NAU Solar Capstone

Spring Progress Report

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2020

NORTHERN
ARIZONA
UNIVERSITY
College of Engineering,
Informatics, and Applied Sciences

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DISCLAIMER

EXECUTIVE SUMMARY

The NAU Solar Capstone team is working to develop a solar-thermal heating system to be put in place on the Engineering building of Northern Arizona University's campus. The goal is to provide heating to the building while decreasing the amount of energy being used by natural gas boilers that are currently in use. The heating system will be used to heat the internal hydronic loop throughout the building year-round while demonstrating a path towards reducing the carbon footprint across campus. The team is working with the NAU Greenfund to fund the system that will consist of evacuated-tubing solar panels that heat a mixture of water and glycol that run through a heat exchanger, which will distribute heat into the building.

The team designed a system of solar panels that could be arranged to theoretically provide a sufficient amount of heat into the building. The design utilized a model of solar panel produced by SunMaxx Solar, which used an evacuated tube system and provided a potentially feasible amount of flow rate and temperature change to fit the project's needs. The full description of the solar thermal system will be further described in the following report.

Originally, the team planned to develop a full proposal for the solar thermal system to the Greenfund for funding by April 24, 2020. Due to the extenuating circumstances the university is facing, the team selected to refocus the project and develop a test that will be performed in the fall. The team has developed a test of an existing solar panel of the same model that was used in a previous project on the NAU Health and Learning Center. This test will test to see the flow rate through the panel as well as how the temperature changes as the water-glycol mixture travels across the panel. The team submitted a proposal to the NAU Greenfund to approve funding for the test, which will ideally be performed in August 2020.

For the Fall 2020 semester, the NAU Solar Capstone team is planning to first test the panel for its performance and convert this data into heat transfer equations to determine the feasibility of using this model of panels. After this, the team will propose a plan to be used in future projects on NAU's campus regarding the possibility of using solar thermal heating for buildings across campus. The main objective of the project has changed due to the surrounding circumstances and the team will focus on performing and analyzing the test in the fall.

The following report outlines the team's progress throughout the entirety of the Spring 2020 semester while proposing the solar panel test to be conducted in the fall semester.

TABLE OF CONTENTS

[Use Word to delete the following Table of Contents and insert a new TOC. Include front matter (except for the cover page), body of the report, and all appendices. The Table should include three levels of headings, e.g., down to 2.3.1, as illustrated below. Front matter should be in Roman numerials.]

Contents

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.

1.3 Original System

The team's design will be implemented supplementally to the existing hydronic loop in the engineering building. The current heating for the engineering building utilizes a series of heat exchangers and water lines. Initially, a high temperature hot water (HTHW) line runs into the basement of the engineering building from external boilers. This HTHW line runs through a heat exchanger to heat the internal hot water line which runs through the school. This internal line runs through each floor via a pump in the basement, and is pumped to other heat exchangers in each room which transfer this heat to the air through another coil.

1.3.1 Original System Operation

The existing boiler system and HTHW line offsets an overall load of approximately 1.3 MMBTUs and a temperature change of 10℉, producing a supply temperature of 140℉ with a return of 130℉. The pump in place already utilizes a flow rate of 150 gallons per minute (GPM) and 50 feet of head. The energy consumption by the building follows the trend depicted below in figure 1; spiking to around 2 MMBTUs at 5AM, then stabilizing at around 1.3 MMBTUs between 8AM and 11PM before dropping down to zero at the end of the day.

