Much of the data accumulated for the HLC can be directly applied to this project because they are so similar overall. The designs are so similar that the team has actually been using the specifications of the HLC panels to determine base calculations until the proposed solar panels can be decided on. The only real difference is that the HLC planned to use the water domestically instead of for heating. The target amount of water for the HLC project is admittedly lower than the amount the team plans for the engineering building. However, the HLC design failed due to an excess of hot water that essentially fried the system. What our team can learn from this project is that even though we don't expect to be able to fulfill the entire demand of hot water for the building, it is crucial to consider that the design may still fail from an overload at any time. While the team will be able to determine the highest amount of heat the system can provide based on past data, the future is unknown and the design should be able to handle a variety of different circumstances. Because of this, the team will include a heat exchanger to air that is connected to the control and balance valves in the proposal to ensure that this does not happen. With this in the proposal, the design will not fail due to overload.

3.2.1.2 Existing Design #2: Natural Gas Heating Plant

In order for the design to meet the Customer and Engineering Requirements, the design must provide enough in savings to pay itself off within 5 years. The building currently demands an average of 1.4MMBTU/hr to provide sufficient heat. Natural Gas is currently priced at \$14.47/MMBTU []. This means that the currently average hourly cost to heat the building is \$20.26. Assuming a daily heating time of 15 hours, the annual heating cost for the Engineering building is \$110,924. In order for the design to pay itself off within 5 years, the design must cover the entire heating load and cost less than \$554,620, in materials and implementation.

To cover the entire heating load, not only does the design have to meet this 1.4MMBTU/hr average, it must exceed it to account for especially cold days. According to figure X in Appendix B, the peak demand for heating is 2.1MMBTU/hr, 50% higher than the average heating cost that the team is targeting. While the team would like to be able to cover all heating costs, it will likely be more cost effective to aim for the average instead of aiming for the max. That way, the team isn’t over designing and implementing more panels than necessary. Designing for the max load will result in heat being dissipated for most of the year to avoid the same failures as the HLC project.

3.2.2 Subsystem Level Benchmarking

A subsystem analysis involves researching the different components within a system and determining all reasonable alternatives. The entire Solar Thermal system can be broken down into three main components: solar panels to collect the radiation from the sun, piping to deliver water to and from the solar collectors, and the valves required to control the flow rate of hot water into areas of need. The best possible combination of these components will be proposed at the team’s design to offset the most amount of natural gas possible.

3.2.2.1 Subsystem #1: Solar Panels

The team’s entire proposal revolves around the specs and orientation of the solar panels. Per the customer requirements, a sufficient amount of hot water needs to be supplied to offset the natural gas demand from the engineering building. Solar Thermal panels are how this will be achieved. The team researched 3 variations of solar thermal panels in order to determine the best fit for the proposed system. These variations include: evacuated tube collectors, flat solar collectors, and concentrating solar collectors. Each variation is discussed at length below.

3.2.2.1.1 Existing Design #1: Evacuated Tube Solar Collectors

Evacuated tube solar collectors utilize parallel rods that are insulated by cylinders of glass. The rod core is generally made of a metal with high thermal conductivity, such as aluminum. The cylindrical shape of the rods and glass insulators allow for more normal thermal radiation as the sun moves throughout the day. Within the rods, there is a heat transfer fluid, alcohol or glycol mixture that vaporizes quickly, that moves heat up the rod to the manifold. The water supply passes through this manifold and captures the heat from the manifold. These panels are the most practical options for industrial and commercial settings due to the amount of heat these panels generate. This will also be the most expensive option per panel.

This is the design the team ultimately moved forward with as the evacuated tubing option will provide the most heat. The cylindrical shape of the rods will allow the most amount of radiation to be captured throughout the day, which is something the team prioritized.

3.2.2.1.2 Existing Design #2: Flat Panel Solar Collectors

Flat Panel Solar Collectors are essentially insulated boxes that contain an absorber plate under multiple layers of glass or other clear insulation panels. The water passes through this box and collects the heat insulated by the panel. These panels can have piping through them, or water can travel freely through them, depending on the orientation of the panel. These panels are generally used for residential applications to save money on water heating.

From the research conducted on this type of panel, supplying the heat and flow rate required by the building will be a massive stretch for these solar panels. While these panels are practical for smaller applications, they simply will not work with a project of this scale.

3.2.2.1.3 Existing Design #3: Concentrating Collectors

Concentrating Collectors capture the heat from the sun and direct it to the focus point of the curve. These designs are often tracking and are excellent when trying to raise the temperature of a small area drastically. These designs don't capture heat, but instead redirects all the heat captured to a single point, the focus.

While this design will likely handle the team’s target change in temperature of 40 degrees celsius easily, the design would have to be tracking because the design can only capture direct radiation. This would lead to a significantly lower amount of heat compared to a non-tracking non-concentrating collector. Because of this, the concentrating solar collector will be insufficient for the proposed design and the team will no longer be able to consider it because the customer has required that the design be a fixed design.

3.2.2.2 Subsystem #2: Building Piping

One of the last major issues that the team faced is determining whether or not the amount of heat the system can provide is worth heating rooms on its own. If the solar panels can’t provide enough heat for the building during the day, the system may run more efficiently as a pre-heating option for the heat exchanger to take off some of the load from the natural gas plant. If the building can be completely heated during the day from the panels, the efficiency will be greatest if the piping runs in series with the heat exchanger as one big hydronic loop. Each of the options will be discussed further below.

3.2.2.2.1 Existing Design #1: In-Series

If the solar panels can heat the water enough to provide sufficient heat throughout the day, then the piping should be run in-series with the heat exchanger. This will be the cheapest and most efficient option for the proposal so this is definitely what the team is hoping for. Running the piping in series with the heat exchanger could shut off the demand for high temperature hot water from the natural gas plant during the day. On top of this, the cost for implementing the pipe needed would be much cheaper as the existing pipe could just be added onto to include the solar panel loop.

