RE Lab Solar Heater

Initial Design Report 1

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Project Sponsor: NAU Department of Mechanical Engineering

Instructor: Carson Pete

DISCLAIMER

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

EXECUTIVE SUMMARY

Our capstone project involves implementing a solar thermal heater whether it uses air or water into the renewable energy lab. The solar thermal heater will play a crucial role during the cold winter months, mainly keeping the batteries stored within the building above a certain temperature of 40° F and keeping the occupants inside warm. To accomplish this task each team member has had to do advanced calculations or CAD modeling. We also had to validate and quantify our engineering requirements that we created based on our customer requirements that were provided by our client Carson Pete. Using these CR's and ER's were able to build our QFD. Benchmarking needed to be done to find the state-of-the-art systems that are used today. We found three different benchmarks that were also used for our competitive evaluation in the QFD. Next, to show our research that we have done so far we all needed to complete the literature review by having at least 7+ sources that are referenced and summarized, each of us needed to have at least two textbooks (or chapters), three academic papers (or whitepapers) that are peer reviewed, and some online sources these can be general websites found on the web. For our next section we each needed to complete an advanced analysis and mathematical modeling and detail how these calculations are beneficial to the progression of our project. We completed these using hand calculations, MATLAB, and our sources from our literature review. As a team we still needed to figure out what system we are going with, whether we are using a solar thermal air heater or solar thermal water heater for the renewable lab. To do this we needed to complete design concepts: functional decomposition, concept generation, selection criteria, and concept selection. The functional decomposition breaks the thermal system down whether it be air or water into its subsystems. The concept generation is where each team member created different concept variants based on our design components or subsystems. For the selection criteria we outline how we came to the conclusion for our design components or subsystems and what the specs are for them. The concept selection is where each team member then chose one concept variant for each subsystem to create a fully functional system, after this we plugged our full design concepts or components into a Pugh chart and gave ratings for each fully designed system compared against two different datums. We have two different datums to account for if a team member chose to do a thermal water heater system or a thermal air heater system. After all of these design systems were compared against our datums and given ratings, we took the best rated designed system for air and for water and put them into a decision matrix. To make sure the last two systems were rated fairly, we gave the criteria for each design concept or subsystem a weighted percentage to be rated by each team member. We did this by putting the two fully designed systems into excel with their subsystems and their corresponding weights and had each team member rate them out of the weight and then averaged the total. The system that came out with the higher score was the solar air system. We then created a CAD model of our final designed system using SolidWorks. Lastly, we have all of our references listed below in its respective section and our appendices includes additional information that was used to complete this report.

TABLE OF CONTENTS

1 BACKGROUND

This section of the report will detail the broad aspects of the Renewable Energy Laboratory (RE Lab) solar heater project. This will include a general project description such as why the project is relevant, important, and the primary objective of the project. Crucial project deliverables will be discussed following the project description. Finally, a detailed description of the success metrics will be provided as well as a determination of what would be considered successful.

1.1 Project Description

The primary objective of this project is to implement a pre-existing solar air or water heater into the RE Lab above the engineering building. The solar heater should be able to operate autonomously using temperature and light sensors and be able to store the thermal energy in the event that heat needs to be supplied to the building when no solar radiation is available. However, the solar thermal system does not need to be the sole contributor to the heating of the building but rather a contributor to the heating that reduces the overall heating load required to maintain an adequate temperature. Completing a project of this nature is extremely important for both NAU but also as a collective to move towards a renewable future. NAU has a net carbon neutrality goal by the year 2030 and this project is a precursor towards helping achieve this goal. To help achieve these goals, the project requires a certain amount of funding. The mechanical engineering department at Northern Arizona University will provide a $500 initial budget. The total budget for the project requires a minimum of $1,000, leaving the project group to fundraise for an additional $500. This is being done with each group member posting a flyer describing the projec t goals and statement at their respective place of employment. This allows for every group member to answer questions that people may have about where the money is going rather than blindly asking organizations for funding.

1.2 Deliverables

The following bullet points will detail the major deadlines for the project in sequential order of their respective deadlines.

1. Individual Analysis – Each student should have their individual analysis (engineering calculations) completed for Report 1 and Presentation 2.
    - Deadline: 17 July, 2025
2. Report 1 (this report) – Initial project report that provides insight into the overall project, group research, goals, fundraising, and concept generation.
    - Deadline: 17 July, 2025
3. Presentation 2 – Present project description, concept generation, engineering calculations, concept evaluations, and project financials.
    - Deadline: 17 July, 2025
4. 1st Prototype Demo – Produce a physical and virtual prototype for the project including photographs, methods used, and results.
    - Deadline: 24 July, 2025
5. 1st Website Check – Provide live link to project website which includes, at a minimum, the project description, team/about us, gallery, and all relevant documents.
    - Deadline: 24 July, 2025

6. 2nd Prototype Demo – Similar to prototype 1, this requires physical and virtual prototyping. This demo must also explain what question is being answered, the results, and how the design informed the group on future iterations.
    - Deadline: 30 July, 2025
7. Presentation 3 – Present project description, design description, design requirements, engineering calculations, design validation, and the final schedule and budgeting.
    - Deadline: 31 July, 2025
8. ME486C Project Management – Setup a rough schedule for the manufacturing of the project for the duration of second semester capstone
    - Deadline: 1 August, 2025
9. 2nd Website Check – The website should be fully operational and entirely up to date with project information.
    - Deadline: 1 August, 2025
10. Report 2 – Compile the background, requirements, research, concept generation, schedule and budget, design validation, and prototyping into a final project proposal.
    - Deadline: 1 August, 2025
11. Fundraising – The financial manager should have coordinated and completed the minimum $500 fundraising goal for the project.
    - Deadline: 1 August, 2025

1.3 Success Metrics

There are many ways that the success of the solar thermal system designed for this project can be analyzed. The first way is by doing a complete system analysis to determine all losses that occur throughout the system, including heat, head pressure, and air flow within the building that can distribute the heat. Each of these will, in some capacity, be analyzed through the mathematical modeling section such as section 3.3..1 through 3.3..4. The other method that will help with this is the building heat load analysis done in section 3.3..5 where a total energy amount will be determined that is the minimum requirement to maintain an adequate temperature within the building. Overall, as long as the energy requirements from the building heat load analysis and the other metrics from thermal performance, heat storage, and radiator analysis are comparable, the system would be considered a success. This is also dependent on the front room of the building maintaining a minimum temperature of 40°F throughout a given day. However, during worst case months in the winter, like December and January, the system must reduce the building heat load requirements by 30% rather than meeting the full requirement.

