RE Lab Solar Heater

Final Design Report

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NORTHERN ARIZONA UNIVERSITY

Project Sponsor: Professor Carson Pete

DISCLAIMER

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, and we were also able to increase the temperature 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 is that our manufacturer's 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 damage 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. For our budget we hit our $500 goal of money raised because Calvin was able to secure 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 generated a BOM (Bill of Materials) which we gave to Home Depot to secure our $500 in store credit. As a team, we performed an FMEA (Failure Mode and Effects Analysis). For this, we used an excel 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. After this, we did hardware status updates where we presented our progress to the class. After this we created a testing proposal in report format and then had two presentations, one with initial testing results and one with our final testing results. The final deliverables included creating our final poster and presentation for EFEST and creating a detailed assembly manual for our client handoff.

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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. 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% on an annual basis. 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 budget. An initial $2500 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 $3000 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 was completed 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. We also created a gofundme which raised an additional +$500.

1.2 Deliverables

These deliverables will be detailed along with an assigned or approximate completion date in chronological order.

1) Project Management 486C Final Draft – This report had us reflect on the previous semester for ME476C and make plans for moving forward.
    - Deadline: 2 September 2025
2) Self-Learning / Individual Analysis – This assignment was completed by each team member where they completed an individual analysis of their choosing to benefit the capstone project. This could

involve performing CAD tutorials or reviewing and redoing previous calculations.

- Deadline: 8 September 2025

3) Engineering Calculations Summary – This report covers design requirements (ERs and CRS), QFD, up to date CAD model, equations and simulations performed so far, and a moving forward / future work section.
   - Deadline: 8 September 2025
4) Hardware Status 33% Update – The first hardware update where the team presents that they are on schedule with the capstone project being 33% done.
   - Deadline: 22 September 2025
5) Website Check 1 – The first website checks where the professor reviews that the website is up and running and is up to date with the latest project deliverables.
   - Deadline: 6 October 2025
6) Hardware Status 67% Update – The second hardware update where the team presents that they are on schedule with the capstone project being 67% done.
   - Deadline: 13 October 2025
7) UGRADS Registration – Submission of project abstract with all team members contact information for final presentation.
   - Deadline: 20 October 2025
8) Draft of Poster – A draft poster of the team's capstone project with figures, abstract, customer requirements, engineering requirements, results, conclusion, and references.
   - Deadline: 27 October 2025
9) Finalized Testing Plan – A detailed finalized testing plan that the team submitted in report format. This testing plan covers how the team will test the design of the project and how it will fulfill both customer and engineering requirements.
   - Deadline: 27 October 2025
10) Hardware Status 100% Update – The third and final hardware update where the team presents that they are on schedule with the capstone project being 100% done.
    - Deadline: 3 November 2025
11) Initial Testing Results – Presentation informing the client of at least 25% of the testing results outlined in the finalized testing plan.
    - Deadline: 17 November 2025
12) Final CAD Packet – A zip file with the final CAD and drawings of our system. Included is a circuit diagram which is the electrical system and a ducting diagram showing the duct sizes and routes.
    - Deadline: 17 November 2025
13) Final Poster and PPT – Submit a final printable version of the project poster. Submit proof of a completed draft of the final E-Fest presentation PowerPoint.

- Deadline: 17 November 2025

14) Final Testing Results – Presentation informing the client of all testing results created in the finalized testing plan.
    - Deadline: 24 November 2025
15) Operation / Assembly Manual – Documentation of the project and how it should be used. This includes details of assembly/disassembly, operation, and maintenance instructions.
    - Deadline: 1 December 2025
16) Expo PPT and Poster Presentation Results – Quality of delivery for both PowerPoint and poster presentation.
    - Deadline: 5 December 2025
17) Client Handoff – Final aspect to the project where client receives product and all relevant information regarding its operation.
    - Deadline: 8 December 2025

1.3 Success Metrics

For this project to be considered successful, several conditions need to 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 be 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. This 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. The system must use a renewable energy source (i.e., solar energy) as the primary input. This means fossil fuels or electricity cannot be used 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 includes 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. The system must have minimal maintenance (<4 hrs/year) and ease of use for maintenance by 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. Systems must have the ability to include temperature and performance monitoring. Enable 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 regulations. 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 client. 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. Thermostat (Watts): To ensure that the system can be operated manually, it is required that a thermostat must be implemented into the system so the client can monitor and control the system. 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. 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.
5. 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.
6. 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.
7. 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.
8. 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:	10/27/2025

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

5	3	1	0
Strong	Moderate	Weak	None

	Energy Stored	Efficient Insulation	Thermostat	[redacted]	Flow Rate	Heat exchanger	Life expectancy	Cost	Mounting system
	0								
	0	0							
	+	0	-						
	+	+	-	[redacted]					
	+	+	0	[redacted]	0				
	+	+	0	[redacted]	0	0			
	+	+	0	[redacted]	+	0	0		
	+	+	0	[redacted]	+	+	0	-	
Desired direction of improvement (↑,0,↓)	↑	↑	↓	[redacted]	↑	↑	↑	↓	↓

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	Thermostat	[redacted]	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
1	5	System must reduce heating load by 30% during worst case months (compared to baseline method)	5	5	0	[redacted]	4	5	0	0	0	50	4	5	5	4	5
2	5	System must operate in winter conditions	5	5	0	[redacted]	5	3	1	0	3	55	3	5	5	4	5
3	5	System must use RE solar as primary input	5	5	0	[redacted]	4	3	0	0	5	65	5	5	5	5	3
4	3	Installation must not require major mods to building	0	1	0	[redacted]	2	0	0	5	5	24	2	3	3	4	5
5	5	System must be safe and comply with codes	3	3	5	[redacted]	3	3	3	0	5	70	5	5	4	5	5
6	3	System must have minimal maintenance	1	1	1	[redacted]	2	5	5	1	4	30	3	4	4	5	5
7	3	Payback period must be under 10 yrs	5	5	3	[redacted]	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	[redacted]	4	3	0	0	1	12	5	5	4	4	5
9	3	System must not overheat or cause interior overheating	5	0	5	[redacted]	4	3	0	0	2	45	5	5	4	4	5
		Technical importance score	126	111	47	[redacted]	114	112	44	27	111	818	37	36	35	38	42
		Importance %	15%	14%	6%	[redacted]	14%	14%	5%	3%	14%	100%					
		Units	kWh	R Value	Watts	[redacted]	m^3/sec	Joules	Years	$	Kilograms						
		Target	30 kWh	10 R-Value	10 W	[redacted]	0.1 m^3/s	5 MJ	10 yrs	$3,000	20 kg						
		Priorities rank	1	5	7	[redacted]	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 ten customer requirements and eight 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 building. With a target of 30 kWh, we will focus most 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 – EG4 12k BTU Hybrid Solar Mini-Split AC/DC R32 *[58]*
This is a hybrid solar heating system that can use solar power or AC grid power, or both simultaneously. The device is designed for maximum efficiency, energy independence, and reducing utility costs. The system has a built-in power limiter, managing the amount of AC power that can be used. It accepts a maximum solar current of 12 Amperes, solar power from 1,100 Watts to 2,200 Watts, and has both a cooling and heating capacity of 12,000 BTU/hour.

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 NAU courses. I focused on chapter six which goes over convection, boundary layers, laminar and turbulent flow, and boundary layer equations. This is 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 NAU 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):
Thisgoogle 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 like 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 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 air panels collecting solar energy from the sun. From team discussions and conceptualizations, it was decided that it would be best for the solar air 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 important to understand how much solar radiation incident on the solar air panel’s surface and how much energy will be provided to the building. The solar air 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 during the prototyping phase.

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 higher-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 the 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 to perform the calculations. From this website, it was found that the photovoltaic 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 heaters were built. This showed me different ideas about 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 structural integrity and alignment are 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 main mathematical modeling and calculations that have 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.

<u>Method: eQUEST</u>

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.

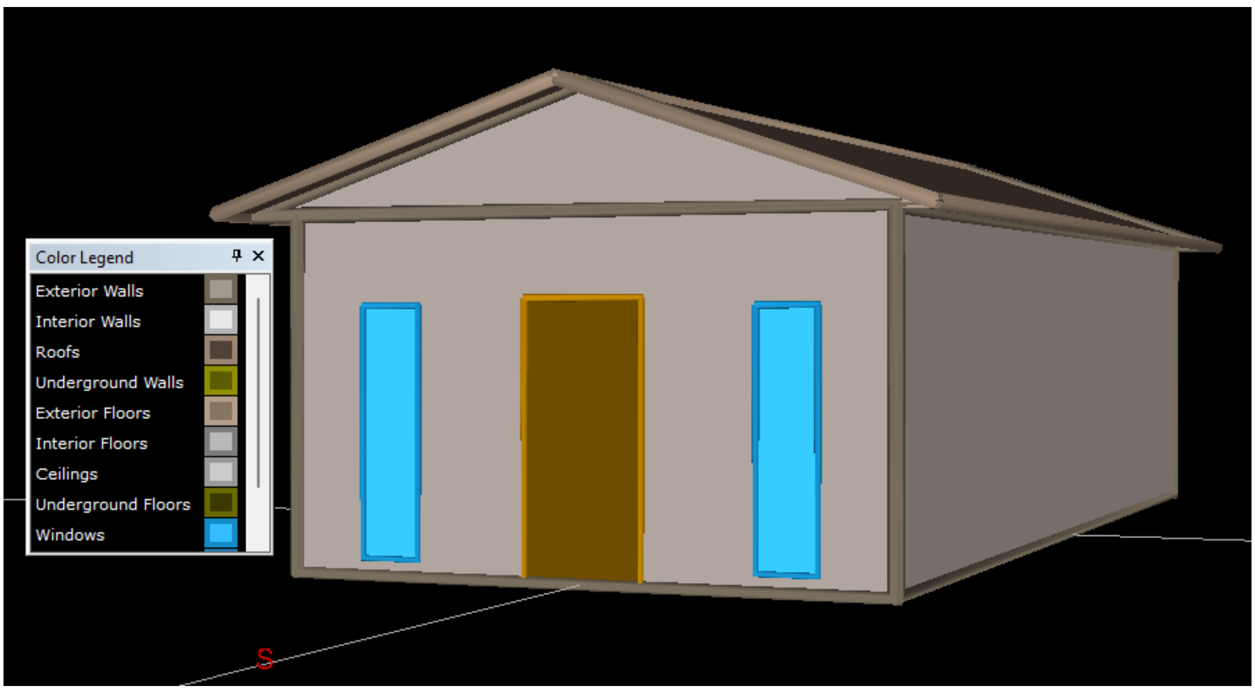


Figure 2: 3D Model of the Solar Shack Generated using eQUEST

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.

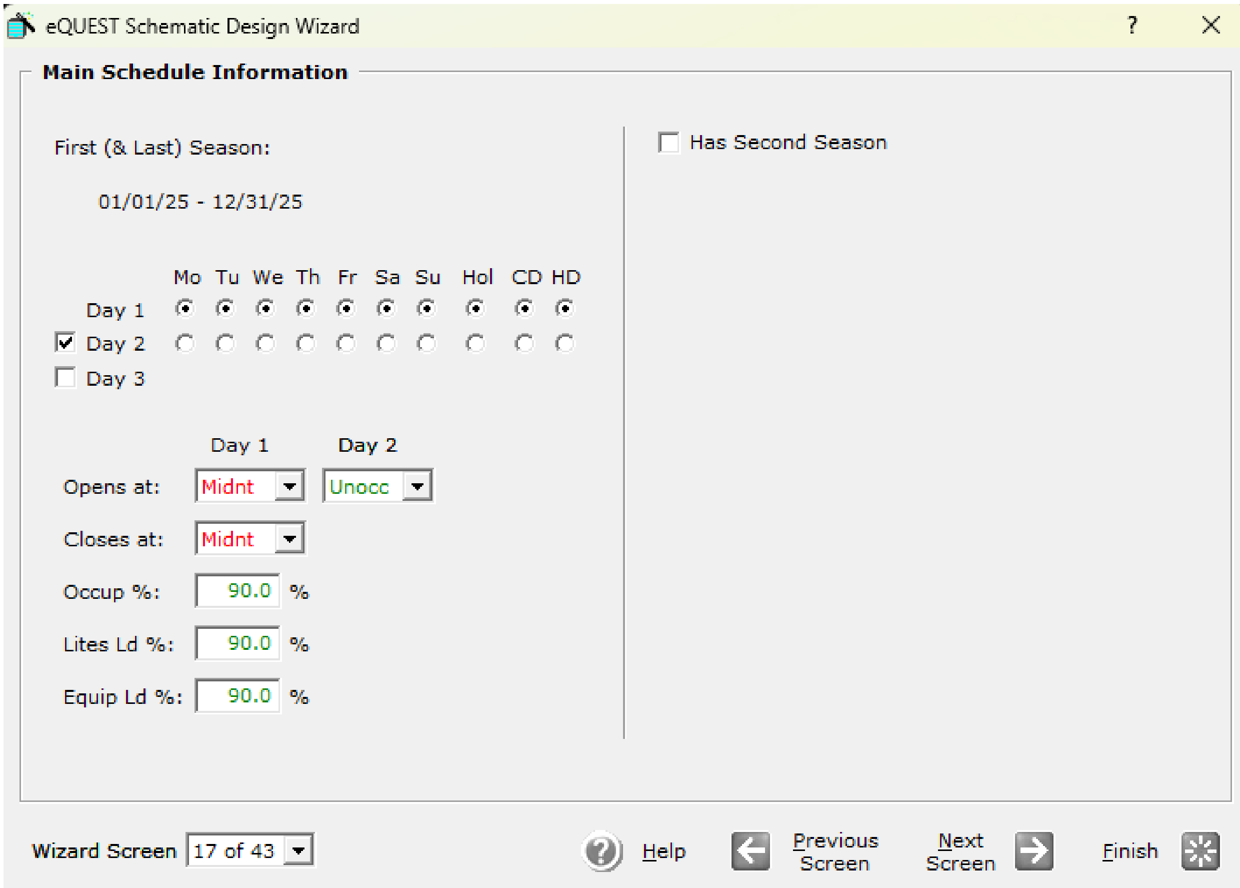


Figure 3: Updated Operating Schedule

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.

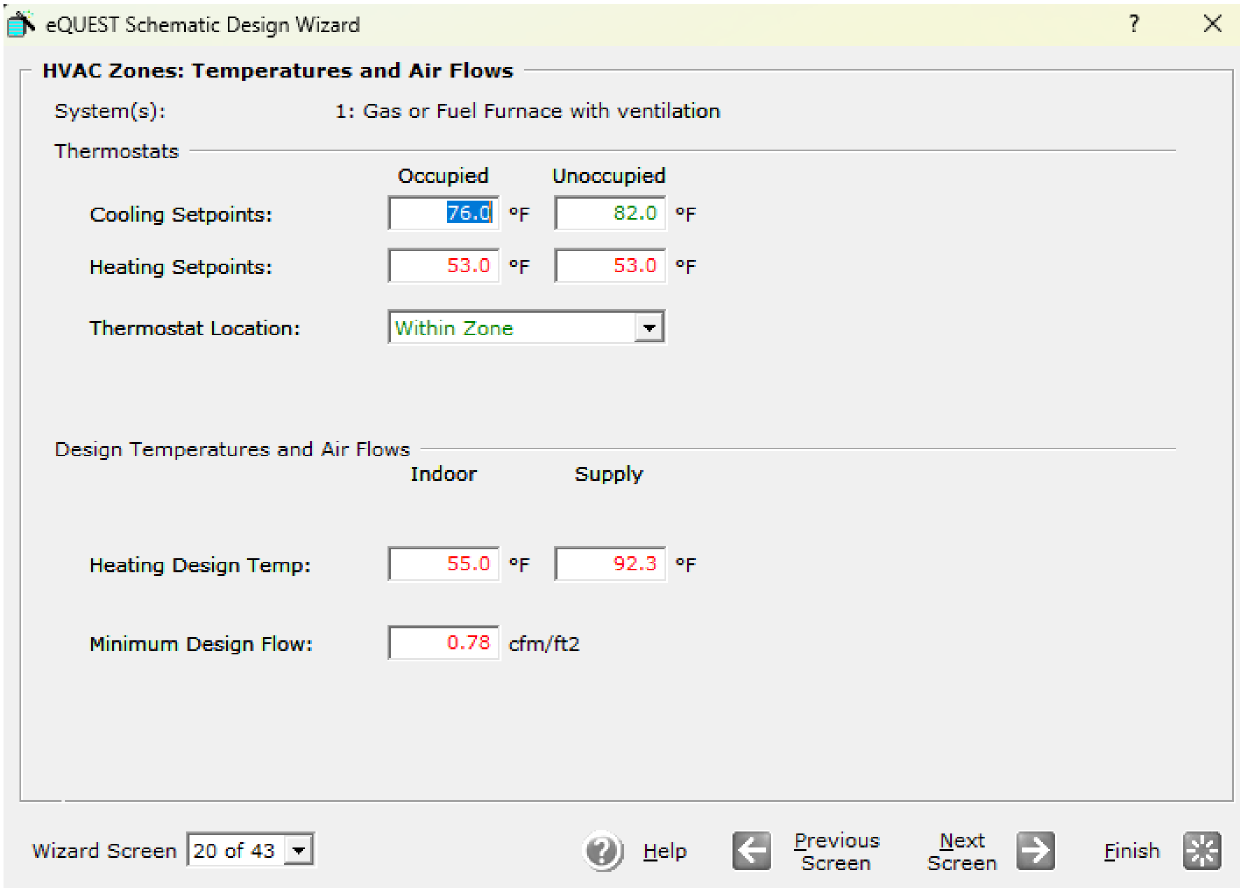


Figure 4: Updated HVAC Zones Page

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.

