RE Lab Solar Heater

Conceptual Design Report 2

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NORTHERN ARIZONA UNIVERSITY

Project Sponsor: Professor Carson Pete

DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

EXECUTIVE SUMMARY

For our capstone project we need to implement and integrate a solar thermal air heater into the renewable energy lab located south of the engineering building on the NAU campus. The reason for installing a solar thermal air heater into the renewable energy lab is to keep occupants inside warm and to keep batteries that are stored within the building above 40 degrees Fahrenheit. This is especially important during the winter months. The system also has to satisfy all of the customer requirements that were supplied by our client, Carson Pete. To satisfy these we had to come up with engineering requirements and build a QFD. For the QFD we also needed to find three different systems that are similar to ours and perform a competitor evaluation. These three different systems were also used for our benchmarks. And later we chose two of these, one air and one water solar thermal system, to be used as datums when performing our concept generations. After conducting our concept generation for report 1 and presentation 2 our final design that had the highest score was an air design. Next for this design we needed to start prototyping, for our prototype we took one of the solar air collectors outside of the renewable energy lab, stripped the wires on the fan and connected it to a dc power supply to see if they still worked. After this we started recording data by measuring the inlet and outlet temperatures of the air. We changed some parameters such as the angle or tilt of the solar air collector and the voltage output of the dc power supply to see how these would affect the temperature output of the air. We found that by optimizing the angle or tilt of the solar air panel we were able to increase the temperature output, we were also able to increase the temp output by lowering the voltage from 12V to 10V because the lower voltage slowed the cfm of the fan down which made the air move slower through the solar air panel which allowed it to heat up more. The downside to this though is that our manufacturer spec sheet for the fans says that they should only operate at a maximum of 70 degrees Celsius but we were able to go well past that and into 80 degrees Celsius. So, we will have to keep this in mind to not melt or break our fans. During this report we also needed to complete another literature review with more sources per student. We also had to perform more mathematical modeling where each team member performs an analysis that is beneficial to the progression of the project. We also had to show our schedule and budget overview, the schedule we have laid out is in the form of a Gantt chart which has a detailed layout for this summer course and shows us if we are on time, behind, or ahead of schedule. We also created a Gantt chart for the fall semester, which we built from a tentative schedule that was provided on canvas. But the dates are guesstimated because the tentative schedule we went off of was from the Spring of 2023. For our budget we hit our $500 goal of money raised because Calvin was able to secure us a Home Depot donation. The donation is not money but an in-store credit that we can use to purchase items needed for our project. To do this, we need a BOM (Bill of Materials) which we have created but not yet fully finalized to give to Home Depot so we can garner our supplies using the $500 in store credit. As a team, we also needed to perform an FMEA (Failure Mode and Effects Analysis), for this we used an excel skeleton sheet that was provided on canvas and went over all the worst-case scenarios if our system failed, how it failed, why, and how to detect the different modes of failure. The last things we need to complete are future testing and prototyping and finalizing our CAD and BOM.

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1 BACKGROUND

This chapter of the report outlines several key aspects of the RE Lab solar heater project. A project description will be provided. This will include the motivation behind the project, individual and local benefits, and budgetary projections. The course and client have developed deliverables that must be met, and they will be detailed along with a deadline for each of the tasks. These tasks will go beyond the duration of ME 476C with manufacturing, testing, and installation timelines. Success metrics, which is the team's determination of how the project is quantifiably considered successful, will be the final portion of this chapter. The quantification will be considered through calculations, testing, and general design requirements.

1.1 Project Description

The primary objective of this project is to implement an air-based solar thermal system into the Renewable Energy Laboratory (RE Lab) building to provide heat to the building. The solar thermal system must be operated entirely individually from the rest of the building to ensure constant operation. Efforts must be made to ensure thermal energy is stored or saved for the night when solar energy is unavailable.

Due to the adverse weather conditions that are seen in Flagstaff the thermal system isn't required to eliminate the buildings heat load requirements but rather must reduce them by at least 30% in the winter. This must be done for the RE Lab specifically because batteries get stored in the front room of the building. These batteries must be stored in a room that remains at or above 40°F to avoid getting damaged. Along with this objective, the RE Lab should make every effort to avoid non-renewable energy usage and to help achieve Northern Arizona University's Climate Action Plan. This initiative by NAU is to become completely carbon neutral by 2030. Additionally, there are many areas in northern Arizona that do not have access to reliable electricity at all. The complete solar thermal system should be designed in a reliable, compact, and affordable manner to allow use for everybody.

While the design should be affordable for accessibility reasons, it must also remain within the project's budget. An initial $500 grant was provided for the project by the Department of Mechanical Engineering at NAU. An additional $500 must be raised by the group for any further expenses. This allows for a minimum total budget of $1000 for project research, prototyping, testing, and final manufacturing and installation. Regarding the fundraising requirement, a $500 donation has been provided to the project by Home Depot for which the money provided must be used at Home Depot for material and equipment purchasing. Further fundraising is still in progress as every team member has a flyer posted at their workplace describing the project with a donation link if people desire. This allows the team to interact with the public about the purpose and importance of the project and answer questions that people may have. From the flyers the project group has gathered just under $100 in fundraising.

1.2 Deliverables

There are many remaining course and client assigned deliverables remaining in the project. These deliverables will be detailed along with an assigned or approximate completion date in chronological order.

1) Presentation #3 – This is a design proposal presentation where the team will present the design selection process and provide a selected design for approval.
    - Deadline: 31 July, 2025
2) Prototype #2 – This prototype must include a physical and a virtual prototype. Both prototypes must be answering a question about the project and inform the team on the design in some capacity,
    - Deadline: 31 July, 2025

3) Project Management for ME 486C (Draft) – This assignment allows the team to reflect on the progress made and find areas for improvement and areas that the team did well on. An outline of remaining tasks needs to be made and discuss the completion status of critical tasks.
   - Deadline: 1 August, 2025
4) Website Check #2 – This deliverable requires that the project website is operational on all browsers. Within the website all documents should be included, team or individual photos, and all CAD or prototyping completed.
   - Deadline: 1 August, 2025
5) Project Management for ME 486C (Final) - Improve and alter the draft project management plan for final submission.
   - Deadline: 25 August, 2025
6) Material Collection – All materials required for manufacturing and installation should be ordered or already in possession.
   - Deadline: 25 August, 2025
7) Remove PVT Covering – This step is the very beginning of the manufacturing and installation process. To set up the team for a successful installation the PVT sheets covering the roof must be removed.
   - Deadline: 25 August, 2025
8) Mounting Setup Installation – This step is to ensure that all parts have been collected or ordered for the mounting system in preparation for full installation of solar heating and PV/T panels.
   - Deadline: 15 September, 2025 (Subject to change)

1.3 Success Metrics

For this project to be considered successful, several conditions should be met. The first being that the building heat load requirements should be reduced by a minimum of 30% in the winter months. This is a metric that has been assigned by the client and serves the purpose of helping maintain a building temperature of at least 40°F for battery storage. Sections 3.3.1 and 3.3.2 cover the building heat load analysis and energy analysis respectively. These sections, when compared, will show the findings of how many solar panels are required to meet the 30% requirement. The system must also use primarily renewable energy even for powering the system, which is why isolating the thermal system from the rest of the building is mandatory. The system should also meet all city codes and safety requirements to be successful. These safety requirements go beyond codes and must also not get damaged by wind or excessive snowfall, meaning that the mounting system should be able to withstand the conditions in Flagstaff without critical failures. The project should also remain affordable for expansive use and provide a 10-year payback period in energy savings.

2 REQUIREMENTS

This chapter provides a complete breakdown of all project requirements. The first section is going to detail all of the customer requirements (CRs) that were assigned by the RE Lab and Professor Carson Pete. These are the goals for the project and the overall operation of the system. The engineering requirements (ERs) are developed by the team based directly on the previously described customer requirements. The ERs will be quantifiable measures of meeting the requirements for the CRs and under each description of an engineering requirement the correlating customer requirement(s) will be listed. The house of quality (HoQ), which is a part of the quality function deployment (QFD), will show the teams grading each ER and CR. This section will also include target values for each of the ERs and calculations will be done for each as well to justify any design decisions.

2.1 Customer Requirements (CRs)

We will list the ten different customer requirements here that were provided by our client:

1. System must reduce building heating load by at least 30% during the worst-case months (i.e. Dec. or Jan.). This would entail comparing the solar thermal heater to the baseline method currently in use to heat up the RE Lab, which is a 1500-Watt oil lamp. The priority of this CR is high.
2. The system must operate in winter climate conditions and should work when the sun is out. This essentially means that the system must function in sub-freezing temperatures and during low solar insolation where insolation is the exposure to the sun's rays or the amount of solar radiation reaching a given area. The priority for this CR is high.
3. Systems must use renewable solar energy as primary input. This means not using any fossil fuels or electricity unless in an emergency. The priority for this CR is high.
4. Installation must not require any major structural modification of the building (some things such as integration into the roof may be necessary). This could include mounting the system next to the building or using a retrofit that is compatible with the existing walls or roof of the building. This CR has a medium priority.
5. The system must be safe and comply with relevant codes. The system must meet ASHRAE, plumbing, electrical, and solar thermal standards for the safety of the occupants inside. The priority is high for this CR.
6. System must have minimal maintenance (<4 hrs/year). The system must have ease of use for maintenance staff or building owners. Medium priority for this CR.
7. The payback period must be under 10 years. This would be based on energy savings from not using the 1500-Watt oil lamp compared to installing and building the system. Priority is medium.
8. The system must have a visual indicator of its operating status. This would include a simple dashboard or indicator to show functionality. Low priority.
9. System must have the ability to include temperature and performance monitoring. Enables data collection for maintenance and performance. Low priority.
10. System must not overheat or cause interior overheating (i.e. thermostat regulated). This must include passive or active thermal regulation. Medium priority.

2.2 Engineering Requirements (ERs)

We will list the engineering requirements that satisfy the customer requirements here along with supporting equations and calculations that quantify each engineering requirement:

1. Energy Stored (kWh): When solar energy is being collected by the solar panels during the winter, it is essential that the product stores that energy and ensures the building can stay warm for the customer. It is important that a sufficient amount of solar energy can be absorbed and stored, during times when days are shorter, so that the system can utilize that existing energy to heat the building.
2. Efficient Insulation (R value): R value is a measurement of how effective insulation is. Different applications require different values. For example, exterior walls in buildings typically use R-13 fiberglass insulation, while pipes use around R-5. While there are many applications in this project where R values may vary, we have decided to aim for an average of R-10.
3. Relays (Watts): to ensure that the system can be operated manually, it is required that relays must be implemented into the system so the client can control the temperature of the building during the winter. For our system to meet the customer's needs, they must be able to adjust the temperature to their liking and ensure their needs are met.
4. Head Pressure (Meters or Pascals): head pressure is the pressure exerted by a fluid due to the weight of the fluid above a certain point. This can include static (fluid at rest) or dynamic (fluid in motion) pressure. This is important because it helps in calculating the efficiency in pumps, is safe because high head pressure can pose risks, and more.
5. Flow Rate (m^3/sec): flow rate is the amount of fluid that moves through a point over a certain period of time. This is important because the force convection that is happening within the solar panel is dependent on this flow rate. The faster the flow rate the lower the temperature the fluid will rise. While the lower the flow rate the higher the fluid temperature will rise but the radiator may not receive enough newly heated fluid.
6. Heat Exchanger (Joules): it is essential that the system must have a heat exchanger so that heat can be transferred from the working fluid whether the design team decides to choose a solar air heater or a solar water heater. In either application, heat exchangers are important to ensure that heat can be evenly distributed, and the customer will be satisfied with the product once it is implemented.
7. Life Expectancy (Years): This project is not worthwhile if it cannot stand the test of time. The client has required that the payback period be under 10 years, so we have set our goal for life expectancy at a minimum of 10 years.
8. Cost ($): This project has a tight budget. The client has provided $500 and has requested that we raise a minimum of $500. This brings us to a minimum of $1000.
9. Mounting system (Kg): this represents the weight that the mounting system would be able to hold. This ER is more based on the solar air system rather than the solar water system because the water system already has a base built while the air system does not.

2.3 House of Quality (HoQ)

Quality Function Deployment

Project title:	RE Lab Solar Heater
Project leader:	Brendan Frazier
Date:	6/10/2025

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

5	3	1	0
Strong	Moderate	Weak	None

0								
0	0							
+	0	-						
+	+	-	0					
+	+	0	0	0				
+	+	0	+	0	0			
+	+	0	+	+	0	0		
+	+	0	+	+	+	0	-	

1: low, 5: high

Competitive evaluation (1: low, 5: high)

	Customer importance rating	Engineering Requirements (How's) → / Customer Requirements - (What's) ↓	Energy Stored	Efficient Insulation	Relay	Head Pressure	Flow Rate	Heat exchanger	Life expectancy	Cost	Mounting system	Weighted Score	Solar Water Rating	Solar Air Rating	Vacuum Tube Solar Collector Kit Rating	4000 Series Artica Solar Air Heater	Hybrid Solar rating
		Desired direction of improvement (↑,0,↓)	↑	↑	↓	↑	↑	↑	↑	↓	↓						
1	5	System must reduce heating load by 30% during worst case months (compared to baseline method)	5	5	0	4	4	5	0	0	0	50	4	3	5	4	5
2	5	System must operate in winter conditions	5	5	0	5	5	3	1	0	3	55	3	3	5	4	5
3	5	System must use RE solar as primary input	5	5	0	4	4	3	0	0	5	65	5	5	5	5	3
4	3	Installation must not require major mods to building	0	1	0	2	2	0	0	3	5	24	2	3	3	4	5
5	5	System must be safe and comply with codes	3	3	3	4	3	3	3	0	5	70	5	5	4	5	5
6	3	System must have minimal maintenance	1	1	1	3	2	5	5	1	4	36	3	4	4	5	5
7	3	Payback period must be under 10 yrs	5	5	3	2	2	5	3	5	4	66	5	5	1	3	4
8	1	System must have ability to include temp. and performance monitoring and visual indicator of operation status	3	0	5	5	4	3	0	0	1	12	5	5	4	4	5
9	3	System must not overheat or cause interior overheating	5	0	5	5	4	3	0	0	2	45	5	5	4	4	5
		Technical importance score	126	111	47	126	114	112	44	27	111	818	37	38	35	38	42
		Importance %	15%	14%	6%	15%	14%	14%	5%	3%	14%	100%					
		Units	kWh	R Value	Watts	meters	m^3/sec	Joules	Years	$	Kilograms						
		Target	30 kWh	10 R-Value	10 W	5 m	0.1 m^3/s	5 MJ	10 yrs	$1,000	20 kg						
		Priorities rank	1	5	7	2	3	4	8	9	6						

Figure 1: Quality Function Deployment (QFD)

The House of Quality, otherwise known as the QFD, is a method for engineers to rank their own requirements and designs using customer requirements. For this project, the nine customer requirements and nine engineering requirements were ranked according to their relevance to each other using the appropriate weights, and the result was a ranked list of engineering requirements. The top priority for this project was determined to be the energy stored in the heat battery. With a target of 30 kWh, we will focus the majority of our attention on reaching this goal. Our lowest priority, although still important, is cost. With a target of staying under $1000, we are confident we can stay within budget using the resources already provided to us. Even if we end up needing to raise more money, in the end the most important thing is to create a product that works.

3 Research Within Your Design Space

3.1 Benchmarking

JACOB – Vacuum Tube Solar Collector Kit [43]
This solar water heater uses evacuated tubes that are designed to work in cold weather. They work by transferring thermal heat to a heat transfer fluid which directly or indirectly heats a thermal storage device by collecting solar energy in the insulated evacuated tubes that have a fluid flowing through them. The kit includes solar vacuum tube pipes, heat transfer fluid collector, 45-degree flat roof mounting aluminum base, assembling accessories, aluminum frame, pipe holder, and a 5-year warranty.

CALVIN – Artica 4000 Series Solar Air Heater [54]
This solar air heater is a state of the art of domestic air heaters. It boasts a 500 square foot heating area at 3,600W and a maximum of 11,800 BTU. It uses around 150 CFM, and it has a relatively light weight for its performance at 159 lbs. The unit alone costs $1599.00 USD.

TYLER – Hybrid Solar [58]
The hybrid solar heater utilizes both solar and electrical energy to power the entire system. It works by collecting solar energy from the solar panels to heat the water. And, whenever the sun is being blocked by clouds or when it's night then the heat pump extracts heat from the air to warm the water. If this system is put into use, then it can provide comfortable temperatures to our client once winter arrives through the combination of solar power and heat pump technology.

3.2 Literature Review

This chapter will discuss all relevant sources that have been used up to this point in the project. A minimum of 10 references per student can be expected with sources ranging from textbooks to websites to peer reviewed papers. Each reference will come with a summary or description of the reference and how it has been or can be useful.

3.2.1 Jacob Apodaca

Fundamentals of Heat and Mass Transfer 8th Edition, Chapter 6 [1] (Textbook):
This textbook covers heat and mass transfer and is utilized in some of NAUs courses. I focused on chapter six which goes over convection, boundary layers, laminar and turbulent flow, and boundary layer equations. This important when conducting engineering calculations and performing analysis on the fluid and its surrounding materials.

Introduction to Fluid Mechanics 10th Edition, [2] (Textbook):
This textbook focuses on fluids at rest or in motion and is utilized in some of NAUs courses. This textbook is useful and important because we will be working with fluid air, and we will need to be able to critically think and apply these textbook principles to our solar thermal air system. This is to promote efficiency in our system when connecting our ducts to our solar air collectors and making sure everything operates as it is intended to.

Review of solar air collectors with thermal storage units [4] (Google Scholar):
This google scholar paper focuses on thermal energy storage. This is an important concept to review because of our system and how it functions. Our man idea is to store the thermal energy inside of the RE Lab and using the building as our thermal battery.

An improved thermal and electrical model for a solar photovoltaic thermal (PV/T) air collector [5] (Google Scholar):
This google scholar paper focuses on a PV/T solar air collector and it's thermal and electrical performance. This is an important paper because we will be utilizing the same kind of set up to power our system. This paper also showcases calculations and models that can be beneficial to our own calculations and simulations.

Screened Solar Air Heater [8] (Website):
This article was produced by a user named CBGjr who create their own DIY thermal air collector and installed it into his home. This is an important article because it shows how an individual created their own thermal air collector at home and built it from the ground up and installed it into their home. We can gain insight from their design and how they went about creating it.

Solar Air Heater – DIY [9] (Website / Forum):
This website is a forum that people use to ask questions and provide answers about all types of solar air panels. This can be utilized to glean information about what peoples thoughts, opinions, and ideas are for how to best operate solar air panels. Not only that but if we wanted to reach a broader audience with specific questions about our solar air panels, we could simply ask the people within this forum.

DIY Solar Air Heater Part #1 [10] (YouTube):
This source is someone's YouTube account where they have posted up to 8+ videos into a playlist about how they went about building their own DIY solar air panel. This source is similiar to the DIY website that CBGjr created but with a more in depth analysis about the system. They also built this solar air panel using more recycled materials such as soda cans. This is an excellent source because it can help show us how to market a cheap solar air system that can be used in residential homes that don't have the advantages of electricity.

Numerical Simulation Study on Transpired Solar Air Collector [11] (PDF):
This pdf talks about how researchers introduced numerical solution tools to the research area pertaining to the unglazed transpired solar air collector. They also analyzed the performance characteristics and compared it to traditional solar air collectors. This pdf can benefit us by showing us how they used CAD and CFD simulation software's to determine the performance of the unglazed transpired solar air collector vs other solar air collectors.

What You Can Do in SOLIDWORKS Flow Simulation [6] (Website):
This is the SolidWorks help website, where you can go through to find out how to use the many different SolidWorks functions. This website is helpful for figuring out how to use the SolidWorks Flow Simulation Module. It's important because we will use this flow simulation to show that our system works for marketing purposes and applications.

An Introduction to Flow Analysis Applications with SolidWorks Flow Simulation, Student Guide [7] (PDF):
This is a student guide pdf showing step by step how to use the SolidWorks Flow Simulation. It is beneficial by giving a detailed breakdown of how to use the flow simulation with descriptions of how everything works. This is important for prototyping our design and for showing that our system works and can be applied for different uses.

3.2.2 Brendan Frazier

Fundamentals of Heat and Mass Transfer 8th Edition, Chapter 3 [1] (Textbook):
This is the textbook used in ME 450 (Heat Transfer) at NAU and provides. The chapter used for this reference specifically is chapter 3, which focuses on heat transfer by means of conduction. While this project is based in fluid mechanics and the heat transfer within a moving fluid, this chapter helps with calculating heat losses throughout the thermal system. These loss calculations are done for surfaces that are poorly or not insulated. This is typically done using the thermal resistance calculations discussed in this chapter in conjunction with the fluid temperature throughout the system. Other chapters from this textbook, which are covered by other team members, assist heavily in the mathematical modeling of this project.

Thermal Performance Improvement Method for Air-Based Solar Heating Systems [15] (Paper):
This paper initially provides information about ExTLA which is a simulation software within excel that allows for building heat load analysis. Using such software will help with validation of the already completed eQUEST building heat load simulation. The paper also covers all the calculations that were completed in order to make the ExTLA software perform accurate heat load simulations. While these calculations and equations are rather specific for the heat load, they can also be used in further analysis for any heat loss in ducts or the building through hand calculations.

Calculation of Optimal Thermal Load of Intermittently Heated Buildings [16] (Paper):
Since the RE Lab will only be heated at certain times throughout the day, like when the sun is out, this paper provides a clear insight into the requirements of an intermittently heated building. The paper introduces, what they call, the "Reduced (lumped parameters) Thermal Model" which provides a simplified method of performing hand calculations for the building heat load requirements of such a building. This, as with other sources, will provide a solid source of validation for any building heat load simulations. This model can also help with optimization of the system through a determination of the best flow rate and size of ducts being used.