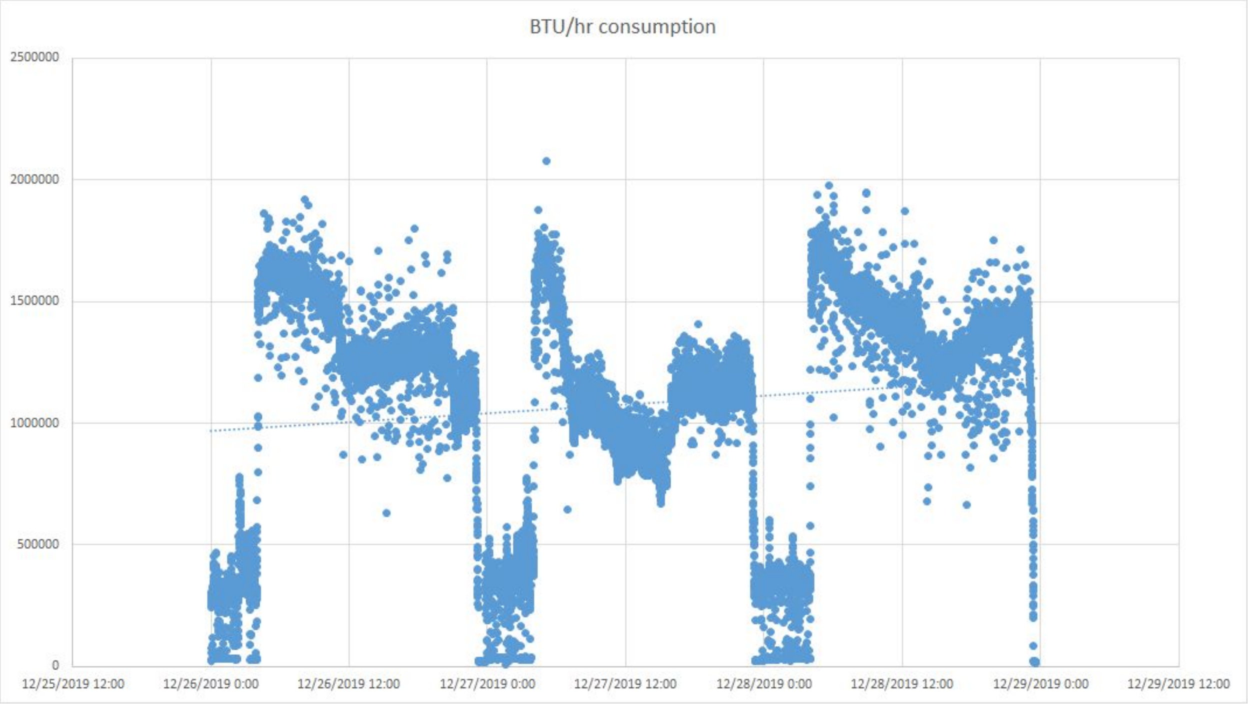


Figure 1: Demand by the engineering building in Btu/hr

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. As such, 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.

2.1 Functional Decomposition

The primary function of the installed design is demonstrated below in figure 2. 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.

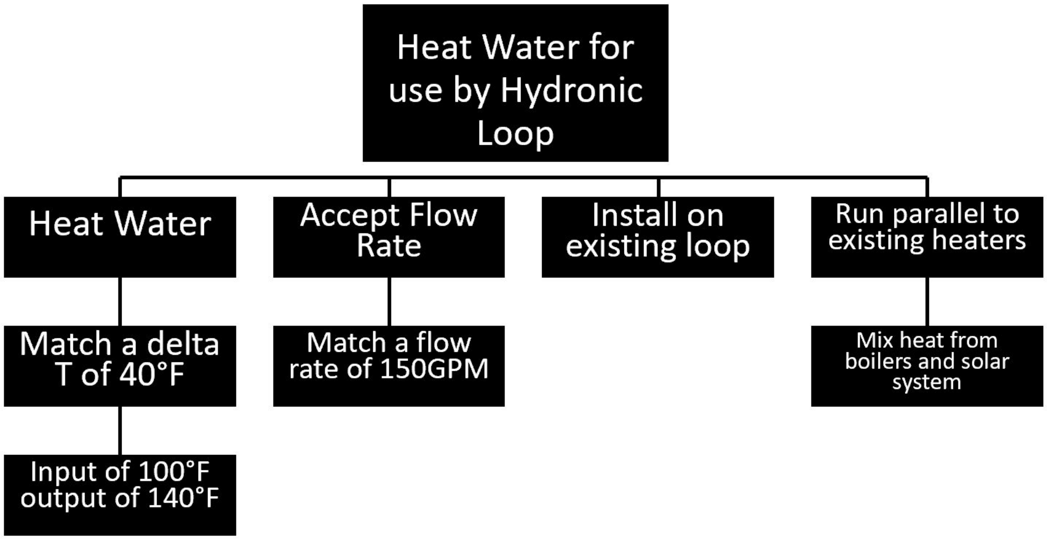


Figure 2: Functional Decomposition

2.1.1 Black Box Model

The Black Box below in figure 3 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.