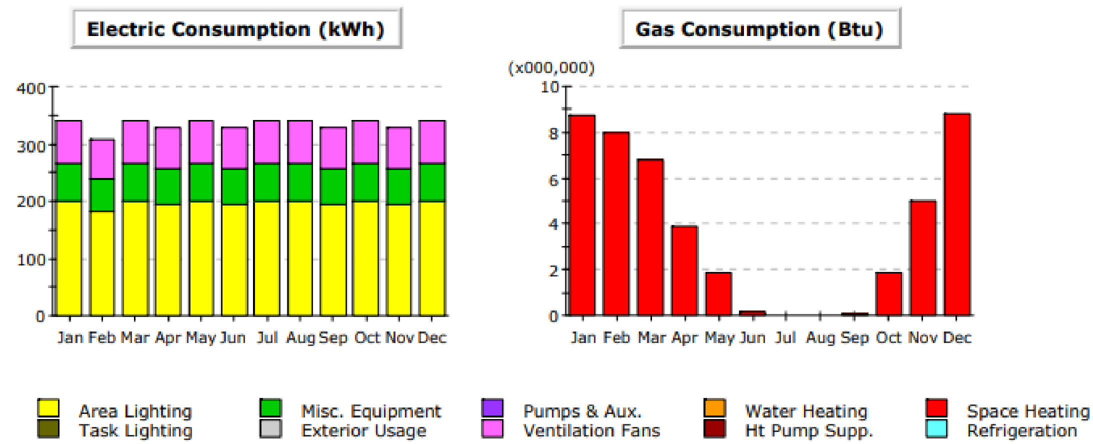
$$Q = 1.08 \cdot CFM \cdot (T_s - T_r) \tag{2}$$

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.

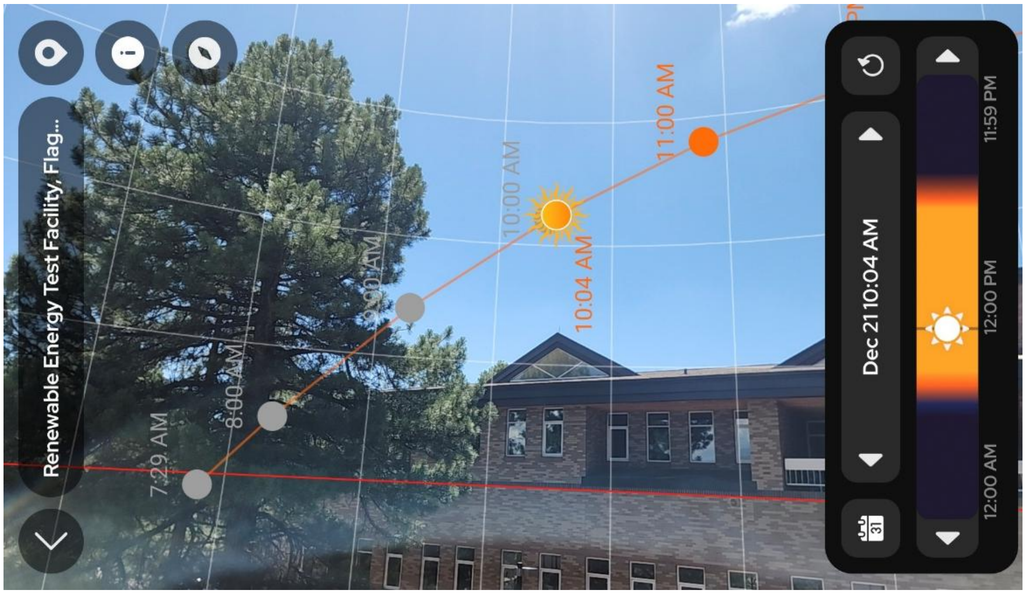


Figure 7: Morning Sun Path from the South Roof (9:00 AM to 11:00 AM)

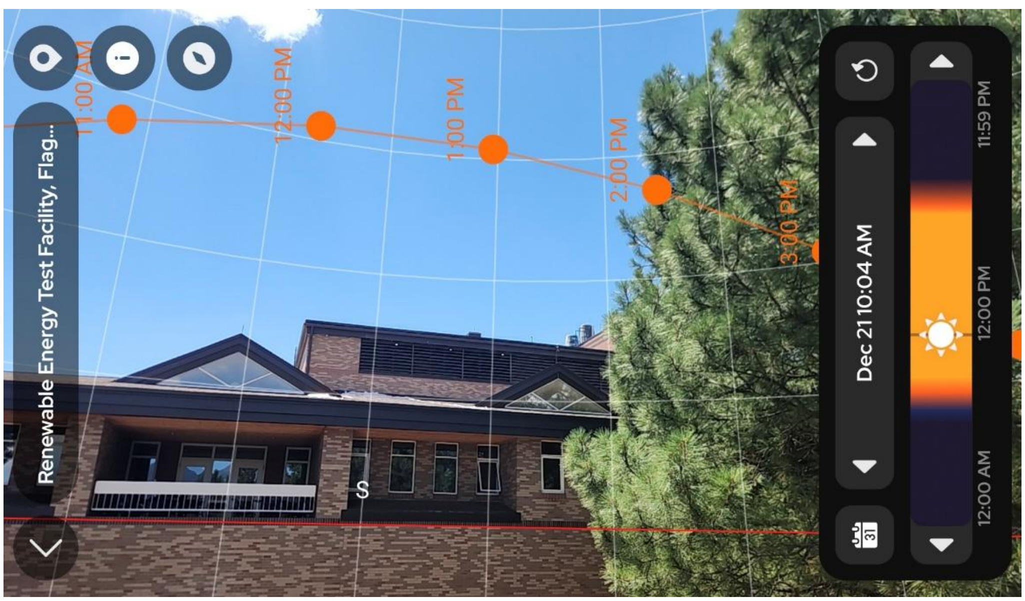


Figure 8: Afternoon Sun Path from the South Roof (11:00 AM to 2:00 PM)

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.

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

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

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℃ 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.

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

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.

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

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 9 shows the plot in total displaying the energy input for the most relevant months for the solar thermal system.

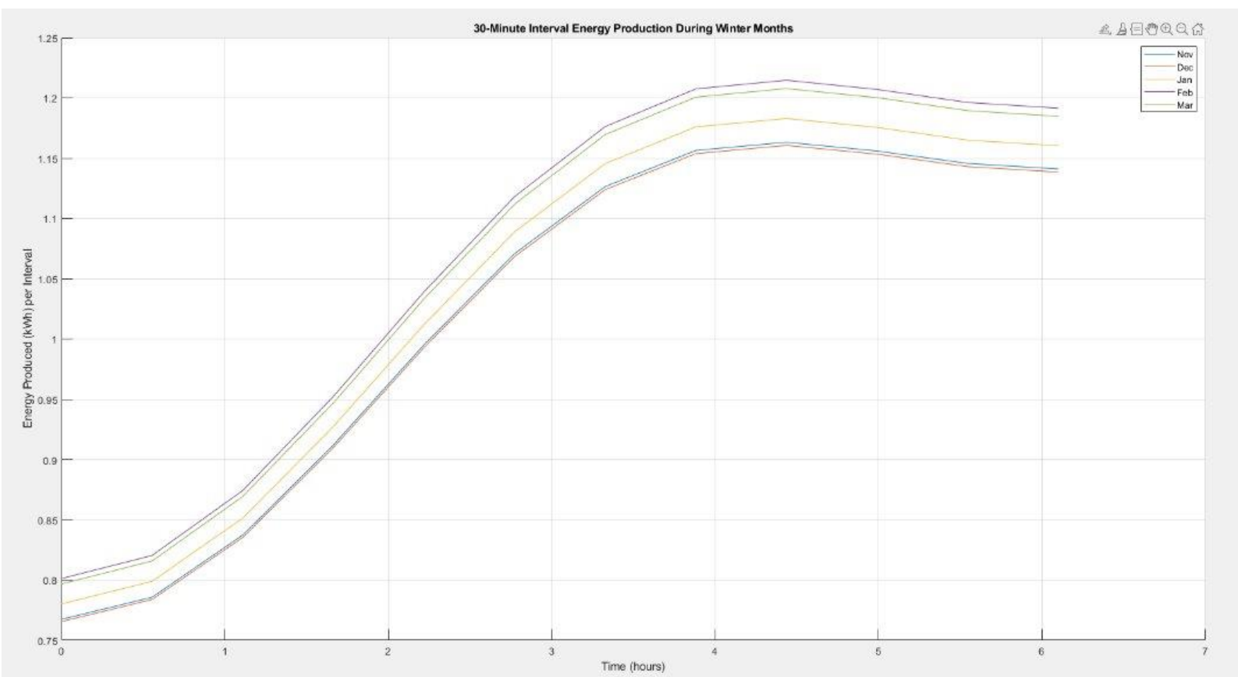


Figure 9: Energy Input Over 6.2 Hours

This plot shows approximately 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 9. 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 meet the customer requirement that states the system must cover 30% of the heat load in the worst-case months.

Figure 10 displays the monthly heat load covered by the heating system each month. This follows the same format for calculating the daily energy supply. The biggest difference is that this model uses NREL irradiation data that is modeled every hour over an entire year. Each month there is also an approximate number of sunny days that happen. The percentage of sunny days each month is multiplied by the total potential monthly supply to get the energy supply based on annual data.

Table 1: Summary of Annual Heat Load Coverage

Heat Load Fulfillment by Month and Year													
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Supplied (KWh)	308	370	549	683	792	907	392	386	468	486	367	264	5971
Supplied (MBtu)	1.05	1.26	1.87	2.33	2.70	3.10	1.34	1.32	1.60	1.66	1.25	0.90	20.37
Required (MBtu)	8.75	7.96	6.77	3.85	1.86	0.18	0.00	0.00	0.09	1.84	5.00	8.77	45.07
Realistic Supply (MBtu)	1.05	1.26	1.87	2.33	1.86	0.18	0.00	0.00	0.09	1.66	1.25	0.90	12.46
Percent Covered	12.0%	15.8%	27.7%	60.5%	100.0%	100.0%	100.0%	100.0%	100.0%	90.1%	25.1%	10.3%	27.6%

The results from the MATLAB simulation show that the lowest heat load coverage occurs in December at 10.3% and from May to September the heaters will cover the entire heat load requirements of the building. When calculating the annual heat load coverage if the potential energy supply from the heaters exceeds that of the building heat load requirements, then the supply is assumed to be the same as the requirements. This is being done to avoid distortion of the results that would indicate we are covering significantly higher heat loads when the energy isn't utilized.

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 10 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 10: 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, 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.

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 ft^2. Multiplying this area by the ceiling height gives a total room volume of approximately 3089.7 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

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

Small Room

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

Fortunately, engineers made an HVAC design chart, which is useful for selecting duct sizes that can handle the calculated airflow shown in figure 11. 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 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 11: 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 the 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 of having 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 that 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 absorbed 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:

$$\lambda_T = \lambda \cdot T \tag{12}$$

$$= 0.85\mu m \cdot 5800K$$
$$= 4930\mu m \cdot K$$

Once the product had been found, 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, 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°.

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

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

$$= 0.8(0.616725) + 0.25(1 - 0.616725)$$
$$= 0.589199$$

$$G_{abs} = \alpha G \cos(90 - \theta) \tag{14}$$
$$= 0.589199 \cdot \left(712.15 \frac{W}{m^2}\right) \cos(90 - 16.77°)$$
$$= 121.07 \frac{W}{m^2}$$

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 0.7μm. It was assumed that the cover plate temperature was 313.15 K and the absorber plate temperature was 333.15K. Emissivity values for the absorber plate were 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 diffused 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:

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

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

$$\varepsilon_a = 0.25$$

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

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

$$\varepsilon_c = 0.75$$

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

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

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

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

$$\overline{T} = \frac{T_a + T_c}{2} \quad (19)$$

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

$$= 323.15\text{K}$$

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

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

$$=168773.51$$

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

$$\overline{Nu_L} = 4.4457$$

$$\overline{h_L} = \frac{\overline{Nu_L} k_f}{L} \quad (21)$$

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

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

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

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

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.

$$\begin{aligned} V &= \frac{W}{I} \\ &= \frac{51.115W}{1.6A} \\ &= 31.9V \end{aligned} \tag{23}$$

As shown in the calculations above, the value is slightly higher than the desired voltage, However, it will ensure that the fans are receiving 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.

Dead Load = weight / Area = 100 lbs / 33 ft^2 = 3.03 psf

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

Wind:

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

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

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:

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

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

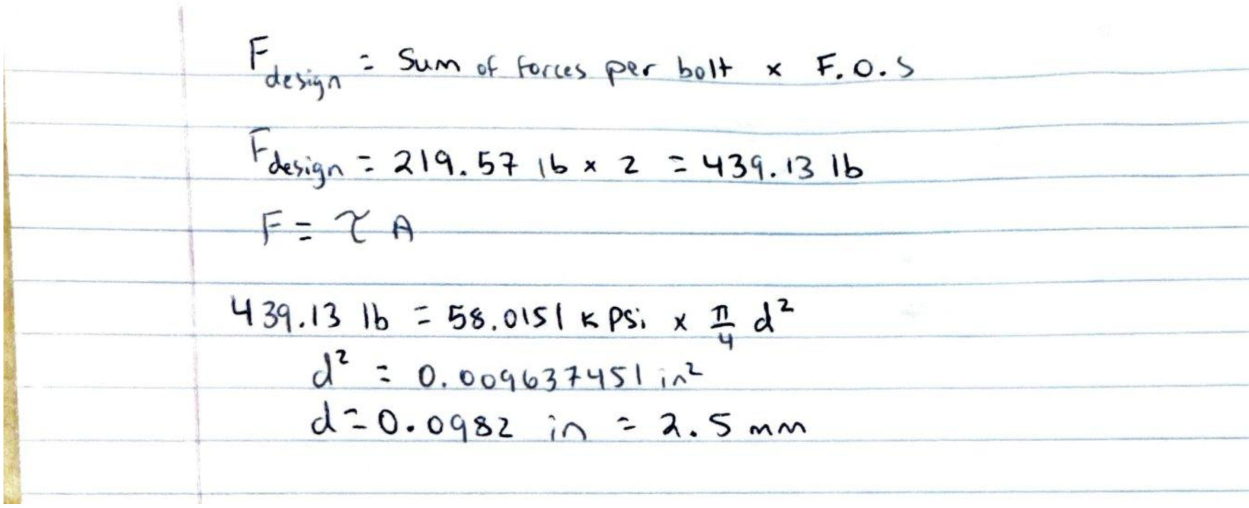
After calculating the live loads from wind and snow I had to calculate the forces that are acting on the bolts. To do this I summed the live and dead loads up and divided it by four because there are four bolts per solar air collector that connect to the L-brackets. I also had to determine the shear 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 12: Bolt Size Table [3]



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

4 Design Concepts

4.1 Functional Decomposition

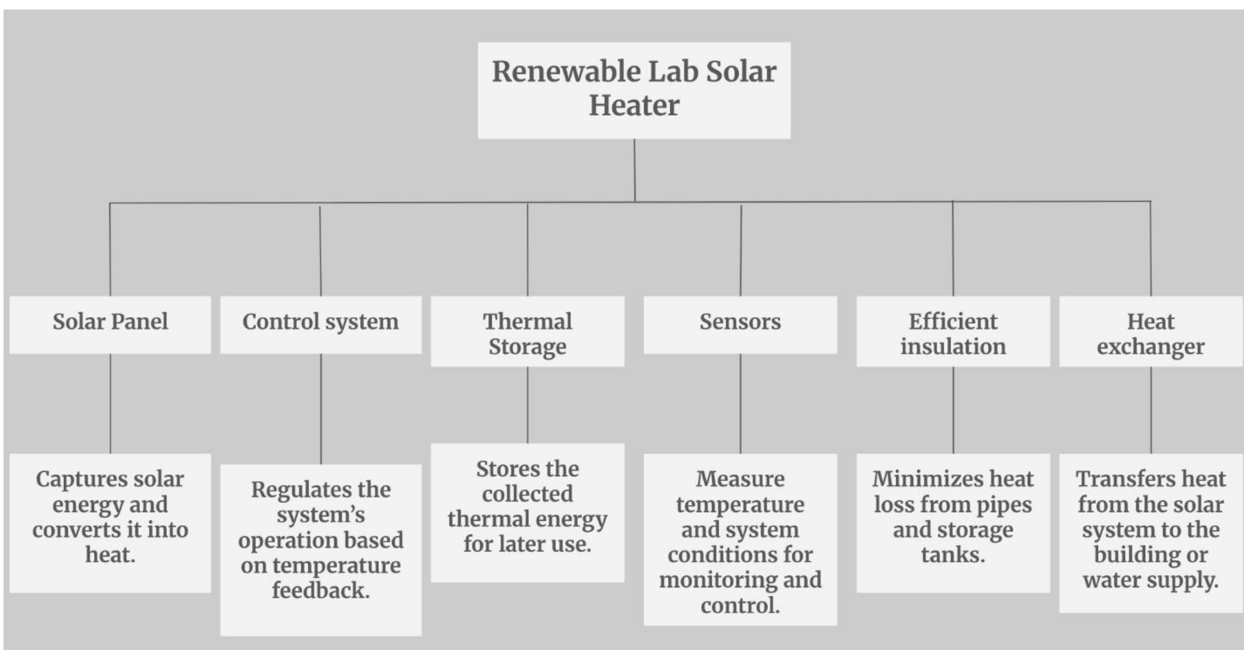


Figure 13: Decomposition Chart

The Functional decomposition of the renewable lab solar heater, figure 15, 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 collects and stores 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 with design decisions, troubleshooting, and structure throughout the project.