2 REQUIREMENTS

For this section we will define our customer requirements, engineering requirements, and how we created our Quality Function Deployment (QFD) with pictures provided. Our client, Professor Carson Pete, created the customer requirements that we need to implement and satisfy. Based off these customer requirements, we were able to create our engineering requirements, quantify them, and validate them with supporting calculations and equations.

2.1 Customer Requirements (CRs)

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

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

2.2 Engineering Requirements (ERs)

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

1. Energy Stored (kWh): When solar energy is being collected by the solar panels during the winter, it is essential that the product stores that energy and ensures the building can stay warm for the customer. It is important that a sufficient amount of solar energy can be absorbed and stored, during

times when days are shorter, so that the system can utilize that existing energy to heat the building.

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

2.3 House of Quality (HoQ)

Quality Function Deployment

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

Correlation:

+	0	-
Positive	No correlation	Negative

Relationships:

5	3	1	0
Strong	Moderate	Weak	None

Correlation matrix (roof):

Energy Stored	Efficient Insulation	Relay	Head Pressure	Flow Rate	Heat exchanger	Life expectancy	Cost	Mounting system
0								
0	0							
+	0	-						
+	+	-	0					
+	+	0	0	0				
+	+	0	+	0	0			
+	+	0	+	+	0	0		
+	+	0	+	+	+	0	-	

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

Figure 1: Quality Function Deployment (QFD)

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

3 Research Within Your Design Space

3.1 Benchmarking

JACOB – Vacuum Tube Solar Collector Kit [26]

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 [37]

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

TYLER – Hybrid Solar [17]

For this system, it involves combining and utilizing solar energy alongside electrical energy. It integrates both solar power and heat pump technology to enhance efficiency and performance. The system works by collecting solar energy by the solar panels so it can heat the water, then the heat pump extracts heat from the surrounding air into the warm water whenever the sun's light is not available. By utilizing this system, involving both renewable and non-renewable energy sources, it can provide better access to heat sources that traditional energy sources, such electrical by itself, cannot provide indefinitely.

3.2 Literature Review

Within this section each group member will detail their state-of-the-art (SOTA) literature review. Each member will introduce the reference title followed by a brief, yet detailed, description as to how the reference is relevant and what information it provided that helped with the project. The references included will consist of textbooks, peer evaluated papers, and general online sources.

3.2..1 Jacob Apodaca

Fundamentals of Heat and Mass Transfer 8th Edition, Chapter 6 [1] (Textbook):

This is the textbook used for the Heat transfer class at NAU. It covers the different types of heat transfer which are conduction, convection, and radiation. These are important concepts that pertain to our project because we will be transferring heat that has been collected from solar energy through a medium such as water or air and putting it into the renewable energy lab. This textbook covers and outlines equations and calculations that we will be utilizing for the progression of this project. I chose to focus on chapter six which goes over convection, boundary layers, laminar and turbulent flow, and boundary layer equations.

Introduction to Fluid Mechanics 10^th Edition, [18] (Textbook):

This is the textbook used for the Fluid Mechanics I and II classes at NAU. Fluid mechanics is the study of fluids at rest or in motion. It details fundamental concepts such as one-, two-, or three-dimensional flows, viscosity, viscous and inviscid flows, laminar and turbulent flows, compressible and incompressible flows, and much more. These concepts are important to our project because we will be working with a fluid such as water or air, and we will need to be able to critically think and apply these principles to our solar thermal system. This is to promote efficiency in our system since we need to look at what type of pump or fan to use, what type of material is to be used for our piping or ducts to minimize friction and head loss, and the assumptions we can apply to simplify our modeling and calculations.

Review on solar air heating system with and without thermal energy storage system [19] (Paper):

This paper talks about the importance of being able to use solar energy for solar air heating purposes. It states that recent research shows that for phase change materials, latent heat storage is more efficient than sensible heat storage. The paper makes an attempt to showcase the holistic view for available solar air heaters, their use in different applications, and how they perform.

Estimation of the heating time of small-scale buildings using dynamic models [20] (Paper):

This paper looks to reduce energy costs by performing calculations to find when the best time to turn the heating system on. This is because the system will be off at night when the buildings are unoccupied and turned on in the morning at the right optimal time to raise the temperature of the building to comfortable conditions for when it becomes occupied. They used a dynamic model to develop the estimated heating time and validated it using four different case studies. It was found that the model can also be used to procure a rough prediction of the space heating energy use. The paper found that starting the heating system at the right time returned the lowest energy cost.

Pipe Flow Calculations [21] (Paper):

In order to perform my advanced analysis which involves calculating head loss throughout the pipes and the system I needed to revisit Fluid Mechanics topics. This paper has step by step examples for different pipe flow calculations along with explanations on how to find the different values. This is important for our project because it will help me when solving my calculations and with choosing the right material for the pipes to reduce corrosion, overall cost optimization, and ease of procurement.

Solar Panels Plus [22] (Website):

This website talks about how solar thermal heating systems work and what components make up the system. It also describes how there are three types of solar collectors classified by the Energy Information Administration which are high, medium, or low temperature collectors. Each of these different temperature collectors have different applications and designs for there respective systems. This is important to understand because it shows us what temperature level collector we are in which is the medium level and it details how the designs function.