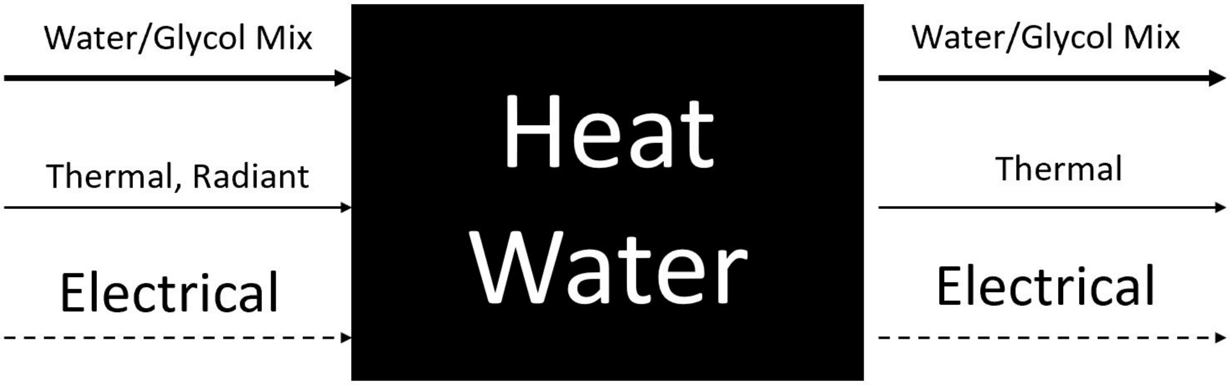


Figure 3: Black Box Model

2.1.2 Functional Model

Figure 4 below depicts the functional model created for this solar system. It details how the various signals, energies, and materials dictating 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.

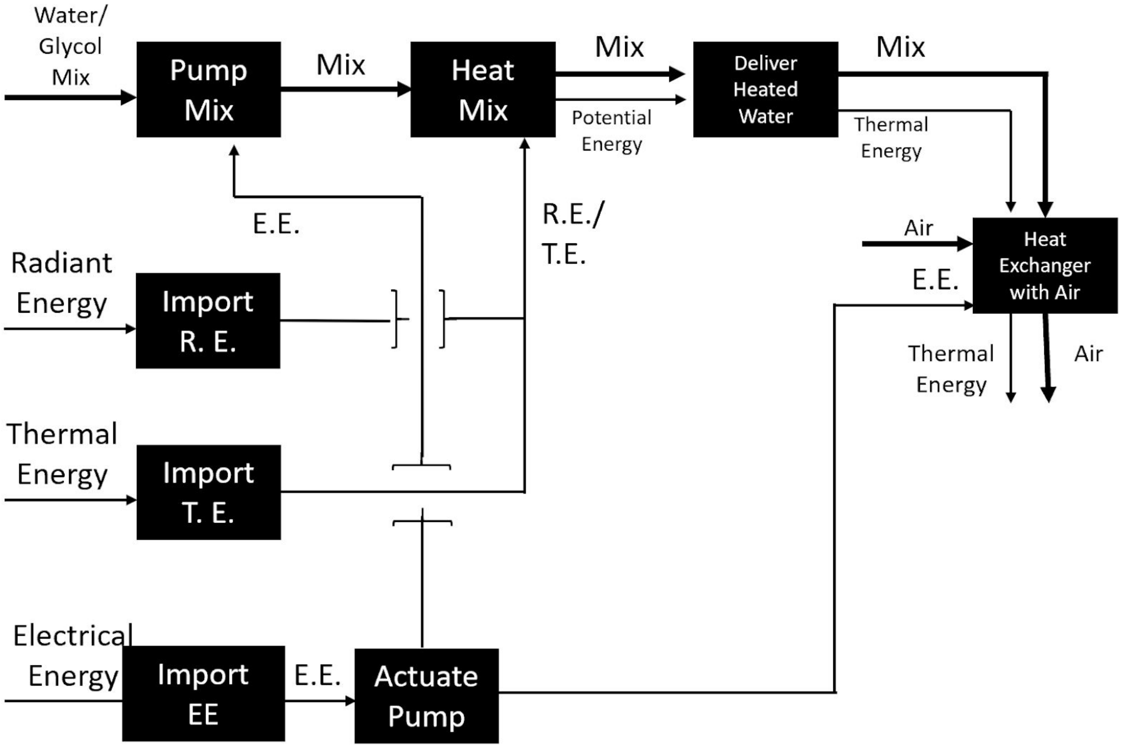
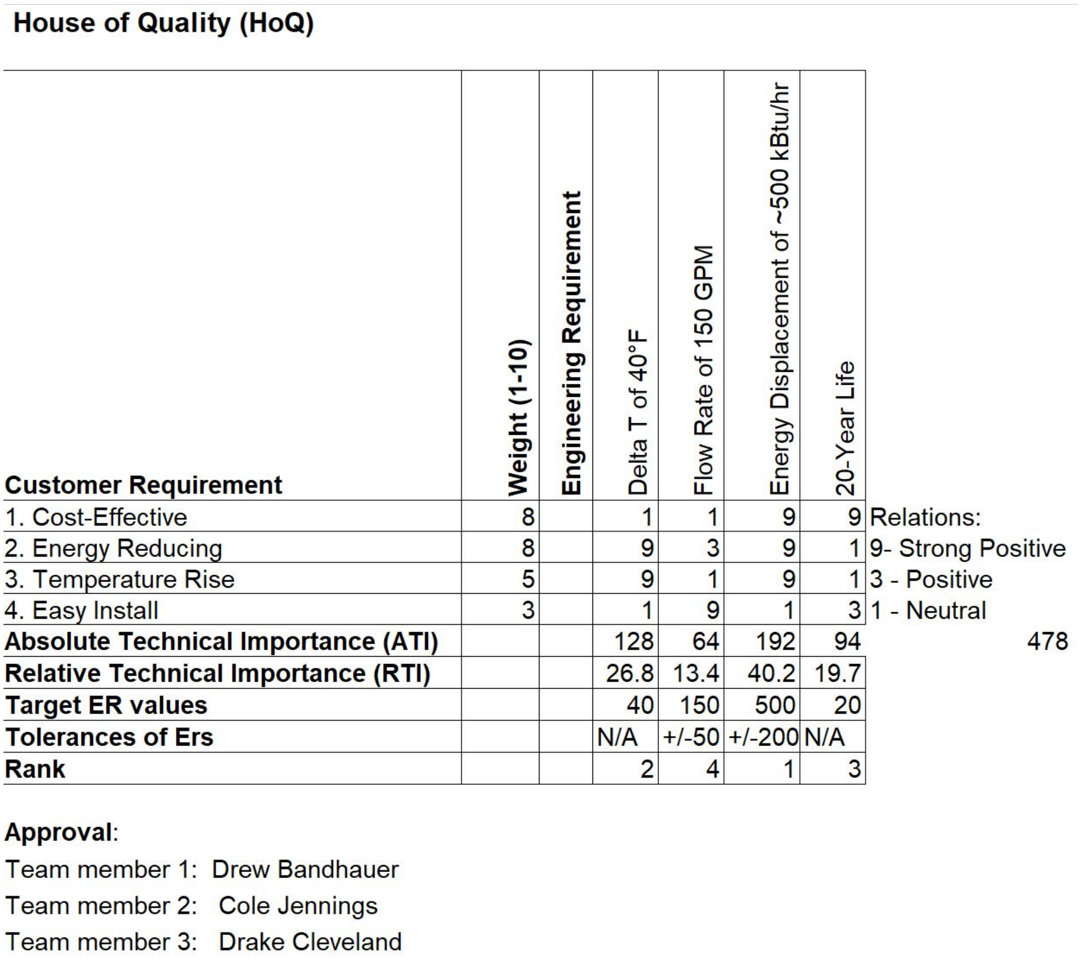