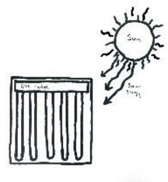
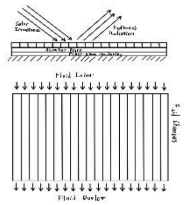
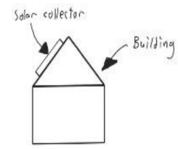
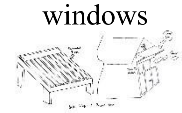
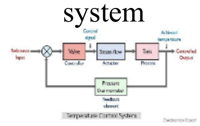
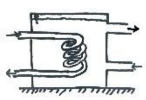
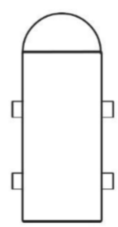
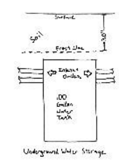
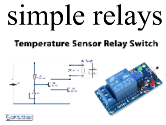
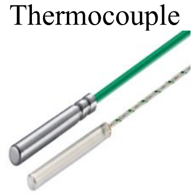
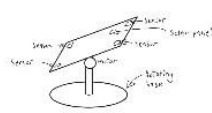
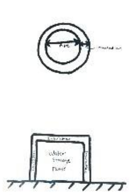
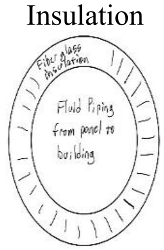
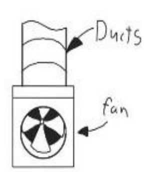
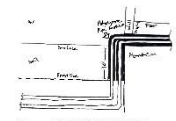
4.2 Concept Generation

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 (A)	Evacuated solar tubes 	Flat Plate Air Heater 	Solar panel attached to roof 	Evacuated tube solar collector 	Solar water 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	Radiator inside of	Silica Fire Bricks	Direct contact heat exchanger	Copper coils submerged in	Hot coils under floor

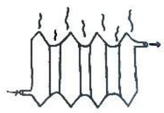
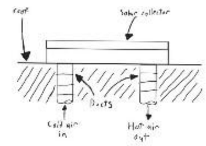
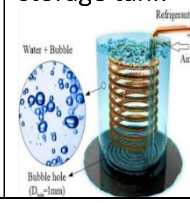
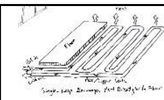
(F)	building 			storage tank 	

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.

Design 1 (Jacob):

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

Concept:

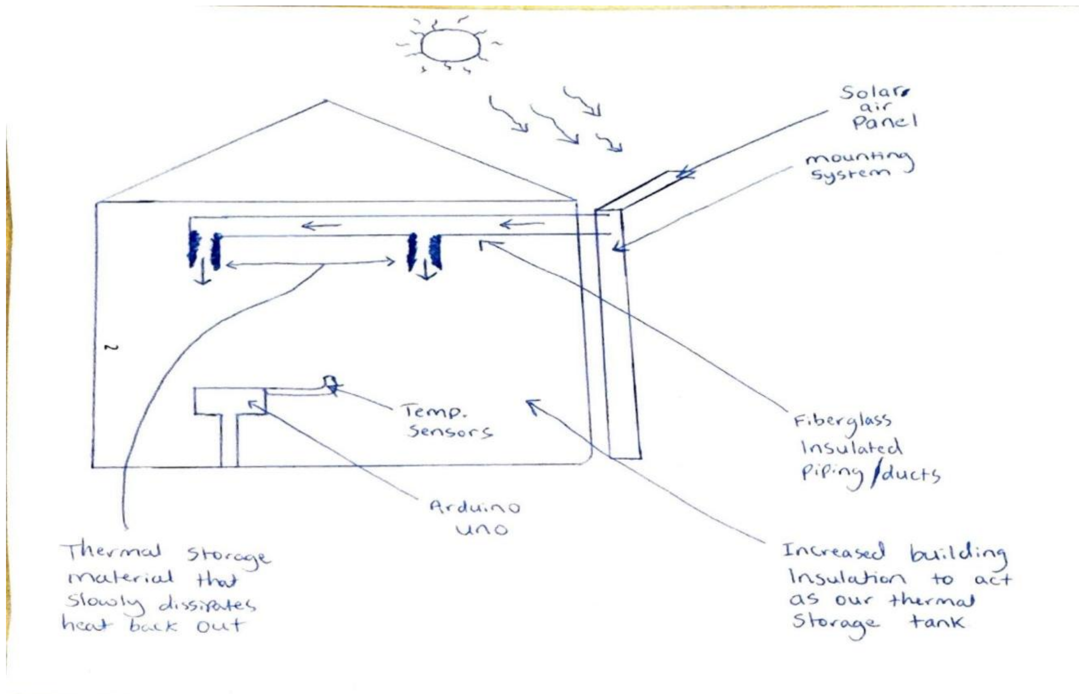


Figure 14: Concept Design #1

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.

Design 2 (Brendan):

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

Concept:

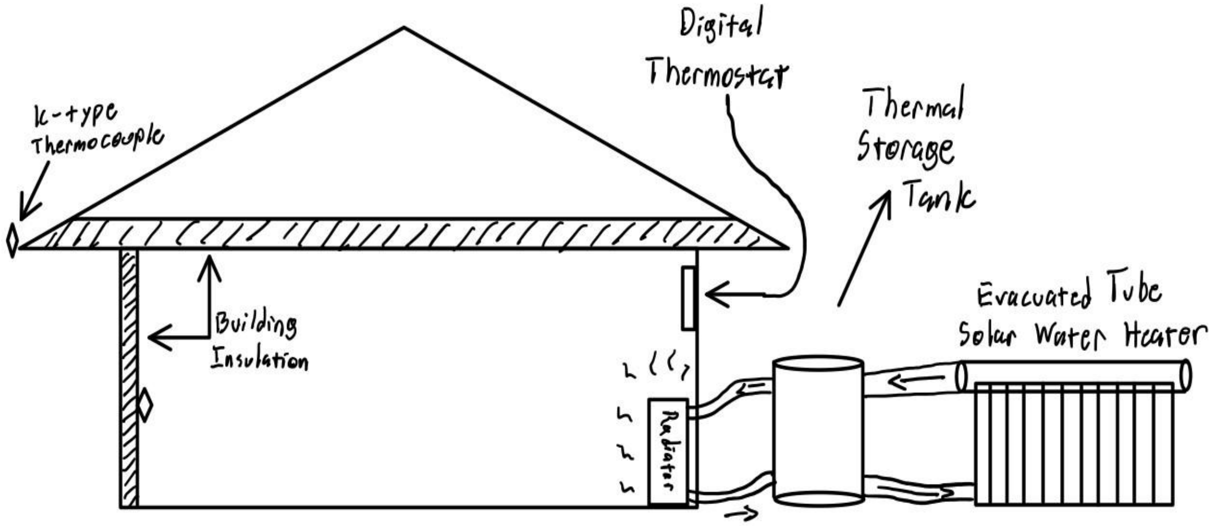


Figure 15: Concept Design #2

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:

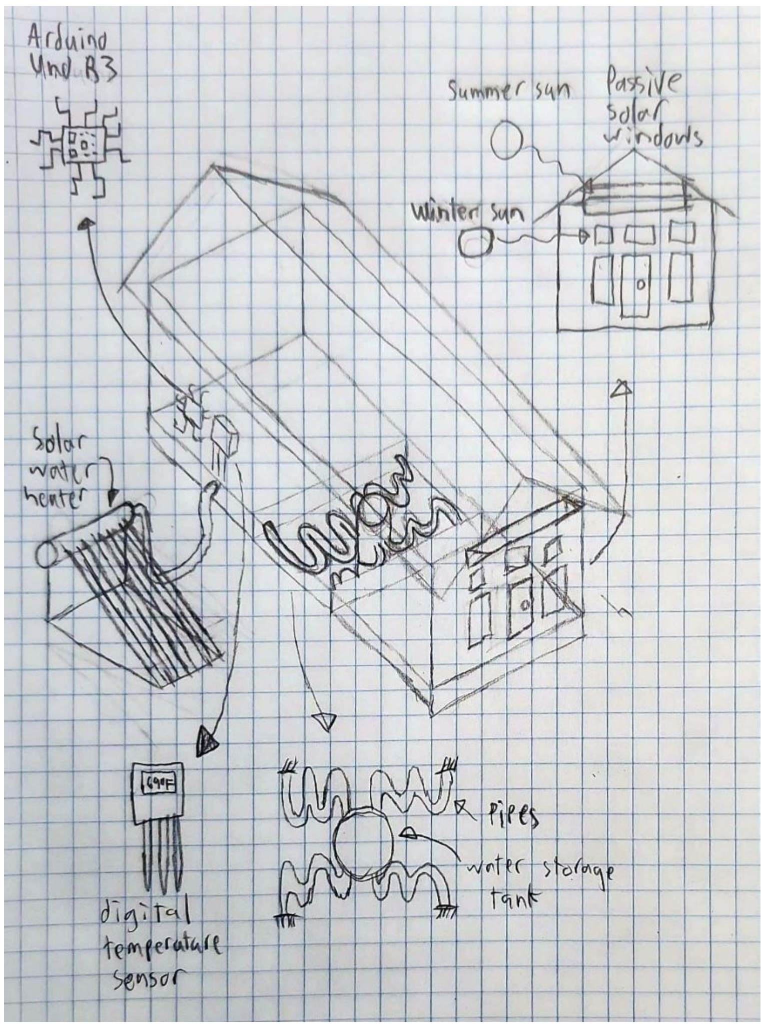


Figure 16: Full Concept Design #3

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 taste.

Thermal storage: When incorporating underground water storage for this design, it is meant to store heat generated by the solar panels so it can be utilized later. 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.

<u>Design 4 (Joseph):</u>

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

Concept:

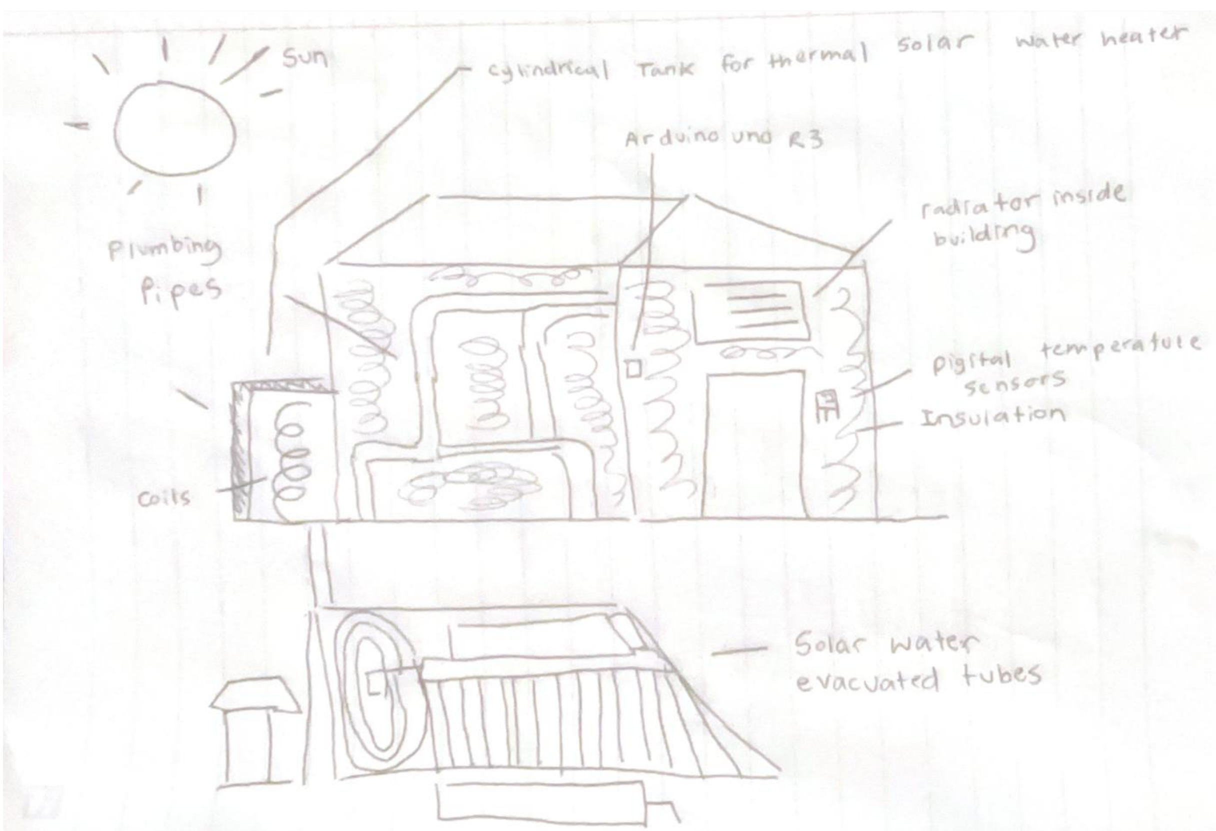


Figure 17: Full Concept Design #4

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. It's affordable and reliable 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 transfer 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:

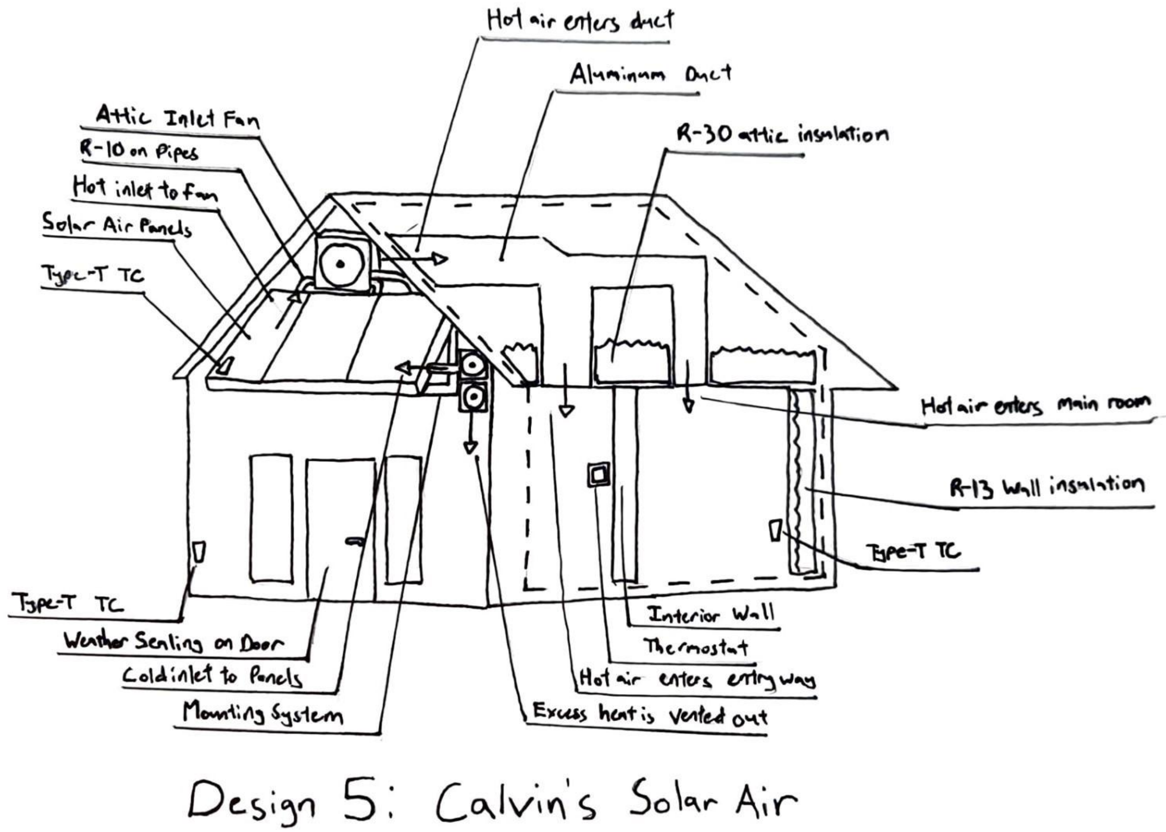


Figure 18: Full Concept Design #5

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.