Solar Water Heaters [23] (Website):

This website discusses how solar water heaters work and the two different types: active, which have circulating pumps and controls, and passive, which don't. It also talks about the subsets of the active solar water heating systems, which are direct circulation systems and indirect circulation systems. There are also two subsets of the passive solar water heating systems which are integral collector storage passive systems and thermosyphon systems. This is important because it shows us the different subsystems that could be implemented and the pros and cons for each.

Rayzon Solar, Solar Thermal Energy System [24] (Website):

This website is similar to the solar panels plus website where it talks about the different types of solar energy systems including the low, medium, and high temp. systems, what applications they can be used for and how they work. It also talks of the advantages of solar energy systems but also the challenges and limitations of them as well. This information is applicable to our project because it helps us understand the different types of solar energy thermal systems, their respective applications, and their pros and cons.

Active Solar Heating [25] (Website):

This website details how active solar heating works, such as when using liquid based active solar heating such as water or an antifreeze liquid such as glycol. It also details how the heat can be stored and distributed throughout the building. It also describes ventilation aspects between solar and water heating. It talks about how air has less efficiency as a heat transfer medium but will not freeze in cold conditions and if a leak were to occur it wouldn't cause significant problems compared to water. This website is beneficial to the project because of how it details the economics of the different types of solar thermal systems, the selecting and sizing of the solar thermal system depending on different factors, and the building codes and regulations for solar heating systems.

3.2..2 Brendan Frazier

Fundamentals of Heat and Mass Transfer 8th Edition, Chapter 3 [10] (Textbook):

This textbook covers all things based in heat transfer. Chapter 3 specifically covers heat transfer by means of conduction. Several subtopics are covered within the chapter and consist of conduction with variable shape and geometry, extended surfaces, and thermal resistances. The chapter also discusses the finite difference method for conduction, which allows for quicker and easier than a typical hand calculation when handling complex shapes such as a heat exchanger. This chapter was extremely helpful when performing any analysis on the heat exchanger and its overall efficiency. The equations included and same finite difference method will help with determining any heat loss from the system through thermal resistance and general heat loss. This chapter, in conjunction with chapters from the same textbook, which are covered by other students, allows for a complete thermal performance analysis on both air and water solar thermal systems. This includes solar irradiation, conduction through the pipes, and finally the temperature of the fluid flowing through the pipes by means of forced convection.

Thermal Performance Improvement Method for Air-Based Solar Heating Systems [2] (Paper):

This paper begins with a description of ExTLA simulation software used in the study which is an excel based thermal load software. This software could very easily be considered for the overall building heat load analysis. After introducing the software, the paper presents equations that can be directly used to calculate the outlet temperature of the fluids flowing through the pipe based on solar irradiation. The storage capabilities of a water storage tank are analyzed next. This is analyzed using an air heater system that has a pipe running through the bottom of the water storage tank to heat the water. This is a definite option for storing thermal energy. However, this paper covers the solar heating of an air system and does not provide detailed information regarding a water-based thermal system. With that being said, the information within the paper provides adequate descriptions on the viability of an air-based thermal system specifically and covers the full system.

Calculation of Optimal Thermal Load of Intermittently Heated Buildings [3] (Paper):

This paper is focused on the building heat load analysis aspect of this project. The initial discussion is a proposal of the analysis being done with the zone temperature and total thermal energy gains (solar, internal or ventilation) all being accounted for. Having hand calculated means of determining the building heat load requirements is crucial for validation during the project. They then introduce a "Reduced (lumped parameters) Thermal Model" which simplifies the initial method of finding the heat load. Since the building heat load will determine the size, flow rate, and potentially even the fluid being used.

Solar Water Heaters with Phase Change Material Thermal Energy Storage Medium [4] (Paper):

This paper explores the possibilities of using a combination of fluids that develop better thermal storage capabilities based on the percentage of each fluid present. There are examples covered that mix regular water with a salt hydrate eutectic mixture to create more ideal thermal conditions. By implementing these different phase change materials (PCM) the specific heat capacity of the mixture can be increased which will, once again, make it harder to heat up the fluid but would also provide greater thermal storage capabilities. This paper can help with thermal performance analysis as different fluids can be modeled and provide the group with a higher quality option.

Central Heating and Cooling [5] (Website):

This website doesn't dive so much into the technical aspects of the design process. However, it does provide a lot of intuitive information about the general design that should be desired. Providing information on storage options for both air and water, general HVAC standards, and suggestions.

Research on Heating Performance of Heating Radiator at Low Temperature [6] (Paper):

This paper covers research that was done on different kinds of radiators for heating at low temperatures. The radiators change in design and in the material that is being used. The paper even goes as far as detailing the heat attenuation rate for all of the materials that were tested. This provides insight for the project on how a radiator should be designed or what specifications to look for if a radiator is going to be purchased.

Building Thermal Performance Analysis by Using MATLAB and SIMULINK [1] (Paper):

This paper introduces the thermal performance analysis requirements for a building through manual calculations. There is a specific mathematical modeling section within the paper that walks the reader through the necessary equations and what variables will be needed from the building. This is a method that can be used in building heat load analysis and the required validation.

ASHRAE Climatic Design Conditions [7] (Website):

This website provides all the necessary weather data that the project may need to perform calculations.

They provide temperature, irradiation, and wet and dry bulb humidity by year or month. This information was taken at Flagstaff Pullium Airport indicating all the data will be nearly identical to what the thermal system will be experiencing.

3.2..3 Tyler Hedgecock

Fundamentals of Engineering Thermodynamics 8th edition, Chapter 4 [11] (Textbook):

To understand the fundamentals of operating machines, specifically heat pumps, heat exchangers, and fans, this textbook provides the information needed for thermodynamic analysis. It covers the importance of how those machines required for our project so the team can analyze how heating loads will affect the pump or the fan's performance, depending on the amount of thermal energy they can carry. This textbook will help the team in the decision-making process whether a pump or a fan would be best for the solar heating system. It is important for either device to carry heat efficiently during the harsh winter months, such as December and January, and to ensure they won't suffer from any malfunctions of a sort. It is also a priority for either one to reduce the heat load by 30%, as with the customer requirements, so that the system won't overheat for the customer who spends time in the Renewable Energy building. Due to the customer requirements, the thermodynamics textbook is required so the team can perform calculations and determine if the heat pump or fan are able to operate during the winter months in Flagstaff and supply heat for the building due to its lack of insulation.