Central Heating and Cooling [17] (Website):
This is a website that doesn't provide as much technical information about the project; however, there is vast HVAC general knowledge that can help inform our design. They also provide general safety practices for solar thermal systems that should be considered throughout the design process.

Building Thermal Performance Analysis by Using MATLAB and SIMULINK [14] (Paper):
This paper discusses thermal performance analysis for solar thermal systems using MATLAB and SIMULINK. The paper goes into extreme detail about the equations, variables, and assumptions that are needed to perform such an analysis. This paper's information along with an AR simulation of solar positioning can help determine the number of solar panels required and based on what percentage of the building heat load is being covered by the solar panels.

ASHRAE Climatic Design Conditions [18] (Website):
This website provides weather data from all around the world, and they have a weather station located at Flagstaff Pullium Airport. At the weather station they provide average temperatures throughout the year which helps with calculating heat losses to externally exposed ducts. They also provide solar irradiation data that is used directly in calculating fluid temperature and the energy input into the building.

How Relays Work [19] (Website):
This website provides information on the basics of an electrical relay and how they operate. The website also discusses different types of relays and certain applications. While there is no real mathematical benefit to this website, the information provided will help in making a decision about which style of relay should be used, which is a critical component to the operation of the entire system.

Analysis and Applications of a Current-Sourced Buck Converter [20] (Paper):
This paper provides vast information and calculations that can be used for a DC-DC buck converter. This component is required as voltage control for both the relay and the DC fans being used. These buck converters provide an accurate and consistent voltage stepdown if the input does not exceed the converters limitations. While very few of the equations from within the paper are used in confirming which buck converter should be used for our applications.

How to Choose the Right-Sized Electrical Wire [21] (Website):
This website is specifically implemented for the electronics required for the project. Most specifically the analysis required in determining the AWG requirements for the wires being used based on the voltage and current being supplied to the system. They also provide the specs for each wire gauge at different temperatures allowing for an in-depth analysis of the wire gauge needed for the solar thermal system.

Review of Photovoltaic Systems: Design, Operation, and Maintenance [22] (Paper):
This paper assists heavily with the configuration and design of photovoltaic solar panels. While the understanding of PV/T panels is understood the design of the full system is less known. This paper goes into extreme detail about the capabilities and limitations of such energy harvesting solar panels. This information also includes various styles of PV/T systems including gridded, stand alone, or hybrid systems. Overall, this paper helps orient the electrical components and ensuring that the part selection will be capable of operating under the current and voltage that the system will experience.

3.2.3 Tyler Hedgecock

Fundamentals of Heat and Mass Transfer, 8th edition, Chapter 13 [1] (Book)
To perform the radiation analysis for the solar air heater system, it was imperative to select this chapter from the textbook. It focuses on radiation, one of the most important factors for our product since it will involve the use of solar panels collecting solar energy from the sun. From team discussions and conceptualizations, it was decided that it would be best for the solar panels to be installed on the roof of the renewable energy building. Since the days will become shorter once winter arrives in Flagstaff, it is essential to understand how much solar radiation incident on the solar panel's surface and how much energy will be provided to the building. The solar panels must provide a sufficient amount of energy so that the product can meet the customer's needs.

Fundamentals of Engineering Thermodynamics 8th edition [26] (book)
For operating machines, such as the pump and the fan, utilizing this textbook is important for the team's decision making. It provides the information needed for thermodynamic analysis and how well certain machinery can operate. One of the customer requirements is that the system must reduce the heat load by 30%, which is why it is important to understand the efficiency of the pump and the fan. By performing this analysis, it can guide the team in designing our product and ensuring it can align with the needs of our client.

Experimental Analysis of Artificial Equilateral Triangle Solar Air Heater Using Zig-zag Channel [23]

(paper)
Different types of absorber plates were tested for the study conducted in this paper. It was to determine whether a flat plate, a triangular plate with one pass each, or a triangular plate with zig-zag flow for the dark and light passes could produce the most energy. At the end of the paper, it was found that the zig-zag plate produced the most energy and thermal efficiency, thus had the most significant advantage of absorbing solar energy. By keeping this in mind, the team can make informed decisions in the prototyping process.

Design and Implementation of Peltier Based Solar Powered Air Conditioning and Water Heating System [27] (paper):
The problem statement for this paper is that HVAC systems produce greenhouse gases due to a high-power consumption than most systems. To circumnavigate this issue, the paper proposed using a Peltier prototype to obtain air conditioning and water heating applications from a single system. According to the paper, utilizing the Peltier element is more resourceful, convenient, consistent, and overall eco-friendly. By understanding this information, it will help guide the team in the conceptualization process and how to go about building the system.

Energy Saving of Air Conditioning System by Oscillating Heat Pipe Heat Recovery Using Binary Fluid [28] (paper)
In this study, it examines oscillating heat pipe heat exchangers to improve energy savings and thermal efficiency. Three fluids were used to conduct the analysis such as water, methanol, and binary fluid including the two liquids. After the experiment, results show that the methanol had the highest thermal performance and energy savings ratios compared to the values shown in water and the binary fluid. If the team decides to use a water heating system, then this study will prove to be useful in how to warm the renewable energy building safely and efficiently.

What Wavelengths do Solar Panels Use? [30] (Website)
To perform the analysis for the Photovoltaic solar panels, it is important to know what wavelength certain solar panels operate at to perform the calculations. From this website, it was found that the solar panels the team aims to utilize operates at a wavelength of 0.85µm. By understanding the wavelength, it will help with calculations so that the team can analyze how much solar flux the solar panels are absorbing and the overall energy it can supply to the entire system.

Absorbed Solar Radiation [24] (Website)
The engineering toolbox website from this section provides information about the absorptivity depending on the surface material and the surface color. When performing calculations for the photovoltaic solar panels, it is essential to understand its surface properties to determine the absorptivity. Once the absorptivity has been determined, calculations can be carried out to determine the solar flux and the amount of energy required to ensure the system can work during the winter.

Everything You Should Know About Inverter Heat Pumps [29] (Website)
This website discusses how an inverter heat pump works and how efficient it is in supplying air conditioning to home buildings. The pump supplies air to the building depending on the outside temperature and shifts speeds automatically. The system is designed to be cost effective through its inverter technology and reduces the amount of energy required for the system. By understanding the functionality of the inverter pump and its cost effectiveness, the team can decide on how to utilize this system and implement it as well to provide sufficient air conditioning for the people who use the Renewable Energy building.

Solar Panel Cost [31] (Website):

When making design decisions for our product, the team aims to purchase items (i.e. solar panels) and ensure it can be cost effective as well. From this website, it shows that the cost of solar panels has been decreasing over the years. The reason for these decreases is due to factors such as maximum production at an industrial and global level over the last decade. By understanding this trend, it will help in the decision-making process to ensure our product can be cost-effective.

Solar power and solar power in Flagstaff, AZ [32] (Website):
This website collects data for solar radiation in Flagstaff, Arizona every month of the year. The values are measured in kWh/m^2/day and shows graphs for different values such as the different types of solar panel installations, the average solar radiation in Flagstaff, and solar power levels. Analyzing this data will be important to determine the amount of energy that the solar panels will be collecting during the winter months such as December and January. Due to shorter days during this time, it is essential to understand how this will impact the final design of our project and what parameters the team needs to set to meet the client's needs.

3.2.4 Joseph Meza

Solar Air Heating [34] (Online)
This website helped me understand how solar air heating systems work by using the sun's energy to heat air, which is then circulated into a living space. It also showed me how duct work in utitlized in a HVAC. This was needed for me to get the best understanding of the project. It breaks down the differences between passive and active systems and gives recommendations on when and where these systems are most effective. I used this resource to better understand system design, including ideal collector placement and airflow control. It helped reinforce my project's goal of using solar energy to heat air efficiently and supported the decision to implement an active air circulation method.

Solar Air Heater [35] (Online):
This DIY guide demonstrates how to build a functional solar air heater using simple materials. I loved this site because it gave an in depth thought process on how renewable solar heater was built. This showed me different ideas in how I would want to make a prototype to see how air can be converted into heat. It also allowed me to be creative in how I would want to design it. It is especially useful for experimenting with passive solar heating methods, absorber surface area, and material selection to improve performance and efficiency and better understand the goals needed to achieve.

A complete guide to home ductwork design: Stack Heating [36] (Online):
This article shows the importance of residential ductwork design, emphasizing how to properly layout, duct sizing, and airflow regulation. It discusses how thoughtful duct planning ensures even air distribution and reduces energy loss. For a solar air renewable energy heater project, this guide is useful in understanding how to channel heated air efficiently through a home or space. This will allow me to approach duct installation in various different ways. It reinforces the idea that performance depends not only on heat generation but also on how well that heat is transported using well-designed duct infrastructure.

Active solar heating [37] [Online):
This article from Energy.gov explains how active solar heating systems work by using mechanical components like fans or blowers to distribute solar-heated air. This allowed me to have a better understanding of the difference between passive and active systems and confirmed that our project falls

under the active solar heating category. This source also highlighted when and why active systems are preferred—mainly when more control and higher efficiency are needed.

How to calculate CFM FOR HVAC: CFM formula + calculator [38] (Online):
This article explains how to calculate the cubic feet per minute (CFM) of airflow using the formula CFM = (Area × Ceiling Height × Air Changes per Hour) / 60. It is important because of how accurate ventilation and airflow in heating, ventilation, and air conditioning (HVAC) systems. For a solar air renewable energy heater project, knowing how to calculate CFM is essential to ensure the correct amount of heated air is delivered into a space. This number is very important to me when looking to see what ducts we want to use. This directly affects thermal comfort, energy efficiency, and humidity control. The source also discusses how CFM impacts room moisture and comfort, which agrees with the proper sizing and airflow regulation in solar-based heating systems.

Residential Duct Sizing Guide [39] (Online):
This reference is useful because it gives me the comprehensive chart for selecting proper duct dimensions based on airflow in cubic feet per minute (CFM). It examines rectangular and round duct options. These are looked at based on air volume and includes key guidelines for duct placement and sizing in residential HVAC systems. For a solar air renewable energy heater project, this chart is important because it helps in ensuring the heated air can be distributed efficiently through space. Matching airflow (CFM) with the correct duct size helps maintain optimal performance, minimizes pressure loss, and supports even heating distribution. This overall is essential for system efficiency and occupant comfort.

How to install solar panels on a roof [40] (Online):
This article outlines the step-by-step process for properly mounting solar panels on a roof. I leaned how critical it is for using secure and weather-resistant hardware. It explains that aluminum rails should be attached to roof stanchions with stainless steel bolts, and the rails must be square to align the panels accurately. These mounts will give the correct tilt we want to get the best results. The article explains how the structural integrity and alignment is essential so the panel can do well in weather conditions, especially since flagstaff is prone to snow.

CFM calculator [41] (Online):
This website has a CFM calculator that provides an interactive tool for estimating the required airflow in cubic feet per minute based on room dimensions and air changes per hour. The tool includes reverse calculation features and explains how to determine CFM from volume and ACH inputs, making it user-friendly for design evaluations. For a solar air renewable energy heater system, this tool can show me what the quick airflow estimations are. This is important because it is used to properly size the heater and ductwork. It ensures that heating demand aligns with ventilation needs, which is essential for energy efficiency and comfort in conditioned spaces. I used this for my calculations on duct analysis.

Solar Air Heating [42] (Online)
The commercial solar air heating manufacturer explains the principles behind their patented SolarWall® technology. This is important because It highlights how heated air is drawn through perforated metal panels and into a building's ventilation system. This will help me with the prototype that I am building. I found this example of a large-scale, real-world application useful for understanding airflow design, efficiency improvements, and collector surface materials. It gave me ideas for how a more advanced system might be implemented and what design strategies help maximize solar gain in colder climates.

Recommended air change rates for different room types [43] (Online)
The engineering toolbox shows me the (ACH) for various room types, including offices, classrooms, industrial spaces, and residential areas. It is directly relevant to the solar air renewable energy heater project

because the values are necessary to calculate the required airflow to maintain thermal comfort and indoor air quality. It also is important because it will show me what type of ducts is needed to get the most efficient air flow in the building.

3.2.5 Calvin Schenkenberger

Fundamentals of Heat and Mass Transfer, 8th Edition, Chapter 12: Radiation [44] (Book)
This chapter of the textbook we used in Heat Transfer provides vital equations needed to calculate the performance of both the solar air and solar water heaters.

Theory And Design for Mechanical Measurements, Chapter 8: Temperature Measurements [45] (Book)
This chapter of the textbook we used in Experimental Methods of Thermal and Fluid Sciences gives us an understanding of how thermocouples work, which types are best suited for each scenario, and how to calibrate and convert the electrical signals to legible data. It will be important for our project if we decide to use thermocouples to measure temperature data when creating our automated temperature regulating system.

ASHRAE Handbook & Product Directory, 1980 Systems [53] (Book)
This handbook is full of tables necessary for the Manual J method of calculating heat loads. Although we will likely use software to calculate heat loads, this method can be used to validate our calculations.

On-Grid Flat Plate Solar Water Heater Collector Application for Electrical Energy Saving Contribution [46] (paper)
This peer reviewed paper explains the results of a study which involved connecting solar water heaters directly to an electric water heater without storage tanks to improve efficiency and decrease electrical energy consumption. Although we will not be using an electric water heater, the results of this study can inform our decision about whether a storage tank is necessary for our design.

Study of the enhancement in the performance of a hybrid flat plate solar collector using water and air as working fluids [47] (paper)
In our project, one of the biggest decisions we need to make is whether we use solar air or solar water to heat the building. This paper offers a third option, which is to combine both options into a hybrid system. The efficiency of the system increased, but it is up to us to decide whether the increase in cost is worth it.

Efficient design of converged ducts in solar air heaters for higher performance [48] (paper)
If we decide to take the solar air route, this article can help us design the air ducts to maximize the efficiency of the solar air panel.

ThermoPowerTM 30 Tube Evacuated Tube Solar Collector [43] (online)
By the solar shack there are many resources available to us for use in our system. One of these is the evacuated tube solar water heater, which we will likely use in our design. This online resource has an excess of variables provided in table format relevant to the performance of our specific evacuated tube solar water heater, which are very important for performance calculations and comparing solar water to solar air.

Solar PV Analysis of Flagstaff, United States [49] (online)
This website has average seasonal data of the electrical output of solar panels in flagstaff. Since our system will require some electrical components, such as pumps and fans, we need to have a good understanding of how much electricity is available to us.

ASHRAE Standards and Guidelines [50] (online)
When we implement our system, we need to make sure that the solar shack is still up to code. The ASHRAE website is a great starting point.

Rocks: The Unexpected Powerhouse of Sustainable Solar Energy Storage – SolarPACES [51] (online)
Because of the harsh winter conditions in flagstaff and the lack of solar energy overnight, it is crucial that we can store heat during the day so we can use it later. Water has a high heat capacity, but air does not. For an air system, we would need another substance to store heat in. Rocks have a high heat capacity, and with clever use of fans and air ducts, we could store and extract heat from them. This online resource explains the viability of such a system.

Solar Energy and Solar Power in Flagstaff, AZ [52] (online)
This website has average seasonal data of the solar energy available in Flagstaff. This is useful for calculating the heat output of each solar system

4000 Series Solar Air Heater [54] (online)
The Artica website has detailed information about their highest performing solar air heater. This is a state-of-the-art solar air heater, and we will use it as our benchmark and reference datum for other solar air heaters.

How Heat Load Calculation Works – Phononic [55] (online)
This online source gives a basic overview of the importance of heat load calculations as well as what they are. It gives a brief introduction to some of the related equations.

Cooling and Heating Equations – Engineering Toolbox [57] (online)
This page on the Engineering Toolbox provides heating and cooling equations. Of particular interest is the Sensible Heat Formula, which allows us to calculate the heat energy of air using its temperature and flowrate.

3.3 Mathematical Modeling

This chapter of the report will discuss the most recent mathematical modeling that has been completed. Due to the extremely dynamic nature of this project many sections are completely different from what they previously were. Sections that are completely different are the PV/T analysis, ducting analysis, and mounting analysis. The solar thermal energy analysis is like previous analysis done on the fluid outlet temperature. However, improvements have been made to approximate solar pathing and angles. Additionally, rather than only showing the fluid outlet temperature the simulation shows the energy input into the building based on the hours of operation.

3.3.1 Building Heat Load Analysis – Calvin Schenkenberger

In the last report we discussed the heat load analysis performed using eQUEST software [56]. Understanding the heat load of the building is vital to this project because we need to know how much heat energy needs to be supplied to the building on any given day. As explained on Phononic, "Heat load is the amount of heat energy that needs to be added to maintain a desired temperature setpoint" [55]. In the last report, we concluded that the month which requires the most heat was January, and the average heat load would be 10.32 KBtu/h. However, in the schematic creation wizard many assumptions were made, and not all of them were accurate. For example, the heating schedule was set for sunrise to sunset, but the batteries need to be maintained at or above 40 °F for all 24 hours of the day. The furnace air temperature was also set to 140 °F, which does not reflect the temperature we now project to achieve (92.3 °F) during our most difficult month (which we now believe to be December due to the reduced sunlight hours). We also know the design flowrate of the fans attached to the solar air panels now (190 cfm). Due to these developments, the initial simulation was deemed invalid, and we ran a new one.

Method: eQUEST

Thankfully much of the tedious work of setting up the simulation during the first run was carried over to the new one. The dimensions of the building and materials remained the same.

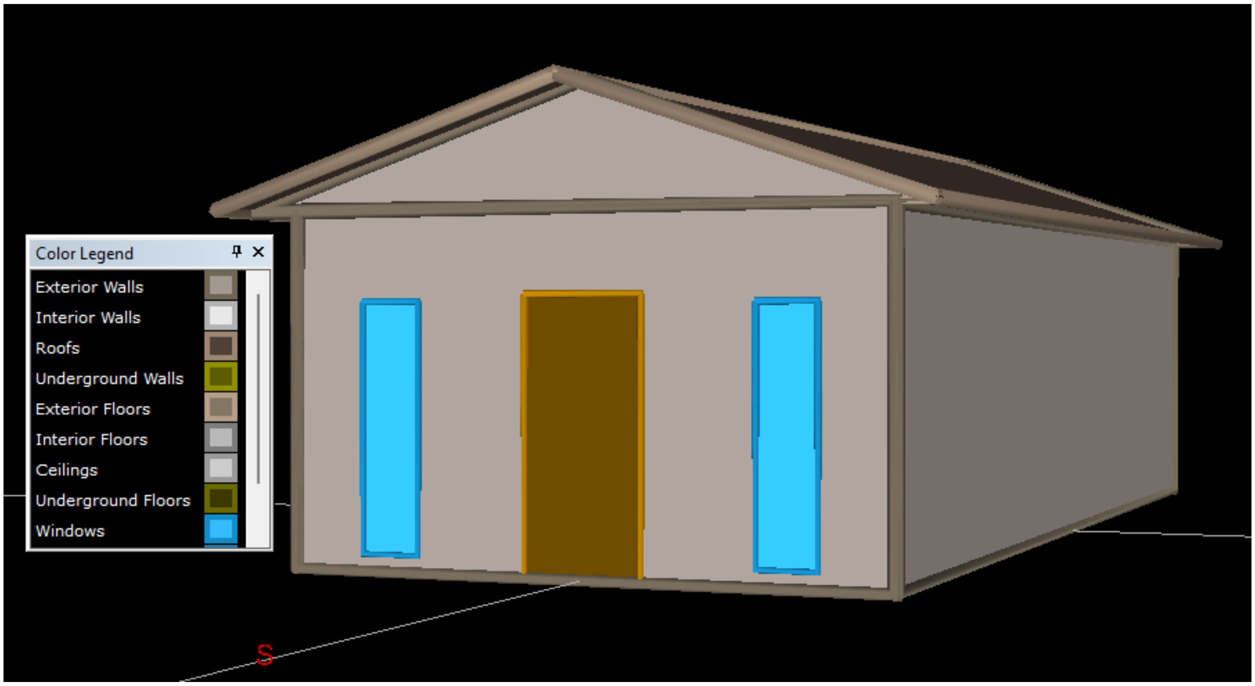


Figure 2: 3D Model of the Solar Shack Generated using eQUEST

However, several variables needed to be recalculated and updated. First, the schedule needed to be changed from sunrise to sunset to a full 24-hour period. Figure 2 shows the updated page in the design wizard.