3.2.2.2.2 Existing Design #2: In-Parallel

If the design will not provide sufficient heat during the day, the team may have to implement the solar panels a different way. Instead of the water from the solar panels heating the building directly, a separate loop may need to be put in place to act as a preheat for the building’s return water supply. In this case, the water from the solar panels would need to be piped down to the basement and heat the return water supply before it enters the heat exchanger. This will still take a lot of the load off of the natural gas plant, but the piping will be an issue. The team will have to determine how to fit an entire new loop of piping alongside the existing piping. This will be both difficult and much more expensive. If the team needed to move forward with this design, the cost would skyrocket when considering materials and labor. This would not be an ideal case for the team, but it is a solid backup plan for the project to move forward with.

3.2.2.3 Subsystem #3: Valves

Control and Balancing valves are used to determine the amount of hot water delivered to certain areas once the water has been heated from the solar panels or heat exchanger. These devices are often overlooked in the design process, but are perhaps the most important component of the design. If the needs for each room continues to change, it might be worth implementing both valves into the design.

3.2.2.3.1 Existing Design #1: Balancing Valves

A balancing valve is a valve that is often used in hydronic loops to ensure optimum flow rate. It does this by creating a consistent output pressure from an inconsistent input pressure. This will be useful in our design because the flow rate changes variably, so having a valve such as this would create a consistent output pressure. This is the type of valve that will be ideal in the pre-heat design as the amount of heat will change throughout the day and will allow the design to work optimally. When the design is producing the most amount of heat, this will cause the building to call for less heat from the heating plant.

3.2.2.3.2 Existing Design #2: Control Valves

The purpose of a control valve is to regulate flow based on a set input. These are very common in hydronic loops because they will continue a certain flow rate until room conditions have been met. This is perfect for what the design requires because this will regulate the flow rate of hot water automatically until the room conditions are met. This valve would work best with the design in series with the heat exchanger. With the design set in series, the flow through the building is going to need to remain constant. A control valve will ensure that this is the case.

4 CONCEPT GENERATION

4.1 Full System Concepts

The following sections include designs developed by the team. The system must be careful not to be over-designed and must be easily installed in conjunction with the existing system.

4.1.1 Full System Design #1: Solar System in Parallel

The first concept under consideration is our ideal circumstance. This involves running the solar panels and boilers in parallel, allowing the water to be sent from the return line directly to the solar panels then back through the building with a similar set-up to the boilers and heat exchanger. Doing this would allow the full daytime load of the boilers to be offset by the solar panels, reducing the carbon footprint and natural gas cost by the boilers to the best of our ability.

4.1.2 Full System Design #2: Solar System in Series

The second concept involves running the solar panels in series with the boilers rather than in parallel. Under this circumstance, the solar panels serve as preheaters for the boilers. This keeps the boilers running throughout the day, but lowers the amount of heat needed by these boilers, still lowering the carbon footprint and cost of natural gas but not to the same extent as running them in parallel.

4.2 Subsystem Concepts

4.2.1 Subsystem #1: Solar System

4.2.1.1 Design #1: Panels in Parallel

This subsystem regarding the solar system deals with the solar panels used and analyzed by the existing project atop NAU’s Health and Learning Center (HLC). These panels can handle a flow rate of 0.84 GPM with a temperature change of 20℉. As such, this design features 180 solar panels in parallel with 1 in series - accommodating our required 150 GPM flow rate. While this design works well with the flow rate, it does not adhere to the 40℉ temperature change we need to design around.

4.2.1.2 Design #2: Panels in Series

This subsystem explores using the solar system as a preheater for the boiler system. This allows the team to design a system which generates nearly enough temperature and a lower flow rate to be integrated. In this case, the water will be warmed at a lower flow rate and deposited into the return line to be heated further, thus offsetting the total load by the boiler system.

4.2.2 Subsystem #2: Piping System, Pumps

4.2.2.1 Design #1: Design Integration

The first design regarding the piping system and pumps involves retaining the same pump already in place while tapping into the third-floor piping. This system serves as the easiest install, however we must first analyze the pump’s head and ensure the head loss through the panels won’t be too much for the pump.

4.2.2.2 Design #2: Pump Redesign

This design retains the piping through the building with a T-tap on the third floor. This case assumes the piping through the solar panels will increase the head loss past what the current pumps are capable of, and a new pump will need to be integrated to the system.

5 DESIGN SELECTED – First Semester

Because of the changes in the plan for the first semester, the team was unable to develop a complete design for the solar thermal heating system as was originally planned. The scope of the project changed to developing a test of one singular solar panel to test its heat and energy production, only designing a full system if these results may demonstrate some ability to offset significant building load. The team has worked with the selected design to achieve these heat and energy production rates and develop multiple designs for the engineering building to be used when financial feasibility is optimal. The following sections outline these designs and design procedures.

5.1 Design Description

5.1.1 Testing Rig Design

The testing procedure implemented in the fall semester tested the energy rate and temperature changes of the SunMaxx VHP30 panel that was acquired from the HLC project previously conducted. The team developed a detailed 3D model of the testing system, which is shown in Figure 6 below.