Fundamentals of Heat and Mass Transfer 8th edition, Chapter 13 [10] (textbook):

From this specific chapter, heat transfer analysis for radiation is required for our product (i.e., solar panels). Radiation is one of the most important factors because the team's heating system involves the use of solar panels. Solar energy will be the primary source of energy, and it is important to consider how the product will be able to operate during the winter months. The sun during this time will not be out on certain parts of the day considering snowy and shorter days during months such as December and January. By utilizing this book and the chapter selected, analysis on the amount of solar radiation the solar panels are collecting was performed to guide the project team's decision-making process. By understanding the amount of solar energy absorbed, the team can make informed decisions about how the system will be able to operate and if any adjustments must be made to design the system.

Experimental Analysis of Artificial Equilateral Triangle Solar Air Heater Using Zig-zag Channel [8] (paper)

In this paper, a study was conducted for a solar air heater to determine the performance of different types of absorber plates. These types are a flat plate, a triangular plate with one pass through all the triangle shape, and a triangular plate with zig-zag flow for the dark and light passes. The experiment was conducted by having the three different absorber plates exposed to halogen lamps set to a radiative flux of 950 W/m^2, the same amount of flux produced by the sun. After the experiment was conducted, the results showed that a 60° zig-zag shape produced the highest amount of energy at 24,354 kW and had the highest thermal efficiency of 55,591%. The reason the zig-zag triangular plate had a significant advantage of absorbing more solar radiation is because more fluid passes through this certain plate type and thus the mas flow rate increases. When there is an increase in mass flow rate, the plate will absorb a greater amount of solar energy and thus thermal efficiency will increase as well. By keeping this in mind, the design team can make informed decisions about how to design the solar collector, ensure that energy will be efficiently absorbed, and will have enough power to supply heat to the Renewable Energy Building during winter months.

Design and Implementation of Peltier Based Solar Powered Air Conditioning and Water Heating System

[12] (paper):

The objective of this paper is to design a prototype of Peltier that can obtain air conditioning and water heating applications from a single system. The synopsis of the paper is that renewable energy sources are becoming the main source of energy due to the decline of non-renewable energy sources such as fossil fuels. In recent studies, it is shown that HVAC systems tend to consume more power and produce greenhouse gases contributing to global warming. The paper proposed using the Peltier prototype as a possible substitute for HVAC systems to address this issue. By using the Peltier element, according to the paper, it is more resourceful, motionless, convenient, consistent, and eco-friendly. By keeping this information in mind, the team can go about designing the solar heater system and what to consider for the product for renewability (i.e., solar energy).

Energy Saving of Air Conditioning System by Oscillating Heat Pipe Heat Recovery Using Binary Fluid [13] (paper)

The purpose of this paper is to investigate ways to improve the thermal performance and energy savings of oscillating heat pipe heat exchangers. By investigating these parameters, the paper aimed to find new ways of using heat exchangers as a heat recovery device for HVAC systems using water, methanol, and binary fluid involving water and methanol. After the study was conducted, it was found that the inlet air temperature and velocity increased, so did the ratio of the thermal effectiveness and energy savings of the heat exchanger. It was also found that water as a working fluid for thermal effectiveness had the lowest value and can be enhanced by 16% if the binary fluid was used instead. As for energy savings, water could be enhanced by 14% if the binary fluid was used instead. In conclusion, it was found that methanol had the highest values, with thermal performance and energy savings ratios at 32% and 18%, respectively. By analyzing this study, the design team can make informed decisions about which type of fluid to use for our solar water heater, if we decide to go down that route.

What Wavelengths do Solar Panels Use? [15] (Website)

When performing calculations for the solar flux the solar panels will be absorbing, it is imperative to understand the different wavelengths they can operate at. Depending on the material property, the wavelength that the solar panel intake can vary. For solar cells made from cadmium telluride, copper indium gallium selenide, and amorphous silicon, they can have a wavelength value range from 400 nm to 1000nm. From this website, it was assumed that the solar panels would be operating at a wavelength of 850nm, or 0.85µm, the same band gap as crystalline silicon. Given the information from this website, the angle of the solar panel will influence how much solar energy it is capable of absorbing. Keeping this in mind, a MATALAB code was executed, and information for the solar flux versus the angle of the solar panels was plotted. By analyzing this trend, the team can make decisions for efficient energy absorption and storage to satisfy the client's needs.

Absorbed Solar Radiation [9] (Website)

From the Engineering Toolbox website, assumptions for the absorptivity were made to perform calculations for the radiation heat transfer analysis on solar panels. It was assumed that the solar panels would have a black surface thus it would have an absorptivity of 0.9. When calculating the solar flux, it is important to consider the absorptivity of the solar panels' surface. The absorptivity needs to be considered because it will vary from surface to surface, from grey to black. And, due to the sun's light hitting the solar panel's surface, the amount of solar flux being absorbed will depend on the fraction of the incident radiation absorbed by the properties of the surface. Once the value of the energy absorbed is known, it will help aid the design team in understanding how much energy will be delivered to the entire system and fulfill the customer's needs during the harsh winter months.

Everything You Should Know About Inverter Heat Pumps [14] (Website)

This website discusses the functionality of inverter heat pumps and how it supplies buildings with sufficient air conditioning. Depending on the temperature outside, the pump will supply the air into the building through a ducted system tunning through the walls and into the building. An automatic variable-speed compressor is used to shift the speed of the air depending on the temperature throughout the day. For example, the inverter heat pump can draw heat from the outside air and supply it to the building during the cold winter months. It is designed to be cost effective by using inverter technology to reduce the amount of energy required to cool or heat the building. By understanding how this system works and how efficient it is in supplying varying temperatures throughout any given time in a certain season (summer or winter), the team can design the solar heating system to fulfill customer needs and ensure the client is warm in the Renewable Energy building by the time winter arrives in Flagstaff.