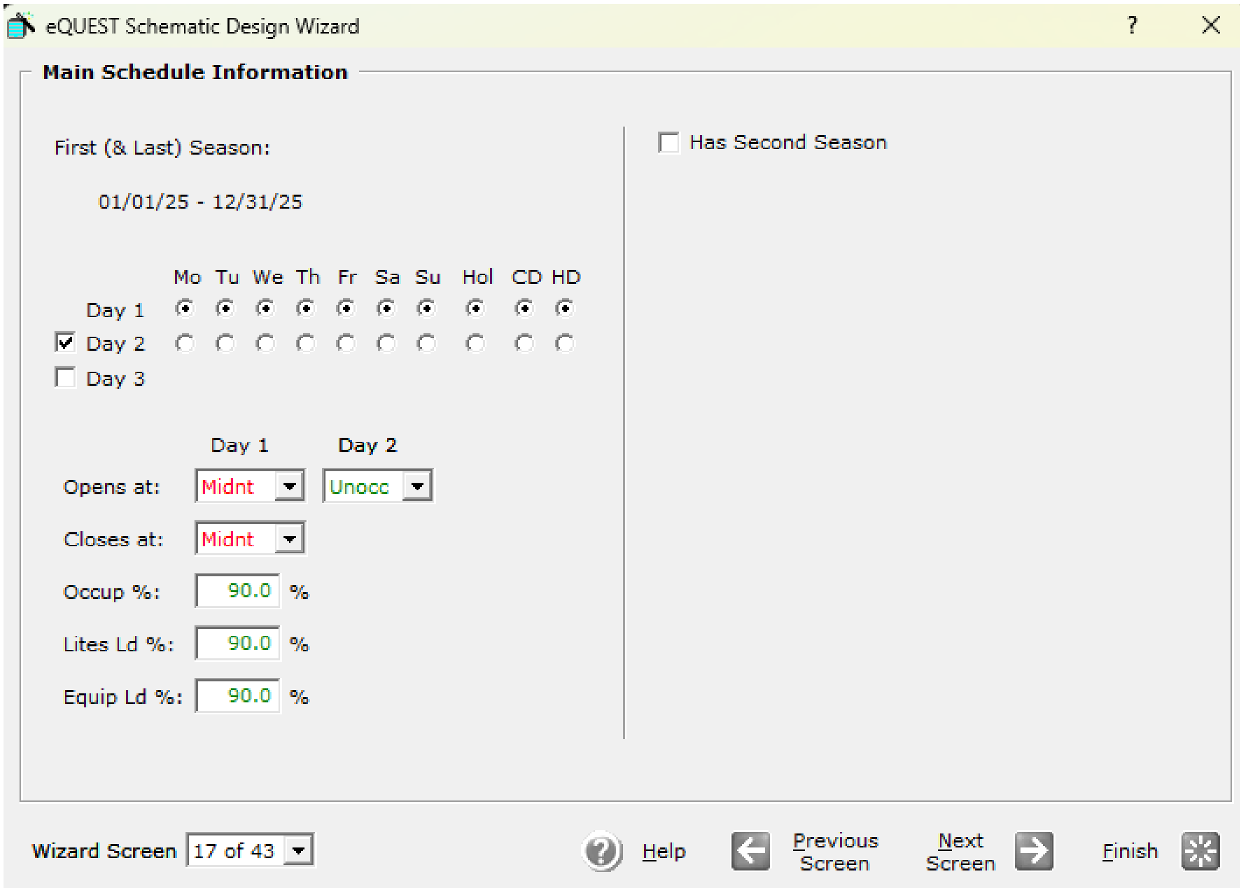


Figure 3: Updated Operating Schedule

Next, the HVAC page needed to be updated. The building design temperature was changed from 72 °F to 55 °F as this seemed to be a more reasonable mid-range target. Consequently, the heating setpoints were set to 53 °F. The supply temperature was changed from the default 140 °F to our newly calculated 92.3 °F as shown in section 3.3.2 of this report. In addition, the cfm/ft^2 box was updated to represent the combined flowrate of two solar air panels running at 190 cfm each, resulting in a total of 0.78 cfm/ft^2. Equation 1 shows how this value was calculated.

$$(190 + 190\,cfm)/(486\,ft^2) = 0.78\,cfm/ft^2 \quad 1)$$

These changes are reflected in Figure 4 below.

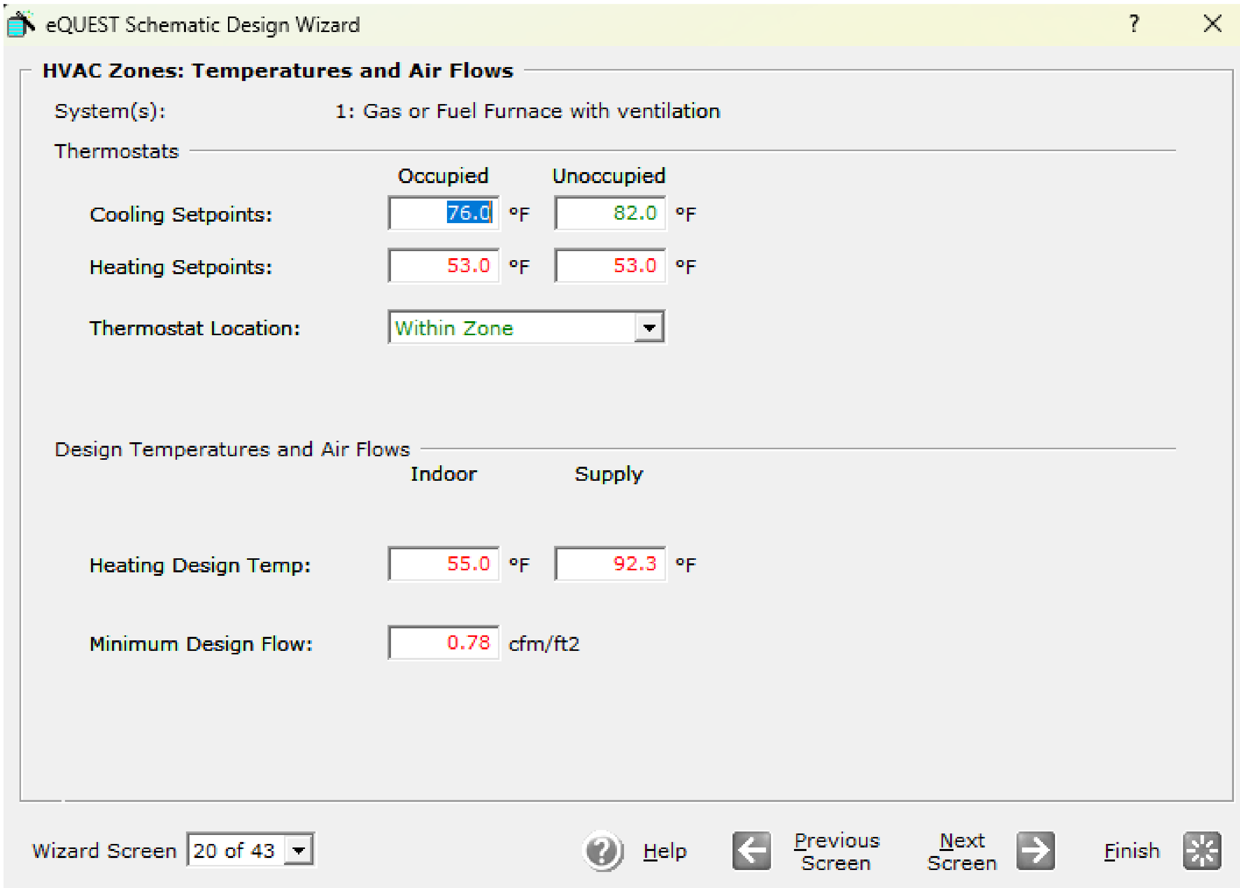


Figure 4: Updated HVAC Zones Page

Finally, the heater size page needed to be updated. This new value was calculated using the sensible heat formula [57] (Equation 2) and the new design temperatures and flow rates.

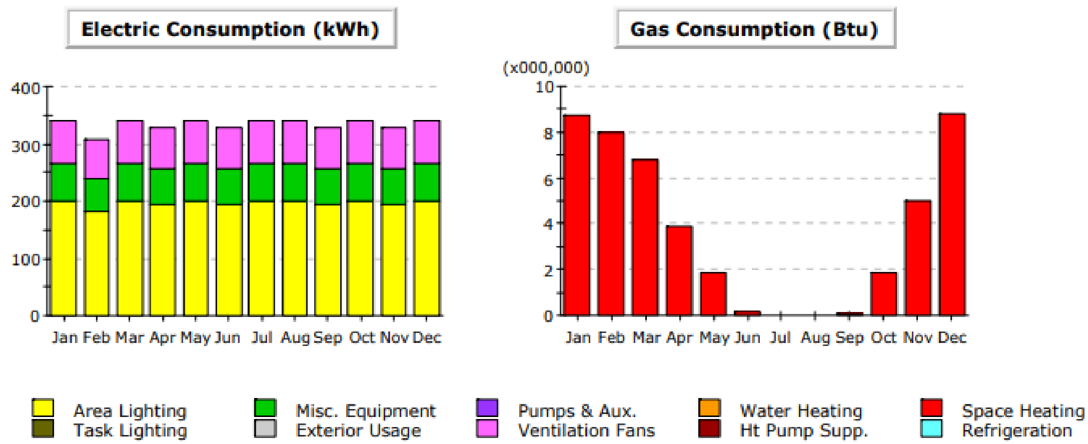
$$Q = 1.08 \cdot CFM \cdot (T_s - T_r) \qquad (2)$$

Where Q is heat in Btu/h, Ts is the air supply temperature and Tr is the room temperature. Using 380 as the CFM, 92.3 °F for Ts, and 55 °F and Tr, Q was calculated to be 15,307 Btu/h, or 15 kBtu/h. This change is reflected in Figure 5 below.

Figure 5: Updated Packaged HVAC Equipment Page

Results: Energy consumption and Heat Load Analysis

Once the simulation was run, the result was that December had the greatest heat load at 8.77 MBtu. Converted to an hourly rate, this is 11.8 KBtu/h. This is a slight increase in heat load compared to the originally calculated 10.32 KBtu/h. This increase can be attributed mostly to the change in operating schedule. Other changes like the CFM would have less of an effect on the heat load because the means of heat delivery do not change the required heat to maintain the shack at a constant temperature. The results of the new simulation are shown below in Figure 6.



Electric Consumption (kWh)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	-	-	-	-	-	-	-	-	-	-	-	-	-
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	73.6	66.5	73.6	71.2	73.6	71.2	73.6	73.6	71.2	73.6	71.2	73.6	866.7
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	65.0	58.7	65.0	62.9	65.0	62.9	65.0	65.0	62.9	65.0	62.9	65.0	765.3
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	200.8	181.4	200.8	194.3	200.8	194.3	200.8	200.8	194.3	200.8	194.3	200.8	2,364.4
Total	339.4	306.6	339.4	328.5	339.4	328.5	339.4	339.4	328.5	339.4	328.5	339.4	3,996.4

Gas Consumption (Btu x000,000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	8.75	7.96	6.77	3.85	1.86	0.18	-	-	0.09	1.84	5.00	8.77	45.08
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	8.75	7.96	6.77	3.85	1.86	0.18	-	-	0.09	1.84	5.00	8.77	45.08

Figure 6: New Simulation Results.

As stated in the last report, this project is not concerned with the electric consumption provided in this summary, although it is nice to have. The only relevant information to this project is the gas consumption by year and month. It is named "Gas Consumption" because the closest available mode of heating available in the eQUEST schematic design wizard is an air furnace that uses gas for heating. There was no "Solar Air Heater" option. This should not matter because, as stated before, the means of heat delivery do not change the required heat to maintain the shack at a constant temperature.

In addition to rerunning the eQUEST simulation, we used an AR solar tracking app (Solar Sun & Position) to find the window of time in which we have usable sunlight on winter solstice. Pictures of the sun's winter solstice path were taken from three locations: the ground in front of the building, the roof of the building on the south side, and the roof of the building on the north side. After comparing the images, we concluded that the roof of the building on the south side offers the most sunlight hours. The solar path from this position is shown below in Figures 7 and 8.

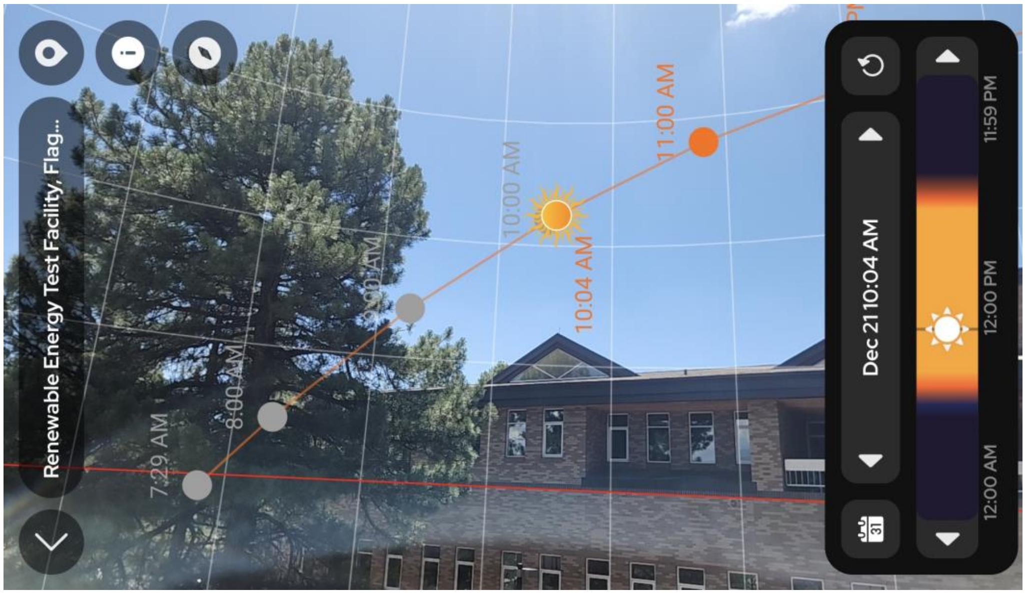


Figure 7: Morning Sun Path from the South Roof (9:00 AM to 11:00 AM)

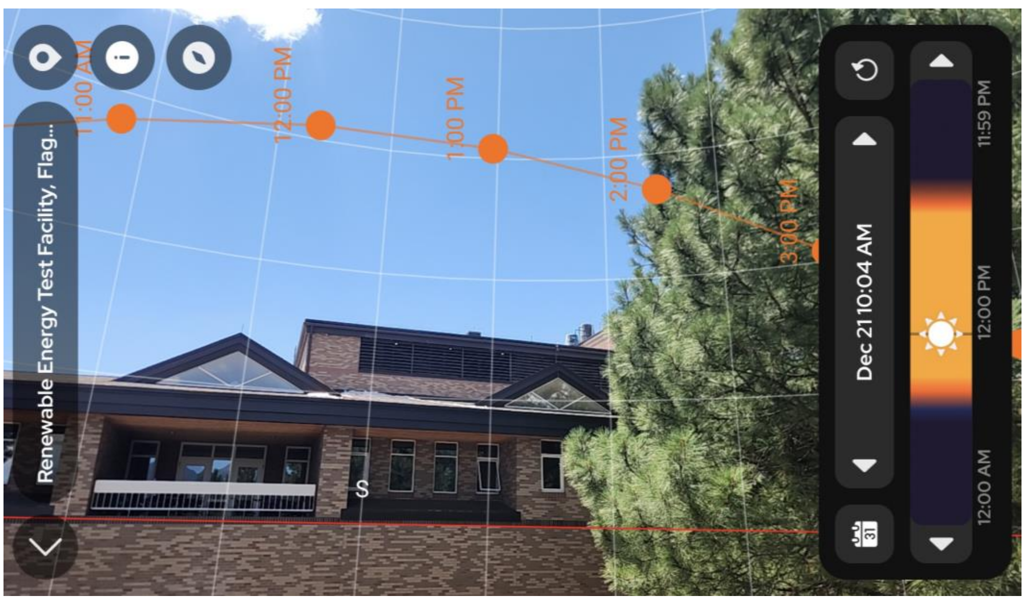


Figure 8: Afternoon Sun Path from the South Roof (11:00 AM to 2:00 PM)

This helped inform our decision to place the solar air panels on the south side of the roof. Because the roof has an east facing side and a west facing side, we also decided to place both of our panels on the southeast corner of the roof. This is because on the winter solstice before solar noon (12:32 pm in Flagstaff) we have 3 hours and 32 minutes of sunlight from the east, whereas after solar noon we only have 1 hour and 28 minutes of sunlight from the west.

3.3.2 Energy Analysis – Brendan Frazier

The energy analysis section of this report relies heavily on already simulated fluid temperature input and output. Those calculations were performed during the previous report and this is, more than anything, an improvement on those previous calculations. The difference between the thermal performance analysis and this energy analysis is that the energy analysis will be able to put it into a comparable numerical output for the building heat load analysis results. The MATLAB code that was developed for this analysis will be described in detail along with the results of the simulations. Due to the results of the building heat load analysis this simulation was not run every month but rather in the months where heat is most required in the winter.

Method: Energy Analysis

Overall, this energy analysis will determine how many solar panels are needed for the solar thermal system to meet the minimum 30% requirement for the building. This is based heavily on the *Fundamental of Heat and Mass Transfer* textbook by using the radiation and convection chapters and analysis. Because the team has established the use of an air-based solar thermal system, the overall analysis can be simplified. This is because in terms of finding the bulk outlet temperature of the fluid all that is need is the fluid properties such as density, viscosity, velocity, and conductive coefficient as well as the absorber plate surface temperature which requires minimal analysis. Losses are accounted for in the simulation as well. However, further analysis will have to be done on the losses when the duct style, material, and length are determined.

The time that the solar panel is exposed to usable solar irradiance is determined by using an AR solar positioning app. Figures 8 and 9, shown in section 3.3.1, shows the AR simulation run on the east facing roof of the RE Lab and provides irradiation over a 5 hour period on the winter solstice when we will have the least amount of energy available. The angle of incident radiation ranges from 0° to 71.25° back to 0° and accounts for the angle of the roof.

The absorber plate temperature must also be calculated to help get the bulk outlet temperature of the air. This is done using equation 3 where the energy absorbed, q_{abs}, is divided by the convective coefficient, h, and the projected area of the absorber plate, A_{plate}. That fraction represents the temperature, based on energy absorption, of the absorber plate. The final addition is the initial inlet temperature, T_{in}., for which we have assumed to be about 55°C from the inside of the building. The absorber solar energy by the absorber plate is calculated using equation 4 where the solar irradiation is multiplied by the absorptivity of the plate, projected area of the plate, and the sin of the angle for which the radiation is incident. Within the MATLAB code this angle is set to change every 30 minutes to provide a more accurate energy input into the building.

$$T_{plate} = T_{in} + \frac{q_{abs}}{h \cdot A_{plate}} \tag{3}$$

$$q_{abs} = \alpha \cdot G \cdot A_{plate} \cdot \sin(\theta) \tag{4}$$

For this calculation, the convective coefficient (h) is calculated using a Nusselt number correlation shown in equation 5. This correlation requires the Reynolds number which is shown in equation 6 and requires the necessary fluid properties like the density, velocity, and viscosity. The correlation also requires that Prandtl number which can be found in Appendix A.5 of the *Fundamental of Heat and Mass Transfer* textbook.

$$\overline{h} = \frac{\overline{Nu} \cdot k_{fluid}}{d_{panel}} \tag{5}$$

$$\overline{Nu} = 0.023 \cdot (Re)^{0.8} \cdot (\mathrm{Pr})^{0.4} \tag{6}$$

The next calculation uses equation 7 where the bulk air outlet temperature is calculated and is a modification of Newtons Law of Cooling. This is necessary because this is one of the reference temperatures when analyzing the energy input into the building. This calculation requires the inlet temperature of the air, assume to be 55°C from the building, as well as the same convective coefficient (h), surface area of the channels, absorber plate temperature, and the mass flow rate and specific heat capacity of the air.

$$T_{out} = T_{in} + \frac{h \cdot A_{channel} \cdot (T_{plate} - T_{in})}{\dot{m} \cdot c_p} \quad (7)$$

Finally, the energy calculations can be completed using these fluid outlet temperatures based on every month. This is done in comparison with the assumed building temperature at 55 Celsius. The energy calculation is shown in equation 8. Beyond the ambient temperature of the building this calculation requires the mass flow rate of the air ($\dot{m}$), specific heat capacity, and the air outlet temperature from the solar panels.

$$q_{in} = \dot{m} \cdot c_p \cdot (T_{in} - T_{amb}) \quad (8)$$

Results: Energy Analysis

The initial output of the MATLAB code is a plot of the approximate kWh of energy provided to the building. The plots show this energy provided over a 6.2-hour period with a change in the incident radiation angle changing every 30 minutes. This is done to simulate the sun rising and setting over the approximate time that the solar panel will be exposed to radiation. Figure 10 shows the plot in total displaying the energy input for the most relevant months for the solar thermal system.

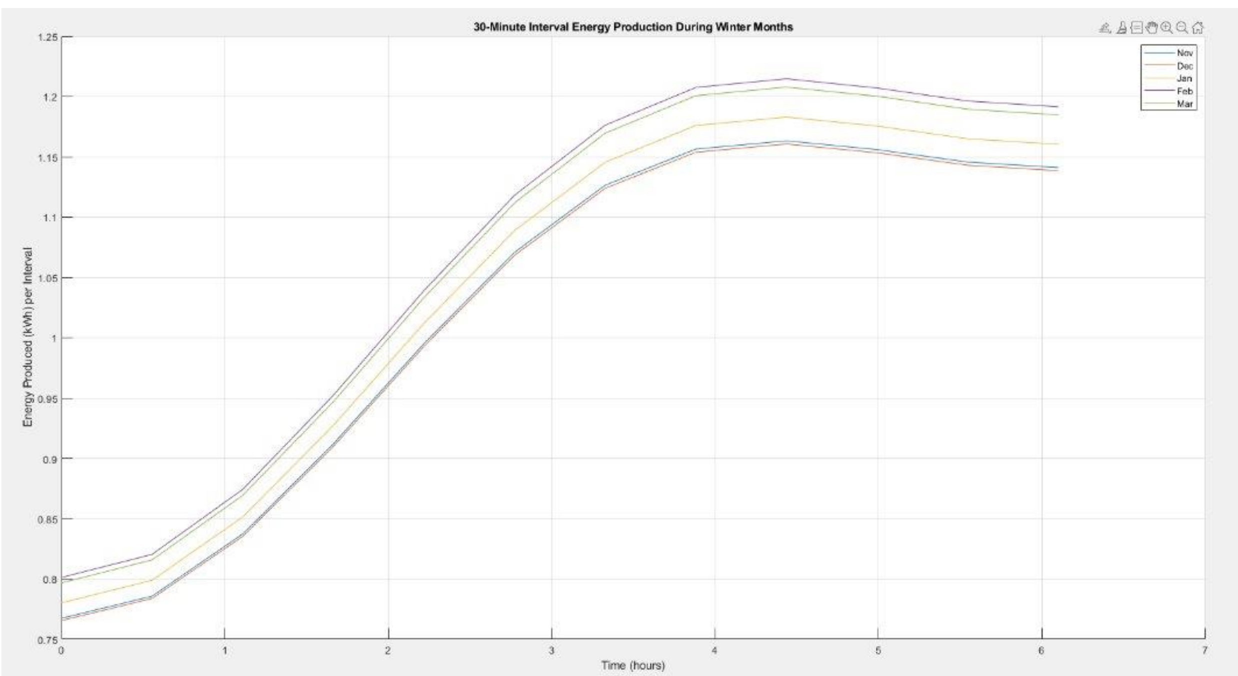


Figure 9: Energy Input Over 6.2 Hours

This plot shows almost exactly what is expected from the system. Early in the morning when the radiation angle is lower there is significantly less energy input into the building. As the day progresses, and the angle increases, a rapid increase in energy input occurs. This plot would typically show a complete normal distribution, but the AR solar pathing simulation indicated that the trees on the west side of the RE lab will block irradiation after about 5 or 6 hours depending on the month. Since the data being used is fixed from ASHRAE and being altered to mimic solar pathing and irradiation the plots are all extremely similar with a peak just after 4 hours from when radiation begins to reach the solar panels. With the AR simulation showing that the window for energy harvesting begins at approximately 9:00am this peak energy input will occur around 1:00pm in the winter.