Figure 4: Functional Model

2.2 House of Quality (HoQ)

Figure 5 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.



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

2.3 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 Testing Procedures (TPs)

Due to the pandemic, the scope of the project for the time being has changed to designing an experiment that will give the team solid data to move forward with. The experiment will need to measure the head loss and temperature change through a single panel, the two largest ambiguities in the project thus far. If there is too great of a head loss through the panels, a different pump is going to need to be implemented. The temperature change data gathered from the experiment will provide the team with a calibration to compare to previously collected data. Once there is concrete evidence of the functionality of the panels, the team will have a much better idea on how to approach the project going forward.

3.1 Testing Procedure 1: 2020 NAU Thermal Solar Experiment

The experiment will measure the head loss and temperature change through a single panel. The results can then be extrapolated to represent the returns of the entire solar system. The change in temperature will give the amount of usable heat a panel can supply the engineering building with. The head loss measurement will be important when considering whether or not the current pump will be sufficient in the final design.
A circuit will be created that will pump water from a 50 gallon tank through an inactive HLC solar thermal panel. The temperature change and head loss will be measured using thermocouples and pressure transducers at the inlet and outlet of the panel. The water will exit the panel and return to the 50 gallon tank to complete the circuit.

3.1.1 Testing Procedure 1: Objective

The panel will be fixed at 30°, the angle at which the panels would be installed on the roof. A brace will need to be constructed that will hold the panel at this angle using 2x4's. A pyranometer will be installed on the brace to measure the amount of irradiance at the time of the experiment. This will give the results a foundation to compare to previously collected data.