Solar Panel Cost [16] (Website):

From this website, it shows the cost of solar panels trends and how much it is to implement them. According to Solar.com, the price of solar panels has been decreasing over the years in terms of residential, commercial, utility, and installations capacity. The cost has been decreasing over time because industries have reached maximum production globally over the last decade. It is expected that the cost of solar panels in the United States will continue to fall due to those reasons. By understanding these trends and the growing popularity of solar power over time, the design team can decide on the funding aspect for our project and how the falling cost of solar panels will affect the design altogether.

3.2..4 ***Joseph Meza***

Active Solar Heating [25] (Website):

An extensive review of active solar heating systems, particularly those that employ liquids as the main heat transfer medium, may be found in this article from the US Department of Energy. It describes how a fluid heated by solar collectors is kept in tanks and then distributed through a heat exchanger to warm air or water. The article outlines control strategies that maximize system performance as well as important system components like insulation, pumps, and controllers. Additionally, it offers insightful information on system design, maintenance issues, and financial advantages including long-term energy savings.It reinforced our decisions regarding fluid circulation, storage, and control mechanisms necessary to maximize system efficiency and reliability.

Fundamentals of Engineering Thermodynamics [11] (Textbook):

The fundamental thermodynamic concepts covered in this textbook are crucial for creating a solar water heating system that works well. In order to represent how energy flows through the solar collector, thermal battery, and water storage unit, Chapter 1 describes how to construct systems, boundaries, and control volumes. Our team was able to categorize our system and identify the locations of energy and mass interactions by using the textbook's explanation of the distinction between closed and open systems. In order to correctly build up our system boundary assumptions and comprehend how to monitor energy transfers between components and the environment, this chapter was essential.

Introduction to Fluid Mechanics [18] (Textbook):

Chapter 6 of this textbook provides detailed coverage of viscous fluid flow in pipes, which is directly applicable to the piping system in our solar water heater. It explains how pressure drops occur due to friction and how different flow regimes (laminar or turbulent) impact heat transfer and pumping requirements. This chapter helped our team calculate head loss through the collector loop and size our pipes to ensure efficient water flow. The concepts of Reynolds number, friction factor, and energy loss from valves and fittings were critical in our thermal efficiency analysis and pump selection.

Review on Solar Air Heating System with and Without Thermal Energy Storage System [19] (Website):

This peer-reviewed article provides a comprehensive review of solar air heating systems, with a focus on comparing those that use thermal energy storage systems to those that do not. It explains how thermal energy storage — especially through the use of phase change materials — can significantly improve system performance by storing solar heat for use during nighttime or cloudy conditions. This is directly relevant to our project, which is focused on maintaining heat availability in the winter months. The article also discusses various solar collector designs, energy efficiency metrics, and performance limitations. This helped inform our decision to include thermal energy storage in the form of a thermal battery in our design and supported the selection of components to improve energy capture and storage efficiency.

Estimation of the Heating Time of Small-Scale Buildings using Dynamic Models [20] (Website):

This peer-reviewed article presents a dynamic simulation model for estimating heating time and energy consumption in small buildings. The model uses variables such as outdoor temperature, solar radiation, insulation material properties, and wall construction type to simulate how fast a building reaches a setpoint temperature. The study included experimental data from an insulated test building in Norway and was validated through multiple case studies. This source is directly relevant to our solar water heater project because it helped us understand how building materials and environmental conditions influence heating efficiency, especially during cold weather. Additionally, the simulation methods described in the paper helped guide our approach to modeling heat gain and loss within our system, which is critical when evaluating the thermal battery's performance in low solar radiation conditions.

Pipe Flow Calculations [21] (Paper):

This educational document explains in detail how to perform pipe flow calculations, including how to estimate head loss, flow rate, Reynolds number, and pressure drop due to friction. The material walks through examples using the Colebrook and Zigrang-Sylvester equations for turbulent flow, while also providing guidance on minor losses and non-circular ducts. This source directly supports our solar water heater project by helping us evaluate the pressure loss and required pump power for circulating water through the system. Understanding these calculations allowed us to properly size piping, select appropriate materials, and account for energy losses caused by fittings and bends, all of which affect system performance and thermal efficiency.

All About Solar: How Solar Heating Works [] (Website):

This article explains the different types of solar thermal collectors used in water and air heating systems, including high, medium, and low temperature collectors. It clearly outlines how heat is transferred from the sun to a working fluid and then to a storage tank using systems like evacuated tube collectors and flat plate collectors.

3.2..5 Calvin Schenkenberger

Fundamentals of Heat and Mass Transfer, 8th Edition, Chapter 12: Radiation [27] (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 [28] (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 [36] (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 [29] (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 [30] (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 [31] (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 [26] (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 [32] (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 [33] (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 [34] (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 [35] (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 [37] (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.

3.3 Mathematical Modeling

3.3..1 Piping and Fluid Analysis – Jacob Apodaca

For my advanced calculation I decided to take a fluid mechanics approach towards the system and conduct a piping and fluid analysis. This would include finding the inlet and outlet velocity of the evacuated tubes solar collector, mass flow rate, volumetric flow rate, total head loss, and. This was done to determine what medium would be more efficient when used to heat up the RE lab building. But I was not able to complete a fluid analysis for air because we were not able to hook up the solar air panels outside the renewable energy lab and run them to find the input or output measurements and we are also not equipped with the tools to even be able to measure them. We also took pictures of the solar air panels, and the fans attached to them but could not find their respective products online to get specifications. So below will just be my calculations, method, and results for the solar water system.