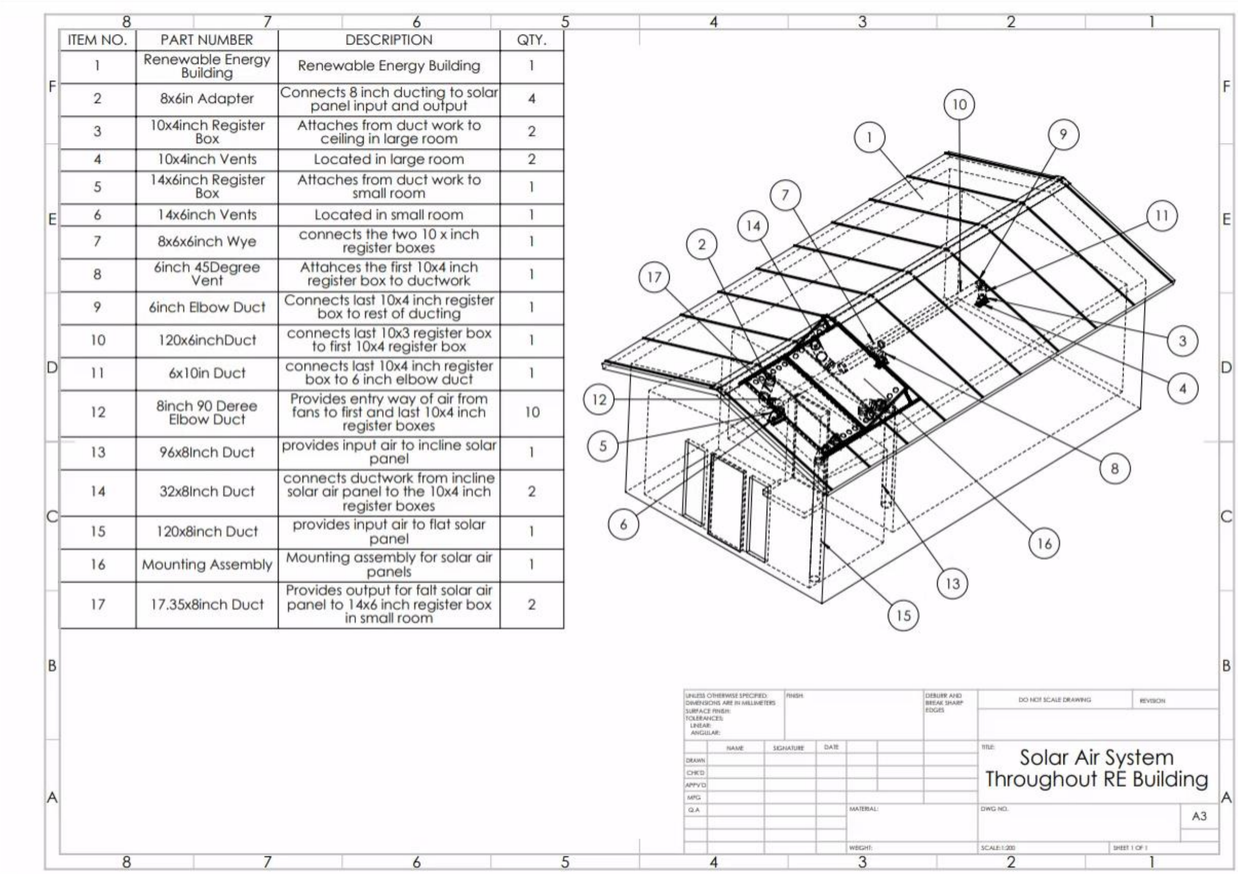
Table 3: Decision Matrix

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

Over the Summer and Fall semesters, Design 5 has seen several iterations resulting in the final CAD design as shown below in Figure 19 with the solar air heating system installed into the building. The design features two solar air panels mounted on the eastern side of the roof; one tilted at 35 degrees toward the south and the other lying flat on the surface. The solar air panels are connected by a series of ductwork that can intake air from each room and distribute the heated air throughout the building using two DC-powered fans (attached to the back of each solar air panel). The smaller room of the building features one 14x6 inch vent installed into the ceiling while the larger room has two 10x4 inch vents. The solar air system was designed this way from calculations to meet both customer and engineering requirements.



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Renewable Energy Building	Renewable Energy Building	1
2	8x6in Adapter	Connects 8 inch ducting to solar panel input and output	4
3	10x4inch Register Box	Attaches from duct work to ceiling in large room	2
4	10x4inch Vents	Located in large room	2
5	14x6inch Register Box	Attaches from duct work to small room	1
6	14x6inch Vents	Located in small room	1
7	8x6x6inch Wye	connects the two 10 x inch register boxes	1
8	6inch 45Degree Vent	Attahces the first 10x4 inch register box to ductwork	1
9	6inch Elbow Duct	Connects last 10x4 inch register box to rest of ducting	1
10	120x6inchDuct	connects last 10x3 register box to first 10x4 register box	1
11	6x10in Duct	connects last 10x4 inch register box to 6 inch elbow duct	1
12	8inch 90 Deree Elbow Duct	Provides entry way of air from fans to first and last 10x4 inch register boxes	10
13	96x8Inch Duct	provides input air to incline solar panel	1
14	32x8Inch Duct	connects ductwork from incline solar air panel to the 10x4 inch register boxes	2
15	120x8inch Duct	provides input air to flat solar panel	1
16	Mounting Assembly	Mounting assembly for solar air panels	1
17	17.35x8inch Duct	Provides output for falt solar air panel to 14x6 inch register box in small room	2

Figure 19: Final CAD Drawing of Air Heating System

5 Schedule and Budget

5.1 Schedule

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

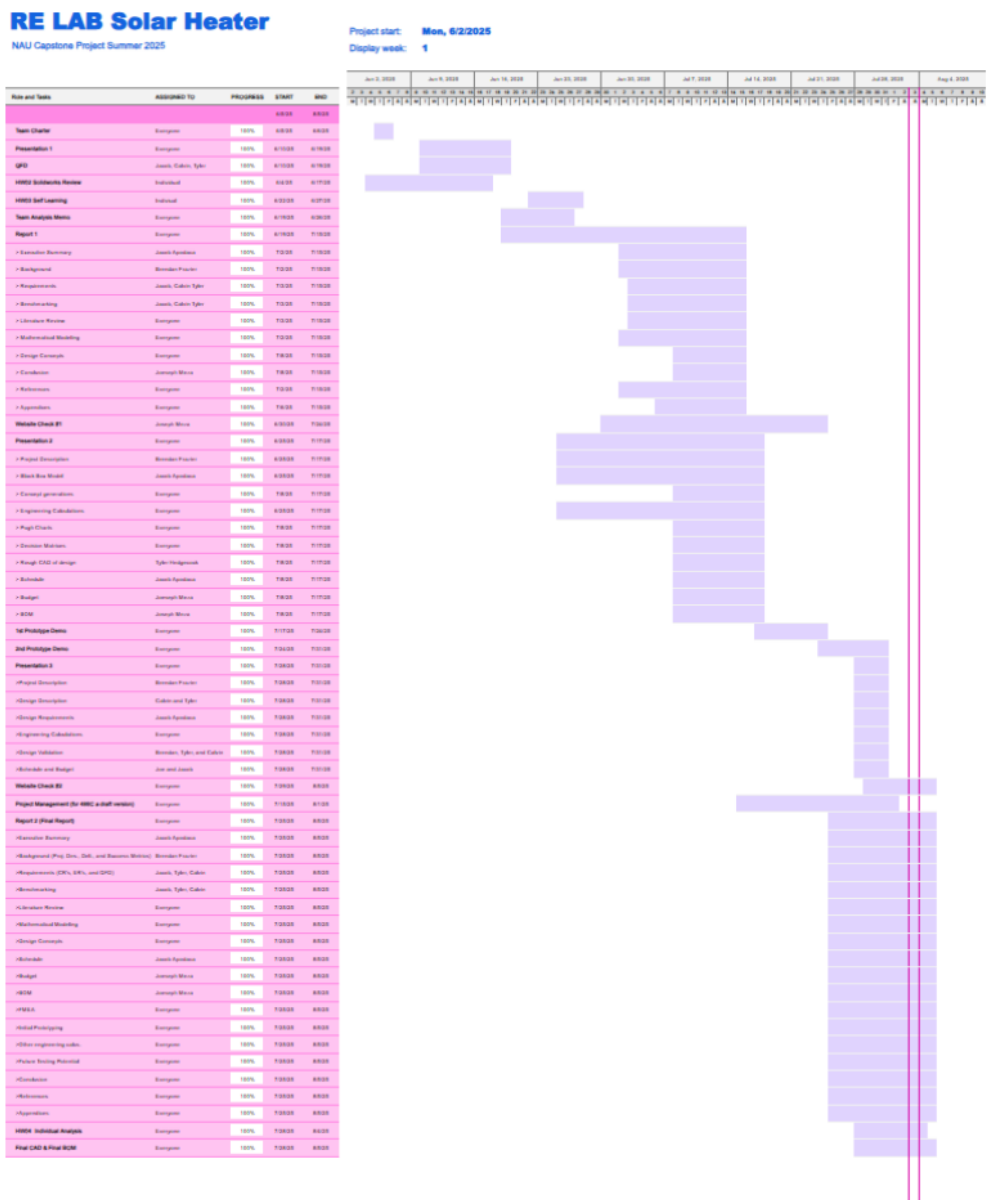
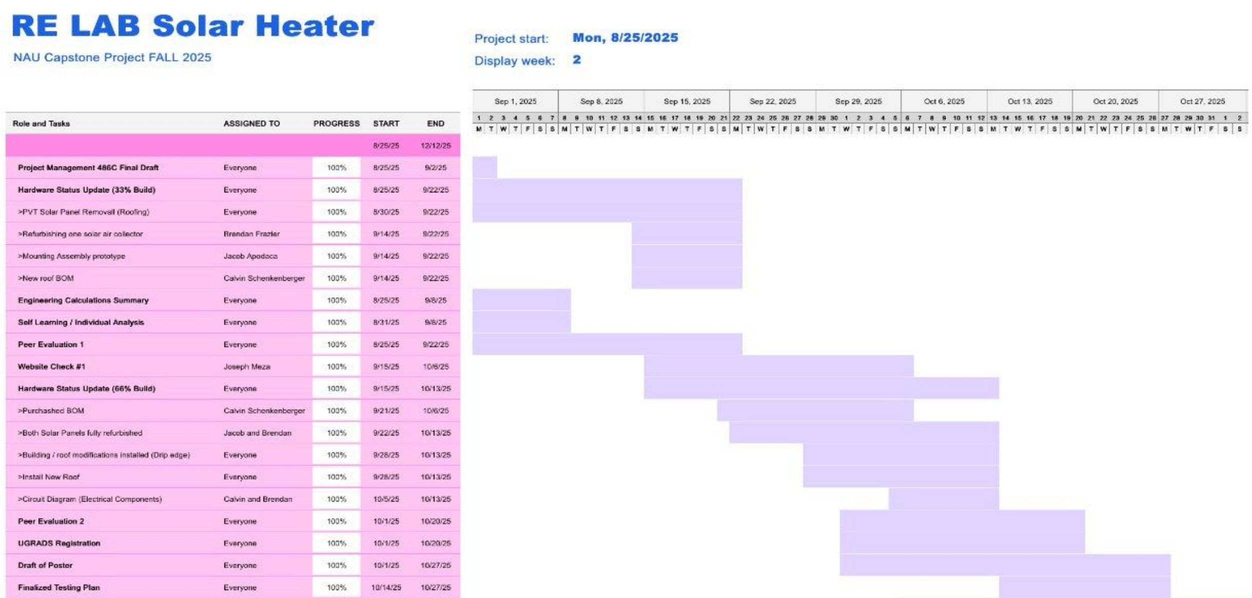


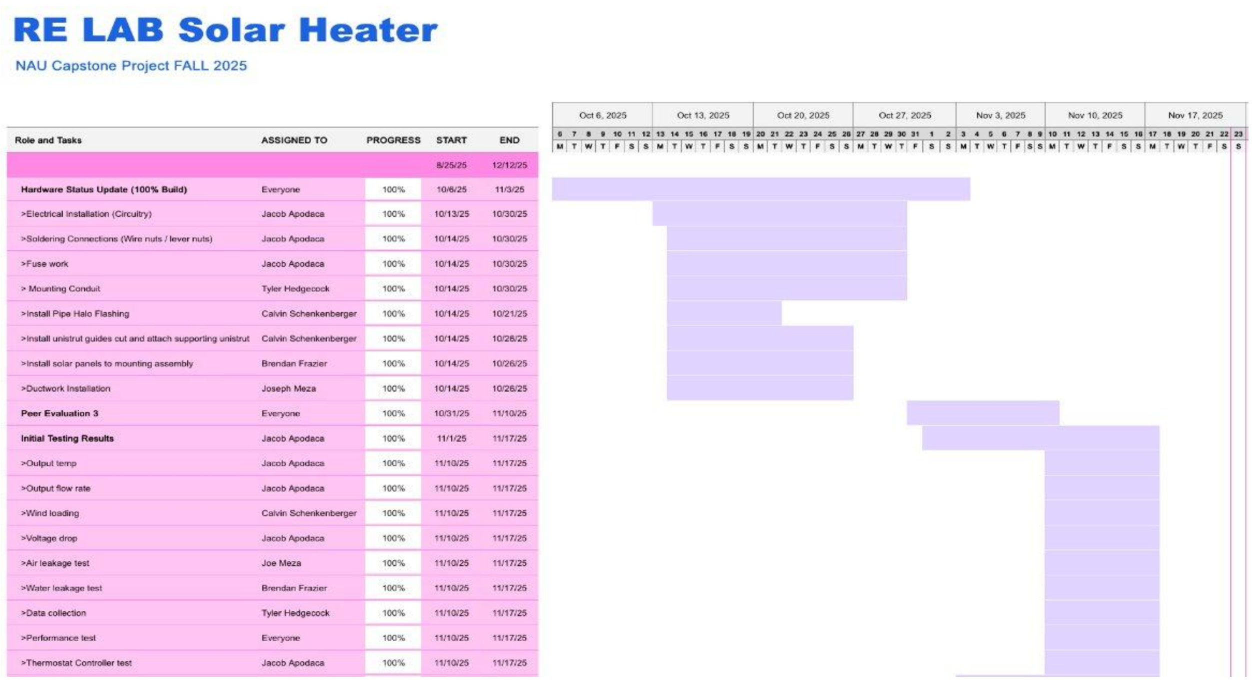
Figure 20: Summer 2025 Gantt chart

Figures 21, 22, and 23 show the 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 fall semester Gantt chart went through many changes throughout the project. This specifically was caused by unexpected tasks, such as installing a new roof, and a certain lack of organization where further decomposition of the project was done, and team leaders were assigned to specific tasks.