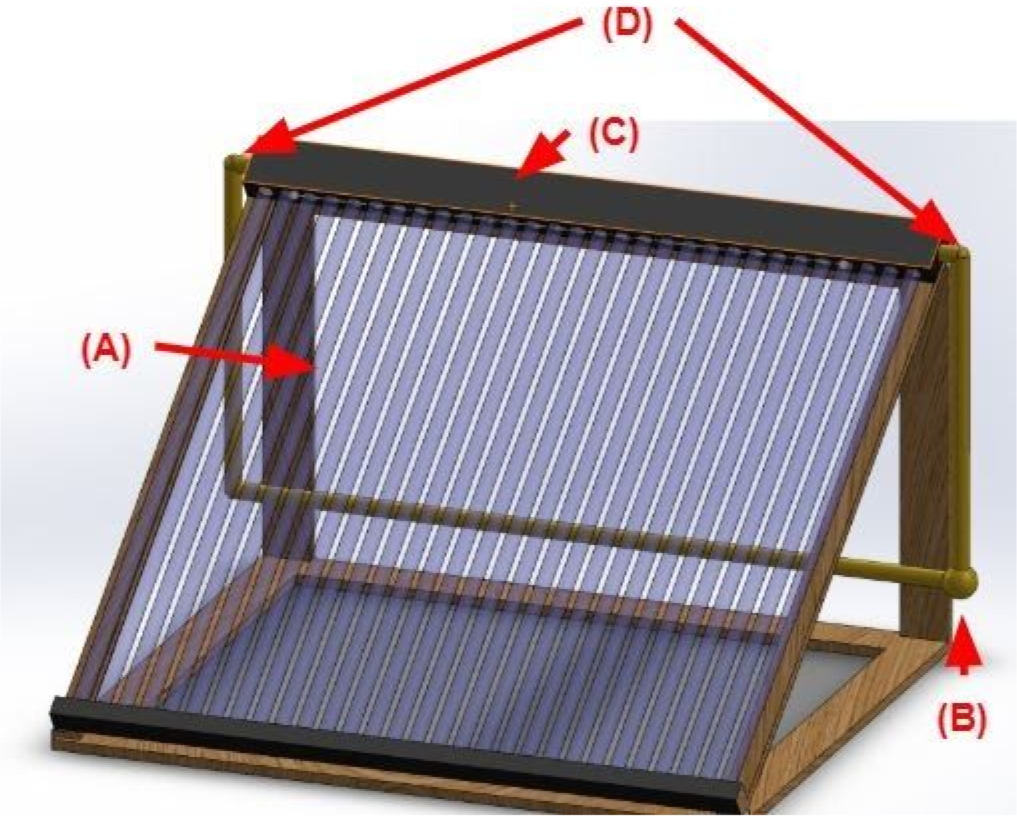


Figure 6. SolidWorks model of testing system

The figure above shows the solar panel fixed to the mounting system that the team constructed. Arrow A shows the panel itself, which will be situated at an angle of 30 degrees above latitude; the optimal angle based on where the sun is most prevalent in Flagstaff during the times the system will require the most light. These are the evacuated tubes that will run through the hydronic loops that will cause the liquid to be heated, resulting in the heat coming out of the system. Arrow B shows the valve was connected to the water pump, where water was pumped into the panel system to be heated. Arrow C is the manifold that operates as a heat exchanger to heat water from the evacuated tubes to the flow line. Arrows D shows the inlet and outlet valves that were connected to thermocouples and pressure gauge that will measure temperature change and inlet pressure, respectively.

5.1.2 Preheater Design

For integration to the engineering building, the solar system is designed as a preheater rather than completely offsetting the load of the building. In the basement, where the internal hydronic loop begins, a supply line will run through each floor of the building to heat exchangers which provide hot air. A return line will originate on the 1st floor and will run to the top floor and out of the building to the solar system. This return line is then heated through the system and run back to the basement where the boilers will finish heating the water to the desired temperature. The supply line is depicted below in figure 7 as the red pipe, the blue pipe is the return line, and the orange pipe is the preheat line. The grey box represents the solar system, and the lines and solar system meet on the top floor’s heating room.

Figure 7. Preheater Design

5.1.3 Design Funds

The team has developed this testing procedure and conducted it during the fall semester. The team proposed a budget for the system to the NAU Green Fund that, upon approval, allowed the team to be financially reimbursed for the costs of the test. Figure 8 shows the budget the team developed for the testing process.

Item	Cost	Cost (After Tax)
Wood	$112.00	$122.28
Water pump	$119.00	$129.92
hose	$29.97	$32.72
valve	$15.30	$16.70
misc. fittings	$200.00	$218.36
		$519.99

Figure 8. Budget for testing procedure

The team purchased all of the materials in the budget during the summer to ensure the testing process could begin as soon as possible. The budget of $520 accounts for the wood to create the mounting system, a pump that will push water through the system, a hose to connect the pump to the mounting system, and valves and other fittings needed to ensure a proper flow rate of water is being measured.

6 IMPLEMENTATION – Second Semester

6.1 Design Changes in Second Semester

After initial design of the testing rig, the team elected to make various changes to accommodate accurate flow rate and data measurement. To do this, garden hoses have been implemented for cost effectiveness and maneuverability. These garden hoses have been suspended using external supports to ensure the hose allows water to flow freely. Additionally, only an inlet pressure gauge is needed to read pressure as outlet pressure is unnecessary.

6.1.1 Design Iteration 1: Change in piping discussion

Initially, the selected piping for testing is galvanized steel piping. This piping allows for uninhibited flow rate through the testing rig and pump, but due to its rigid nature, does not allow the rig to be maneuvered and therefore does not allow changes to be made in positioning of the pumps and gauges. These issues have been alleviated through implementation of garden hoses suspended by external supports to maintain a consistent flow while also allowing alterations in positioning.

6.1.2 Design Iteration 2: Change in gauge discussion

The first iteration of the testing design features pressure gauges at the inlet and outlet of the solar panel. This presented issues as a result of additional joints in the piping and therefore more risk of leaks. To alleviate this, the team removed the outlet pressure gauge as this information is unnecessary in determining feasibility of the project. The inlet pressure gauge is still included.

6.1.3 Design Iteration 3: Solar array discussion

After acquiring the necessary data, the team determined that the solar panel's energy production rate is lower than expected. The total load required by the engineering building is approximately 1.4MMBtu/hr, whereas each panel only produces approximately 0.027MMBtu/hr. This being said, 518 panels would be required to fully offset the load of the engineering building, whereas the area of the roof and panels only permits 180 panels. Using this maximum number of allowable panels, nearly half of the load may be offset with this design. Other designs yield less of a load offset, but may still prove feasible depending on changing costs for natural gas and carbon emissions. The data provided below depicts the energy outputs graphically where the lowest point is at 9:17AM when the sun is beginning to hit the panel, and the end is where the panel reaches its maximum energy produced.