Method: Water Analysis

The evacuated tube solar collector that is outside the renewable energy lab is a product of sunmaxx solar and I was able to find their materials used and specifications in a provided data sheet online. First, I estimated by hand the heat transferred to the water in the EVC (evacuated) tubes. But I needed to find the mass flow rate first which is the volumetric flow rate times the density of water. The volumetric flow rate was provided by sunmaxx solar online and so I used that value and multiplied by the density of water with unit conversions as well.

$$\dot{m} = Q \cdot \rho \tag{1}$$

Where mdot is the mass flowrate, Q is the volumetric flowrate, and rho is the density. I then plugged this mass flow rate into an equation to find the thermal power which is the heat transferred to the fluid in the EVC tubes.

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in}) \quad (2)$$

Where Qdot is in watts, Cp is the specific heat capacity of water, and Tout and Tin are the temperatures of the water when they enter and leave the EVC tubes which are based off assumptions. Then I calculated the velocity of the water in the EVC tubes by dividing the volumetric flow rate by the cross-sectional area of the inner tubes in the EVC tubes.

$$u = \frac{Q}{A} \quad (3)$$

Where u is the velocity, Q is the volume metric flow rate, and A is the cross-sectional area of the inner tubes. Then taking the average of the temperatures assumed for in and out of the system, I was able to use that which is 60 degrees Celsius and find the absolute (dynamic) viscosity of water using Fig. A.2 from the fluids mechanics textbook [18]. I was then able to find the Reynolds number.

$$Re = \frac{u \cdot D \cdot \rho}{\mu} \quad (4)$$

Where u is the velocity, D is the diameter of the inner tubes, rho is the density of water, and mu is the dynamic viscosity of water at 60 degrees C. After finding Reynolds number I was able to find the friction factor for laminar flow because my calculated Reynolds number was less than 2000.

$$f_{lam} = \frac{64}{Re} \quad (5)$$

After finding the friction factor for laminar flow, I was able to plug this into a major head loss equation.

$$h_L = f_{lam} \cdot \frac{L}{D} \cdot \frac{u^2}{2g} \quad (6)$$

Where L is the total length of the evc tubes, D is the inner tube diameter, and u is the velocity of the water. I also found the minor head loss by finding the loss coefficient, K, in the fluid mechanics textbook [18] Table 8.4. On EVC tubes of the solar water system there are approximately four 90-degree elbow fittings with a geometry of threaded regular and using this is how I found my K value.

$$h_{Lm} = K \cdot \frac{u^2}{2g} \quad (7)$$

Now I am able to find the total head loss of the EVC tubes solar collector water system by summing the major and minor head loss equations.

$$h_{LT} = h_L + h_{Lm} \quad (8)$$

Lastly I calculated the total dynamic head in the EVC tubes water system which just adds the elevation head of the system to the total head loss which I approximated to be 1 meter (for the elevation). Then we are able to find the pressure head which is required from the pump to circulate the water through the EVS tubes.

$$P = \rho \cdot g \cdot h \quad (9)$$

Where P is the pressure, rho is the density, g is gravity, and h is the total dynamic head.

<u>Results: Water fluid analysis</u>

$$\dot{m} = Q \cdot \rho = 0.11 \frac{L}{min} \cdot \frac{1min}{60\,sec} \cdot \frac{1\,m^3}{1000\,L} \cdot 997 \frac{kg}{m^3} = 0.001827 \frac{kg}{s}$$

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_{out} - T_{in}) = 0.001827\ \frac{kg}{s} \cdot 4.184\ \frac{J}{g \cdot °C} \cdot (100°C - 20°C) = 611.53\,W$$

*Note for this above equation I did do the unit conversion from g to kg, so the output value is correct of 611.53 W, I just can't fix the above equation for some reason.

$$u = \frac{Q}{A} = \frac{0.11\ \frac{L}{min} \cdot \frac{1min}{60sec} \cdot \frac{1000000mm^3}{1L}}{1452.2mm^2} = 1.262\ \frac{mm}{s} = 0.0012\ \frac{m}{s}$$

$$Re = \frac{u \cdot D \cdot \rho}{\mu} = \frac{1.262\ \frac{mm}{s} \cdot \frac{0.001m}{1mm} \cdot 43mm \cdot \frac{0.001m}{1mm} \cdot 997\ \frac{kg}{m^3}}{5 \cdot 10^{-4}\ \frac{N \cdot s}{m^2}} = 108.206$$

$$f_{lam} = \frac{64}{Re} = \frac{64}{108.206} = 0.5915$$

$$h_L = f_{lam} \cdot \frac{L}{D} \cdot \frac{u^2}{2g} = 0.5915 \cdot \frac{\left((2.0066m \cdot 30) + 2.61366m\right) \cdot 0.0012\ \frac{m}{s}}{43mm \cdot \frac{1m}{1000mm} \cdot 2 \cdot 9.81\ \frac{m}{s^2}} = 0.053m h_{Lm} = K \cdot \frac{u^2}{2g}$$

$$= 4\left(1.5 \cdot \frac{\left(0.0012\ \frac{m}{s}\right)^2}{2 \cdot 9.81\ \frac{m}{s^2}}\right) = 4.128 \cdot 10^{-7}m$$

$$h_{LT} = h_L + h_{Lm} = 0.053m + 4.128 \cdot 10^{-7}m = 0.0530004\,m$$

$$P = \rho \cdot g \cdot h\ = 997\ \frac{kg}{m^3} \cdot 9.81\ \frac{m}{s^2} \cdot 1.0530004\,m = 10298.9\,Pa$$

Since our fluid flow through the EVC tubes solar collector has a low Reynolds number, it means our flow is laminar. We want turbulent because turbulent flow ensures efficient heat transfer in solar collectors. The friction factor depends on the Reynolds number and pipe roughness and it affects the pumping power required to circulate the fluid. The mass flow rate is important because if it's to low then there is insufficient heat transfer and if it's too high then there is excess pumping energy. The thermal energy is important because it quantifies how much heat gain we are getting in the solar collector. The velocity is important because it also affects the Reynolds number and friction losses and needs to be within an optimal range. The value I calculated seems to be rather low and would need to be increased. The minor head loss is significant in the system and depends on pipe fittings, expansion or contractions, and bends. I approximated that there were four 90 degree elbow fittings used in my control volume and I assumed that the pipe sizing was uniform so it didn't have any expansion or contraction in the pipes. I got a really low value for this since I only accounted for the pipe fittings. The major head loss depends on pipe length and material (for roughness) and helps determine what material would be best to use and the size of it. We would probably use a pvc pipe because this has essentially no roughness. Pressure head is important because it represents the required pump pressure needed and helps with choosing a correct pump (if we need a second one). These values help us understand our system on a numerical level and will help us choose a correct sized pump, designing pipe layouts, avoiding cavitation or overheating, and optimizing the water system.