A 50 gallon tank will be connected to a pump so the collected water can move through the circuit. The circuit will hold less than 15 gallons of water, so the tank should have at least 20 gallons of water so the pump will always have water to pull. A nozzle will be installed at the bottom of the tank for the pump to pull from.

The pump will be attached to the first garden hose. The garden hose will run from the pump to the garden hose to the ball valve. The ball valve will be used to set the flow rate. The team will run the experiment with a flow rate of .84 gallons per minute(GPM). This is because the rated flow rate of the panel is .84GPM and this will give the team the ceiling of what to expect from these panels. The reducing connector will bring the garden hose through multiple fittings that house the thermocouple and pressure transducer, and lead to the inlet of the panel. Thermocouples and pressure transducers will measure the temperature and pressure just before the inlet and after the outlet of the panel. After the readings at the outlet of the panel, another garden hose will return the water to the original tank.

The results of this test will give the team actual evidence of the functionality of these panels, not just projections from simulations. With the expected cost of this project, running this test will be entirely necessary for the team’s final proposal.

3.1.2 Testing Procedure 1: Resources Required

The test can ideally be run of the roof of the engineering building, but would work in the field just outside the building. Either place will give reputable results. The members of the NAU Solar Thermal capstone team will be present for the set up and experiment, as well as the project faculty.

3.1.3 Testing Procedure 1: Schedule

The test will be run tentatively in August, but is subject to change due to the pandemic. The setup of the experiment will take the most time, but it has been designed for the parts to essentially snap together. We are expecting a setup time of about 3 hours. Once the test is set up, the flow rate will need to be set, which could take numerous trials with the bucket-timer method. Once the desired flow rate is achieved, the experiment will have 3 trials and each is only expected to take a minute. With all this said, a set up in the morning will set the team up with an experiment in the early afternoon, where there is the greatest amount of irradiance.

4 Risk Analysis and Mitigation

The risks associated with this project are very similar to a project done on the HLC upon its construction. In this problem, the main risk which led to failure occurred at the soldered joints of the piping. In this instance, the water circulating through the pipes got too hot and caused the joints to melt and eventually leak. As such, this is a major concern for this project, but also allows the team to analyze all points of failure already tested as well as design around these. As there are going to be many connections between the solar panels, this alludes to a large room for failure, and said subsystems will be detailed below.

4.1 Critical Failures

4.1.1 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.

4.1.2 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.

4.1.3 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.

4.1.4 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.

4.1.5 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.

4.2 Risks and Trade-offs Analysis

The first two risks which contradict one another are the water overheating and the water underheating. This problem poses two separate issues, however the water overheating is a more avoidable problem. As such, the team will choose to address the water underheating by ensuring the water reaches its necessary temperature. The problems associated with overheating can be mostly dealt with through welded joints and a run-off valve for surplus water and heat.

The other risks that must be accounted for despite their contradicting behavior are the connections and financial feasibility. As it is, the financial feasibility of this project is borderline as the energy they generate might not offset enough of the natural-gas-generated energy. When considering the connections it is clear that to beat the risks associated, a larger financial burden must be placed. The design can be stored for a later time, but the connections must not fail and are a critical part of this project, so this financial burden must be designed into 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 production, as described above. The team is prepared to work with the selected design to implement the testing and to eventually work towards developing a complete design for the entire system. The following section justifies the testing procedure.

5.1 Design Description

The testing procedure, outlined in section 3.1, will be implemented in the fall semester to test the head loss and temperature changes of the SunMaxx VHP30 panel that was acquired from the HLC project previously conducted. The team developed a detailed engineering drawing of the testing system, which is shown below in Figure 6 below.