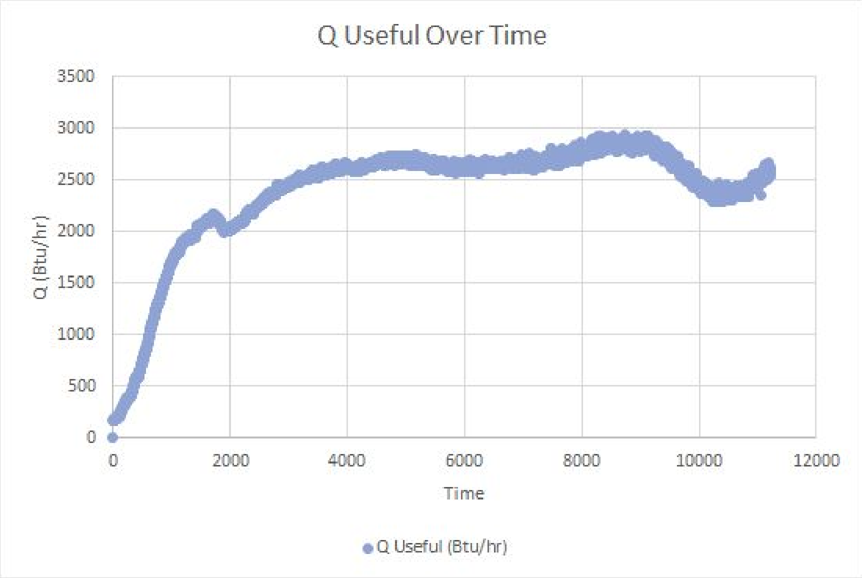


Figure 9. Usable Energy over time

Exploring only temperature outputs, each panel provides approximately a 10℉ rise, yielding a requirement of 4 panels in series to achieve the desired temperature change of 40℉. Figure 10 below shows the inlet and outlet temperatures through the panel, and Figure 11 displays the temperature change.

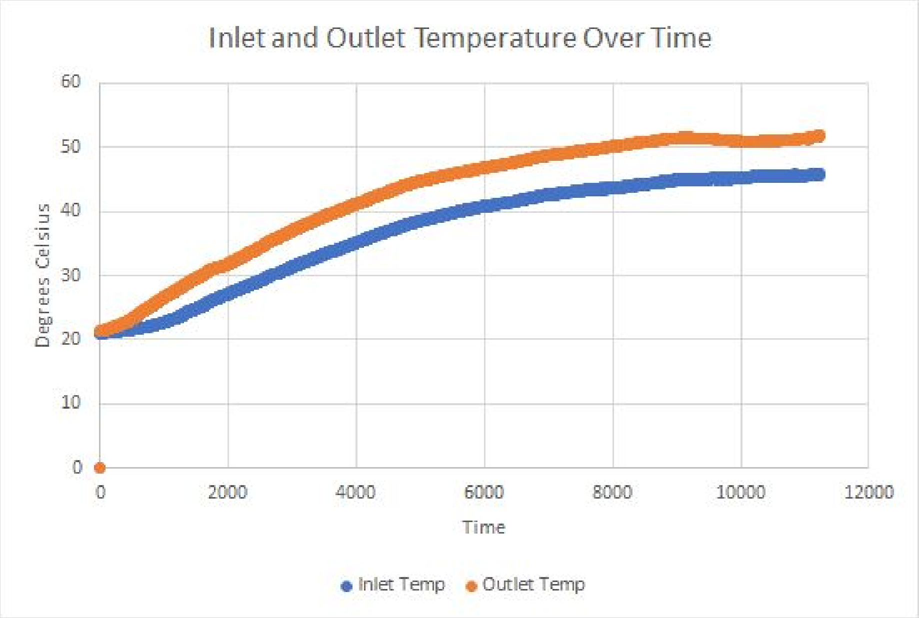


Figure 10. Inlet and Outlet Temperature over time

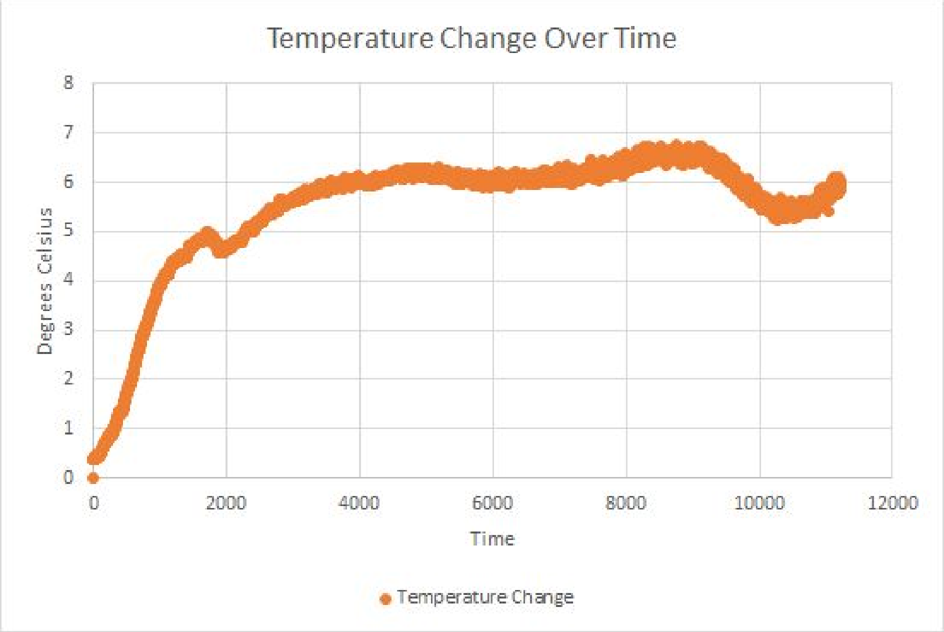


Figure 11. Temperature change over time

Disparities in the data are present and accounted for. The first disparity, consisting of a rapid spike and drop, are a result of abrupt change in cloud cover, yielding a sharp transition of temperature rate of change. The second disparity, a gradual decline in temperature change tending toward a plateau, results in both an increase in wind thus lowering the temperature, and the system beginning to hit its max rate of transfer at nearly 10℉.

7 RISK ANALYSIS AND MITIGATION

7.1 Potential Critical Failures Identified First Semester

7.1.1 Potential Critical Failure 1: Water not reaching required temperature

The water circulating through the panels may succumb to a lack of heat transfer from the panels. This may be the cause of the sun not shining bright enough, the flow rate being too high, or not enough panels existing in series. In order to combat this, the team plans to test a single panel over multiple days and weather conditions to figure out what flow rate is best and how many panels need to be in series.