3.3..2 Thermal Performance Analysis – Brendan Frazier

Considering that the project has a baseline where either a solar water or air heater may be used, a thermal performance analysis must happen. This analysis will help determine which fluid medium should be used for the final installation. The computational descriptions will begin with the water thermal performance analysis and followed by the air thermal performance analysis. Each will include the respective equations used, process followed, MATLAB code descriptions, and the results of each simulation tested. For both simulations run they will be based on average solar irradiance data taken at solar noon with minimal cloud cover provided by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). This is the data selected to determine each thermal system performance during ideal and operable conditions.

Method: Water Performance

The water-based thermal system will solve the bulk outlet temperature of the fluid based on a multitude of fluid variables. The process to get to the outlet temperature will go as follows. The beginning will determine the outer surface temperature of the evacuated tubes based on the ASHRAE solar irradiance data [] and absorptivity information on the tubes. The material of the pipes is known, and the inner temperature of the pipes is found based on the conductive properties of the pipe material. Finally, a forced internal convection analysis is done with the fluid to determine the outlet temperature of the fluid.

The first step of this process is to find the surface temperature of the pipes from the irradiance data collected. Equation # shows the total absorbed radiation where G is the solar irradiation in units of $\frac{W}{m^2}$. The absorptivity, α , is gathered from the evacuated tube specification sheet and is valued at 92%. A_s is the surface area in square meters that the irradiation is incident on. This provides the total absorbed energy from solar radiation.

$$q_{total} = \alpha \cdot G \cdot A_s \tag{10}$$

However, within the MATLAB code this is adjusted to account for the fluid reducing the temperature of the pipe. Because of this method for finding the outer surface temperature, an iterative solution is used. The code begins by converting the total energy absorbed into an energy flux by negating the surface area of the pipes. A reconfiguration of Fourier's law for conduction shown in equation # to get the inner wall temperature of the pipes. The equation needs to initial guess for the surface temperature (T_s) for the temperature from which the heat is transferred. The equation also requires the total flux (q"), thickness of the pipe (t_{pipe}), and the conductive coefficient (k_{pipe}).

$$T_{inner} = T_s - \frac{\dot{q} \cdot t_{pipe}}{k_{pipe}} \tag{11}$$

Once that has been calculated the fluid temperature within the pipe can be approximated. This begins with finding the appropriate Nusselt number correlation to use for the type of flow. Based on the spec sheet provided for the evacuated tubes the volumetric flow rate ($\dot{V}$) should be around $5.3 \cdot 10^{-4}\ \frac{m^3}{s}$. With this established volumetric flow rate and an assumption that the fluid inlet temperature is that of the ambient temperature (~ 300 Kelvin) we can take the fluid properties from Appendix A.5 from the *Fundamentals of Heat and Mass Transfer []* such as the density (ρ), thermal conductivity (k_{fluid}), and the specific heat capacity (c_p). Using these fluid properties, volumetric flow rate, and dimensions of the pipes, we can determine the Reynolds number in equation #. This produced a Reynolds number of ~62 so the flow can be classified as laminar, so the Nusselt number correlation shown in equation # is for fully developed laminar flow in a cylindrical pipe. The final aspect of this is to gather the convective heat transfer coefficient ($\bar{h}$) throughout the pipe length. This is done through a reconfiguration of the Nusselt number equation shown in equation #.

$$Re = \frac{\rho \cdot V \cdot d_{inner}}{\mu} \tag{12}$$

$$\overline{Nu} = 0.023 \cdot (Re)^{0.8} \cdot (\Pr\quad)^{0.4} \tag{13}$$

$$\overline{h} = \frac{\overline{Nu} \cdot k_{fluid}}{d_{inner}} \tag{14}$$

Once this step is completed, the fluid temperature throughout the pipe can be calculated. This is done, once again, with a reconfiguration for Newtons law of cooling to get this outlet temperature shown in equation #.

$$T_{outlet} = T_{inlet} + \frac{h \cdot A_{inner} \cdot (T_{inner} - T_{inlet})}{\dot{m} \cdot c_p} \tag{15}$$

Results: Water Performance

There are multiple outputs for water thermal performance analysis. The first being the mean outlet temperature of the fluid. When the inlet and outlet temperature are compared a total efficiency can be determined based on the Watts of solar energy incident on the solar panel. The other aspect that is analyzed is the temperature of the fluid as it flows through the pipe. This is to say the temperature of the fluid is analyzed at 100 equidistant nodes throughout the pipe. This helps to show the rate at which the fluid is increasing temperature and may provide some insight into the ideal pipe length of volumetric flow rate.