Role and Tasks	ASSIGNED TO	PROGRESS	START	END
			8/25/25	12/12/25
Project Management 486C Final Draft	Everyone	100%	8/25/25	9/2/25
Hardware Status Update (33% Build)	Everyone	100%	8/25/25	9/22/25
>PVT Solar Panel Removall (Roofing)	Everyone	100%	8/30/25	9/22/25
>Refurbishing one solar air collector	Brendan Frazier	100%	9/14/25	9/22/25
>Mounting Assembly prototype	Jacob Apodaca	100%	9/14/25	9/22/25
>New roof BOM	Calvin Schenkenberger	100%	9/14/25	9/22/25
Engineering Calculations Summary	Everyone	100%	8/25/25	9/8/25
Self Learning / Individual Analysis	Everyone	100%	8/31/25	9/8/25
Peer Evaluation 1	Everyone	100%	8/25/25	9/22/25
Website Check #1	Joseph Meza	100%	9/15/25	10/6/25
Hardware Status Update (66% Build)	Everyone	100%	9/15/25	10/13/25
>Purchashed BOM	Calvin Schenkenberger	100%	9/21/25	10/6/25
>Both Solar Panels fully refurbished	Jacob and Brendan	100%	9/22/25	10/13/25
>Building / roof modifications installed (Drip edge)	Everyone	100%	9/28/25	10/13/25
>Install New Roof	Everyone	100%	9/28/25	10/13/25
>Circuit Diagram (Electrical Components)	Calvin and Brendan	100%	10/5/25	10/13/25
Peer Evaluation 2	Everyone	100%	10/1/25	10/20/25
UGRADS Registration	Everyone	100%	10/1/25	10/20/25
Draft of Poster	Everyone	100%	10/1/25	10/27/25
Finalized Testing Plan	Everyone	100%	10/14/25	10/27/25

Figure 21: Fall 2025 Gantt Chart Part 1



Role and Tasks	ASSIGNED TO	PROGRESS	START	END
			8/25/25	12/12/25
Hardware Status Update (100% Build)	Everyone	100%	10/6/25	11/3/25
>Electrical Installation (Circuitry)	Jacob Apodaca	100%	10/13/25	10/30/25
>Soldering Connections (Wire nuts / lever nuts)	Jacob Apodaca	100%	10/14/25	10/30/25
>Fuse work	Jacob Apodaca	100%	10/14/25	10/30/25
> Mounting Conduit	Tyler Hedgecock	100%	10/14/25	10/30/25
>Install Pipe Halo Flashing	Calvin Schenkenberger	100%	10/14/25	10/21/25
>Install unistrut guides cut and attach supporting unistrut	Calvin Schenkenberger	100%	10/14/25	10/26/25
>Install solar panels to mounting assembly	Brendan Frazier	100%	10/14/25	10/26/25
>Ductwork Installation	Joseph Meza	100%	10/14/25	10/26/25
Peer Evaluation 3	Everyone	100%	10/31/25	11/10/25
Initial Testing Results	Jacob Apodaca	100%	11/1/25	11/17/25
>Output temp	Jacob Apodaca	100%	11/10/25	11/17/25
>Output flow rate	Jacob Apodaca	100%	11/10/25	11/17/25
>Wind loading	Calvin Schenkenberger	100%	11/10/25	11/17/25
>Voltage drop	Jacob Apodaca	100%	11/10/25	11/17/25
>Air leakage test	Joe Meza	100%	11/10/25	11/17/25
>Water leakage test	Brendan Frazier	100%	11/10/25	11/17/25
>Data collection	Tyler Hedgecock	100%	11/10/25	11/17/25
>Performance test	Everyone	100%	11/10/25	11/17/25
>Thermostat Controller test	Jacob Apodaca	100%	11/10/25	11/17/25

Figure 22: Fall 2025 Gantt Chart Part 2

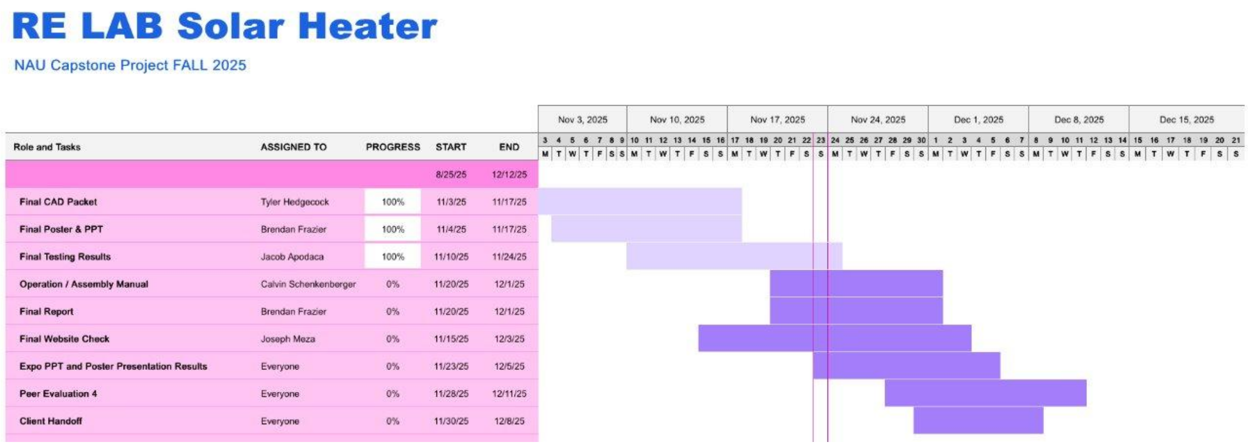


Figure 23: Fall 2025 Gantt Chart Part 3

5.2 Budget

The West Side Flagstaff Home Depot provided \$500 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 \$2500 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)

Bill of Materials					
Item	Category	Description	Unit Cost	Quanti	Cost
14 Gauge Unistrut	Materials: Mounting	10ft section for mounting frame	$41.00	3	$123.00
1/2" by 5" Lag Screws	Materials: Mounting	Mounting unistrut to roof	$1.76	10	$17.60
Gold Galv Sqr Washer	Materials: Mounting	Mounting unistrut to roof	$2.12	18	$38.16
Gold Galv 2-hole L Bracket	Materials: Mounting	Mounting panels to unistrut	$3.44	8	$27.52
1/2" Nylon Cone Nuts	Materials: Mounting	Connecting unistrut or L brackets	$1.31	24	$31.44
1/2" Locking Washer	Materials: Mounting	Safety measure for mounting	$0.47	30	$14.10
1/2" Washer	Materials: Mounting	Spacers and securing	$0.45	30	$13.50
1/2" x 5/16" galv bolt	Materials: Mounting	Mounting L bracket to unistrut	$0.62	8	$4.96
1/2 x 1-1/2 galv bolt	Materials: Mounting	Mounting panel to L bracket	$1.01	8	$8.08
1/2 x 13 tpi galv bolt	Materials: Mounting	Matched to bolt size and tpi	$0.52	8	$4.16
Pivoting Strut Brkt	Materials: Mounting	For angling rear panel	$55.97	2	$111.94
GAF Roll Roofing	Materials: Roofing	New roof material	$133.40	9	$1,200.60
Drip Edge Flashsing	Materials: Roofing	Prevent water leakage at roof edge	$8.73	2	$17.46
Roofing Nails	Materials: Roofing	Secure DE flashing (50 pk)	$6.10	1	$6.10
SKYSHALO Pipe Flashing	Materials: Roofing	Sealing location of ducts	$39.87	4	$159.48
Henry 900	Materials: Roofing	Waterproofing screws and flashing	$12.01	2	$24.02
Sunon 12V DC Fan	Materials: Electrical	Fans used to transport heated air	$79.51	2	$159.02
Weewooday Thermostat	Materials: Electrical	Engage or disengage the system	$6.99	1	$6.99
Flexible Conduit	Materials: Electrical	Route wiring in attic	$27.00	1	$27.00
EMT Conduit	Materials: Electrical	Route wiring in main room	$6.83	1	$6.83
Junction Box	Materials: Electrical	Storage for electrical components	$3.73	2	$7.46
10 AWG PV Wire	Materials: Electrical	Wires exposed to outdoors	$0.60	30	$18.00
16 AWG Wire	Materials: Electrical	Wires internal of the building	$17.98	1	$17.98
5A Fuse	Materials: Electrical	Over current protection	$1.40	1	$1.40
Fuse Housing	Materials: Electrical	Holds fuse in circuit	$5.99	1	$5.99
Single Pole Togle Switch	Materials: Electrical	Used as master switch for system	$4.40	1	$4.40

Figure 24: First Section of BoM

Bill of Materials					
Item	Category	Description	Unit Cost	Quant	Cost
8"x6"x6" Wye	Materials: Ducting	Splits air for main room	$17.98	1	$17.98
8" 90	Materials: Ducting	Used at inlets ducts	$9.98	10	$99.80
6 inch 90	Materials: Ducting	Used at angled panel to direct ducts	$8.68	2	$17.36
8 x 6 adapter	Materials: Ducting	All transitions for attaching to panel	$14.28	4	$57.12
6 inch duct	Materials: Ducting	Routes air to main room	$59.68	1	$59.68
8 inch duct	Materials: Ducting	Routes air to front room	$67.98	1	$67.98
Duct Insulation	Materials: Ducting	Additional insulation energy retentior	$27.98	1	$27.98
10 x 4 to 6 register box	Materials: Ducting	For vents in main and front room	$12.49	3	$37.47
10 x 4 vent	Materials: Ducting	General purpose vents for dispersion	$13.98	3	$41.94
Duct Tape	Materials: Ducting	Duct connections and sealing	$13.98	1	$13.98
4 x 8 White Polywall Panel	Materials: Panels	Replacing backing on panels	$28.42	2	$56.84
1 x 4 x 8 R-6	Materials: Panels	1 inch thick insulation for panels	$36.02	3	$108.06
Nashua 324A Premium Foil	Materials: Panels	For reassembling panel interiors	$26.22	1	$26.22
1/2 In 4 x 8 Polystyrene	Materials: Panels	1/2 inch thick insulation for panels	$13.09	1	$13.09
			Total Budget		$3,000
			Total Cost		$2,484.50
			Remaining Budget		$515.50

Figure 25: Second Section BoM

This bill of materials (BoM) covers all the currently required parts based on the CAD design shown at the end of chapter 4 of this report. Additional expenses that are not accounted for within the CAD design are all covered in the “roofing” materials section. The GAF roof rolling, which is the most expensive aspect of the project, was an unexpected expense and required additional funding from the university. The remaining items on the BoM were expected purchases. The additional funding received for the roof totaled $2000 and with the initial budget of $500 and the $500 grant from Home Depot the project budget rose to $3000. All parts used in the project totaled $2,484.50, leaving the project under budget.

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 26: 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 of 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 requirements, 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℃ when in all reality the inlet temperature will be that of the building since the inlet ducts will pull from inside the building.

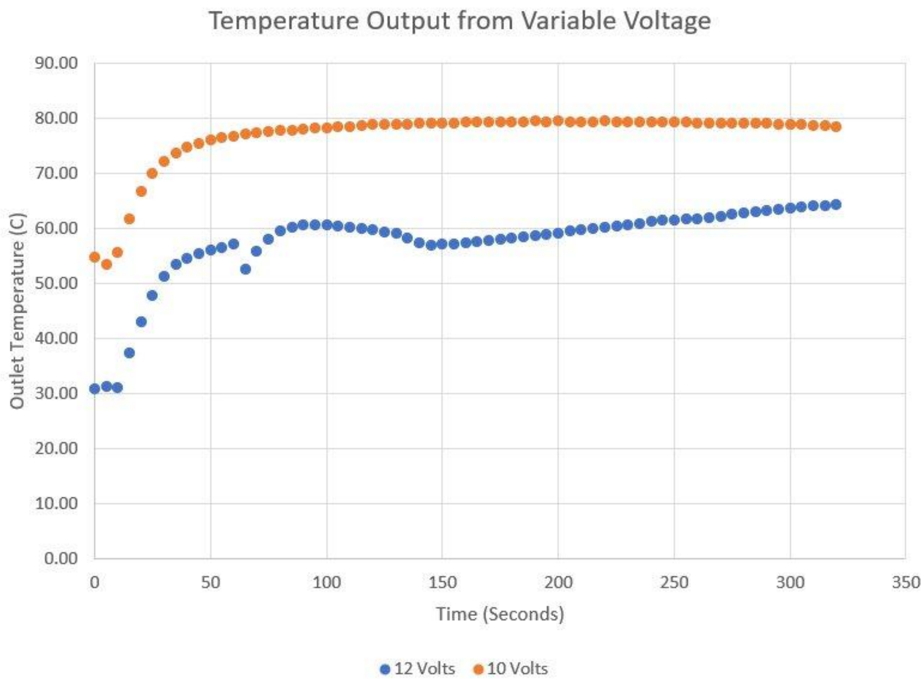


Figure 27: Outlet Temperature from Variable Voltage

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 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 building a 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 28 and 29 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.

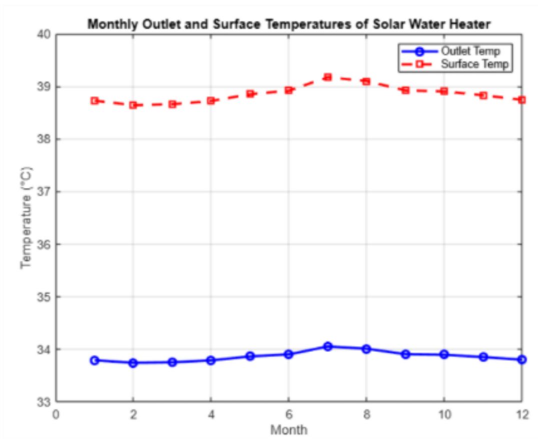


Figure 28: Water Performance

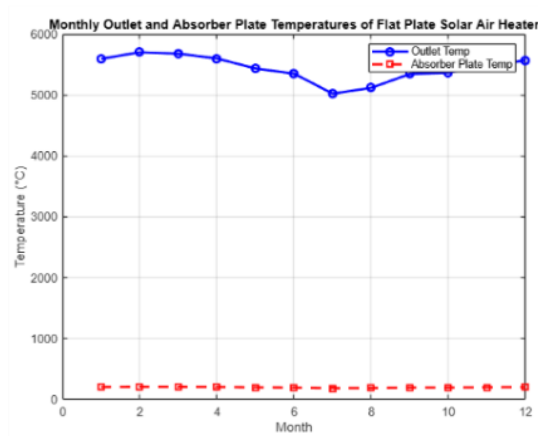


Figure 29: Air Performance

6.3.2 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 heating system and the solar air heating system, respectively. For the pump, both the work and the temperature were calculated by hand, and it was found that the system overheated. As for the fan, a MATLAB code was generated to plot the temperature, in Farenheight, over the flow rate, in CFM, as shown in Figure 30 below. A wavelength and absorptivity of 0.3μm [60] and 0.98, respectively, was used to calculate the thermal diffusivity, α, to analyze how much solar energy the solar air panel would be absorbing at a 35-degree tilt, and the solar irradiation flagstaff receives on the winter solstice at solar noon [59].

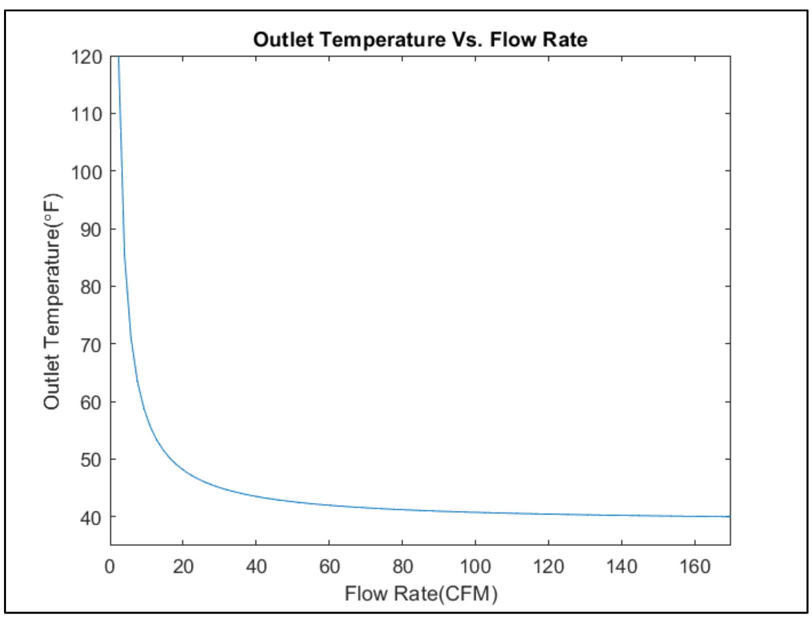


Figure 30: Fan Analysis Calculations

After the results for both the pump and fan were analyzed, it was decided that the team should utilize a solar air heating system since it has an adjustable temperature ensuring the system won't overheat, in accordance with customer requirements. It also meets another customer requirement, that no major modifications will be made to the building. The team decided that a fan should be used since the solar water heating system will require the building to be modified to implement the system.