7.1.2 Potential Critical Failure 2: Water overheating

Similarly to the first failure mode, if the water reaches too high of a temperature, this may cause a multitude of problems. The first of these problems is melting of the piping joints and leaks. To prevent this, the team plans to meet with the install team to ideally have the joints welded, or follow their professional opinion. Another problem that may arise from this is overheating of the air being sent throughout the building causing damages and discomfort for the consumer.

7.1.3 Potential Critical Failure 3: Connections

As mentioned above, the connections to all the panels provides a large point of failure. As there are so many, if one connection does not meet the standards of the design, the whole system may experience failure. These failures may come as a result of over or underheating of the water, temperature and external conditions, or install error. All of these connections will be heavily monitored throughout the first few months of installation to ensure their performance is adequate.

7.1.4 Potential Critical Failure 4: Head loss and pumping

Assuming the piping head loss through the panels does not match the calculations performed by the team, the pump may not be able to match the requirements of the system. This might lead to a lack of proper circulation throughout the building resulting in no heat, or no circulation at all. Both circumstances may overload the pump and result in a large financial burden.

7.1.5 Potential Critical Failure 5: Energy displacement and financial feasibility

As the load of the building remains very high (1.3MMBtu/hr), it is possible that the panels available will not offset enough of this load to financially justify their purchase. If the payback for the panels is not feasible, purchasing them may not be the most sensible decision. If this is the case, the team will continue to design a system for implementation in the future if financial reasonability becomes favorable.

7.2 Potential Critical Failures Identified This Semester

7.2.3 Potential Critical Failure 1: Connections

As mentioned above, the connections to all the panels provides a large point of failure. As there are so many, if one connection does not meet the standards of the design, the whole system may experience failure. These failures may come as a result of over or underheating of the water, temperature and external conditions, or install error. All of these connections will be heavily monitored throughout the first few months of installation to ensure their performance is adequate.

7.2.2 Potential Critical Failure 2: Water not reaching required temperature

The water circulating through the panels may succumb to a lack of heat transfer from the panels. This may be the cause of the sun not shining bright enough, the flow rate being too high, or not enough panels existing in series. In order to combat this, the team plans to test a single panel over multiple days and weather conditions to figure out what flow rate is best and how many panels need to be in series.

7.3 Risk Mitigation

In fully designing and running the test, only two main risks are present: leaking connections and a lack of energy/temperature output. In order to mitigate these, the team began by wrapping all threaded connections with PTFE tape and using a pipe wrench to fully tighten all connections. This alleviated all leaks in the system, leaving only temperature rise and energy output as prevalent risks. This temperature rise proved to be achieved naturally through the system, however, energy output remains an obstacle. This will be dealt with in configuring the system as a preheater so the system does not need to offset the total load, as depicted below in section 6.1.3.

8 ER Proofs

The team met Engineering Requirements for the solar thermal system by testing the existing panel and extracting that data to propose a theoretical array of panels. The three main requirements were achieving a flow rate of 150 GPM, a temperature change of 40℉, and a heat production of 1.4 MMBTU/hr across the array of panels. By performing the panel test, the team was able to account for the three requirements and develop data that could be used to create a full proposal. The test was conducted on a cloudy day that lacked full sun exposure, and it was conducted between 9:17 AM and 12:24 PM. The following section describes the individual requirements and how they were met.

8.1 ER Proof #1 – Flow Rate

To account for the flow rate across the system, the team used the bucket timer method to measure the flow rate of the water that left the system into the hydraulic bench. Figure 12 displays the testing set up where the hydraulic bench can be seen.

Figure 12. Full testing system with hydraulic bench and panel frame

In the hydraulic bench, the water left the hose after being heated in the panel, and the flow rate was measured to be 0.87 gallons per minute (GPM). Because flow rate will increase with more panels in series, this flow rate can be accomplished by

8.2 ER Proof #2 – Temperature Change

The temperature change was measured in the test by using the LABVIEW software that was connected to thermocouples at the inlet and the outlet of the panel. Figure 13 and Figure 14 show the LABVIEW setup and the thermocouples attached to the testing system.

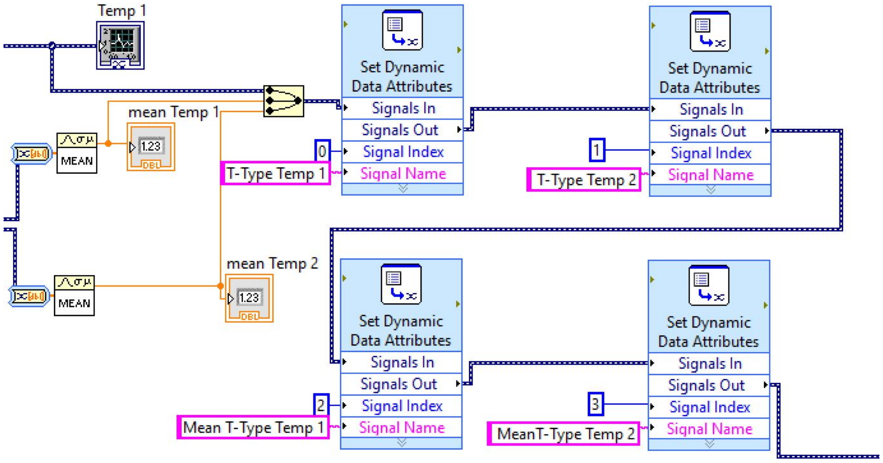
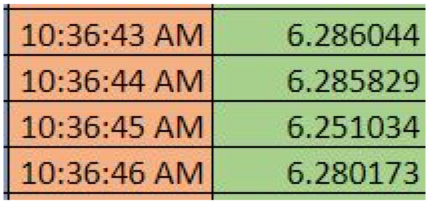


Figure 13. LABVIEW setup for temperature measurements

Figure 14. Thermocouple and Pressure Gauge at inlet of panel

From the temperature test, it was determined that the temperature change surpassed 42 degrees Fahrenheit at its peak. By this measurement, the panel system would be able to account for the temperature change necessary to heat the water for the Engineering building.