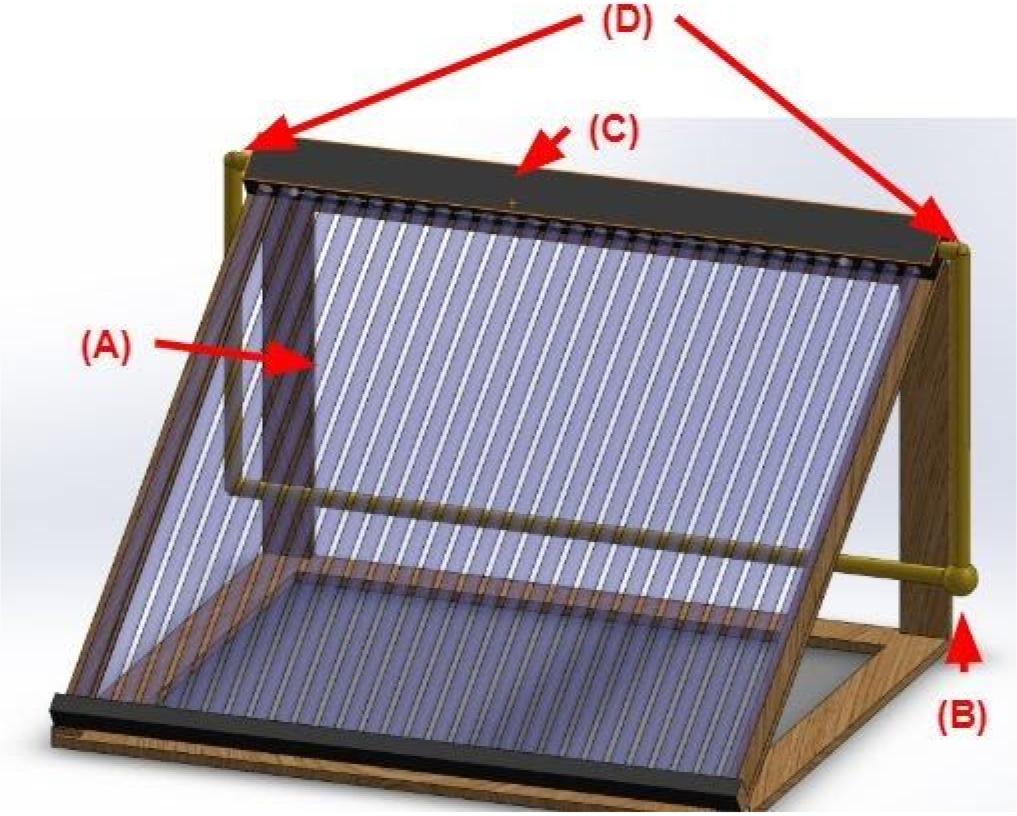


Figure 6. SolidWorks model of testing system

The figure above shows the solar panel fixed to the mounting system that the team plans to construct. Arrow A shows the panel itself, which will be situated at an angle of 30 degrees above latitude, which was found to be the optimal angle based on where the sun is most prevalent in Flagstaff during the times the system will be needing to take in 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 that will be connected to the water pump, where water will be 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 show the inlet and outlet valves that will be connected to thermocouples and barometers that will measure temperature change and head loss, respectively.

The team has developed this testing procedure and hopes to begin construction of the mounting apparatus during the beginning of the fall semester. The team proposed a budget for the system to the NAU Greenfund that, upon approval, will allow the team to be financially reimbursed for the costs of the test. Figure 7 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 7. Budget for testing procedure

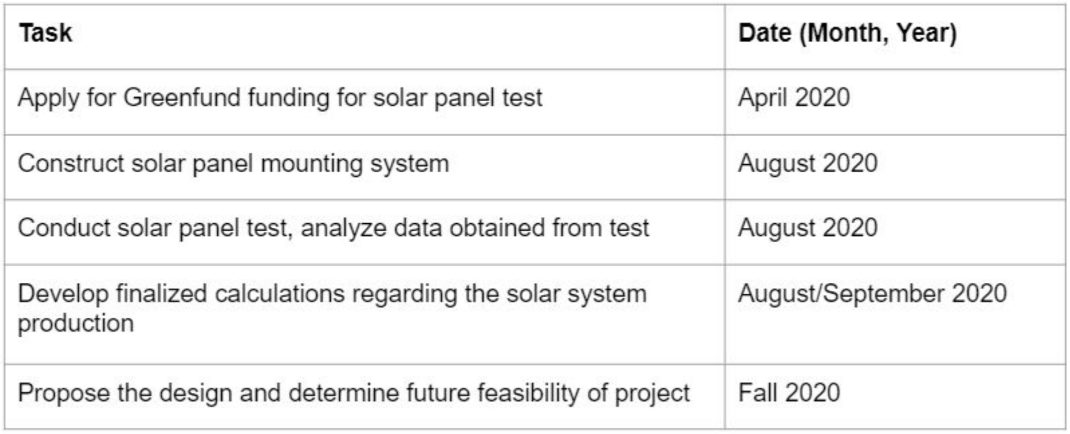
The team plans on purchasing all of the materials in the budget during the summer to ensure the testing process can be begun as soon as possible. The budget of $520 accounts for the wood to create the mounting system, a pump that will push water through the system, a hose to connect the pump to the mounting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

The team justifies the need for this test by analyzing the theoretical production of one panel in Appendix A. This shows the back-of-the-envelope calculation of a control volume analysis of the panel the team is working with. Based on these calculations, the team estimates that approximately 40 panels are needed to produce the amount of kBTU/day that the project desires. The team needs to conduct the test to determine how accurate the calculations are and if the estimations were correct.