6.3.3 Cost Analysis

One of the customer requirements is to have a 10-year payback period for the product. This calculation was completed in comparison with the energy simulation discussed in chapter 3.3.2 of this report. In total, the model indicates that the heater will supply 3651.2 kWh to the building on an annual basis. NAU is also grandfathered into a cheaper energy cost than the rest of the city where the cost per kWh is around 10 cents. By multiplying the annual energy supply by the cost per kWh, the heaters save $365.12 per year. With an initial investment of $3000 in the project, the total payback period ends up being 8.22 years.

```
============================================================
                     PAYBACK & SAVINGS
============================================================
System cost (initial investment):    $  3000.00
Annual heat supplied to building:       3651.2 kWh/year
Assumed energy price:                $  0.100 / kWh
Estimated annual monetary savings:   $  365.12 / year
Estimated payback period:               8 years,  2 months, 18 days
 (Equivalent to 8.22 years)
```

Figure 31: Consolidation of Payback Period Results

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 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. Additional testing that should be completed is more temperature data but rather than only measuring the outlet temperature; multiple thermocouples should be placed throughout 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 Final Hardware

The final physical status of the project can be broken up into 4 primary subsystems. There is an electrical system, ducting system, mounting system, and solar air heater systems. This section will detail the assembly and installation of all of those subsystems.

7.1 Solar Panels and Mounting

The air heating solar panels follow a very standard design consisting of a cover plate, absorber plate, insulation backing, and a bolted metal frame. During the refurbishment process, a half inch thick piece of insulation was taped around the boarder of the solar panel between the cover and absorber plate. This serves two purposes; act as a spacer between the panels to allow a large enough chamber for air to flow, and the layer makes the internal thicknesses fit tightly into the metal frame. When attaching all components of the solar panel, a combination of aluminum weather sealant tape and caulking was used to seal the solar panel directing the air and keeping water out. When all the internal layers were cut and assembled, the frame was installed. A final bead of caulking was used around the front and back edges of the frame as a final waterproofing measure. All the mounting points were also installed on the solar panels. This consisted of a 1.5-inch bolt and a square washer fed through the interior of the metal frame with a one-hole L-bracket on the exterior. Figure 32 shows the look of these mounting locations on the angled solar panel.

Figure 32: Mounting Location on Solar Panel

The mounting system was the next component installed to the building. The frame consists of 10-foot-long sections of 14-gauge Unistrut. Two of these sections are mounted directly along the length of the building. To mount them to the building 0.5-inch x 5-inch lag screws were used at every truss (2-feet apart). To properly attach the Unistrut to the roof $\frac{15}{64}$-inch pilot holes for the lag screws at every point of mounting and all the pilot holes are filled with Henry 900 for weather sealing. The Unistrut is then lined up with a circular washer between the roof and Unistrut as a small spacer and a square washer and locking washer on the top of the Unistrut where the lag screw is fed threw. On the northernmost end of the Unistrut, 2 pivoted brackets are attached with 2.3-foot sections of Unistrut that are used to prop up the angled solar panel. Figure 33 shows the mounting system fully attached to the roof without solar panels. While this isn’t clearly shown in the figure, the bottom piece of Unistrut was cut into 4.5-foot and 5.5-foot sections. This was done because the front solar panel is 97-inches wide, and the rear solar panel is 95.5-inches wide. So, the front section of the lower Unistrut is located 1.5-inches lower on the roof than the rear section.

Figure 33: Panel Mounting Assembly

Installing the solar panels at Unistrut required multiple people to lift the solar panels up to the roof and align the L-brackets on the solar panels to Unistrut. Once the brackets were aligned with the nylon cone nuts 0.5-inch by 0.75-inch bolts and locking washers were secured in place. Figure 34 shows the initial installation of the angled solar panel.

Figure 34: Mounted Angled Solar Panel

7.2 Electrical System

Figure 35 shows the circuit diagram used for powering the fans in the solar panels. The 12V power supply is a sequence of batteries stored in the front room that are powered from PV panels located directly outside of the building. The first J-box is the housing that splits power between two outlets and the fan circuit. This J-box also contains a 5A fuse. This fuse is used because both fans are rated for 12V and 1.2A, but brushless DC fans tend to overdraw current when initially turned on. By using a 5A fuse, the fans are allotted sufficient current for this overdraw. The second J-box houses the master switch for the system as well as the thermostat. The master switch allows for complete control over the system if weather does not permit the use of the system. The thermostat has an integrated temperature switch so when the temperature of the building exceeds the setting on the thermostat, the system will be powered off. On the thermostat is also a red LED that will indicate to the user whether the system is on or off, which fulfills CR8. Note that the thermostat and master switch are wired in series with the thermostat located first in the circuit. This was done, so the thermostat provided users with constant information about building temperatures. The final J-box is used to split the wires to go to each fan, respectively. This is also where PV wire is used since these wires will be outside at the connections to the fans. Note that the fans are wired in parallel, so if one fan no longer works, the other fan will still operate. The only event where this may not hold true is if a short occurs in one fan and blows the fuse.

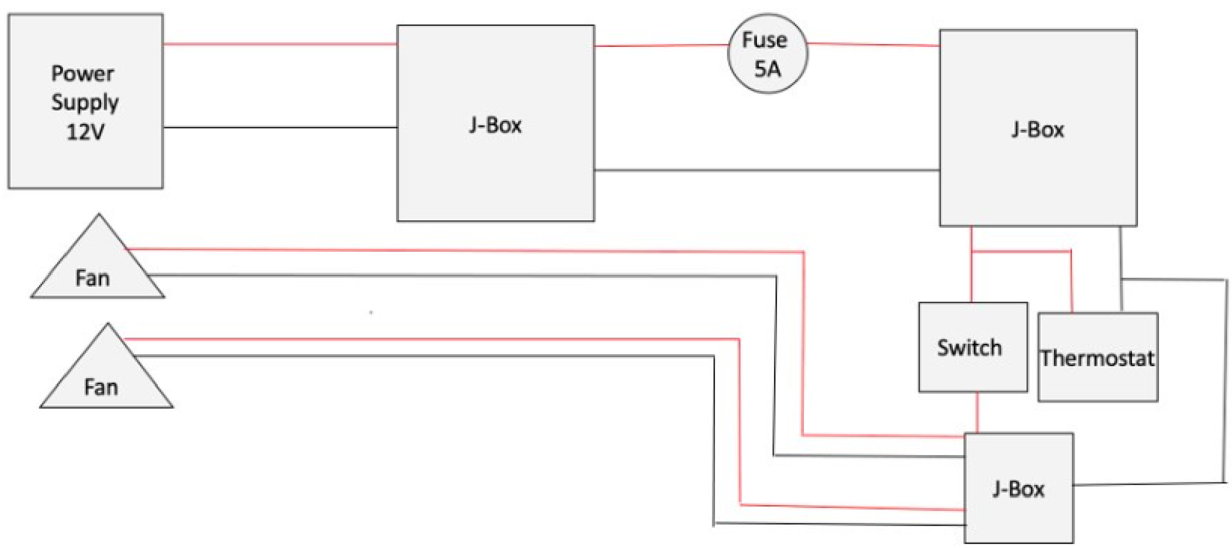


Figure 35: Circuit Diagram

A combination of EMT and flexible conduit was used to route all the wiring. From the batteries to the third J-box uses only EMT conduit, shown in figure 36, where that final J-box ends in the attic of the building. From that point, sections of flexible conduit are used to route the wires to each fan. The flexible conduit being routed from the last J-box can be seen in figure 37.

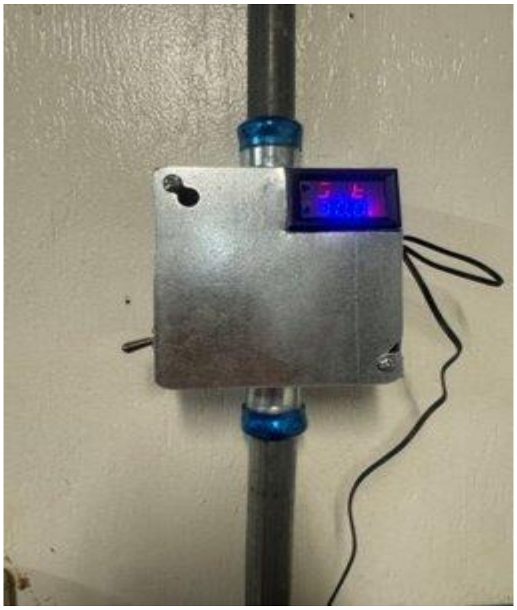


Figure 36: J-box with Thermostat and Switch

Figure 37: Flexible Conduit from Final J-box

7.3 Duct System

The duct system connects solar air collectors to the building and is divided into two major sections across the Upper Half Backroom and the Upper Half Front room as seen in Figure 38. The important sections are Solar air heater 1 and Solar air heater 2. Each with its own inlet, outlet, and return airflow pathways.

In the Upper Half Backroom, an inlet duct transitions through an 8" × 6" adapter and uses three R8 90° elbows to route air into the system. Flexible R6 ducting connects to two 10" × 4" to 6" register boxes, distributing airflow across the backroom. A 6" × 6" × 8" wye fitting connects the smaller branches into the main duct run. This configuration allows heated air entering the collectors to spread evenly before moving toward the outlet side. The backroom is connected to the Solar air heater 2 and the inlet is located in the same room.

In the Upper Half Front room, the ductwork mirrors a similar layout but uses larger components to accommodate higher airflow. The inlet uses 8" × 6" adapters and R8 flexible ducting, while a 14" × 6" to 8" register box transitions flow into the distribution system. Additional R8 90° elbows guide airflow through tight geometry. The outlet ducts in this room also use 8" × 6" adapters and 90° fittings before venting conditioned air into the space.

In both Solar air heaters 1 and 2 they use R6 and R8 ducts, which helped with easy installation, reduced vibration and easy navigating in both rooms. Overall, the ducting allows the system to transfer the ambient air in each room, to the solar air heater and back out through the vents.

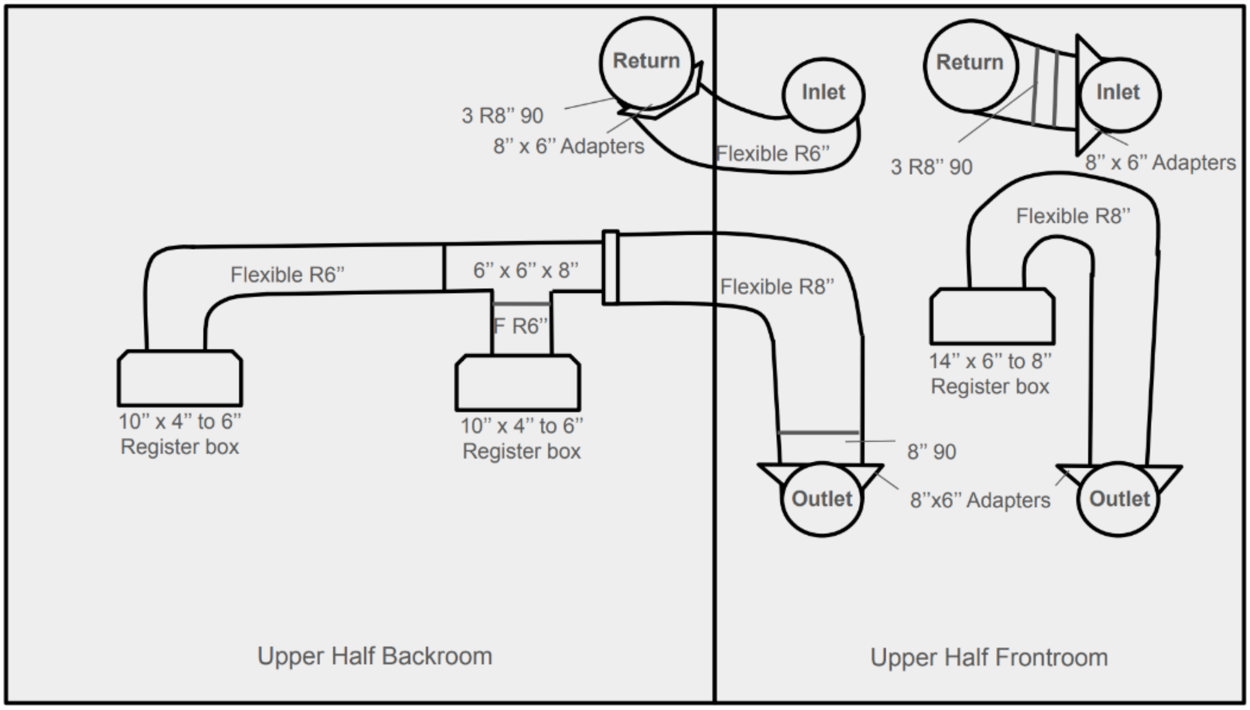


Figure 38: Duct Flow Diagram

8 Final Testing

8.1 Top Level Testing Summary Table

Experiment	Relevant DR's	Testing Equipment Needed	Other Resources
EX1 – Temperature Performance	CR1, CR2, CR3, CR8, CR10, ER1, ER2, ER3	Hotwire Anemometer	Sunny Day and NWS Irradiation Data
EX2 – Flow Rate	CR1, ER1, ER4	Vane / Hotwire Anemometer	NA
EX3 – Wind Loading	CR5, ER5, ER6, ER7	NA	NWS Wind Data
EX4 – Voltage Drop	CR5, CR10, ER3, ER6	Multimeter	NA
EX5 – Air Leak	CR9, ER2, ER6	Fog Machine	NA
EX6 – Water Leak	CR6, ER5, ER7	NA	Rainy day
EX7 – Data Collection	ER5, ER7	NA	NREL and NWS Weather Data
EX8 – Energy Performance	CR1, CR2, CR7, CR8, CR10, ER5, ER6	Hotwire Anemometer and RTD	EX1 Temperature Data

8.2 Detailed Testing Plan

8.2.1 EX1 – Temperature Performance

8.2.1.1 Summary

From the initial testing data gathered during the prototyping phase of the project, the air heating solar panels output sufficiently high temperatures. However, prior to this test it has not been proven that the input temperature to the building is high enough to meet the 30% building heat load reduction (CR1). In addition to gathering the necessary data needed to calculate the building heat load coverage, this test will also determine where any major heat losses come through the ducting. The losses in this test will be primarily attributed to poor or lacking insulation as the air leak test has already been completed.

8.2.1.2 Procedure

This test is performed using a hotwire anemometer and an RTD at each of the outlets in the building. Temperature measurements will begin prior to any incident irradiation on the solar panels and will continue until the solar working time is over. Due to obstructions, this testing will end around 3:30 p.m. The temperature measurements will be taken every 30 minutes with the temperature at each vent and the current solar irradiation being recorded.

8.2.1.3 Results

On the day of testing the temperature supply to the building, there was light to heavy cloud coverage. Figure 39 shows the recorded values over a 4 our period where the solar panels received irradiation. Because of the inclement weather, the irradiation values are about half of what is expected on a standard sunny day where the max irradiation achieved was $522\frac{W}{m^2}$. However, the max input temperature to the front room, which utilizes the flat mounted solar panel, reached 89.0°F . This value is lower than what is expected based on mathematical modeling; however, the panel is still supplying sufficient temperature with minimal losses. For vents 2 and 3, which supply heat to the primary room and are fed by the angled panel, a maximum temperature of 109.4°F and 104.5respectively. This shows a 4.5% drop in temperature between these vents.

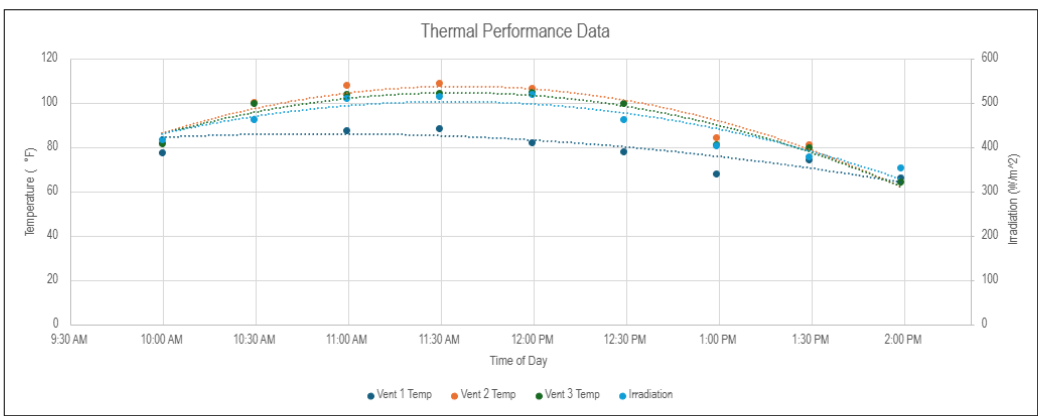


Figure 39: Temperature and Irradiation Data

Figure 40, shown below, shows the expected output temperature of these vents based on a day with a max irradiation of $522\frac{W}{m^2}$. The maximum temperature reached in this model is 99.8°F indicating that the model is sufficiently accurate in determining the output temperature of the panels. This figure indicates the validity of the modeling completed in the energy calculations discussed in section 8.2.8.3 of the report.