Figure 15 shows the data collected with the LABVIEW software that was converted to an Excel file. The temperature was originally recorded in degrees Celsius, shown in the green column. Figure 10, shown within the results of the report, shows the data graphed over time



10:36:43 AM	6.286044
10:36:44 AM	6.285829
10:36:45 AM	6.251034
10:36:46 AM	6.280173

Figure 15. Temperature measurements during the test.

By using the LABVIEW software for the temperature measurements, the team found that the panels were able to meet the requirement easily.

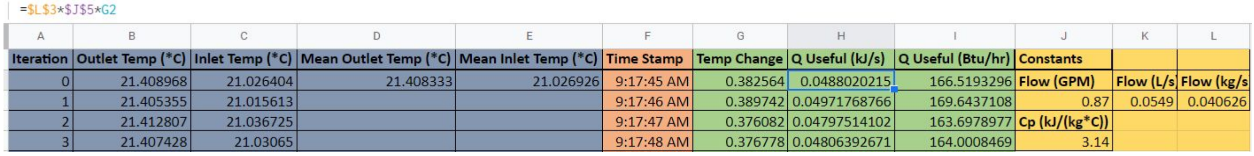
8.3 ER Proof #3 – Heat Output

The team also tested the heat output by calculating the Useful Heat during the test. This calculation was done with the following equation shown in Figure 16.

$$Q = m \cdot C_P \cdot dT$$

Figure 16. Heat equation used to calculate useful heat

In this equation, mass flow rate of the water is multiplied by specific heat of the water as well as the water's change in temperature. From this, values were calculated in Kilojoules per second, which was then converted to BTU per hour (BTU/hr). This data was calculated in an Excel sheet, where the formula can be seen in Figure 17.



```
=$L$3*$J$5*G2
```

A	B	C	D	E	F	G	H	I	J	K	L
Iteration	Outlet Temp (*C)	Inlet Temp (*C)	Mean Outlet Temp (*C)	Mean Inlet Temp (*C)	Time Stamp	Temp Change	Q Useful (kJ/s)	Q Useful (Btu/hr)	Constants		
0	21.408968	21.026404	21.408333	21.026926	9:17:45 AM	0.382564	0.0488020215	166.5193296	Flow (GPM)	Flow (L/s	Flow (kg/s
1	21.405355	21.015613			9:17:46 AM	0.389742	0.04971768766	169.6437108	0.87	0.0549	0.040626
2	21.412807	21.036725			9:17:47 AM	0.376082	0.04797514102	163.6978977	Cp (kJ/(kg*C))		
3	21.407428	21.03065			9:17:48 AM	0.376778	0.04806392671	164.0008469	3.14		

Figure 17. Excel sheet and formula for heat equation

From the short testing conducted, the panel produced a peak of close to 2900 BTU/hr. This data shows that if this is the expected heat per panel, it would take approximately 480 panels to account for the full 1.4MMBTU/hr. However, it is believed that a system could be created that could offset a significant portion of the load that is being heated by the current system.

In conclusion, between the three main Engineering Requirements, it is clear that a solar thermal system could be implemented that would make a substantial impact on the building's heating supply while doing so in an environmentally conscious manner.

9 Future Work

The NAU Solar team was able to develop conclusions regarding the solar thermal heating system and its place within NAU's campus. By testing the solar collectors, calculating the potential heating production, and comparing it to the heating demands of the Engineering building, the team developed a theoretical system that could be installed. As discussed in the results section, the system does not appear to meet all of the requirements as desired by the school at the beginning of the project. To approve upon the design, future teams can extrapolate the data developed and propose a system that offsets parts of the load to an extent that will prove to be cost effective. With the current cost of heating the building from natural gas, the project will never be viable financially.

Another potential way to improve the system without changing the design would be to investigate the use of larger panels that can collect more radiation to convert it to heat. As stated, the design currently does not provide enough heat to offset the heating demand of the Engineering building due to the production of a single panel, as determined by the team's testing. By simply upgrading the panel being used, more production could be expected. The NAU Solar team worked exclusively with the panel they chose due to its accessibility from the previous project on the HLC. It is feasible that with a more productive panel built for more large-scale systems, more production would be seen and the project could be further carried out.

Aside from solar panels, another direction the university can take to reduce the demand from the heating plant would be a Geothermal Ground-Source Heat Pump. These heat pumps utilize Earth's near infinite ground heat as a source of building heat. Just under 5 feet below the surface, the ground is a constant temperature around 55°F deep into the Earth's crust. Piping carrying refrigerant can be orientated either horizontally or vertically in the ground, depending on available space. The piping system can be built any size to support the needed flow rate to heat the building. While this option is likely to be expensive, it will not be limited by roof space. Therefore, this system can be designed large enough vertically to accommodate the entire heating demand of the building.

10 CONCLUSIONS

Throughout the course of the capstone project, the NAU Solar team was able to conduct research, perform tests, and develop conclusions about the feasibility of a solar thermal system on the roof of the Engineering building. The following section outlines the final reflection and analysis of the project and its results.

10.1 Reflection

During the Spring and Fall 2020 semesters, the NAU Solar capstone team aimed to develop a solar thermal heating system for the Engineering building at NAU that was able to promote environmental sustainability while demonstrating the potential to be cost-efficient. The team created a proposed system that could provide the necessary temperature change and flow rate to heat the building, with the only shortcoming being the heat energy being produced by the panels. These engineering requirements guided the project as the team aimed to create the system.

To account for the safety requirements, the team studied the existing plumbing system of the building, the weight capacity of the roof, and the standard codes for installing solar panels in Coconino county. By doing so, the final proposed design will fit under those constraints and can be safely installed and maintained.

Aside from the engineering requirements stated above, the project provided the opportunity to create a system that would work towards decreasing the carbon footprint at NAU. By utilizing the solar radiation in Flagstaff to provide heat during the year, the system serves as an example of how NAU can promote environmental consciousness and potentially expand this system to other buildings across camping. By working in the field of environmental sustainability, this capstone project promotes the idea of utilizing solar power for heat and other forms of energy. Solar power is a relatively underutilized form of energy that has the potential to clean the air of the Flagstaff community, and the NAU Solar team was proud to work on a project that promoted its use.

10.2 Post Mortem Analysis of Capstone

The following Post Mortem Analysis describes the successes and áreas of improvement of the team throughout the project. The team used tactical strategies to ensure the project maintained a level of structure and organization that ensured the project could result in viable results.