The next calculation that is done takes the 5 highest heat load requirement months and approximates the hours and angles of solar irradiance and calculates the total energy input over a 5-, 5.5-, or 6-hour period depending on the AR solar pathing data. This is essentially a sum of the energy input shown in the transient energy plot from figure #. This is crucial data to collect for overall performance of the system and can be compared with the building heat load requirements for these winter months. This is primarily done to ensure that we are meeting the customer requirement that states the system must cover 30% of the heat load in the worst-case months. Figure 11 shows the absorber plate temperature, fluid outlet temperature, and finally the energy input over the full radiation collecting time.

```
--- Energy Inputs for Winter Season (Dynamic Angle) ---

Month: November
 Tilted Irradiance (peak): 939.35 W/m^2
 Absorber Plate Temp (est.): 63.53 °C
 Outlet Temperature (est.): 24.41 °C
 Energy Input: 12.26 kWh or 41823.18 BTU

Month: December
 Tilted Irradiance (peak): 937.46 W/m^2
 Absorber Plate Temp (est.): 63.39 °C
 Outlet Temperature (est.): 24.36 °C
 Energy Input: 12.23 kWh or 41726.93 BTU

Month: January
 Tilted Irradiance (peak): 955.45 W/m^2
 Absorber Plate Temp (est.): 64.51 °C
 Outlet Temperature (est.): 24.74 °C
 Energy Input: 12.46 kWh or 42528.31 BTU

Month: February
 Tilted Irradiance (peak): 981.02 W/m^2
 Absorber Plate Temp (est.): 66.11 °C
 Outlet Temperature (est.): 25.27 °C
 Energy Input: 12.80 kWh or 43670.39 BTU

Month: March
 Tilted Irradiance (peak): 975.34 W/m^2
 Absorber Plate Temp (est.): 65.77 °C
 Outlet Temperature (est.): 25.15 °C
 Energy Input: 12.73 kWh or 43423.75 BTU
```

Figure 10: Daily Energy Input from Air Heater

This data shows a maximum daily energy input occurring in February with 12.80 kWh. Some of the other more critical months like December and January are producing an energy input of 12.23 and 12.46 kWh every day. The energy input of an individual solar panel, when compared with the building heat load, covers just over 15% of the building heat load requirements. Since one of the customer requirements is to cover 30% of the heat load in the winter this indicates that we should use at least 2 of the solar thermal panels.

Figure 12, shown below, details by each month what percentage of the heat load will be covered on a monthly basis. This table was made by Calvin to show a complete annual summary of the heat load covered by the solar panels. It can be seen in July and August that no additional heating is needed for those months, so we assumed that 100% of the heat load was covered despite the solar thermal systems' operation is irrelevant. In total 1 solar panel will cover __% of the building's heat load and two covering __%. By doing this summarized annual comparison we can check the total heat load reduction the solar thermal system will provide for the building.

Gas Consumption by Month														
Month		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Monthly	Mbtu	8.75	7.96	6.77	3.85	1.86	0.18	0	0	0.09	1.84	5	8.77	45.08
Daily	Kbtu	282.2581	284.2857	218.3871	128.3333	60	6	0	0	3	59.35484	166.6667	282.9032	123.5068
Hourly	Kbtu	11.76075	11.84524	9.099462	5.347222	2.5	0.25	0	0	0.125	2.473118	6.944444	11.78763	5.146119
Daily Supplied	Kbtu	45.93	51.1	50.81	50.53	53.4	52.9	50.45	50.18	52.25	48.26	45.17	41.31	-
Percent Supplied	%	16.27%	17.97%	23.27%	39.37%	89.00%	100.00%	100.00%	100.00%	100.00%	81.31%	27.10%	14.60%	-
Monthly Supplied	Mbtu	1.42383	1.4308	1.57511	1.5159	1.6554	0.18	0	0	0.09	1.49606	1.3551	1.28061	12.00281
Yearly Heat Load Reduction From 1 Panel	%	-	-	-	-	-	-	-	-	-	-	-	-	26.63%
Yearly Heat Load Reduction From 2 Panels	%	-	-	-	-	-	-	-	-	-	-	-	-	53.25%

Figure 11: Summarized Annual Heat Load Coverage

3.3.3 HVAC Routing Analysis Joseph Meza -

In the HVAC Routing Analysis, it is necessary to calculate the cubic feet per minute (CFM) (for the solar air heater) of airflow using an anemometer; however, for preliminary estimates, I am assuming airflow values of 180, 190, and 200 CFM. These estimates allow us to size the ducts and understand how the system will perform under different conditions. When designing and installing ductwork, it is critical that the ducts are not drastically oversized or undersized. Figure 13 reveals the correct way to choose a duct.

Rectangular and Round Duct

Air Volume CFM	Rectangular Duct Height (inches)					Equivalent Round Duct (inches)	Air Volume CFM
	4"	6"	8"	10"	12"		
50	6 x 4					5	50
75	6 x 4					6	75
100	8 x 4	6 x 6				6	100
125	10 x 4	6 x 6				7	125
150	10 x 4	8 x 6				7	150
175	12 x 4	8 x 6				8	175
200	14 x 4	8 x 6				8	200
225	16 x 4	10 x 6				8	225
250	16 x 4	10 x 6				9	250
275		12 x 6	8 x 8			9	275
300		12 x 6	8 x 8			9	300
400		14 x 6	10 x 8			10	400
500		18 x 6	12 x 8	10 x 10		11	500
600		20 x 6	14 x 8	12 x 10		12	600
700		24 x 6	16 x 8	12 x 10		12	700
800		26 x 6	18 x 8	14 x 10	12 x 12	13	800
900		30 x 6	20 x 8	16 x 10	12 x 12	14	900
1000			22 x 8	16 x 10	14 x 12	14	1000
1100			24 x 8	18 x 10	16 x 12	15	1100
1200			26 x 8	20 x 10	16 x 12	15	1200
1300			28 x 8	20 x 10	18 x 12	16	1300
1400			30 x 8	22 x 10	18 x 12	16	1400
1500				24 x 10	20 x 12	16	1500
1600				24 x 10	20 x 12	17	1600
1700				26 x 10	22 x 12	17	1700
1800				28 x 10	22 x 12	18	1800
1900				30 x 10	22 x 12	18	1900
2000					24 x 10	18	2000

Figure 12: Chart of different ducts based on Air Volume CFM Figure Blank

When placing an oversized duct on a system, it will reduce air velocity and prevent airflow distribution. tentatively, pressure loss and efficiency would be a result if it was too small. Often times, air in an HVAC system moves based on static pressure, so the system must first pressurize the duct before efficiently moving air through it. Our objective for the duct design is to maintain sufficient pressure so that air from the solar air heater reaches the supply ducts with a small amount of loss, to ensure it still heats up in the building.

After doing research it was found, HVAC systems in residential or commercial buildings connect to a supply plenum to distribute airflow into multiple rooms. However, the building we will be installing our heated air flow system in only has two rooms. This means our ductwork design can be simpler, but it is pivotal that we confirm the airflow meets the heating requirements.

In order to achieve this goal, we must determine the required CFM (the building needs), we calculate the volume of the space to be heated and then apply the recommended air changes per hour (ACH). For our test facility, we first calculate the floor area by multiplying length and width, which yields 356.5 ft². Multiplying this area by the ceiling height gives a total room volume of approximately 3 089.7 cu ft. Then we do the same with the small room to get 1006.3 cu ft. Furthermore, we add them together to get a total of 4,096.0 cu ft. This volume is then combined with the target ACH to estimate the required CFM needed to heat and circulate the air effectively. The minimum CFM needed to heat up the building is 273.15.

$$L \times W = F_{Floor\ Area} \tag{9}$$

$$F_{Floor\ Area} \times H = V_{Room} \tag{10}$$

Big Room

$279\ in \times 184\ in = 356.5\ ft^2$ $\quad$ $356.5\ ft^2 \times 104\ in = 3089.7\ cu\ ft$

Small Room

$90\ in \times 184\ in = 115\ ft^2$ $\quad$ $115\ ft^2 \times 105\ in = 1006.3\ cu\ ft$

Fortunately, engineers made an HVAC design chart, which is useful for selecting duct sizes that can handle the calculated airflow shown in figure 14. For our project, we will choose duct configurations based on the balance between efficient airflow and ease of installation. It is essential to acknowledge the room layout, design, and anything that can cause an interference in the duct routing. The correct routing ensures that air travels the shortest practical path, reducing friction losses and maintaining static pressure.

Building / Room	Air Change Rate - n - (1/h)
Photo dark rooms	10 - 15
Pig houses	6 - 10
Police Stations	4 - 10
Post Offices	4 - 10
Poultry houses	6 - 10
Precision Manufacturing	10 - 50
Pump rooms	5
Railroad shops	4
Residences	1 - 2
Restaurants	8 - 12
Retail	6 - 10
School Classrooms	4 - 12
Shoe Shops	6 - 10
Shopping Centers	6 - 10
Shops, machine	5
Shops, paint	15 - 20
Shops, woodworking	5
Substation, electric	5 - 10
Supermarkets	4 - 10
Swimming pools	20 - 30
Textile mills	4
Textile mills dye houses	15 - 20
Town Halls	4 - 10
Taverns	20 - 30
Theaters	8 - 15
Transformer rooms	10 - 30
Turbine rooms, electric	5 - 10
Warehouses	2
Waiting rooms, public	4
Warehouses	6 - 30
Wood-working shops	8

Figure 13 : Chart of ACH

According to the chart, the building's estimated ACH is 1. Since the facility lacks ventilation, we chose the lowest number on the table, which is 1, even though there isn't a building that looks like the lab. Our goal is to meet a building's ASHRAE criteria. We must ensure that our CFM is higher than 273.15, as we are working with a building that has a lot of electrical components and minimal installation. The large room in the building will require a minimum of 205.98 CFM, and 67.08 CFM

$$AirFlow = RFL_{Rooms\,floor\,area} \times Ceiling\ height(ft) \times \frac{ACH}{60}$$
(11)

Big Room

$$205.98\ CFM = 356.5\ ft^2 \times\ 104in\ \times \frac{4}{60}$$

Small Room

$$67.08\ CFM = 115\ ft^2\ \times\ 105in\ \times \frac{4}{60}$$

Additionally, we have to recognize the thermal performance of the system. The solar air heater is pumping the heat through the ducts and has to reach the entire room. The Final design has to have the ducts placed in spots where the heat can travel the best. Overall, this routing analysis is used to predict system performance before putting parts together. The calculations will be able to be adjusted and will be used to navigate the ducts to make the system function. We combine the CFM measurements, volume calculations, and static pressure, it allows us to have a few different options in the ducts we desire to use, achieving the goal have a proper airflow distribution within the building.

3.3.4 Photovoltaic Solar Analysis – Tyler Hedgecock

Once the team decided to use a photovoltaic (PVT) solar panel for the project, it was necessary to decide the dimensions to produce a voltage of 30V. It was also decided it would be necessary to use one PVT panel to provide voltage to each fan connected to two solar air heaters. To determine the solar flux during the winter month of flagstaff, data was taken from the solar energy local website [32] and calculations were performed as shown below:

$$\frac{5.46\frac{kWh}{m^2}}{7.667hrs} = 0.71217\frac{kW}{m^2}\cdot\frac{1000W}{kw} = 712.17\frac{W}{m^2}$$

To determine how much voltage the PVT panel was producing, it was important to calculate the amount of heat flux it was absorbing as with a previous heat transfer calculation. To begin the calculation, it was important to determine the product between the wavelength of the panel, which was assumed to be polycrystalline and thus would have a wavelength of 0.85µm [30]. The temperature was also set to be at the sun's, 5800K [10], and is as follows:

$$\lambda_T = \lambda \cdot T \quad (12)$$

$$= 0.85\mu m \cdot 5800K$$

$$= 4930\mu m \cdot K$$

Once the product had been found, the fractional radiation needed to be found. The value was taken from Table 12.2 from the Fundamentals of Mass and Heat Transfer Textbook [10]. Afterwards, the absorptivity needed to be found to calculate the absorbed heat flux, which was assumed to be mounted on the roof at an angle of approximately 16.77°.

$$F(\lambda \rightarrow 0.85\mu m) = 0.616725$$

$$\alpha = \frac{\int_0^\infty \alpha_\lambda(\lambda)\, G_\lambda(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda} \quad (13)$$

$$= 0.8(0.616725) + 0.25(1 - 0.616725)$$

$$= 0.589199$$

$$G_{abs} = \alpha G \cos(90 - \theta) \quad (14)$$

$$= 0.589199 \cdot \left(712.15\frac{W}{m^2}\right)\cos(90 - 16.77°)$$

$$= 121.07\frac{W}{m^2}$$

As with the absorbed Heat flux, the first few steps were repeated to find the product between the wavelength and the temperature albeit with different values. The wavelength for the absorber plate remained unchanged, although the wavelength for the cover plate was found to be about 0.7 µm. It was assumed that the cover plate temperature was at 313.15 K and the absorber plate temperature was 333.15K. Emissivity values for the absorber plate was set to 0.8 and 0.25 [24], and to 0.75 for the cover plate. It was also assumed that the PVT panel's surface was diffuse thus the absorptivity is equal to the emissivity. Once these values were set, it was necessary to find the heat loss and the difference between that value and the value of the solar energy absorbed as shown below:

$$\lambda_a * T_a = 283.1775\mu m * K$$

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda E_{\lambda,b}\, d\lambda}{E_b} \tag{15}$$

$$\varepsilon_a = 0.25$$

$$\lambda_c * T_c = 219\mu m * K$$

$$\varepsilon = \frac{\int_0^\infty \varepsilon_\lambda E_{\lambda,b}\, d\lambda}{E_b} \tag{16}$$

$$\varepsilon_c = 0.75$$

$$q_{rad} = \frac{\sigma(T_a^4 - T_c^4)}{\left(\frac{1}{\varepsilon_a} + \frac{1}{\varepsilon_c} - 1\right)} \tag{17}$$

$$= \frac{\left(5.670 \cdot 10^{-8}\frac{W}{m^2 \cdot K^4}\right)[(333.15K)^4 - (313.15K)^4]}{\left(\frac{1}{0.25} + \frac{1}{0.75} - 1\right)}$$

$$= 35.36\frac{W}{m^2}$$

$$q_{conv} = \overline{h_L}(T_a - T_c) \tag{18}$$

$$\overline{T} = \frac{T_a + T_c}{2} \tag{19}$$

$$= \frac{333.15K + 313.15K}{2}$$

$$= 323.15\text{K}$$

$$Ra_L = \frac{g\beta(T_a - T_c)L^3}{\nu\alpha} \tag{20}$$

$$= \frac{9.81\frac{m}{s^2} \cdot \frac{1}{323.15K} \cdot (333.15K - 313.15K) \cdot (0.0508m)^3}{\left(18.22 \cdot 10^{-6}\frac{m^2}{s}\right)\left(25.93 \cdot 10^{-6}\frac{m^2}{s}\right)}$$

$$=168773.51$$

$$\overline{Nu_L} = 1 + 1.44\left[1 - \frac{1708}{Ra_L\cos(\tau)}\right]\left[1 - \frac{1708(\sin(1.8\tau))^{1.6}}{Ra_L\cos(\tau)}\right] + \left[\left(\frac{Ra_L\cos(\tau)}{5830}\right)^{\frac{1}{3}} - 1\right]$$

$$\overline{Nu_L} = 4.4457$$

$$\overline{h_L} = \frac{\overline{Nu_L}k_f}{L} \tag{21}$$

$$= 2.4513\frac{W}{m^2 \cdot K}$$

$$q"_{conv} = \bar{h}_L(T_a - T_c) \tag{22}$$

$$= 49.03\frac{w}{m^2}$$

$$q"_{total} = 121.07\frac{W}{m^2} - \left(49.03\frac{w}{m^2} + 35.36\frac{W}{m^2}\right) = 36.68\frac{W}{m^2}$$

Once the difference had been found, it was necessary to convert the total from W/m^2 to m^2. The length and width of the PVT panel are 3ftx5ft, respectively, or 0.9144mx1.524m.

$$36.68\frac{W}{m^2} * 0.9144m * 1.524m = 51.115W$$

After the wattage had been found, it needed to be converted into volts by dividing it by the amperes of the panel, with a value of 1.6A.

$$V = \frac{W}{I} \tag{23}$$

$$= \frac{51.115W}{1.6A}$$

$$= 31.9V$$

As shown in the calculations above, the value is slightly higher than the desired voltage, However, it will ensure that the fans are recieving the necessary voltage to work during the shorter winter days.

3.3.5 Mounting Method Analysis – Jacob Apodaca

Since we are going with a solar thermal air system, we need somewhere to mount our solar air collectors. The plan for our final design is to mount our solar air collectors and photovoltaic panels on top of the roof of the renewable energy lab. This analysis will be conducted to determine what size bolts to use to mount all of the panels on the roof so that they are in accordance with standard safety codes and can withstand the pressure and forces of the environment which include wind and snow.

First, I made some assumptions to simplify my calculations. My assumptions include uniform snow distribution of 20.9 inches on the solar collector [12], 35-degree tilt of the solar air collector, wind speed is 25 mph or 11.176 m/s [13], and the snow is "normal". To start off my analysis I calculated the dead load which is just the weight of the system.

$$\text{Dead Load} = \text{weight}/\text{Area} = 100\,\text{lbs}/33\,\text{ft}^2 = 3.03\,\text{psf}$$

Then from there I calculated the live load which includes the forces from wind and snow.

Wind:

$$\text{dynamic pressure} = \frac{1}{2}\rho v^2 = \frac{1}{2}\left(1.125\ \frac{kg}{m^3}\right)\left(11.176\ m/s\right)^2 = 70.26\ \frac{kg \cdot m}{s^2}$$

$$\text{Surface Area} = 33.\ ft^2 \times \sin(35^\circ) = 18.93\ ft^2 = 0.83\ m^2$$

$$\text{live load} = 70.26\ \frac{kg}{m \cdot s^2} \times 0.83\ m^2 = 58.31\ \frac{kg \cdot m}{s^2} = 58.31\ N$$

Snow:

$$\text{live load} = \rho \times h = 1.25\ \frac{psf}{in} \times 20.9\ in = 26.125\ psf$$

$$\text{Weight} = \text{live load} \times A = 26.125\ psf \times 33\ ft^2 = 862.125\ lb$$

After calculating the live loads from wind and snow I had to calculate the forces that are acting on the bolts. To do this I summed the live and dead loads up and divided it by four because there are four bolts per solar air collector that connect to the L-brackets. I also had to determine the shear stress of the material being used for the bolt and to find this I used a bolt size table from Shigley's Mechanical Engineering Design Textbook [3]. From this table I used the minimum tensile strength value provided for the shear stress. I also used a factor of safety of two to account for any uncertainties. After this I was able to determine the minimum size of the bolts to withstand the forces.

Table 8–11

Metric Mechanical-Property Classes for Steel Bolts, Screws, and Studs

Property Class	Size Range, Inclusive	Minimum Proof Strength,* MPa	Minimum Tensile Strength,* MPa	Minimum Yield Strength,* MPa	Material	Head Marking
4.6	M5–M36	225	400	240	Low or medium carbon	4.6

Figure 14: Bolt Size Table [3]

$$F_{design} = \text{Sum of forces per bolt} \times F.O.S$$

$$F_{design} = 219.57 \text{ lb} \times 2 = 439.13 \text{ lb}$$

$$F = \tau A$$

$$439.13 \text{ lb} = 58.0151 \text{ kPsi} \times \frac{\pi}{4} d^2$$

$$d^2 = 0.009637451 \text{ in}^2$$

$$d = 0.0982 \text{ in} = 2.5 \text{ mm}$$

The results for the minimum sized diameter of the bolt is 0.0982 inches or 2.5mm. Since I did not validate this analysis, we are going to use a larger diameter bolt around a quarter of an inch which is around 6mm to accommodate any errors made in the calculations. The final result would be an M6 Steel bolt or bigger.