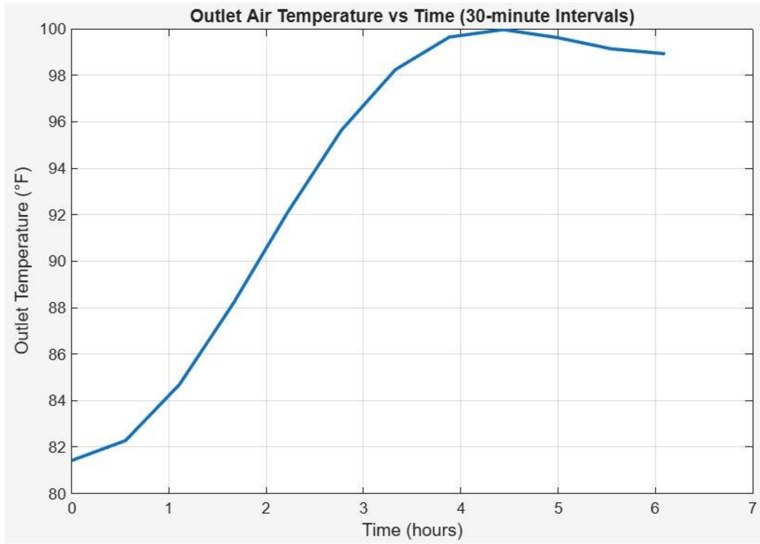


Figure 40: Projected Output Temperature Profile

8.2.2 EX2 – Flow Rate

8.2.2.1 Summary

During initial tests over the summer, the fans that were used were recycled and supposedly had a CFM of 190. However, they had spent an unknown amount of time outdoors and likely did not operate at the stated flow rate. For this test, a vane and hotwire anemometer will be used to establish the flow rate into and out of the ducts. This value is expected to be lower than the specified 190CFM due to friction losses in the ducts. However, the flow rate should be within 40CFM to be considered acceptable. The measured values from this experiment are also required for EX8 to determine the total energy supply to the building.

8.2.2.2 Procedure

Using the vane and hotwire anemometer, flow rate measurements will be gathered at the inlets for each solar panel as well as at each of the outlet vents. For the inlet ducts, the anemometer will be placed at the center of the duct since they both possess a circular cross section. For the returns, the measurements will be taken across a grid of the register box and averaged since there is a rectangular cross section. This discretization of the returns is also done due to the flow being underdeveloped and turbulent, so there is no consistency in the location of the measurement.

8.2.2.3 Results

To test the volumetric flow rate input and outputs of our fans used in the solar air heaters, we used a hot wire anemometer at the input ducts and output vents. The anemometer would provide the velocity of the air in feet per minute which we would then multiply by the area of the output vent or input duct to get the volumetric flow rate in cubic feet per minute (CFM). The input in the small front room was 115 CFM and the main room had an input of 143.5 CFM. Vent 1 in the small front room had an output of 160.5 CFM, vent 2 and 3 in the main room had outputs of 53 CFM and 100.5 CFM. Due to the conservation of mass, the input should equal the output, but the flow rate measured at the inputs and outputs is underdeveloped, turbulent, and has a huge velocity gradient. After summing and averaging the outputs the volumetric flow rate is 157 CFM.

8.2.3 EX3 – Wind Loading

8.2.3.1 Summary

Using the wind data provided by the Flagstaff Pulliam Airport over the past 30 years, we will be able to determine the maximum wind speeds at the RE Lab with a power law profile and a surface roughness correlation. Determining the actual wind speeds at the RE Lab will allow us to determine the magnitude of wind loads the solar collectors will be experiencing. By comparing the peak gust speed measured by the airport to the 120mph used to calculate the mounting system requirements, we can validate our mounting system's ability to withstand said speeds. The isolated variable that will be measured is wind speed. The results that will be calculated are the wind loads on the solar air collectors on the roof.

8.2.3.2 Procedure

To perform this test, the Flagstaff airports data will be utilized, and the variables will be plugged into our existing equations to determine wind load. The results we are looking for should be in the ballpark of our existing wind load calculations which is around 1,000 lbf of wind load that the solar air collectors will experience if the wind speed is 120mph. The equations that will be used is $Fn = Q \cdot s \cdot Cn$, $Fd = Q \cdot s \cdot Cd$, and $Fl = Q \cdot s \cdot Cl$. The data collected for wind speed will alter the dynamic pressure and using these equations and taking the root sum of squares allows us to calculate the wind load. Where Q is dynamic pressure, S is the module height (height of solar collector), Cn is normal force coefficient, Cd is the drag coefficient, and Cl is the lift coefficient.

8.2.3.3 Results

Using the equations provided, the maximum wind gusts at the airport over the past 30 years were used to calculate the maximum wind load the panels will experience at the RE Lab. This was calculated to be 991.8 lbs, which is well within the limits that our mounting system was designed for.

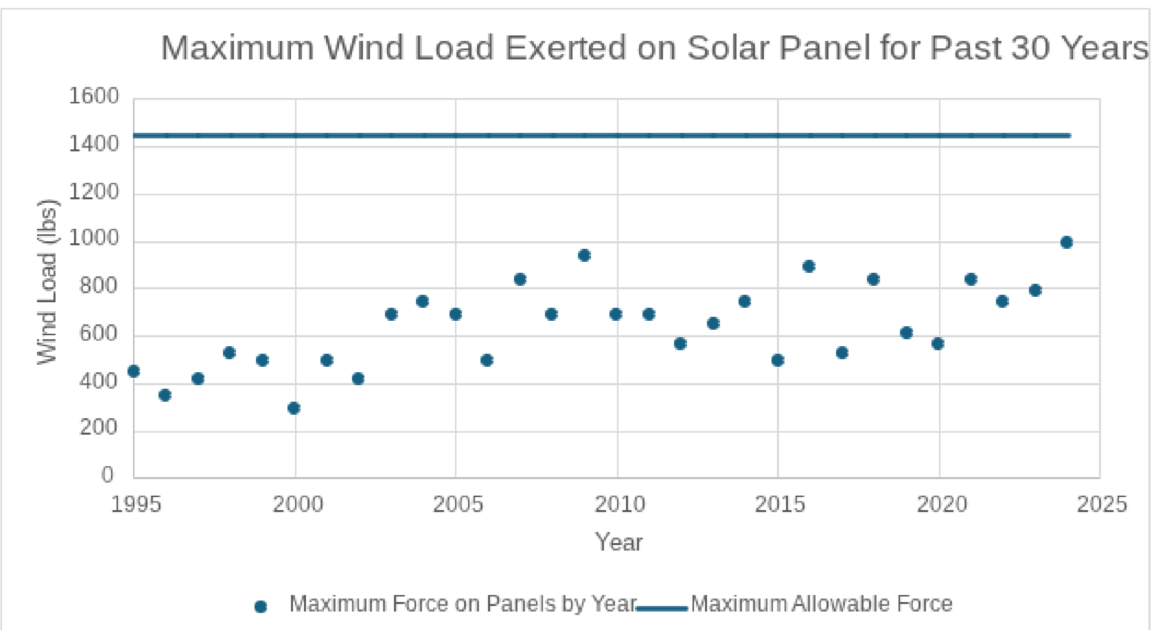


Figure 41: Maximum Hypothetical Wind Load on Solar Panels over Past 30 Years

Assuming the maximum loading of 1450 lbs that our mounting system was designed for, this leaves us with a factor of safety of 1.46.

8.2.4 EX4 – Voltage Drop

8.2.4.1 Summary

Voltage drop occurs due to wire gauge size and length of wires. To determine the voltage drop from the power supply (i.e. batteries) to the fans, we will measure the voltage at different points along the electrical system to find the percentage of voltage drop which should be around 2%.

8.2.4.2 Procedure

A multimeter will be used to take voltage measurements at all junctions in the electrical circuit. The first location will be directly at the batteries for which this voltage will be variable based on the charge of the batteries. The following locations will be at the J-box that houses the switch and thermostat, J-box in the attic where the wires split to the fans in parallel, and finally at the fans.

8.2.4.3 Results

When conducting this test, a multimeter, set to DCV readings, was placed at all the locations mentioned in the procedure. The tests began at the load box where the fans are tapped into the battery power which read where the reading was 12.84V. The J-box that houses the thermostat and master switches, located approximately 4 feet from the load box, read 12.72V. The J-box that splits the wires to go for each fan reads 12.57V and each fan reads 12.39V. Note that these values are dependent on the charge in the batteries and can change based on how long the system has been operating. Figure 41 shows the voltage measurement across the approximate length of the wires from each junction to the next. For the values from the load box to the fans, the voltage drop is 3.5%, which is larger than the target. However, this was deemed to be within an acceptable range.

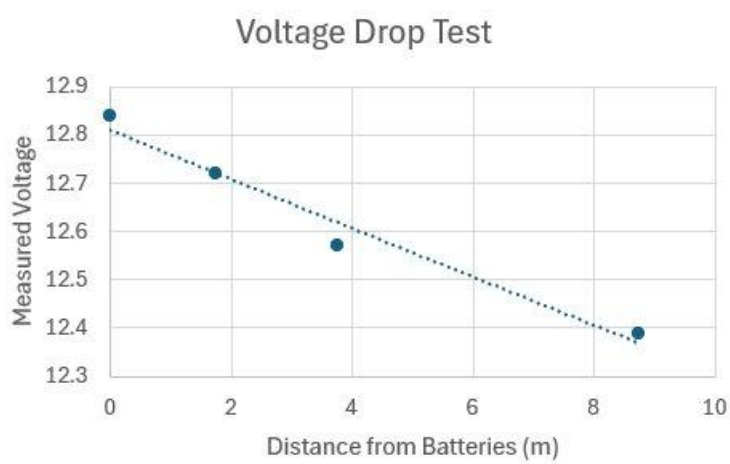


Figure 42: Voltage Measurements at Junctions

8.2.5 EX5 – Air Leak

8.2.5.1 Summary

The purpose of this test is to determine whether air leaks are present within the solar air heating ducting and collector system. This will reveal if the system meets the standards of being sealed tight all around. The tools required will be a fog machine, air blower, and visual inspections. This is important because if there is air leakage then the system's efficiency will be affected. The primary variable measured will be air leakage visibility, identified by fog escaping from joints, seams, or fittings. From these observations, the leakage rate and potential loss and the system efficiency will be estimated to evaluate how well the system meets design requirements for airtightness and thermal performance.

8.2.5.2 Procedure

To conduct the air leak test, a fog machine will be placed at the inlet ducts for both rooms. After turning on the fans the fog machine will be turned on and begin pumping air through the system. As this is happening, team members will be located on the roof and in the attic to perform visual inspection of the test. Any points that present any leakage will be marked with blue tape to be resealed.

8.2.5.3 Results

When the test was initially run and fog was pumped through the system, air leaks were observed at ducts that connect directly to the fan housing. These were patched up with duct masking and given time to cure. After the masking was cured, the test was run again, and no more leaks were observed in the system. The members on the roof inspecting the solar panels during the test observed no fog leakage from the solar panels indicating they are properly sealed.

8.2.6 EX6 – Water Leak

8.2.6.1 Summary

No major modifications were applied to the building; however, many points on the roof required screws, bolts, or holes that pose a threat to water leakage into the attic. To check that all points were sealed properly with either Henry 900 or the pipe halo flashing, a visual inspection is done during any rainstorm. To quantify the success of the sealing, a total volume of rainfall will be calculated based on the surface area covered by both solar panels.

8.2.6.2 Procedure

During any rainstorm a team member will stay at the RE Lab and every 30 minutes perform a visual inspection of the attic. Any points that present a water leak will be marked with blue tape for additional sealant. Any points that are observed to have leaked, if any, will be resealed after the storm passes.

8.2.6.3 Results

This test was conducted on November 15th when a sufficient rainstorm impacted the RE Lab. During the storm visual inspection was done around all points that may leak every 30 minutes. Along with this precipitation data was taken from the NWS at Flagstaff Pulliam Airport. The total area for the space being inspected is 72 square feet. No points of vulnerability showed any sign of leakage. While data was not collected after this initial test, visual inspection continued during and after any storms.

8.2.7 EX7 – Data Collection

8.2.7.1 Summary

This test involves analyzing annual weather patterns in Flagstaff, AZ to understand how they will affect the design of the solar air heating system. These annual weather patterns include the amount of solar irradiation Flagstaff receives per month, and the precipitation and snow fall over a course of twenty-five years. No measuring tools were required for this experiment, although data from the National Renewable Energy Laboratory (NREL) and from the National Weather Station (NWS) websites were to be collected. Variables that were calculated were the amount of solar radiation the solar air panels would be collecting per month, in kWh/day, the volume of rain fall, in gallons, and the weight of snow, in lb. Other variables that were ignored when performing the experiment were heat losses due to conduction in the solar air heaters and that the weight of snow fall and volume of rainfall for any given month was non-uniform across any area. Other assumptions were that the solar air panels operated at a wavelength of 0.3 μm and the absorptivity is 0.9.

8.2.7.2 Procedure

The general procedure for this experiment was to collect data for the annual solar irradiance on Flagstaff, AZ, and to collect data for both the precipitation and snowfall over a course of twenty-five years from the NREL and NWS websites, respectively. Once the absorbed solar radiation, volume of rain fall, and weight of snow fall were calculated, they were plotted on three histograms in Microsoft Excel to analyze the data in retrospect.

8.2.7.3 Results

Data for solar energy absorbed by the solar air panels were distributed in the graph generated by Excel as shown in Figure 44 below. The maximum solar energy absorbed was in the month of June with a value of 0.016241 kWh/day, while the minimum value was 0.011289 kWh/day in December. The data exhibited fluctuations, however, as the absorbed solar radiation increased from January to June then started decreasing by the time it was July. The data spiked in September, then decreased again until December.

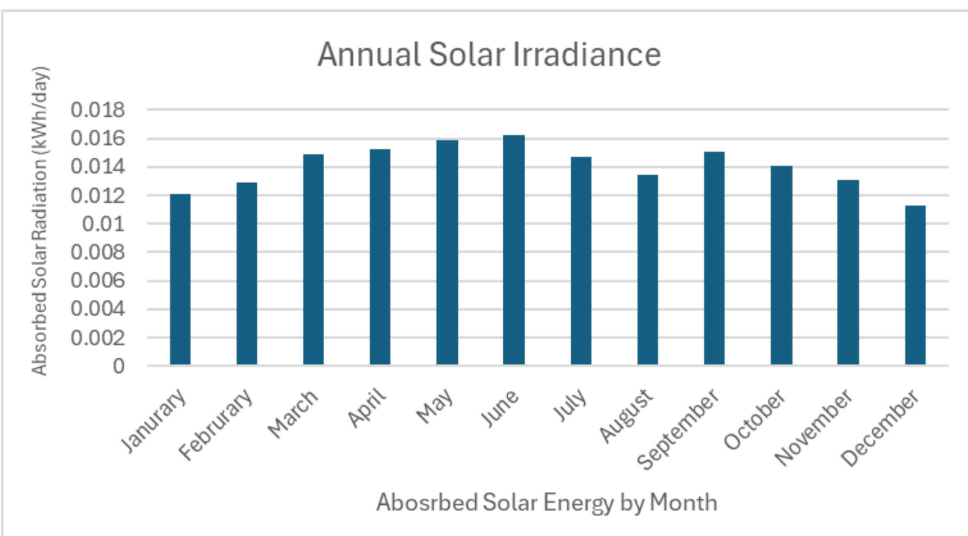


Figure 42: Plot for Absorbed Solar Energy

As for the wight of snowfall, the data shows that the maximum value is 2941.125 lb in the year 2019 in February. As for the minimum value, it was 0.4125lb for September 2013. Note, the data is monthly meaning that the maximum and minimum weight of snow fall is from an entire month. The trends in data for the weight of snow fall are visualized in Figure 43 as shown below.