10.2.1 Contributors to Project Success

At the beginning of the project, the team outlined a specific purpose and goals that could be attained by the project’s completion. The team followed the Charter closely to maintain their original roles and ensure responsibilities were equally distributed. Ground rules were followed regarding communication, conflict management, and workload, which allowed the team to work coherently throughout the year.

The ground rules explicitly stated that the team would remain in contact throughout all the decision making and design processes. By maintaining this constant communication, the team was always able to be on the same page when working.

Due to the extenuating circumstances surrounding the Spring semester, the team was unable to meet the goal of implementing the heating system over the summer. Testing became the new priority for the Fall semester, so the team designed a test to determine the effectiveness of the solar panel model the team plans to use. The second half of the Spring semester was centered on finalizing calculations for energy output and temperature change, designing a test for the solar panel, and applying for funding from the Greenfund so the test could be conducted in the Fall semester.

The Fall semester focused on testing the single panel that was obtained from the HLC project, which allowed the team to save money and time that would have been spent acquiring a panel for testing and research. After designing a test procedure, building the frame and system, and running the test multiple times, the team was able to gather data and extrapolate the results to develop the final proposal. The team's time management and efficiency allowed all of this to be accomplished in a timely manner. The time management, communication, and dependability of each team member was a significant factor in the success of the project.

The team also developed an extensive understanding of solar heating along with thermodynamics principles throughout the project. These topics will be useful in the future in the field of Mechanical Engineering for each team member. Additionally, technical skills learned include LABVIEW software, increased use of SolidWorks modeling, data manipulation and forecasting of datasets. The team is confident that the project yielded a successful product while serving as an opportunity to further develop experience in the world of engineering.

10.2.2 Opportunities/areas for improvement

The team has identified tangible areas for potential improvement based on the results of the project. The most notable source of negative performance is in regards to the schedule change due to the pandemic. Because of this, the team needed to push back testing to the fall semester and had to change the goals of the project. Initially, the team aimed to test the panel in the Spring semester and attempt to implement the physical system during the summer, which would leave the Fall semester for testing the actual system. The team adjusted well to the changes and was able to successfully test the panel and obtain data from it during the Fall.

Aside from the schedule, the team determined that the design could be improved by providing more detailed information regarding other aspects of the project such as budget, installation processes, and maintenance information. While this information is attainable, the team's main focus was manipulating the data and producing a proposal surrounding it. By providing additional information to a future group wanting to implement the design, the team would have eliminated work to be done. The team would recommend that a future capstone team continues upon the progress made to fully account for the outside details and potentially install the system.