4 Design Concepts

4.1 Functional Decomposition

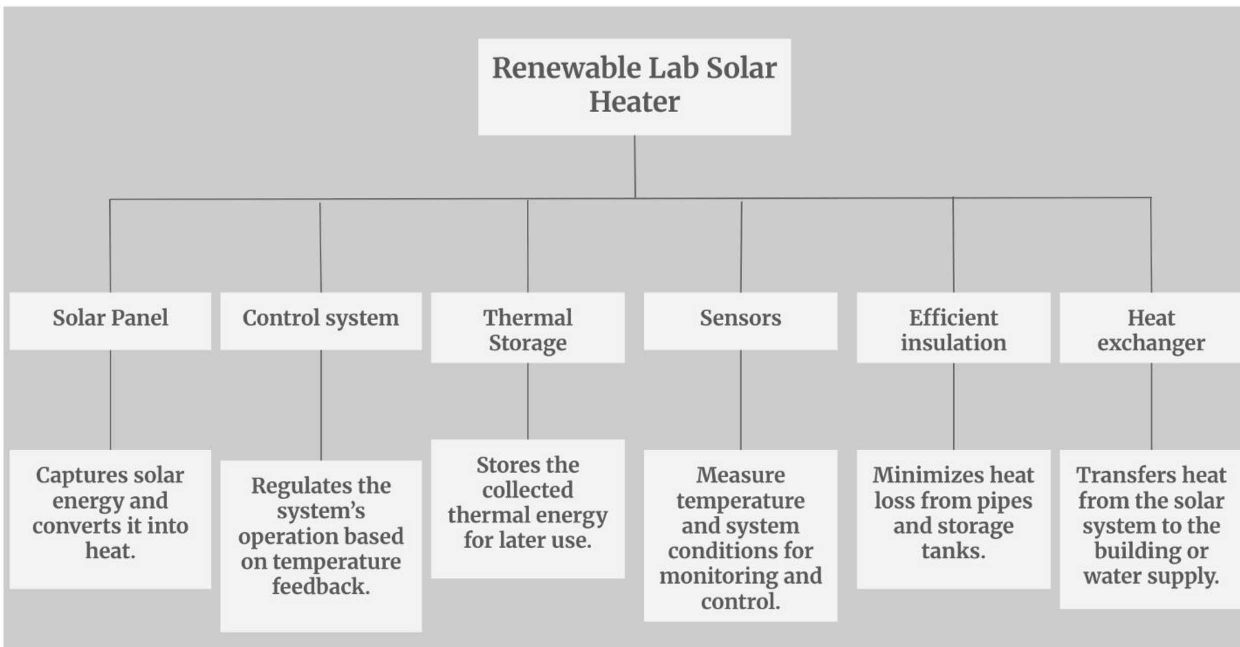


Figure 15: Decomposition Chart

The Functional decomposition of the renewable lab solar heater (figure blank) shows how the system has 6 critical components being the: Solar panel, control system, thermal storage, sensors, efficient insulation, and heat exchanger. Each of the components and functions plays an important role in the overall performance and reliability of the heater. The solar panel is used to capture energy from the sun and convert it into heat. The control system is used to navigate the system using real-time temperature feedback.

Thermal storage stores collect heat for use during low sunlight hours, while sensors monitor temperatures and system conditions to ensure efficiency and safety. Efficient insulation is used to bring down heat loss within the system, and the heat exchanger will transfer stored thermal energy to the building or tank. The functional decomposition clarifies each of the components' contributions to the purpose of the system. This helps design decisions, troubleshooting, and structure throughout the project.

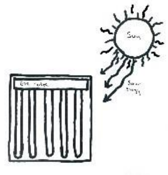
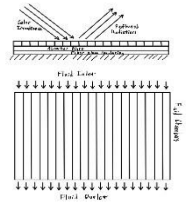
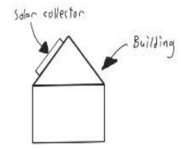
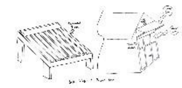
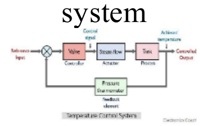
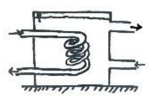
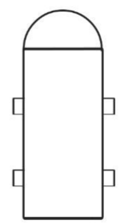
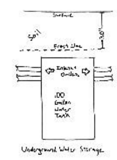
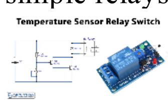
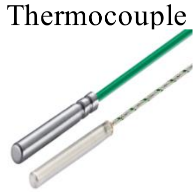
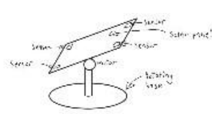
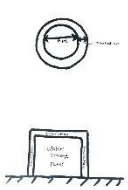
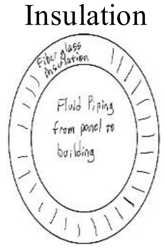
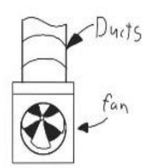
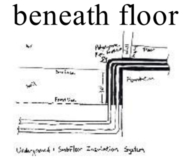
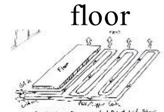
4.2 Concept Generation

To begin the design process, a series of concept variants (CVs) are created from a series of subsystems that are required for the project. The subsystems are a full breakdown of the purchasable, machined, and 3D printed components that are applicable to the system. For the RE Lab solar heater, the subsystems have been broken up as follows.

1) Solar Panel
    - This entails the style of solar panel including the orientation/position and the fluid medium that is used to transfer heat to the building.
2) Control System
    - This component will determine when and for how long the system is operating. The time aspect will be determined by the total amount of temperature increase needed within the building. The control system will also have integrated ties with any sensors being used.
3) Thermal Storage
    - This is how the system will save some of the solar energy collected to be used for a later time. This aspect is specifically applicable to winter months when solar energy and temperature decrease, but the building still needs to remain heated.
4) Sensors
    - Multiple sensors can be used for this project. This includes but is not limited to temperature sensors to determine if the system is worth turning on, photovoltaic or light sensors to determine if the solar panel pump or fan should be turned on, and tracking sensors to optimize the direction the solar panel is facing.
5) Thermal Insulation
    - To minimize heat losses throughout the system, thermal insulation will be used throughout. This will consist of building insulation, back-side solar panel insulation, and piping insulation as the fluid is in transit to the building or radiator.
6) Heat Exchanger
    - Each system will integrate a heat exchanger with some assisting with the overall heat transfer into the building and others helping with thermal storage capabilities of the system.

Table 1: Concept Generation Table

	Jacob	**Brendan**	**Tyler**	**Joseph**	**Calvin**
Subsystems	**1**	**2**	**3**	**4**	**5**
Solar Panel	Evacuated	Flat Plate Air	Solar panel	Evacuated tube	Solar water

(A)	solar tubes 	Heater 	attached to roof 	solar collector 	heater and Passive solar windows 
Control System (B)	Thermostat 	Arduino Uno 	Closed loop system 	Smart Digital Thermostat 	Raspberry Pi 
Thermal Storage (C)	Storage tank with CFWH 	Building Insulation 	Compressed air tank 	Insulated cylindrical tank for thermal 	Underground storage tank with OFWH 
Sensors (D)	Arduino, sensor inside building with simple relays 	186K-type Thermocouple 	Solar tracking sensors 	Digital temperature sensors 	Type T Thermocouple 
Thermal Insulation (E)	Insulated piping and storage tank 	Fiber Glass Pipe Insulation 	Fans to circulate air flow 	Tank wrap and foam pipe insulation 	Pipes below frost line and beneath floor 
Heat Exchanger (F)	Radiator inside of building	Silica Fire Bricks	Direct contact heat exchanger	Copper coils submerged in storage tank	Hot coils under floor 

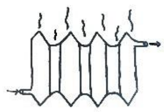
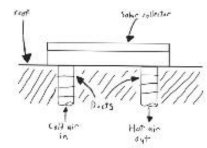
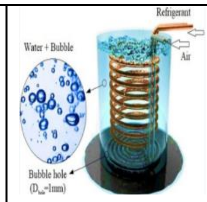
					

Table 1 shows a complete breakdown of each subsystem as well as a correlating CV that each group member has made. However, not every CV that was developed was used in a final concept design. Certain CVs, while conceptually valid, were not feasible due to weather, ground, or safety conditions. From the concept variants, the ones that were primarily used were the evacuated tube solar water heater (Located in cell A1) and the flat plate solar air heater (Located in cell A3). These selections provide both air and water thermal systems which allow for extensive freedom in the overall design until a full thermal performance analysis is completed. The control systems that were most selected for full concept designs were the Arduino Uno R3 to create a smart system using temperature and light sensors and a smart digital thermostat for manual control of the heating. The primary thermal insulation methods implemented into full concepts were fiberglass pipe insulation and general foam wrap for all the external piping. The advantage to the fiberglass insulation, while designed for pipes, is they are sold in sheets allowing for more expansive applications over the preformed and fitted foam wrap. Some of these additional applications are insulating the back of the solar panel and insulation of a potential storage tank. Finally, the water-based heat exchanger that is most suitable for this project's applications is the radiator fitted inside the building. The best suited air-based radiator is more of a specialized direct contact heat exchanger that is used on the north campus of NAU. The solid material retains heat extremely well and slowly releases heat into the rest of the building.

4.3 Selection Criteria

We evaluated each subsystem based on performance, feasibility, cost and compatibility for the Renewable Energy Lab structure, and using equations. Our objective was to find a system that could operate reliably during cold winter months, while keeping heat loss down and maximizing energy capture and storage. In the decision process that was rooted in fundamental thermodynamics and heat transfer principles, along with the known engineering specifications.

4.4 Concept Selection

Located below are a series of full design concepts for the solar heating system. Each design takes one concept variant from each of the subsystems. They are then sketched to create a full concept for the project. Each concept will list and detail which of the concept variants was selected and why. They will also introduce the pros and cons of some of the decisions made before they are assessed.

<u>Design 1 (Jacob):</u>

Components: A3, B2, C2, D4, E2, F2

Concept:

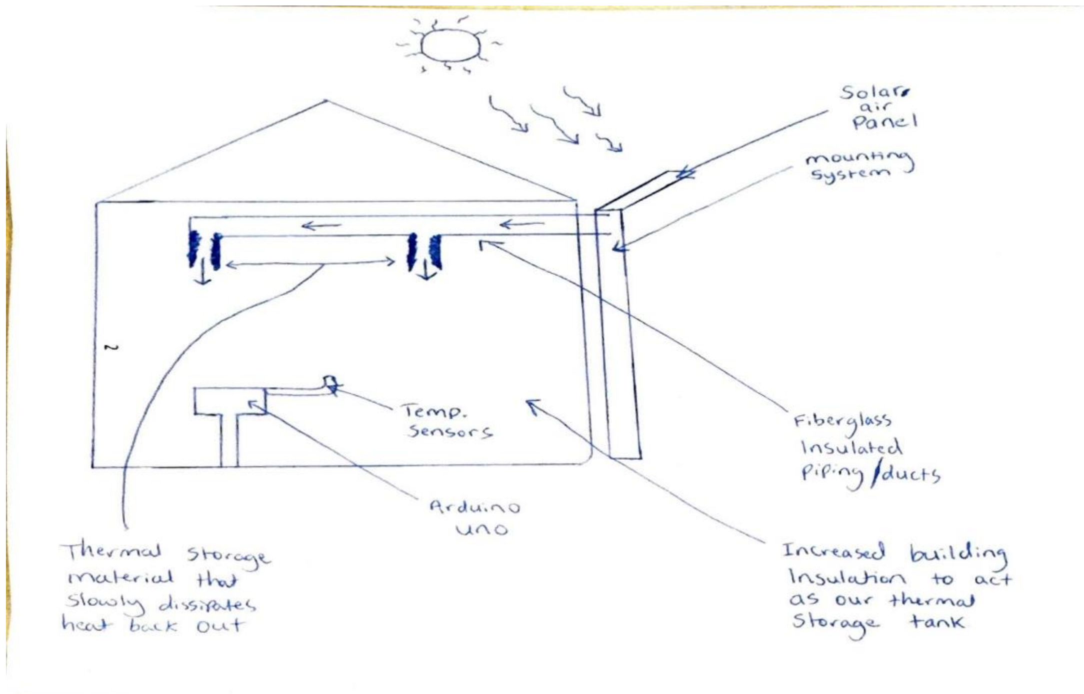


Figure 16: Concept Design #1

Solar Panel: For this design concept I decided to choose the air solar panel that is connected to the roof of the renewable energy lab. But since our design is not supposed to have any major modifications to the building, this design component more than likely will incorporate a mount to hold the system in the front of the building which is what I drew in my full design concept.

Control System: To control the system, I decided to choose the Arduino uno design concept because it is a cheap and smart way to tell the system to turn on and off. It also has analog input pins which can be used for the temperature sensors that may be inside the building to tell the system to turn on or off depending on how hot or cold the inside of the building is.

Thermal Storage: The design concept for thermal storage includes incorporating building insulation. This design concept is unique because it essentially does not need a thermal storage tank to store the heat but rather stores the heat in the building and we would accomplish this by improving the insulation in the building.

Sensors: Temperature sensors would be used and connected to the Arduino inside the building so that as they record data on how warm the inside of the building is it can tell the Arduino so it can turn the system off or keep running.

Thermal Insulation: The ducts or pipes used to transfer the hot air into the building from the solar air collector will be insulated using an insulation material like fiberglass.

Heat Exchanger: The heat exchanger that would be utilized for this design concept would be to incorporate a thermal storage material in the ducts or attic that will absorb the heat of the hot air and slowly dissipate it back out when the system is off i.e. overnight.

<u>Design 2 (Brendan):</u>

Components: A1, B4, C4, D2, E2, F1

Concept:

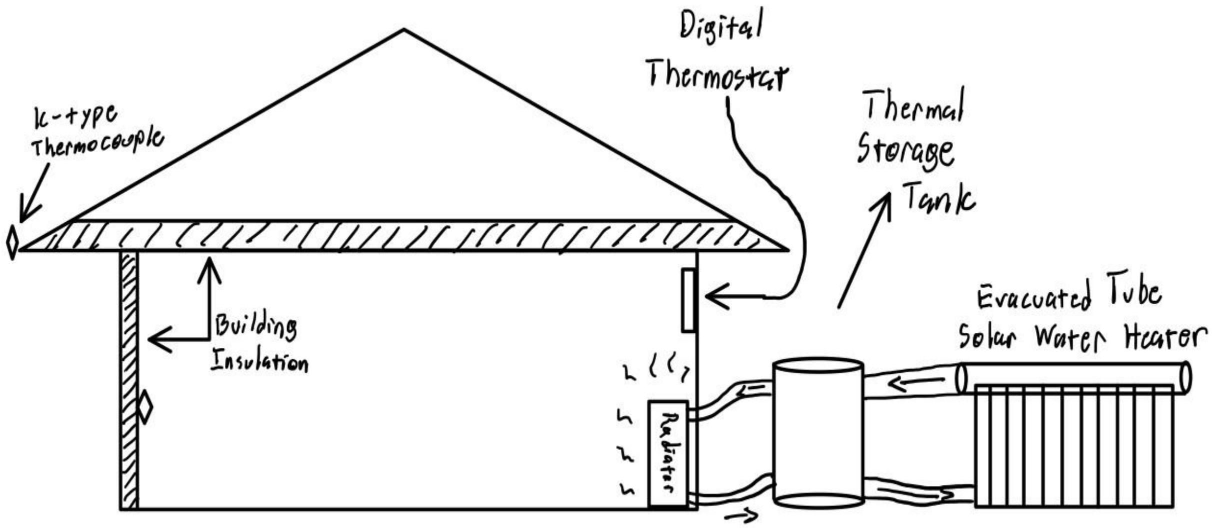


Figure 17: Concept Design #2

Solar Panel: The advantage to the water-based solar thermal system is the static water increases temperature much more dramatically than a constantly flowing fluid would. This additional increase in energy absorbers will provide more solar thermal energy to the building than other water based solar panel designs.

Control System: The system must still be controlled, and some variations have been made to this design specifically. The electrical components for this design will consist of a photovoltaic (PVT) solar panel to supply a voltage which will be directed through a buck converter or charge controller to moderate the voltage supply to the fans. This supply and a thermostat will be connected to a mechanical relay where the thermostat will tell the relay to be on or off with a small voltage input. When the sun is out and the relay is activated, voltage will be supplied to the fans for operation. However, if the relay is activated and there is no solar energy to be harvested the PVT panels won't supply any voltage to the pumps. This should have the system operate only when solar energy is available without entirely shutting down the system at night.

Thermal Storage: To store the thermal energy that is absorbed by the fluid, this design implements an insulated storage tank for the heated water. The storage tank will have two pumps where the initial pump brings the hot water into the storage tank from the solar panel. A secondary pump will take the hot water from the storage tank to the building to begin the heating process. Having two pumps will allow the first pump to bring additional thermal energy into the storage tank without also bringing additional heat into the building in the event that the building is already heated to its minimum standard.

Sensors: Multiple sensors will be used for this system. The first being K-type thermocouples which will act as temperature sensors; however, they will need to be calibrated with a data acquisition software to convert the output from the thermocouples into temperature readings. The advantage to using these thermocouples is the high precision that they provide if calibrated properly.

Thermal Insulation: For any sort of heating, ventilation, or air conditioning (HVAC) system thermal insulation must be considered. For this concept, thermal insulation consists of fiberglass piping insulation. This style of insulation is specifically useful in harsh environments where the pipes will be exposed to unknown or difficult conditions.

Heat Exchanger: Because this system is a water-based thermal system, there must be a radiator/heat exchanger to extract heat from the water and move it to the air in the building. This will be done with a radiator inside the building. The water will flow through the radiator and a fan will blow across the radiator to increase the advection happening across the radiator.

Design 3 (Tyler):

Components: A5, B2, C5, D4, E1, F5

Concept:

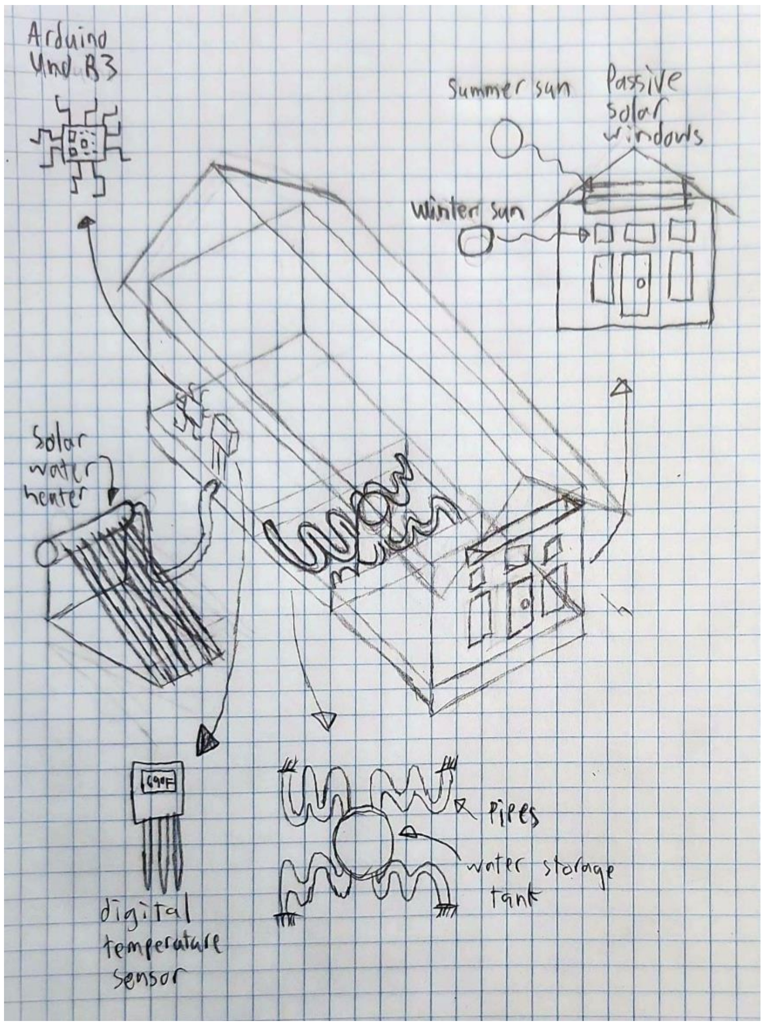


Figure 18: Full Concept Design #3

Solar panel: A solar water heater and passive solar windows are incorporated into this design. Evacuated tubes are used to collect solar energy for the solar water heater while the passive solar windows perform a similar function with the exception that it also stores and reflects solar radiation.

Control system: This system utilizes an Arduino Uno R3, a microcontroller board that is simplistic in terms of design, coding, and electronics. The reason this was selected for this design concept was because it is affordable, replaceable, and useful for controlling the entire system and ensuring that the temperature can be set to the customer's liking.

Thermal storage: When incorporating the underground water storage for this design, it is meant to store heat generated by the solar panels so it can be utilized at a later time. Since this is a water-based system, it is important to store the heat somewhere and be provided whenever needed.

Sensors: For the digital temperature sensor for this design, it functions to provide accurate temperature readings for the client to view. It is designed to be a reliable and trustworthy device for the client to adjust to their liking when the readings show that the building is not at a comfortable temperature.

Thermal insulation:

Heat Exchanger: For this component, it utilizes a single loop exchanging heat directly with the floor. This system operates by distributing heat evenly throughout the building and ensuring that the product does not overheat. The single loop runs throughout the building and is designed to distribute temperatures thoroughly so that the building won't get too warm nor cause system failure.