Tentatively, the team is aiming to conduct the test during August or September of the fall semester. This gives the team the remaining months of the semester to extrapolate data from the test to fully design the system for the Engineering building. The team plans to fully propose the implementation of the system in the fall.

5.2 Implementation Plan

The testing process will be implemented in the fall assuming all students are allowed to meet together given the extenuating circumstances currently in place. Below in Figure 8 is a tentative schedule the team has developed for the entire semester.



Task	Date (Month, Year)
Apply for Greenfund funding for solar panel test	April 2020
Construct solar panel mounting system	August 2020
Conduct solar panel test, analyze data obtained from test	August 2020
Develop finalized calculations regarding the solar system production	August/September 2020
Propose the design and determine future feasibility of project	Fall 2020

Figure 8. Fall 2020 Schedule

As seen above, the team has already completed the application to the Greenfund for the test funding. The next steps include constructing the mounting system, then conducting the test and analyzing the data from the test. Once the testing stage is complete, the team will be able to develop a full proposal based on what has been determined from the testing. The team plans to propose the design as well as determine the feasibility of the project in the future, dependent on the price of natural gas and how that affects the financial aspect of the system. Updates regarding full implementation of the solar thermal heating system will be developed over the course of the fall semester and the team plans to create the system proposal by the end of the semester.

6 CONCLUSIONS

The NAU Solar thermal capstone team has put extensive research into developing a solar system that will reduce the natural gas demand of campus and, in turn, reducing the carbon footprint for the campus as a whole. The team has considered many different panel arrangements in regard to having the panels in series and parallel to develop the right system for the engineering building. The team researched different solar collectors and determined that Evacuated Tube solar collectors will be the most efficient in Flagstaff's climate, due to fluctuating temperature. In addition to panel shape and orientation, resources such as the System Advisory Model and SRCC panel ratings were utilized to get an idea of the amount of heat the system will be able to provide.

As it stands right now, the project scope has shifted to designing an experiment that gives the team and faculty a better idea of the impact that this design will have. The original goal was to produce 1.3MMBTU/hr at a flow rate around 150GPM, as this would cover the entire natural gas demand during the day. However, the System Advisory Model and SRCC rating data shows that this will not be achievable given the roof space and financial commitment required to produce this amount of heat.

For this reason, the team has designed an experiment that will give the team concrete data and submitted the experiment proposal to the GreenFund for experiment funding. If the funding is approved by the GreenFund, the team will run the experiment either during the summer or early in the fall semester. Based on the data collected from this experiment, the team will either continue working towards a design proposal or develop a model that can be used at a later date when the project becomes more financially favorable.

If the funding is not approved, the team will likely abandon the hope of implementing a design this year and work towards creating a model for a future team. With a material and installation cost of roughly $750,000, the team needs to be sure that the design we propose is solid, with all possible modes of failure accounted for. If the experiment is unable to be run, the team simply won't have the required data to propose implementation of a design this expensive.