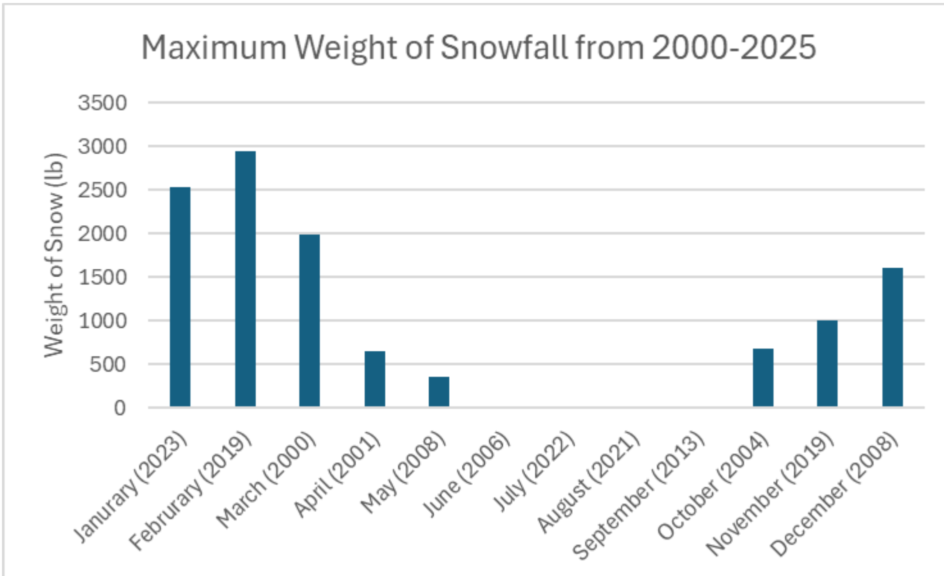


Figure 43: Weight of Snow Fall Over a Course of Twenty-Five Years

Lastly, data for the precipitation, in gallons, is shown in Figure 44 below and exhibits a maximum value of 399.787 gallons in July 2013. The minimum value is 76.302 gallons and was from the year 2015 in the month of June.

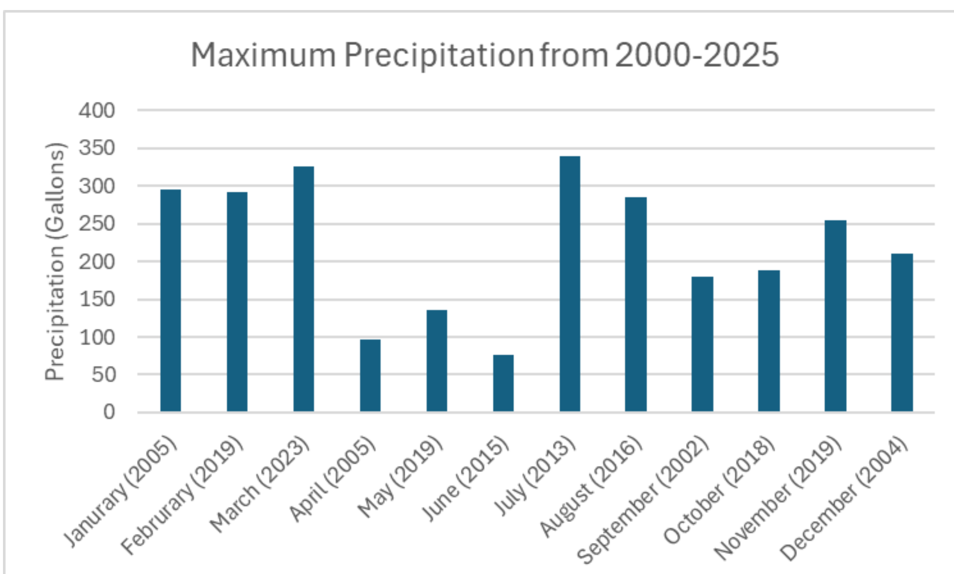


Figure 44: Precipitation Over a Course of Twenty-Five Years

These variables were important when considering several factors. The most important one is knowing how much solar radiation the solar panels will be absorbing throughout different parts of the year (although the system is designed to heat the Renewable Energy building during the winter) since it is expected for the solar air system to last for ten years. Another factor is considering the weight of snowfall throughout the year and how it will affect the mounting assembly. Lastly, precipitation was analyzed for water leakage and temperature testing, comparing the data to the ones collected over a twenty-five-year basis. These factors were analyzed to consider design factors for the solar air system and ensure that factors such as clouds, rain, temperature, snow fall, and anything related to the environment will not become an obstruction for the project.

8.2.8 EX8 – Energy Performance

8.2.8.1 Summary

Performance testing will establish energy input into the building. This will be done using a hot wire anemometer at the outlet of the ducting and using the time rate calculation based on the temperature input to gather the energy supplied. This will be done over any sunny day. The results will be in units of kWh compared with the building heat load simulation. Based on the established customer requirements, the comparison should indicate that 30% of the total building heat load requirements are equal to that of the energy supplied from solar panels.

8.2.8.2 Procedure

The procedure for this experiment is very similar to EX1 and requires temperature results from that experiment as well as the flow results from EX2. All measurements are recorded every 30 minutes. The required measurements include vent outlet temperature (RTD and hot-wire anemometer), solar irradiance (National Weather Service), and building temperature (building thermostat). This information will be used to calculate the total energy supply to the building, which can be calculated using the fundamental heat transfer equation $Q = \dot{m} \cdot C_p\left(T_{in} - T_{building}\right)$.

8.2.8.3 Results

Within the excel where all the data collection is gathered, there are records of the output temperature at each vent and the ambient building temperature at the time of the collection. With the flow rate information from EX2, the energy supply at the given time is calculated. To get the total energy supply from the entire day, each instantaneous point is multiplied by 0.5 hours and summed. When doing this vent 1 supplied the least energy at 2.39kWh. Vents 2 and 3 supply significantly more energy with 4.59kWh and 4.29kWh respectively. This totals 11.37kWh which does not cover 30% of the building heat load requirements, but the irradiation was significantly lower than a sunny day and a shorter working timeframe. Figure 44 shows the energy supply at specific times of the day.

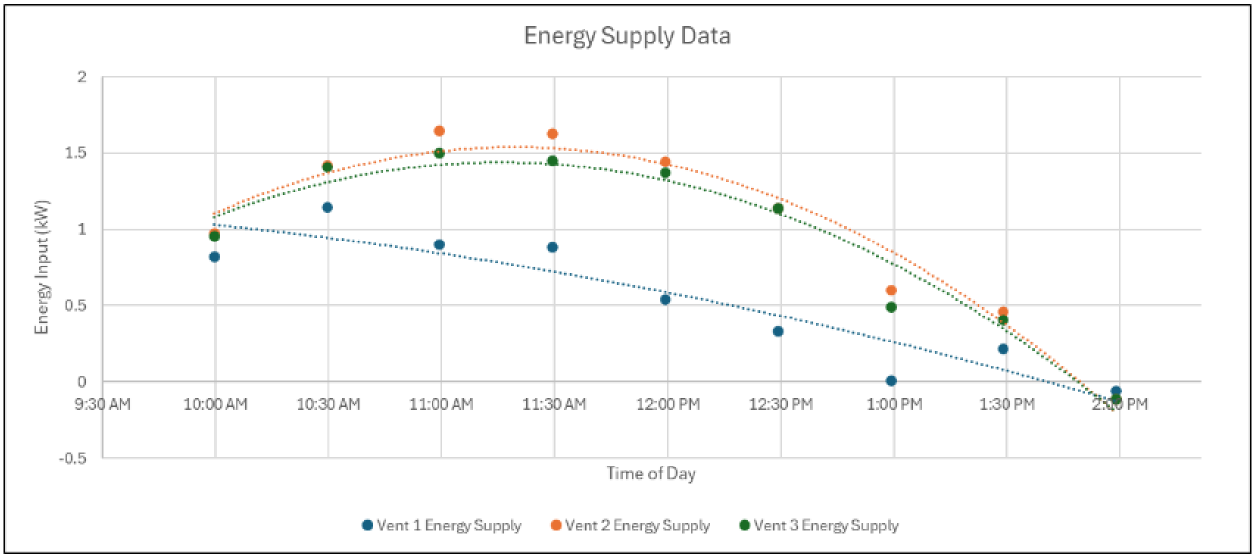


Figure 44: Instantaneous Energy Supply

9 Future Work

If future iterations or improvements to this project were to be completed, there are several changes that should be made. The first aspect would be to make the system fully autonomous. While there are many methods of making the system autonomous, one method of doing so would be to use a pyranometer to read the current solar irradiation and when irradiation is present, a relay, mechanical or steady state would turn the system on. This would need to be powered in series with the thermostat relay to maintain maximum temperature control of the building to avoid overheating. In addition to automating the system, the solar panel size could also be increased to cover more of the building's heat load requirements. With the current panel size covering 27.6% and the current solar panel size being 8 feet by 4 feet, the size would likely need to be 8 feet by 6 feet. The 8-foot section cannot be altered due to a 9-foot truss length in the attic and a 6-inch buffer needed on either end of the trusses for where the lag screws are installed. By increasing the size of the panels, the 30% reduction in heat load customer requirement would be more adequately fulfilled. While this would be a small change, the absorber plate on the solar panels could also be improved with the use of a Vantaa black coating to increase the amount of absorbed energy as well as a higher transparency cover plate. The cover plate improvement would improve the amount of energy impacting the absorber plate.

10 CONCLUSIONS

The project started with research and design selections to determine how the project was going to be manufactured, assembled, and installed. This started with the research aspect to determine the fluid medium that was going to be used where the two options were air or water. Air was determined to be the ideal selection due to being more optimized for space heating, and a water-based solar thermal system would have required major building modifications. To help validate this decision, multiple design options were made for both air-based and water-based heating systems, and this is where major building modifications were observed to be needed for the water-based system. During our prototyping of the air-based solar thermal system the testing was used to check the output temperature with variable voltage since at this point in the project it was assumed that a separate PV system would need to be integrated for the system. During the manufacturing process careful steps were carried out to ensure the system would be not only operable, but efficient and meet the necessary requirements set forth by the client, Carson Pete. During the manufacturing process the solar panels were refurbished and a Unistrut based mounting system was developed for the roof. The mounting required several iterations due to the solar panels being 1.5 inches different in width and spacers were needed to lift the panels far enough off the roof. The electrical system utilizes a thermostat control and a master switch to guarantee the building doesn't overheat and users have absolute control over the system operation. The testing of the energy performance for the system did not supply sufficient heat to cover the 30% heat load coverage for the day of testing, however, the testing was conducted on a partly cloudy. The MATLAB simulation indicated that on an annual basis the heater system will cover 27.6% of the building heat load and this was deemed acceptable by our client. Overall, the project has been considered successful by both the team and client.

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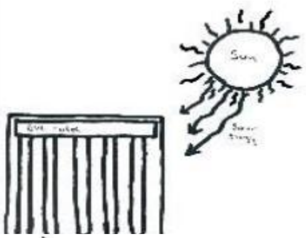
[60] H. Tyagi, “Solar Air Heaters,” THERMOPEDIA, https://www.thermopedia.com/content/3835/ (accessed Dec. 3, 2025).

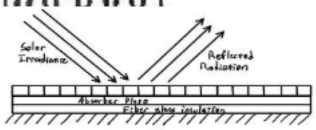
12 APPENDICES

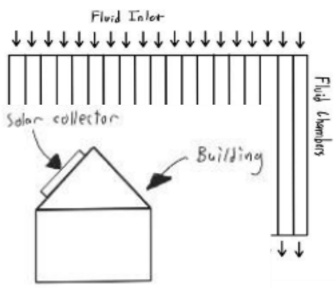
Earlier in the body of the report, many subsystems were listed in Table 1: Concept Generation Table. These concepts are explored in detail here in Appendix A.

12.1 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





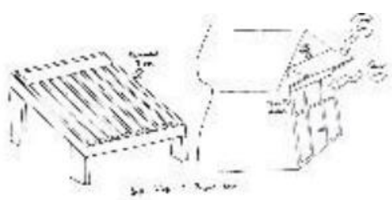
This solar panel concept variant equates to what is essentially a pool solar heater that can be fitted for household HVAC systems. This is done by feeding the water through a series of pipes from the bottom up until the fluid can self-siphon out of the other side.
Figure 30 – A2

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



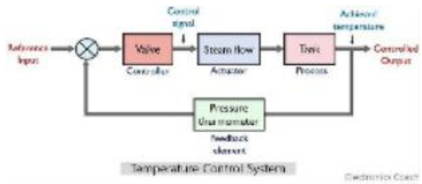
This subsystem combines the principles of passive solar window design with the pre-existing solar water heater. The concept of passive solar windows is to allow the winter sun to radiate inside the building, but block the summer sun with carefully placed eaves.

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.

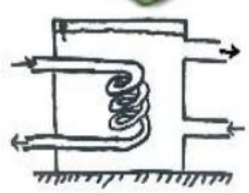
Figure 35 - B2



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

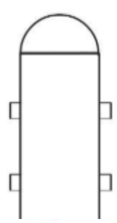
A Raspberry Pi can be programmed to turn fans or pumps on or off given certain triggering conditions. When connected to Wi-Fi, remote monitoring would still be possible.
Figure 38 – B5



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

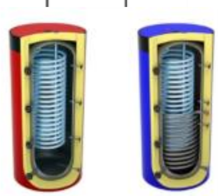
This R13 insulation can be used to improve the overall insulation. This is important for the concept that implements the building as the thermal storage system. This idea will begin with slightly overheating the building and using this improved insulation to retain the heat overnight.

Figure 40 - C2

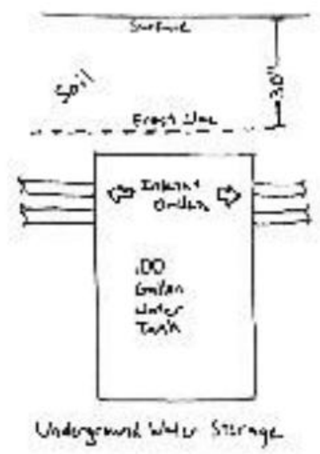


As shown in figure 27 on the right, a compressed air tank was one of the concepts for the solar system. The design idea was for the tank to store heat which will later be used to heat the building during the winter.

Figure 41 – C3



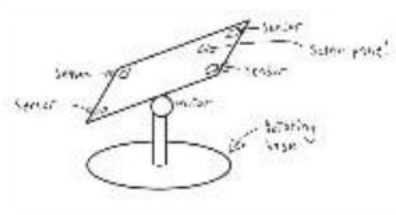
Insulated cylindrical tank for thermal This one shows an insulated cylindrical tank designed for thermal energy storage, helping retain heat for extended periods. These tanks are essential in solar water heating systems to maintain consistent water temperature and improve overall energy efficiency.
Figure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



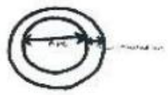
For one of the sensors concepts, solar tracking was one of the ideas proposed to the team. The Senors, as shown in figure 28, would be attached to the solar panels themselves and would send signals to the motor so it can move the solar panels around to effectively collect solar energy.

Figure 46 – D3

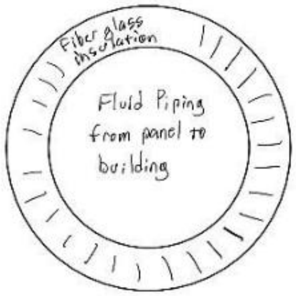

Figure 47 – D4

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.

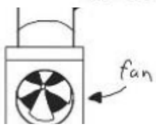
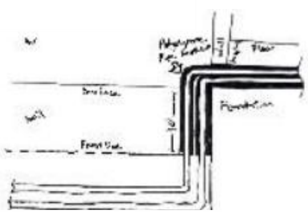
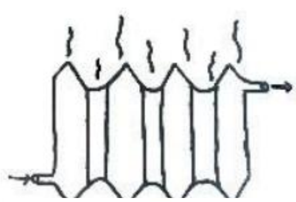


Figure 51 – E3

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

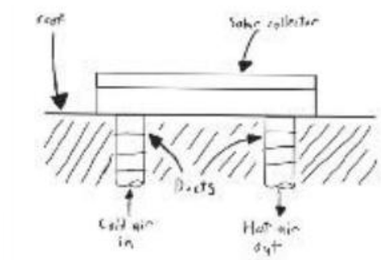


Keeping pipes buried under the frost line would keep them insulated from the freezing winter temperatures. Similarly, pipes could be run underneath the floor when inside the building.
Figure 53 – E5



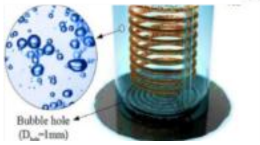
This concept uses a radiator located inside the building. Not only will the natural convection heat up the building but providing fans around the radiator the forced convection will provide additional heat if needed.
Figure 54 – F1

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



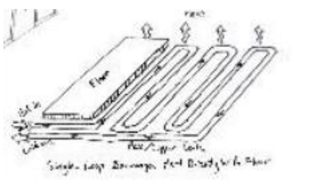
For the heat exchanger concept, one of the concepts was to design it as direct contact and would heat the cool air in the building from the solar panels attached to the top of it.

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