Design 4 (Joseph):

Components: A1, B2, C4, D4, E4, F1

Concept:

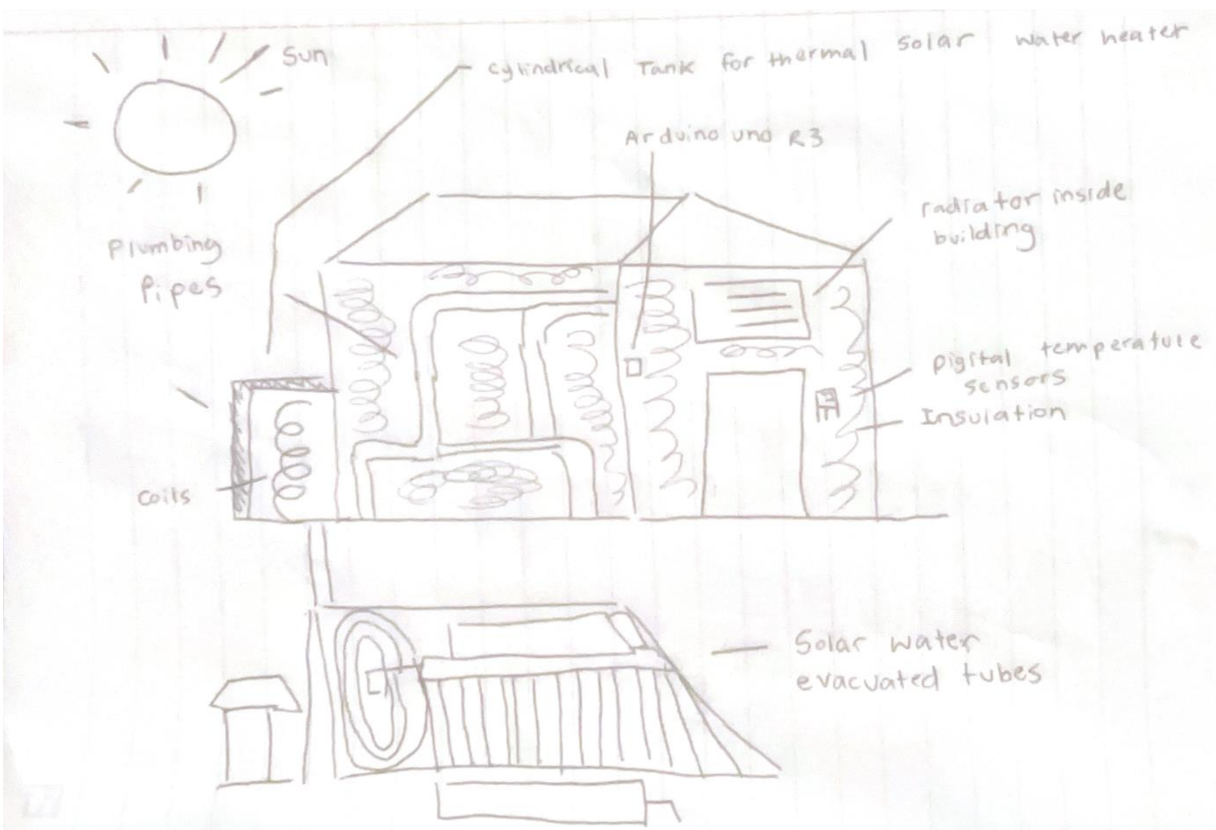


Figure 19: Full Concept Design #4

Solar Panel: This design uses evacuated solar water tubes as the primary method for capturing and converting solar energy into heat. These tubes are placed outside and angled to maximize sun exposure. Solar radiation heats the liquid inside the tubes, which is then circulated through the system to store and distribute thermal energy.

Control System: The control system in this model uses an Arduino Uno R3 microcontroller. Its job is to activate or shut off parts of the system based on temperature readings. The Arduino has simple logic from sensors and can be programmed to keep the system efficient. Its affordable and reliable in order to automate system operation.

Thermal Storage: Thermal energy is stored in a cylindrical tank wrapped in insulation. When looking inside the tank, there are copper coils that carry heated fluid which transfers warmth to the water or air stored. This setup allows for temporary heat storage, which can then be released into the building when needed. Overall, keeping the building warm.

Sensors: Digital temperature sensors are placed inside the thermal storage and in the building. They constantly monitor system conditions and feed data to Arduino. If the indoor temperature falls below the desired amount, the Arduino activates the radiator to release heat.

Thermal Insulation: When trying to reduce heat loss, the design includes foam pipe wrap around plumbing lines and an insulating jacket around the thermal storage tank. These materials help maintain temperature and increase system efficiency.

Heat Exchanger: The radiator is installed inside the building to act as a heat exchanger. As the device is activated, it releases stored thermal energy into the interior space. This ultimately warms the building without needing external electricity or a conventional heating source.

Design 5 (Calvin):

Components: A3, B4, C2, D5, E3, F3

Concept:

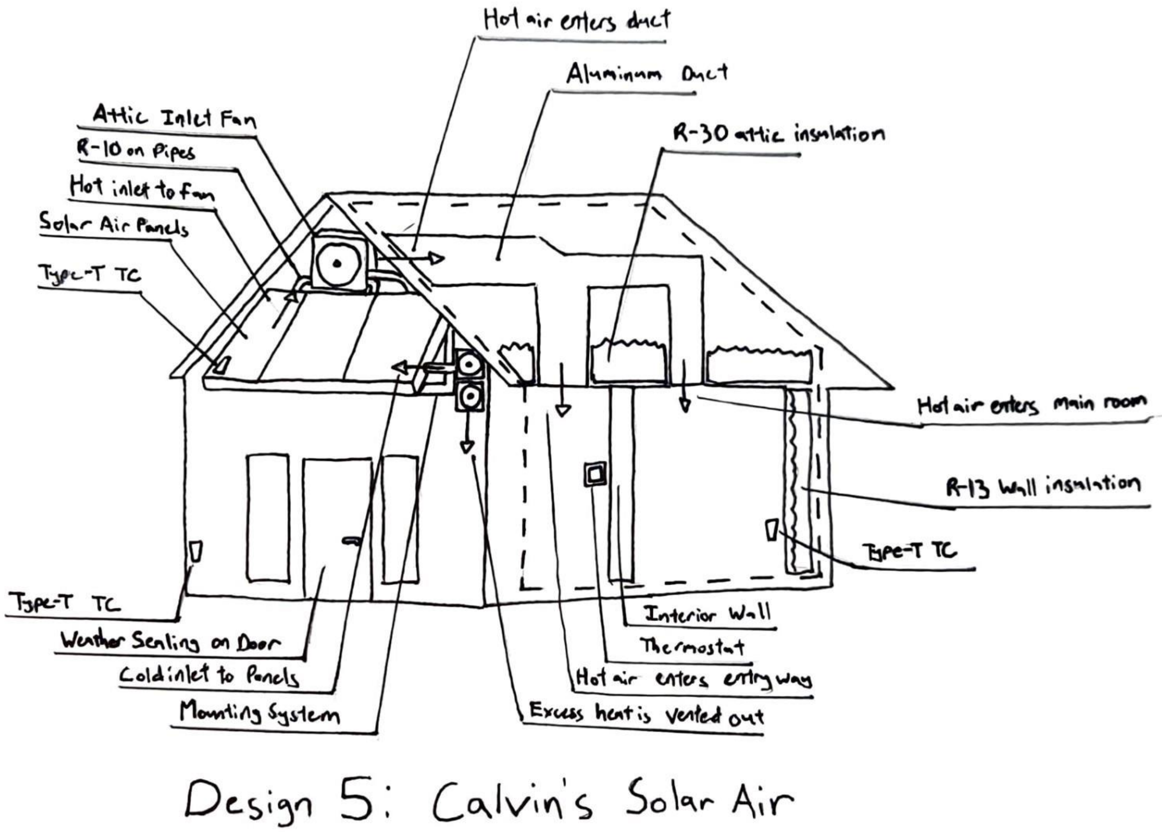


Figure 20: Full Concept Design #5

Solar Panel: This design uses one or several air solar panels attached to the roof. Since the roof of the solar shack does not have any south facing inclines, we will make one. The panels will be mounted on the roof of a new south facing covered porch.

Control System: To control when the fans are blowing hot air or venting excess heat, a basic thermostat will be used. It will have Wi-Fi capabilities for remote control.

Thermal Storage: Unlike other designs, this one will not have a designated tank for storing heat. Instead, this system will heat the solar shack in excess during the day, and it will be insulated well enough that it will not lose enough heat overnight to dip below 40 °F.

Sensors: This design uses Type T thermocouples to measure temperatures at various locations. The advantage of Type T specifically is its wide range of temperatures at which it is accurate and responsive. This is important for telling the relay when to switch on and off. For example, the system will be programmed to turn off if the temperature inside the building ever exceeds the temperature of the solar air panel.

Thermal Insulation: As stated previously, this design uses the insulation of the building itself to insulate the system. Since the panels will be mounted right against the building, very minimal insulation is required outdoors. Inside, the attic may be insulated more, but it already has about 12 inches of fiberglass insulation, so more is probably unnecessary. Beyond this, the only other insulation that may be needed is weather sealing around doors, windows, and vents.

Heat Exchanger: This design does not have a designated heat exchanger for transferring excess heat to a storage system. Rather, it exchanges heat directly with the building itself using a closed loop of air ducts and fans. Excess heat will be vented using an additional fan that blows air from inside to outside.

Table 2: Pugh Chart

Criteria	Design 1 (Jacob Air)	Design 2 (Brendan Water)	Design 3 (Tyler water)	Design 4 (Joseph water)	Design 5 (Calvin air)	Water Datum	Air Datum
Energy Stored	s	s	+	-	s	Water Datum	Air Datum
Insulating Power	s	-	+	-	+	Water Datum	Air Datum
Head Pressure	s	+	-	+	s	Water Datum	Air Datum
Exchanger Efficiency	+	s	+	s	-	Water Datum	Air Datum
Life Expectancy	-	+	-	+	+	Water Datum	Air Datum
Cost	+	+	-	+	+	Water Datum	Air Datum
Total	+1	+2	0	+1	+2	Water Datum	Air Datum

The above Pugh Chart, Table 2, shows the rating process taken for each of the five full design concepts. Each of the designs is designated as having either air or water as the fluid medium for heat to travel through. Each of these respective systems will be compared with a datum that matches the overall concept being used. Air-based solar thermal systems will be compared with the Arctica 4000 Series Solar Air Heater. This style and design of solar air heating is rated for a 500 square foot room with a maximum heating capacity of 3600W. The cost of this solar air heater is also quite large at $1,599. The water-based solar thermal systems are compared with the Vacuum Tube Solar Collector Kit VT58 Series comes at a cost of $1,420 for a 30-tube setup and has a static fluid temperature of ~300 °C.

As each design concept is rated against their respective datum and the design criteria, the design is given a score that determines if the design concept is better than, worse than, or the same as the datum. Based on the assessment done on each of the five designs, the top 2 designs consisted of one water and one air-based solar thermal system. Each of these full design concepts are then analyzed in the decision matrix.

Table 3: Decision Matrix

Criterion	Weight	Design 2 (Water)	Design 5 (Air)
Energy Stored	25%	21.2	19
Insulating Power	20%	13.2	14.6

Head Pressure	5%	2.6	3.4
Exchanger Efficiency	15%	11.6	11.2
Life Expectancy	20%	15.4	18.2
Cost	15%	9.8	12.8
Total	100%	73.8	79.2

Table 3, shown above, details the decision matrix where the first step is to provide a weight to each design criteria based on the determined importance. The weight assigned to each criterion can be seen in the table, and the grade assigned to each design is a total out of the percentage assigned to the criterion. The method used to gather these values is each person confidentially assigned a value to the design, and these values were averaged for each design. After all that has been completed the scores are summed to determine the most suitable design for the project. In this case design 5, which is an air-based solar thermal system, scored the highest with a 79.2.

CAD Drawing

Design 5 has seen several iterations over the course of the semester, but below is our final cad drawing with parts labeled with balloons. The two solar air panels are mounted on the eastern side of the roof at a 35 degree tilt toward the south. They are spaced out so that the shadow of one does not cover the other. The cold air intakes come up from the floor of each room and are then blown back into the room as hot air through the ceiling. Each room is its own closed loop of hot and cold air.

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	solaraircollector	Mounted on the roof	2
2	FinalCAD_Building - Copy	Renewable Energy Building	1
3	8x6adapter		4
4	10x4RegisterBoxSLDPRT		2
5	10x4Vents	Located in large room	2
6	14x6inchRegisterBox		1
7	14x6Vents	Located in small room	1
8	8x6x6		1
9	6inch45		1
10	6inchelbow		1
11	120x6inchDuct		1
12	6Diax10inDuct		1
13	L-Bracket	Mounts solar air collector	8
14	PVT_Panel	Mounted in front of building	1
15	Railmount	Mounts solar air collector	4
16	steelbarmount	Mounts solar air collector	4
17	8inch90elbow		10
18	8diax42inchduct		1
19	96x8InchDuct		1
20	32x8InchDuct (1)		1
21	120x8inchDuct (1)		1

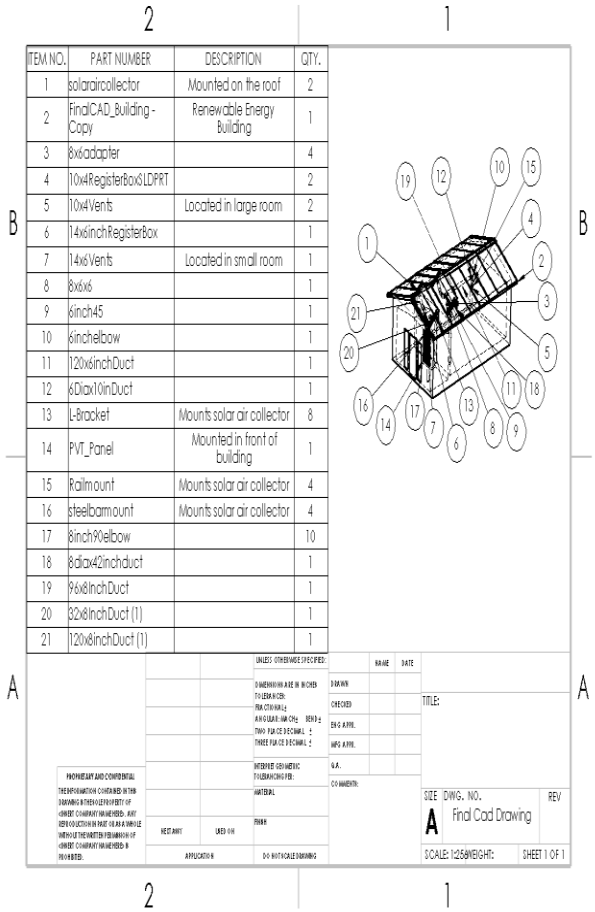


Figure 21: CAD Drawing

5 Schedule and Budget

5.1 Schedule

Here is our detailed Gantt chart that we utilized throughout the 2025 summer semester. It shows what needs to be done, who is doing it, what their progression is at, and start and end dates for the task. By the submission of this report every assignment has been accomplished for the summer.

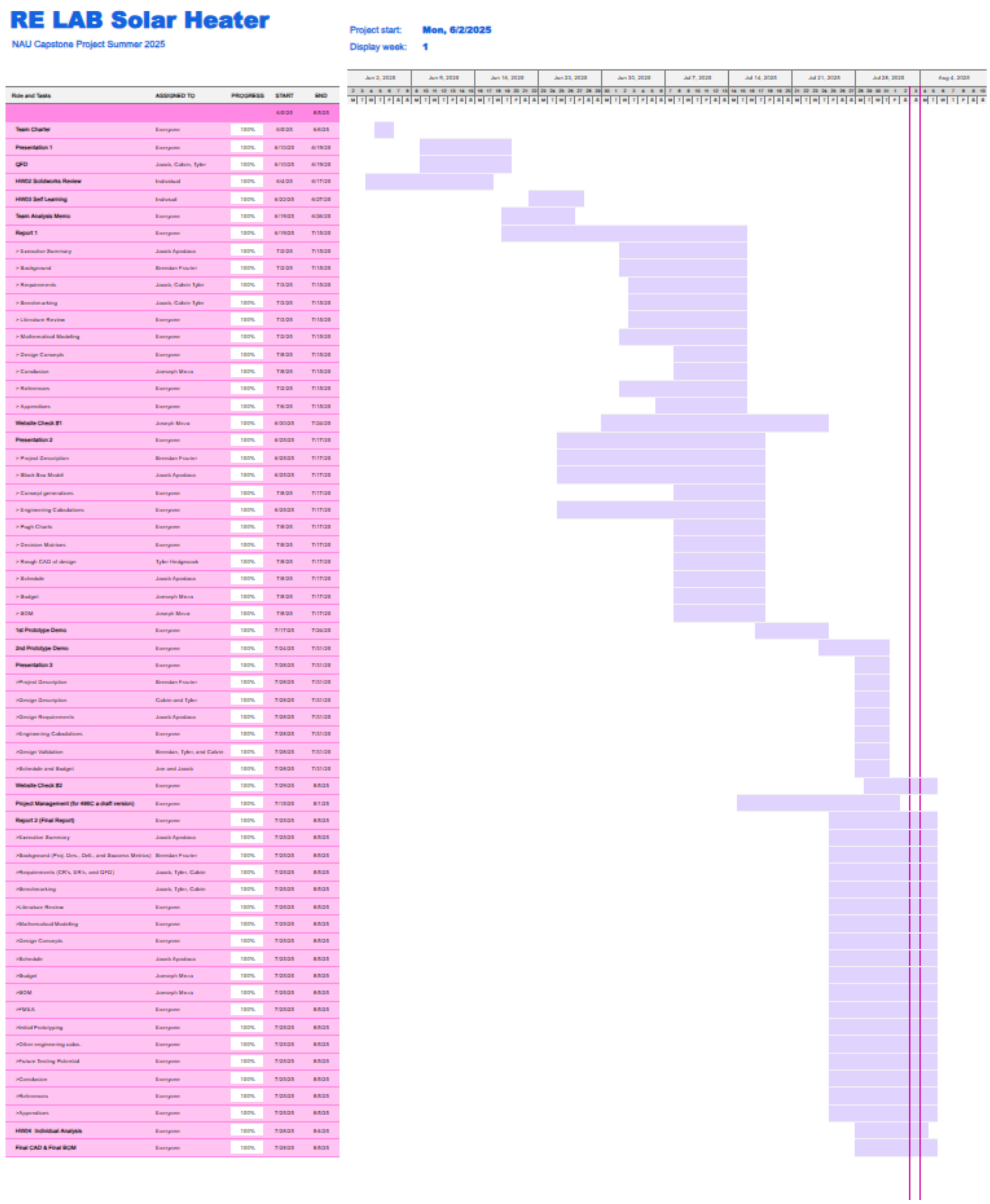


Figure 22: Summer 2025 Gantt chart

Here is our Gantt chart for the start of the 2025 fall semester. It is the same layout as the summer Gantt chart with what needs to be done, who is doing it, what their progression is at, and start and end dates for the task. The first tasks that we will be undertaking are submitting our 486C Project management final, getting started on our manufacturing and installation of the solar air panels to stay ahead of our 33% status hardware update, completing an engineering model summary, doing a self-learning / individual analysis, being up to date on our website, peer evaluations, and getting a draft for our testing plan. The Gantt chart will be updated accordingly as we near the fall semester and get a more detailed schedule.

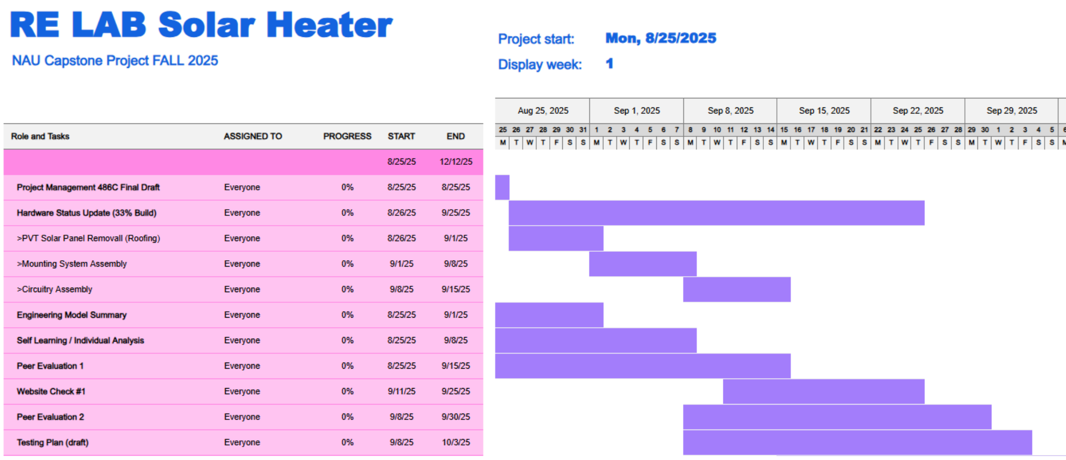


Figure 23: Fall 2025 Gantt Chart

5.2 Budget

The West Side Flagstaff Home Depot is providing $500 dollars' worth of supplies. The condition of this donation is that all materials must be presented in a bill of materials that the Pro Desk will then quote to the store manager, Mike. It goes without saying, but this budget must be spent at Home Depot. These conditions are reasonable and attainable because we are required to generate a bill of materials anyway, and most of the supplies we need for our heating system (air ducts, insulation, lumber, etc.) are available at the store. An additional $500 budget has been provided to the project by NAU as a preliminary budget. Additional funding is constantly being brought in through Grand Canyon Brewery where an additional $96 has been raised. This funding will go towards any components and unexpected expenditures.