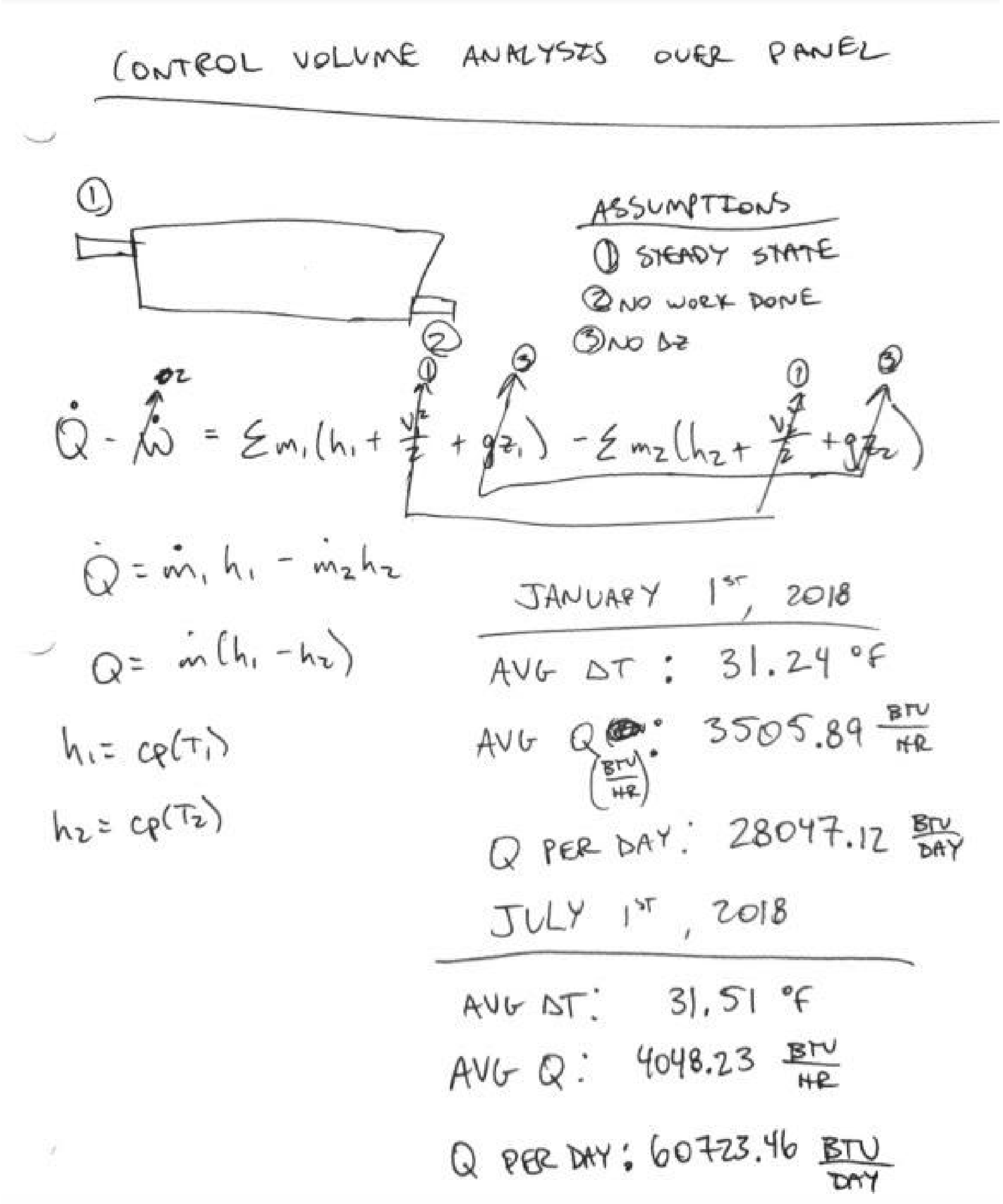
Looking towards next semester, the team expects to run the experiment this summer and analyze the results before choosing a next step. If the results are favorable, we will work towards creating a design. If the results are not favorable, the team will generate a model for a future team to use when the cost of natural gas rises and the price of the panels drops.

7 REFERENCES

[1] S. M. Solar LLC, Bainbridge, NY, 25-Apr-2012.

8 APPENDICES

8.1 Appendix A: Control Volume Analysis of Single Panel



CONTROL VOLUME ANALYSIS OVER PANEL

ASSUMPTIONS

① STEADY STATE

② NO WORK DONE

③ NO ΔZ

$$\dot{Q} - \overset{②}{\cancel{\dot{W}}} = \sum \dot{m}_1\left(h_1 + \overset{①}{\cancel{\frac{V_1^2}{2}}} + \overset{③}{\cancel{gz_1}}\right) - \sum \dot{m}_2\left(h_2 + \overset{①}{\cancel{\frac{V_2^2}{2}}} + \overset{③}{\cancel{gz_2}}\right)$$

$$\dot{Q} = \dot{m}_1 h_1 - \dot{m}_2 h_2$$

$$Q = \dot{m}(h_1 - h_2)$$

$$h_1 = c_p(T_1)$$

$$h_2 = c_p(T_2)$$

JANUARY 1ST, 2018

AVG ΔT : 31.24 °F

AVG $\dot{Q}$ $\left(\frac{BTU}{HR}\right)$: 3505.89 $\frac{BTU}{HR}$

Q PER DAY: 28047.12 $\frac{BTU}{DAY}$

JULY 1ST, 2018

AVG ΔT: 31.51 °F

AVG Q: 4048.23 $\frac{BTU}{HR}$

Q PER DAY: 60723.46 $\frac{BTU}{DAY}$