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12 APPENDICES

12.1 Appendix A: Plumbing Designs

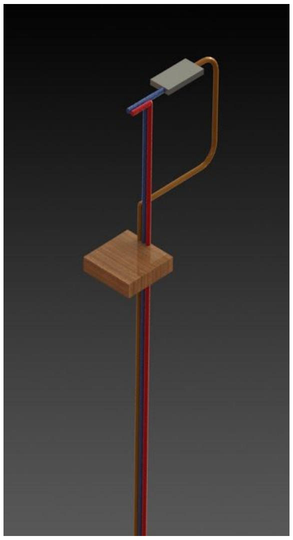

Figure 18. Series Design

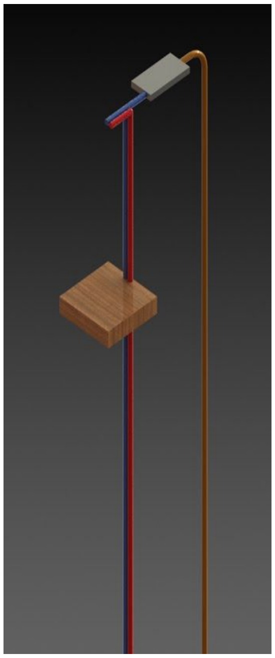

Figure 19. Parallel Design

12.2 Appendix B: Energy and Temperature

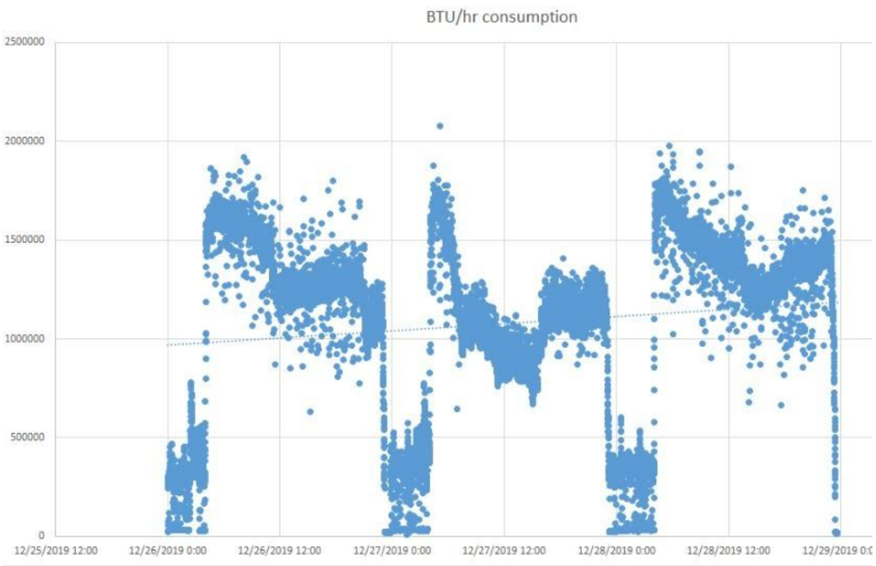

Figure 20. Building Load

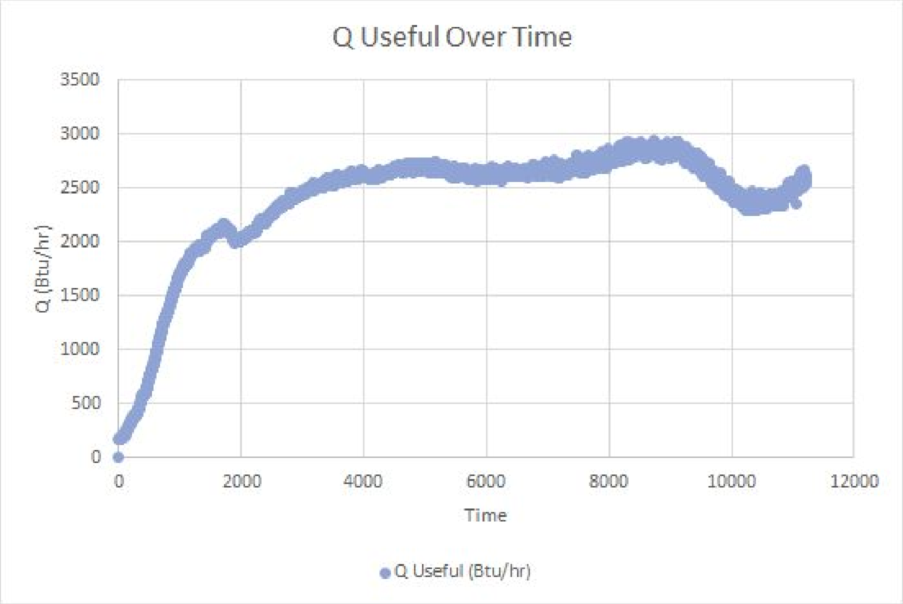

Figure 21. Panel Production Rate

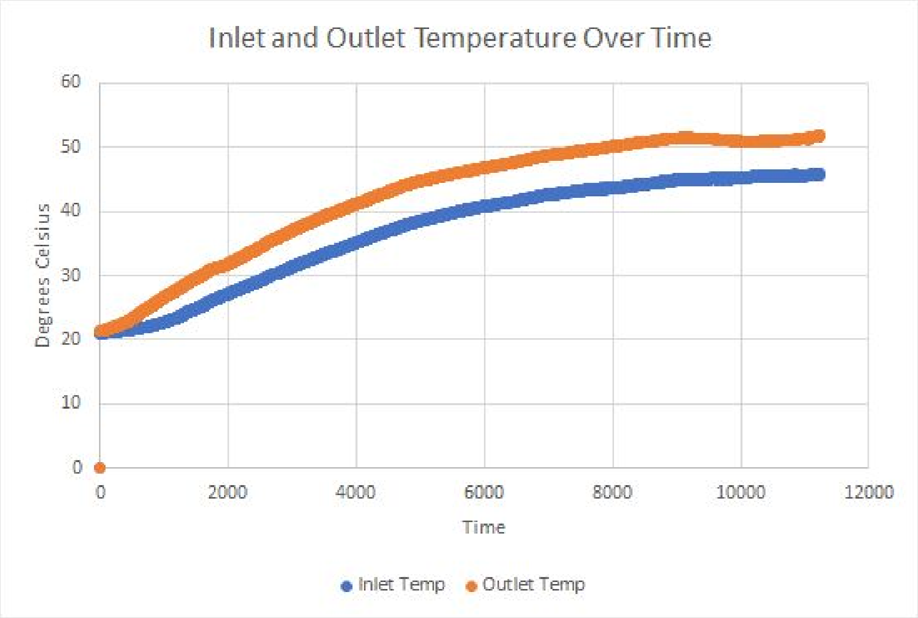

Figure 22. Inlet and Outlet Temperature Rate

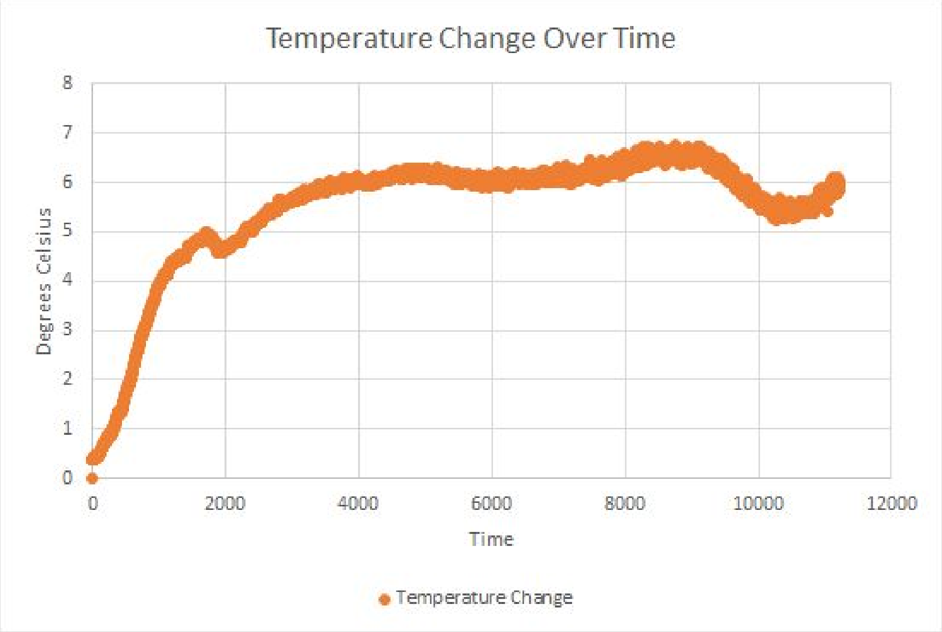

Figure 23. Temperature Change Through Panel

12.3 Appendix C: Panel Design

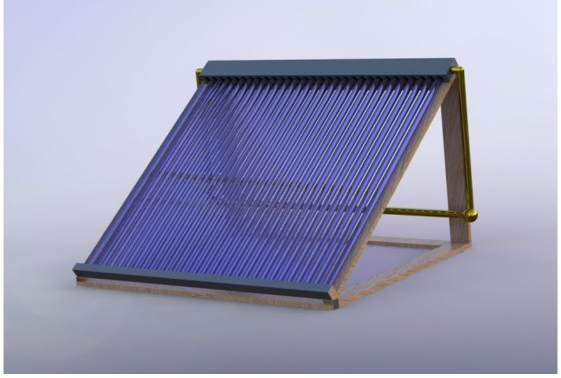

Figure 24. 3D Panel Design