5.3 Bill of Materials (BoM)

Table 4: Current Bill of Materials

Bill of Materials									
Name	Part Number	Quantity	Cost	Make/Buy	Primary Vendor	Manufacturer	Part Status	Total Cost	Vendor Subtotal
L Bracket	236244	8	3.37	Buy	The Home Depot	Superstrut	25-Aug	26.96	
8x6x6 Wye	643092	1	17.98	Buy	The Home Depot	Master Flow	15-Sep	17.98	
8 inch 90	148768	10	9.98	Buy	The Home Depot	Master Flow	15-Sep	99.8	
6 inch 90	148733	2	8.68	Buy	The Home Depot	Master Flow	15-Sep	17.36	
8 x 6 adapter	148857	4	14.28	Buy	The Home Depot	Master Flow	15-Sep	57.12	
Steel Bar	548932	4	11.81	Buy	The Home Depot	Everbilt	25-Aug	47.24	
6 inch duct	1013032134	1	59.98	Buy	The Home Depot	Master Flow	15-Sep	59.98	
8 inch duct	1013032129	1	67.98	Buy	The Home Depot	Master Flow	15-Sep	67.98	
Duct Insulation	1002502317	1	27.98	N/A	The Home Depot	Master Flow	Donated	27.98	
10 x 4 to 6 register box	148962	2	12.49	Buy	The Home Depot	Master Flow	15-Sep	24.98	
14 x 6 to 8 register box	351407	1	14.98	Buy	The Home Depot	Master Flow	15-Sep	14.98	
10 x 4 vent	324411	2	13.98	Buy	The Home Depot	Master Flow	15-Sep	27.96	
14 x 6 vent	497808	1	14.98	Buy	The Home Depot	Master Flow	15-Sep	14.98	
Super Strut	863322	4	0	Buy	The Home Depot	Superstrut	Donated	0	
M5 bolts	561380	4	3.75	Buy	The Home Depot	NA	25-Aug	15	
M5 nuts	204801180	1	4.19	Buy	The Home Depot	Hillman	25-Aug	4.19	
16 AWG Wire	B0CP1SGHK7	1	17.99	Buy	The Home Depot	NAOEVO	Acquired	17.99	
Henry Roof Sealant	111806	1	10.98	Buy	The Home Depot	Henry	25-Aug	10.98	
Roofing Screws	780972	1	9.98	Buy	The Home Depot	NA	25-Aug	9.98	
L Bracket	537896	10	0.313	Buy	The Home Depot	Superstrut	25-Aug	3.13	
8x8x4 Junction Box	1007810624	1	40.55	Buy	The Home Depot	Cantex	25-Aug	40.55	607.12
PVT panel	NA	1	0	Buy	RE Lab	NA	Donated	0	
Solar air panel	NA	2	0	Buy	RE Lab	Thermix	Donated	0	0
Thermostat	B0DNDS8PKF	1	23.15	Buy	Amazon	Riseem	25-Aug	23.15	
Conduit	B0B6VGJCNJ	1	47.48	Buy	Amazon	Ansgery	25-Aug	47.48	
Mesh	B0D59XWYQZ	2	17.99	Buy	Amazon	ASHXFSH	25-Aug	35.98	
Fuse	B07K4DV8PV	1	0.5	Buy	Amazon	SIXQJZML	25-Aug	0.5	
Buck Converter	B085T73CSD	1	7.85	Buy	Amazon	Valefod	Acquired	7.85	
Low Voltage Disocnnet	B09ZTHRD3G	1	17.99	Buy	Amazon	IS	25-Aug	17.99	132.95
Mechanical Relay	39-G2R-1DC5-ND	1	5.63	Buy	DigiKey	Omron Electronics	25-Aug	5.63	
Fan	N/A	2	0	Buy	DigiKey	SUNON	Donated	0	5.63
Total								745.7	

This bill of materials (BoM) covers all of the currently required parts based on the CAD design shown at the end of chapter 4 of this report. Most of the components are coming from Home Depot because of the $500 grant that the project received from them. The vendor total for Home Depot goes beyond this $500 allotment provided by them so the remaining balance will be covered by the additional $500 received from the mechanical engineering department. The department budget provided will also be used for the remaining electrical and safety components. Totaling to $850.55 the project is currently still within the $1000 budget goal to keep the system as cost effective as possible to help with achieving a 10-year payback period as well as making it obtainable for low infrastructure areas.

6 Design Validation and Initial Prototyping

6.1 Failure Modes and Effects Analysis (FMEA)

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
Electrical Fuse	Fuse popping	Overheating & Fire Hazard	9	Over Current	2	Inspection 2x Per year	4	72	Follow safety standards
Buck Converter	Excessive Voltage Supply	Burn out fans	7	Over Voltage	3	Display of output voltage	1	21	Follow safety standards
Relay	Over cycled	Constant or zero operation	7	Over Cycled	1	Inspection 1x Per year	6	42	Moderate cycles completed
	Contact or Coil corrosion	Constant or zero operation	7	Over current/voltage	1	Inspection 1x Per year	6	42	None
Fans	Short circuit	Burn out fans resulting in no operation	7	Assembly error	1	Inspection as needed	3	21	Follow electrical safety standards
Thermostat	Under powered	Unable to supply power to relay	4	Assembly error	4	Battery Charge Display	2	32	Provide battery storage for thermostat
L Bracket	Buckling	Loss of optimal angle	4	Excessive snow fall	2	Inspection 2x Per year	4	32	Apply FOS ~2
	Shear failure	Complete system failure	10	Excessive wind	1	Inspection 2x Per year	4	40	Apply FOS ~2.5
Rail	Bending	Loss of optimal angle	5	Excessive snow fall	2	Inspection 2x Per year	4	40	Apply FOS ~2
	Shear failure	Complete system failure	10	Excessive wind	1	Inspection 2x Per year	4	40	Apply FOS ~2.5
Bolts	Shear failure	Complete system failure	10	Excessive wind	1	Inspection 2x Per year	4	40	Apply FOS ~2.5
Ducts	Compressive Load	Lack of air flow	5	Excessive snow fall	3	Inspection 2x Per year	4	60	Rigid outdoor ducts
	Dust Collection	Decreased energy absorption	2	Lack of maintenance	5	Inspection as needed	6	60	None
	Blocked Inlet	Lack of air flow	1	Lack of maintenance	3	Inspection as needed	9	27	None
	Humidity	Uncomfortable environment	3	System overuse	1	None	10	30	None
Solar Heater	Excessive bending moment	Lack of air flow	2	Excessive snow fall	2	Inspection 2x Per year	4	16	Improve structural setup of panels
		System failure	10	Excessive snow fall	1	Inspection 2x Per year	4	40	Improve structural setup of panels
	Particulates covering solar panel	Lack of energy absorption	2	Lack of maintenance	2	Inspection as needed	9	36	None
PV/T Panel	Excessive bending moment	No electrical power	9	Excessive snow fall	1	Inspection 2x Per year	4	36	Change PV/T panel selection (improved strength)
	Particulates covering solar panel	Low voltage and current output	3	Lack of maintenance	2	Inspection as needed	9	54	None
Mesh	Rodent breaking and entering	Loss of efficiency and air flow	1	Lack of maintenance	3	Inspection as needed	9	27	None
Weather Sealant	Cracking or lack if fill	Leaking water	5	Assembly error	4	None	10	200	None

Figure 24: Failure Mode and Effects Analysis

The failure mode and effects analysis break the entire solar thermal system down to individual components. These components are assessed to find vulnerabilities and areas that may lead to potential failure as well as what those potential failures may do to the entire system. Within this analysis the severity, occurrence, and detection are rated on a scale from 1-10. This gives an individual breakdown of securities that are in place for protecting the system. The product of these scores provides the risk protection number (RPN). The components that provide the least severity in the event of a failure are the non-crucial components like weather sealant, partially blocked inlet ducts, and general humidity of the building. If failure occurs in any of these areas the system will remain operable with potentially less effectiveness or efficiency. Several components in the mounting system are susceptible to similar but more detrimental failures. The rails, bolts, and brackets used on the mounting system can experience a failure with buckling or bending moment from the added weight of snow in the winter months. These failures will likely only cause a change in the angle of the solar panels, reducing efficiency. However, these same components will experience wind and the shear forces created by the wind. The shear forces present the possibility of the solar thermal system being ripped off the roof of the RE Lab. The electrical components introduce a high-risk section of the design. This is because in the event of any electrical failure the system will lose its operational capability. For example, if the buck converter fails the fans will be supplied with more voltage than they can withstand and become inoperable leaving the system useless until the fans are replaced. If the circuit shorts current will be continually drawn leading to overheating of the wires and potential fire hazards.

To limit the failures or the catastrophic effects that some failures may cause several actions will be implemented. For the electrical components in the system, all electrical engineering and electrician safety standards will be followed. This includes but is not limited to current and voltage control as well as proper AWG wires. To protect the fans, a low voltage disconnect (LVD) will also be installed. For the mounting system, a factor of safety (FoS) of at least 2 will be applied to all components where this may be applied such as the nuts, bolts, rails, and beams.

6.2 Initial Prototyping

This chapter of the report will detail the prototyping that has been completed to this point in the project. While physical prototypes will be discussed and help with improving the design and testing the efficiency of a system, this chapter will also discuss software and mathematical simulations that were completed. Each of these prototypes will have a question that is trying to be answered. Along with this question there will be a final answer based on the prototyping as well as a brief discussion on how the prototype informed the design. This will be done for all prototypes completed in the project.

6.2.1 Building Heat Load Simulation

The building heat load simulation was completed through the eQUEST simulation software. This simulation is used to inform the team on the energy requirements on an annual and monthly basis. Further information on this simulation and its iterations can be found earlier in the Mathematical Modeling section.

6.2.2 Mathematical Energy Simulation

The mathematical simulation to gather the energy input into the building is crucial information to have. This energy input when compared with the building heat load analysis will tell us what percentage of the heat load being covered over a 24-hour period. This simulation aims to answer the question of how many solar panels will be needed to meet the 30% requirement in the winter. This simulation is covered in significantly more detail in Chapter 3.3.2 of this report. However, the key findings of the simulation, which uses a dynamic angle to approximate solar pathing, are that in the worst of the winter months one solar panel will cover 15% of the heat load. Knowing that one solar panel covers approximately half of the requirement our design was significantly informed. This simulation indicates that a minimum of two thermal solar panels should be used to cover the heat load requirements. This is a valid design decision as the energy input into the building is dependent on the mass flow rate of the air being pumped into the building. By doubling this mass flow rate with the addition of a second solar panel the energy input into the building will also be doubled.

6.2.3 Physical Prototyping – Temperature Increase

The initial physical prototype that was made utilized a professionally manufactured solar air heating panel with a 12V and 1.6A fan where a general DC power supply was used for the fan. The testing that was completed looked at the air outlet temperature with a variation in the supplied voltage. The first test supplied the full 12V that the fan is rated for. The following measurement took the outlet temperature with a 10V supply. Figure# shows the transient temperature data from when the fan was turned on until the temperature reached steady state. With the 12V supply the outlet temperature reached steady state at approximately 62 while the 10V supply reached a steady state temperature of about 81℃. These outlet temperatures are immediately larger than what is expected in the final product primarily because there is no inlet temperature control. The air that was being pulled in was about 30°C when in all reality the inlet temperature will be that of the building since the inlet ducts will pull from inside the building.

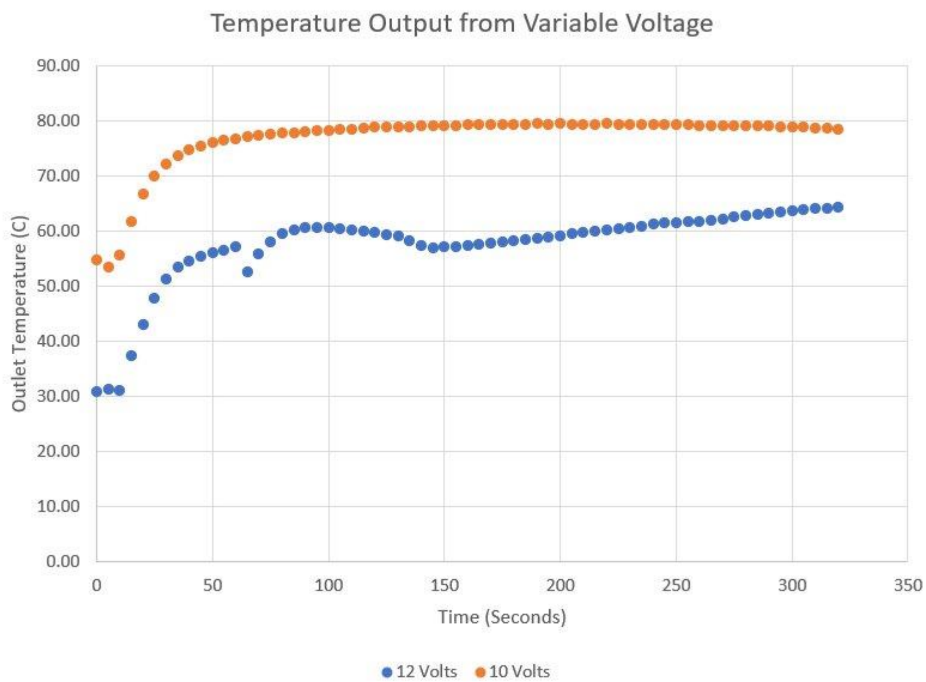


Figure 25: Outlet Temperature from Variable Voltage

The question this prototype is trying to answer is how different the outlet temperatures will be from a variable voltage supply. This question needs to be asked because the DC power supply that is going to be used is a sequence of PV/T solar panels which produce different voltages based on time of year, cloud cover, and any physical obstacles that may block the sun. From this there is a substantial increase in the temperature of the air based on a smaller voltage. While this is expected because the air takes longer to flow through the heating chamber of the solar panel the information dramatically informed our design. It does so by indicating that a constant 12V supply will have a generally safer system that shouldn't cause any sort of internal overheating. Obtaining a constant 12V supply can be done using several methods such as a charge controller so batteries can supply the power to the fans or having a DC voltage multiplier. However, further testing should be conducted on these options before a final decision is made.

6.3 Other Engineering Calculations

All former calculations performed for this project will be detailed in this section of the report. This includes all calculations performed since the design stage of the project.

6.3.1 Thermal Performance (Water vs Air)

The thermal performance analysis helped determine which fluid medium should be used for a building heating solar thermal system. These calculations were done using the same equations discussed in chapter 3.3.2 of this report so they will not be further detailed. However, the thermal performance analyzed the general temperature performance of air and water. Figures 27 and 28 show the absorber plate and outlet temperatures for air and water. Because of the massive difference in specific heat capacity of water and air the air temperature outlet is significantly larger than that of the water. This was one of the leading factors, as well as complexity, that led to the decision to use an air-based solar thermal system.

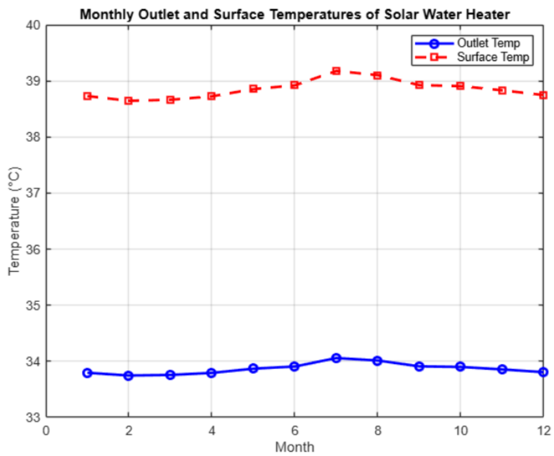


Figure 26: Water Performance

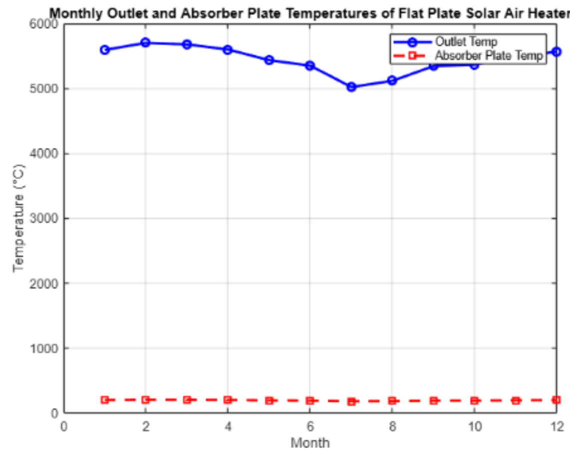


Figure 27: Air Performance

Heat Exchanger Analysis

This analysis was to help guide the team in the conceptualization process and decide whether to utilize a solar water heater or a solar air heater for the project. A thermodynamic analysis was performed to analyze both systems and decide how well each one could function, ensure they would meet customer requirements, and so forth. It was visualized that the pump and the fan were connected to the heat exchanger, and both were the solar water and air heater systems, respectively. For the pump, both the work and the temperature were calculated, and it was found that the system overheated. As for the fan, a MATLAB code was generated to plot the temperature over the mass flow rate as shown in Figure 29 below:

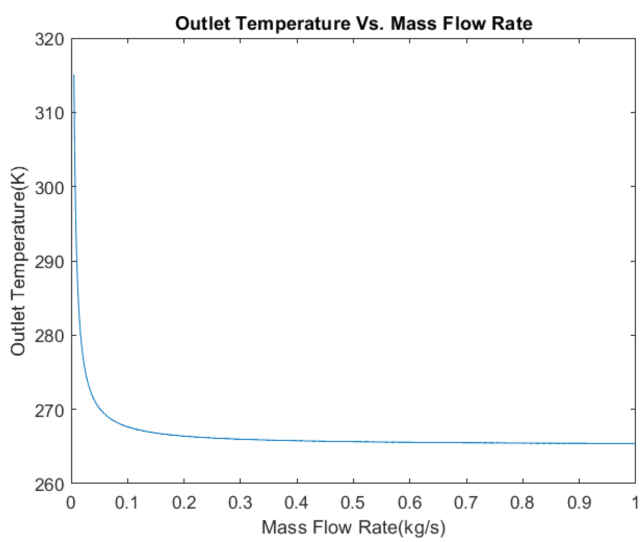


Figure 28: Fan Analysis Calculations

After the results for both the pump and fan calculations were analyzed, it was decided that the team should utilize a solar air heating system since it has an adjustable temperature thus ensures that the system won’t overheat and will meet customer requirements.

6.4 Future Testing Potential

While the initial prototyping that has been completed to this point has been extremely beneficial and informative regarding the design of the system, further testing needs to be done. The first test that the team would like to perform is the volumetric flow rate testing with variable voltage. This has already been done but was completed using a hand help anemometer that didn’t fit the duct size that we connected the fan to. This means that additional flow likely missed the anemometer, and we had poor or inaccurate readings. To correct this and collect better data the next test should use a hot wire anemometer. This is a style of anemometer that is specifically designed for testing in HVAC systems and will provide significantly more accurate data. Addition testing that should be completed is more temperature data but rather than only measuring the outlet temperature multiple thermocouples should be placed through out the duct work that the system requires. By doing these losses throughout the system can be accurately quantified as well as find potential weaknesses within the ducting that may cause excessive temperature loss. Such testing could also help inform the design of where more insulation may be necessary and where less insulation might be sufficient. The final testing that would be extremely helpful for the project, especially in terms of final testing and validation, is to plot the outlet temperature to the building over some solar window using the same thermocouples and likely the LabVIEW digital data acquisition software. This will help analyze the overall performance of the system.

7 CONCLUSIONS

Over the course of the semester our group has done research, calculations and modeling in order to set ourselves up for success in the pursuit of creating a self-sufficient renewable solar air heating system. We were given the task of reducing the RE Lab's heating load by 30 percent in winter, with the obstacles of below freezing temperatures and solar insulation. The goal is to have very minimal building modifications, meet ASHRAE standards, and have minimum to no maintenance. This system must also have a payback period of 10 years. We have done extensive calculations including building heat load analysis, Energy, photovoltaic Solar, mounting, and HVAC routing. We originally were in pursuit of two concepts including water vs air heating. After reviewing multiple models, we placed air heating vs water heating in a decision matrix and Pugh chart. After creating 6 subsystems and 30 concept variants a series of full concept designs were graded through a Pugh Chart and Decision Matrix to determine the most viable option. The Group decided the most efficient system for the project was the solar air heating system. We decided to go with the design of mounting two renewable solar air heaters, connected to PVT solar panels, on the roof. This system has ducts leading inside the building in order to have an input and output channel. There will be two inlet ducts that run the air into the system and three outlet ducts that circulate the heat into the room. The system will be self-sufficient and maintain the building at the desired temperature chosen or otherwise reduce the total heating load by 30%. We ran multiple simulations and created models preparing for the installation and accuracy of the design. Overall, the team has accomplished many goals throughout the semester and is in a position to set themselves up for success entering the second semester.

8 REFERENCES

[1] T. L. Bergman, *Fundamentals of Heat and Mass Transfer, 8th Edition*. New York: John Wiley & Sons, Incorporated, 2016.

[2] "Fox and McDonald's introduction to Fluid Mechanics, 10th edition," Wiley.com, https://www.wiley.com/en-us/Fox+and+McDonald's+Introduction+to+Fluid+Mechanics,+10th+Edition-p-00045065 (accessed Jul. 15, 2025).

[3] R. G. Budynas, J Keith Nisbett, and Joseph Edward Shigley, *Shigley's mechanical engineering design*. New York: Mcgraw-Hill, 2016.

[4] Author links open overlay panelMahmud M. Alkilani et al., "Review of Solar Air Collectors with thermal storage units," Renewable and Sustainable Energy Reviews, https://www.sciencedirect.com/science/article/pii/S1364032110003692?casa_token=imC8wl52iaoAAAAA%3AgJn0hw4EsNwPIcfU2zucccigoPdGm3Ij5glcFfbMeGmGJQfwtDF7Ui0p2-HbLZkkI-xPS8Xn (accessed Jul. 28, 2025).

[5] Author links open overlay panelF. Sarhaddi et al., "An improved thermal and electrical model for a solar photovoltaic thermal (PV/t) air collector," Applied Energy, https://www.sciencedirect.com/science/article/pii/S0306261910000024?casa_token=Z299y3rgBBgAAAAA%3A2YjK5DDa6Izxp5u24z-t7UcpO-6zYYs3093COwdsFkjL_BKy_Kpj_Cp63g8S_ZqkOBQmDGOQ (accessed Jul. 28, 2025).

[6] "What you can do in solidworks flow simulation," What You Can Do in SOLIDWORKS Flow Simulation - 2025 - SOLIDWORKS Help, https://help.solidworks.com/2025/English/SolidWorks/floxpress/r_what_do_flow_simulation.htm (accessed Jul. 28, 2025).

[7] An introduction to flow analysis applications with ..., https://www.solidworks.com/sw/docs/Flow_Sim_StudentWB_2011_ENG.pdf (accessed Jul. 28, 2025).

[8] CBGjr and Instructables, "Screened Solar Air Heater," Instructables, https://www.instructables.com/Screened-Solar-Air-Heater/ (accessed Jul. 28, 2025).

[9] Russ et al., "Solar Air Heater - DIY," Solar Panels - Solar Panels Forum, https://www.solarpaneltalk.com/forum/solar-thermal/solar-air-heating/3900-solar-air-heater-diy (accessed Jul. 28, 2025).

[10] Life is Short DIY, "DIY Solar Air Heater Part #1," YouTube, https://www.youtube.com/watch?v=JwlT-4zdau8&list=PL6YanwREcLx7h747VhKjJLClqvBmy5cF5&index=1 (accessed Jul. 28, 2025).

[11] C. Wang, Z. Guan, X. Zhao, and D. Wang , "Numerical Simulation Study on Transpired Solar Air Collector," Tamu , https://oaktrust.library.tamu.edu/server/api/core/bitstreams/82759033-c21f-4e57-9b21-786e487ce6f4/content (accessed Jul. 29, 2025).

[12] “Flagstaff Snowfall Totals & Accumulation averages,” Flagstaff AZ Snowfall Totals & Snow Accumulation Averages - Current Results, https://www.currentresults.com/Weather/Arizona/Places/flagstaff-snowfall-totals-snow-accumulation-averages.php (accessed Jul. 30, 2025).

[13] Windfinder.com, “Wind and weather statistic Flagstaff Pulliam Airport,” Windfinder.com, https://www.windfinder.com/windstatistics/flagstaff (accessed Jul. 31, 2025).

[14] N. Mendes, G. Oliveira, and H. De Araújo, “BUILDING THERMAL PERFORMANCE ANALYSIS BY USING MATLAB/SIMULINK.” Accessed: Oct. 14, 2024. [Online]. Available: https://publications.ibpsa.org/proceedings/bs/2001/papers/bs2001_0473_480.pdf

[15] Y. Choi, M. Mae, and H. Bae Kim, “Thermal performance improvement method for air-based solar heating systems,” *Solar Energy*, vol. 186, pp. 277–290, Jul. 2019, doi: https://doi.org/10.1016/j.solener.2019.04.061.

[16] C. Ghiaus and I. Hazyuk, “Calculation of optimal thermal load of intermittently heated buildings,” *Energy and Buildings*, vol. 42, no. 8, pp. 1248–1258, Aug. 2010, doi: https://doi.org/10.1016/j.enbuild.2010.02.017.

[17] “How Does Central Heating and Cooling Work? - Trane®,” *Trane Residential*. https://www.trane.com/residential/en/buyers-guide/hvac-basics/how-does-a-central-heating-cooling-system-work/

[18] “ASHRAE climatic design conditions 2009/2013/2017/2021,” *Ashrae-meteo.info*, 2017. https://ashrae-meteo.info/v2.0/index.php?lat=35.13&lng=-111.67&place=%27%27&wmo=723750&ashrae_version=2009 (accessed Jul. 15, 2025).

[19] “Relays - How Relays Work,” *Galco.com*, 2025. https://www.galco.com/comp/prod/relay.htm?srsltid=AfmBOoqD1K8WTkmxR_MA0MLizfI6uPWPSbcJl9u5LNphhcRO1p4Cgvc9 (accessed Aug. 03, 2025).

[20] W. W. Weaver and P. T. Krein, "Analysis and applications of a current-sourced buck converter," APEC 07 - Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition, Anaheim, CA, USA, 2007, pp. 1664-1670, doi: 10.1109/APEX.2007.357742. keywords: {Buck converters;Topology;Inductors;Equations;Steady-state;Transfer functions;Voltage;Application software;DC-DC power converters;Circuits;dc-dc converter;converter topology;power-factor correction;coupled inductor},

[21] https://www.facebook.com/thespruceofficial, “How to Choose the Right-Sized Electrical Wire,” *The Spruce*, 2019. https://www.thespruce.com/matching-wire-size-to-circuit-amperage-1152865

[22] L. Hernández-Callejo, S. Gallardo-Saavedra, and V. Alonso-Gómez, “A review of photovoltaic systems: Design, operation and maintenance,” *Solar Energy*, vol. 188, pp. 426–440, Aug. 2019, doi: https://doi.org/10.1016/j.solener.2019.06.017.

[23] A. G. Safitra, L. Diana, F. H. Sholihah and C. P. Rahayu, "Experimental Analysis of Artificial Equilateral Triangle Solar Air Heater Using Zig-zag Channel," 2021 International Electronics Symposium (IES), Surabaya, Indonesia, 2021, pp. 494-498, doi: 10.1109/IES53407.2021.9593967. keywords: {Fluids;Shape;Solar radiation;Solar

heating;Sun;Thermal energy;solar air heater;zig-zag;temperature;absorber;efficiency},

[24] E. Engineeringtoolbox, "Absorbed solar radiation," Engineering ToolBox, https://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html (accessed Jun. 18, 2025).

[25] T. L. Bergman, *Fundamentals of Heat and Mass Transfer, 8th Edition*. New York: John Wiley & Sons, Incorporated, 2016.

[26] M. J. Moran and H. N. Shapiro, *Fundamentals of Engineering Thermodynamics Michel J. Moran ; Howard N. Shapiro. Hauptbd.* Hoboken, NJ: Wiley, 2010.

[27] A. Kumar GB, S. Sushma, L. Priyanka, S. G. Vijay, and G. A. Thouqhir Pasha, "Design and implementation of peltier based solar powered air conditioning and water heating system," *2018 3rd IEEE International Conference on Recent Trends in Electronics, Information & Communication Technology (RTEICT)*, pp. 2604–2607, May 2018. doi:10.1109/rteict42901.2018.9012255

[28] A. S. Barrak, A. A. Saleh, and Z. H. Naji, "Energy saving of Air Conditioning System by oscillating heat pipe heat recovery using binary fluid," *2019 4th Scientific International Conference Najaf (SICN)*, pp. 178–183, Apr. 2019. doi:10.1109/sicn47020.2019.9019354

[29] T. A. H. & Cooling, "What is an inverter heat pump: Temp Air," Temp Air System Inc., https://tempairsystem.com/everything-you-should-know-about-inverter-heat-pumps/ (accessed Jul. 15, 2025).

[30] "What wavelength do solar panels use? the ultimate answer," ShopSolar.com, https://shopsolarkits.com/blogs/learning-center/what-wavelength-do-solar-panels-use (accessed Jul. 15, 2025).

[31] "Solar Panel Cost Archives," Solar.com, https://www.solar.com/learn/solar-panel-cost/ (accessed Jul. 15, 2025).

[32] "Solar Energy and Solar Power in Flagstaff, AZ," Solar Energy Local, 2025. https://www.solarenergylocal.com/states/arizona/flagstaff/

[33] "ThermoPowerTM 30 Tube Evacuated Tube Solar Collector," SunMaxx Solar - Solar Hot Water Systems, Aug. 22, 2023.

[34] C. Stack Heating, "A complete guide to home ductwork design: Stack Heating," Stack Heating Cooling Plumbing and Electric, https://stackheating.com/air-conditioning/a-complete-guide-to-home-ductwork-design/ (accessed Aug. 4, 2025).

[35] "Solar Air Heating," Arctica Solar, https://www.arcticasolar.com/ (accessed Aug. 4, 2025).

[36] C. Stack Heating, "A complete guide to home ductwork design: Stack Heating," Stack Heating Cooling Plumbing and Electric, https://stackheating.com/air-conditioning/a-complete-guide-to-home-ductwork-design/ (accessed Aug. 4, 2025).

[37] “Active solar heating,” Energy.gov, https://www.energy.gov/energysaver/active-solar-heating (accessed Aug. 5, 2025).

[38] K. Alambra, “CFM calculator,” Omni Calculator, https://www.omnicalculator.com/construction/cfm (accessed Aug. 4, 2025).

[39] “HVAC duct calculator: Duct Size calculator,” ServiceTitan, https://www.servicetitan.com/tools/hvac-duct-calculator (accessed Aug. 4, 2025).

[40] R. Trethewey, “How to install solar panels on a roof,” This Old House. [Online]. Available: https://www.thisoldhouse.com/solar-alternative-energy/21017107/how-to-install-solar-panels-on-a-roof (accessed Jul. 28, 2025).

[41] R. Womeldorf, “How to calculate CFM FOR HVAC: CFM formula + calculator,” Housecall Pro, Aug. 9, 2024. [Online]. Available: https://www.housecallpro.com/resources/how-to-calculate-cfm-for-hvac/

[42] L. tech Lab and Instructables, “Solar Air Heater,” Instructables. [Online]. Available: https://www.instructables.com/Solar-Air-Heater/ (accessed Jul. 28, 2025).

[43] E. Engineeringtoolbox, “Recommended air change rates for different room types,” Engineering ToolBox, https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html (accessed Aug. 4, 2025).

[44] T. L. Bergman, "Chapter 12: Radiation," in Fundamentals of Heat and Mass Transfer, 8th Edition. New York: John Wiley & Sons, Incorporated, 2016.

[45] R. S. Figliola, "Chapter 8: Temperature Measurements," in Theory And Design For Mechanical Measurements. S.L.: John Wiley, 2020.

[46] A. I. Owaid, S. M. Hadi, M. S. Mahdi, Husam Sabeeh Al-arab, and H. I. Mohammed, “On-Grid Flat Plate Solar Water Heater Collector Application for Electrical Energy Saving Contribution,” GAZI UNIVERSITY JOURNAL OF SCIENCE, Nov. 2024, doi: https://doi.org/10.35378/gujs.1463435.

[47] S. K. Kutafa and A. M. A. Muhammed, “Study of the enhancement in the performance of a hybrid flat plate solar collector using water and air as working fluids,” Heat Transfer, vol. 53, no. 6, pp. 2736–2748, Apr. 2024, doi: https://doi.org/10.1002/htj.23048.

[48] S. A. Gandjalikhan Nassab, “Efficient design of converged ducts in solar air heaters for higher performance,” Heat and Mass Transfer, Jul. 2022, doi: https://doi.org/10.1007/s00231-022-03228-9.

[49] A. Robinson, “Solar PV Analysis of Flagstaff, United States,” Profilesolar.com, Apr. 16, 2024. https://profilesolar.com/locations/United-States/Flagstaff/#google_vignette (accessed Jul. 08, 2025).

[50] ASHRAE, “Standards and Guidelines,” Ashrae.org, 2009. https://www.ashrae.org/technical-resources/standards-and-guidelines

[51] S. Kraemer, “Rocks: The Unexpected Powerhouse of Sustainable Solar Energy Storage -

SolarPACES," SolarPACES, Jun. 11, 2023. https://www.solarpaces.org/rocks-the-unexpected-powerhouse-of-sustainable-solar-energy-storage/

[52] "Solar Energy and Solar Power in Flagstaff, AZ," Solar Energy Local, 2025. https://www.solarenergylocal.com/states/arizona/flagstaff/

[53] ASHRAE Handbook & Product Directory, 1980 Systems. 1980.

[54] "4000 Series Solar Air Heater," Arctica Solar, 2022. https://www.arcticasolar.com/products/4000-series-solar-air-heater-gen-1 (accessed Jul. 14, 2025).

[55]"How Heat Load Calculation Works," *Phononic*. https://phononic.com/resources/how-heat-load-calculation-works/

[56] "eQUEST," *www.doe2.com*. https://www.doe2.com/equest/

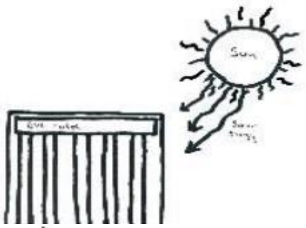
[57] "Cooling and Heating Equations," *Engineeringtoolbox.com*, 2019. https://www.engineeringtoolbox.com/cooling-heating-equations-d_747.html

[58] "Learn about hybrid water heaters: Energy-efficient heating.," Zenith, https://zenithheater.com/hybrid-water-heater/ (accessed Jul. 15, 2025).

9 APPENDICES

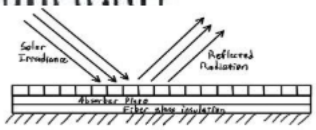
Earlier in the body of the report, many subsystems were listed in Table 1: Concept Generation Table. These concepts are explored in detail here in Appendix A.

9.1 Appendix A: Concept Variant Breakdown



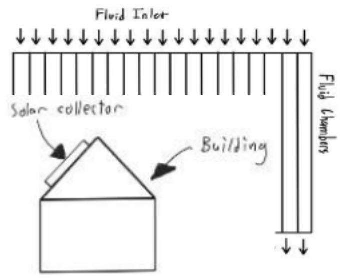
This water-based solar thermal system is an evacuated tube setup. The water flows through the tubes and achieves a phase change since the water is static and absorbs all the solar energy. The non-changing water flows over the top retaining the rising superheated fluid.

Figure 29 – A1



This solar panel concept variant equates to what is essentially a pool solar heater that can be fitted for household HVAC systems. This is done by feeding the water through a series of pipes from the bottom up until the fluid can self-siphon out of the other side.

Figure 30 – A2

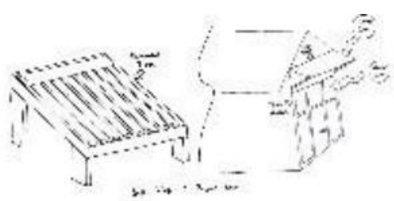


From Figure 25 on the left, it shows a design idea of implementing a solar panel on the roof of the renewable energy building.

Figure 31 – A3

Evacuated Tube Solar Collector. This component uses vacuum-sealed glass tubes to absorb solar energy with high efficiency, even in cold conditions. The captured heat is estimated using $Q = A \cdot G \cdot \eta$, where Q is the heat gained, A is area, G is solar irradiance, and η is efficiency.

Figure 32 – A4



This subsystem combines the principles of passive solar window design with the pre-existing solar water heater. The concept of passive solar windows is to allow the winter sun to radiate inside the building, but block the summer sun with carefully placed eaves.

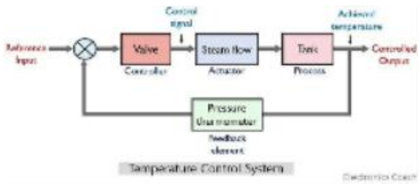
Figure 33 – A5

This baseline thermostat provides the option for manual control of the system. This device would provide the services of turning on and off the system as well as general temperature adjustments.

Figure 34 – B1

An Arduino Uno R3 is one of the control system CVs. This Arduino can connect to temperature and light sensors that can inform the system if the solar panel should be operated or not. This device can also control the pumps throughout the system.

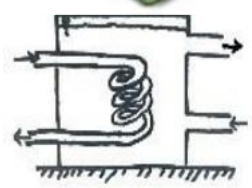
Figure 35 - B2



For the control system, a closed loop system was included. The design idea for this was that the input would directly impact the output. For example, the solar energy collected would activate the system and cause it to distribute heat throughout the building.
Figure 36 – B3

This displays a smart digital thermostat, which allows precise indoor temperature control through programmable settings and remote access. This device improves energy efficiency and user comfort by maintaining consistent thermal conditions based on user preferences.
Figure 37 – B4

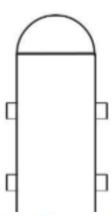
A Raspberry Pi can be programmed to turn fans or pumps on or off given certain triggering conditions. When connected to Wi-Fi, remote monitoring would still be possible.
Figure 38 – B5



A large storage tank that absorbs heat through a closed feedwater heater system. This will allow the fluids to stay separate with the potential for using a higher thermal capacity fluid.
Figure 39 – C1

This R13 insulation can be used to improve the overall insulation. This is important for the concept that implements the building as the thermal storage system. This idea will begin with slightly overheating the building and using this improved insulation to retain the heat overnight.

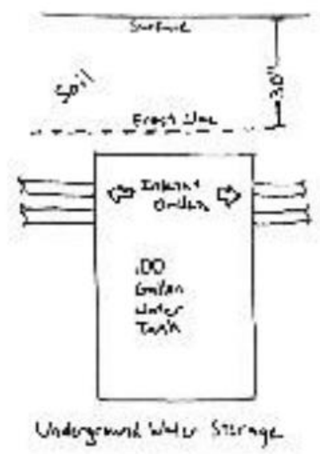
Figure 40 - C2



As shown in figure 27 on the right, a compressed air tank was one of the concepts for the solar system. The design idea was for the tank to store heat which will later be used to heat the building during the winter.

Figure 41 – C3

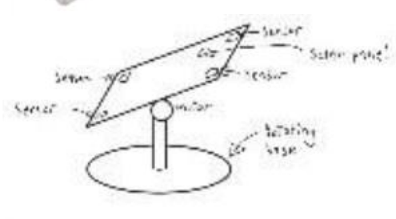
Insulated cylindrical tank for thermal This one shows an insulated cylindrical tank designed for thermal energy storage, helping retain heat for extended periods. These tanks are essential in solar water heating systems to maintain consistent water temperature and improve overall energy efficiency.
Figure 42 – C4



An underground water tank would solve the problem of insulation if it were below the frost line. This subsystem would correspond with other systems that use solar water heaters as their source of energy.
Figure 43 – C5

This control system uses an Arduino with a sequence of relays, temperature sensors, and light sensors to control whatever components of the system that the thermostat can handle.
Figure 44 – D1

K-type thermocouples are one of the sensor concept variants. These devices need to be calibrated because the output from the thermocouple is a voltage and needs to be converted to a temperature using a calibration curve. These devices are extremely accurate as long as the calibration is done properly.
Figure 45 – D2



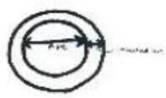
For one of the sensors concepts, solar tracking was one of the ideas proposed to the team. The Senors, as shown in figure 28, would be attached to the solar panels themselves and would send signals to the motor so it can move the solar panels around to effectively collect solar energy.

Figure 46 – D3

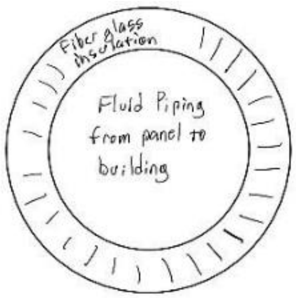
Figure 47 – D4

Digital temperature sensors displays digital temperature sensors, which are used to accurately measure and transmit temperature data in real time. These sensors are vital for monitoring system performance and ensuring efficient thermal regulation in heating applications.

A type T Thermocouple, when calibrated and used in conjunction with DAQ software, would quickly and accurately read temperature data inside the building, inside the heaters, and outside in the freezing temperatures thanks to its wide range of operation.
Figure 48 – D5



The insulation concept for this design is to provide general purpose insulation (R6) for the pipes that are externally exposed and for the storage tank.
Figure 49 – E1



Fiberglass piping insulation can be used to protect any exposed pipes from cold and snowy Flagstaff conditions. This will reduce some of the more extreme heat losses the system may experience.

Figure 50 - E2

As shown in figure 29, a fan was one of the concepts for selected insulation, circulating heat throughout the building from the ducts it was connected to.

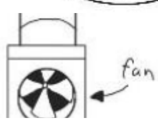
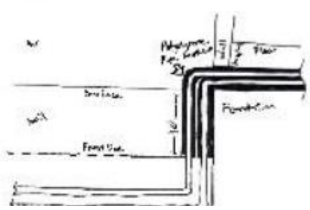
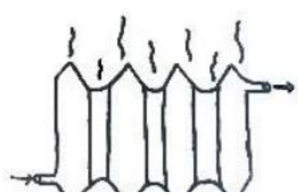


Figure 51 – E3

Shows tank wrap and foam pipe insulation, which are used to reduce heat loss in thermal systems. These materials help maintain water temperature by minimizing thermal exchange with the surrounding environment.
Figure 52 – E4



Keeping pipes buried under the frost line would keep them insulated from the freezing winter temperatures. Similarly, pipes could be run underneath the floor when inside the building.
Figure 53 – E5



This concept uses a radiator located inside the building. Not only will the natural convection heat up the building but providing fans around the radiator the forced convection will provide additional heat if needed.
Figure 54 – F1

Silica fire bricks have an extremely high thermal capacity and are often used in air-based thermal systems as a way of retaining extremely high temperatures.
Figure 55 – F2

For the heat exchanger concept, one of the concepts was to design it as direct contact and would heat the cool air in the building from the solar panels attached to the top of it.

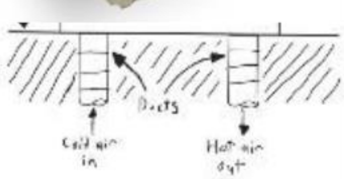
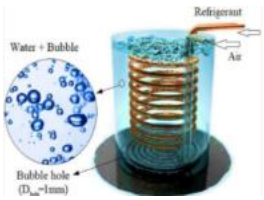
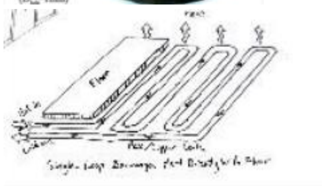


Figure 56 – F3



This shows copper coils submerged in a thermal storage tank, serving as a heat exchanger to transfer energy between the fluid inside the coil and surrounding water.

Figure 57 – F4



Instead of exchanging heat in a separate designated heat exchanger, the solar water heater could be connected in one closed loop with coils running under the floor of the building. The hot water would transfer this heat directly through the floor and to the rest of the building and then get pumped back to the heater.

Figure 58 - F5