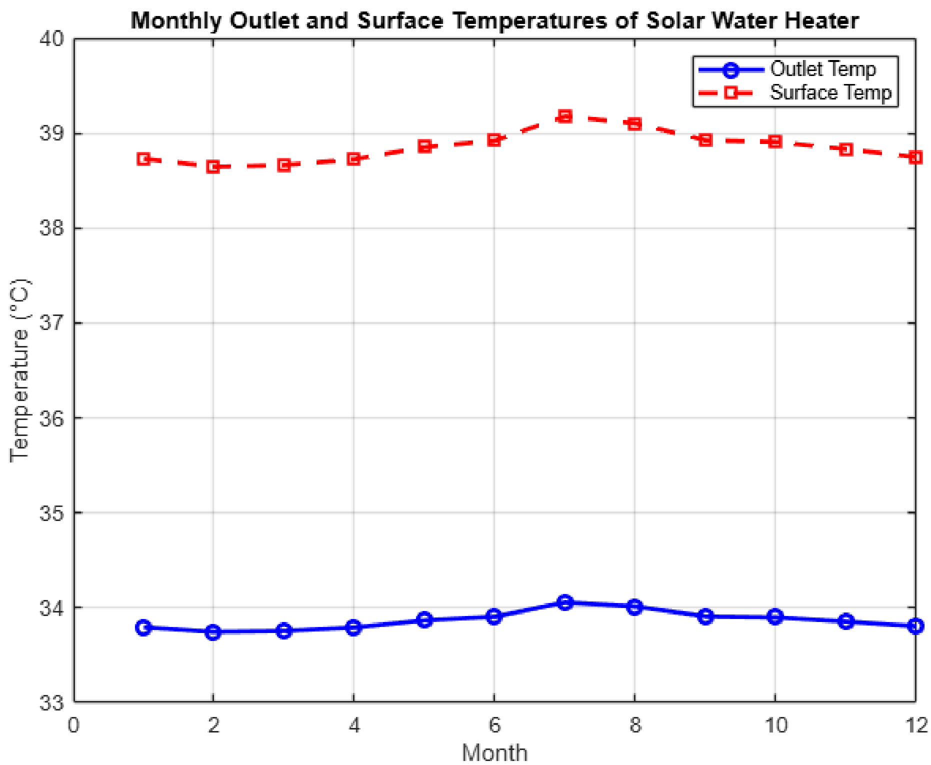


Figure 2: Monthly Water Temperature at Solar Noon

Figure 2 shows the bulk temperature outlet of the solar water panel for each month of the year. This is done with the ASHRAE solar irradiation data taken at solar noon with minimal cloud cover. Once again, these are very ideal conditions. However, this simulation is run on the assumption that conditions will allow for the heating system to be operable. It can be seen in the figure that at the beginning and ending months of the calendar year (winter months) that the bulk outlet temperature is lower than in the summer months. The maximum outlet temperature is achieved in July with a bulk outlet temperature of 34°C and a minimum outlet temperature happening in December at 33.8°C . The minimal temperature difference between the most dramatic months is because this simulation does not account for the difference in time that solar radiation is incident on the earth. A further analysis will be completed later to gather the kilowatt hours (kWH) based on each month's exposure to irradiation. Figure 3 shows the temperature of the water as it flows through an individual pipe. This is calculated to show if any modifications need to be performed on the tubes. Optimization can be done by analyzing the temperature increase along an infinitely long tube and finding where the temperature increase begins to converge to a maximum temperature. The temperature in this figure is plotted from February and shows that the temperature begins to slow its increase around 1 meter through the pipe reaching a temperature of about 32.1℃ , but there is still minimal change in this rate of change. This means it would be worth considering extending the length of the evacuated tube pipes to increase the bulk outlet temperature even more.

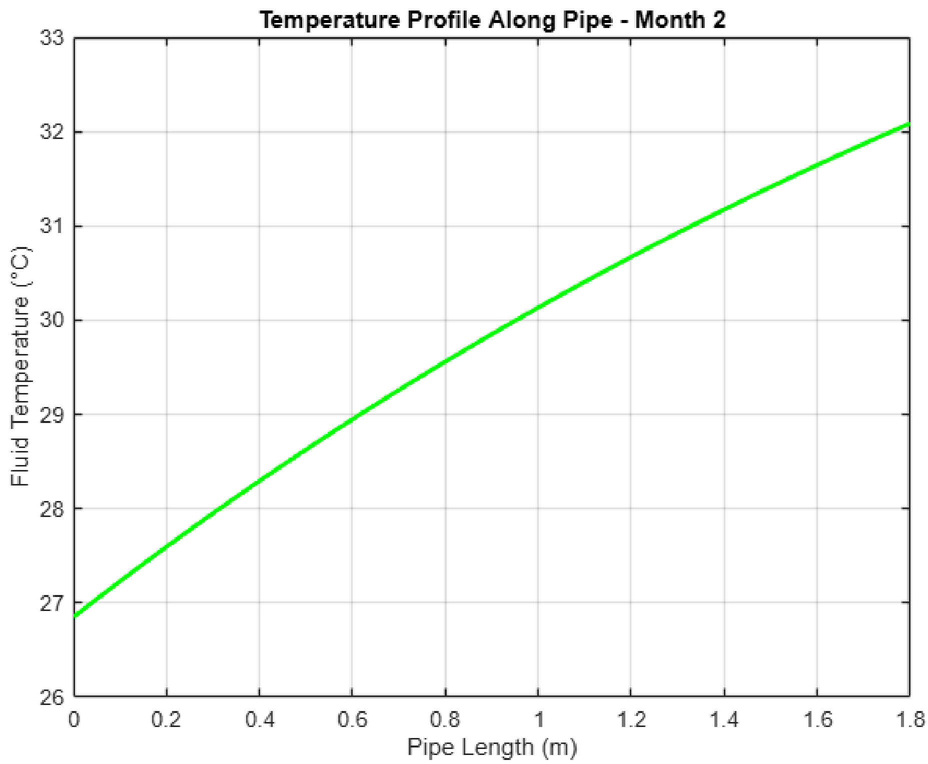


Figure 3: Water Temperature Throughout the Pipe

Method: Air Performance

The methodology used for air performance, when compared with the water performance method, is extremely similar. The primary difference for air analysis is that there is no conduction that occurs before the air is heated up. This is because for the solar air heater the only components of the solar panel are a translucent cover plate, a black absorber plate, and several dividers to separate the air into approximately 100 chambers. Because of this difference, the initial steps are very similar where the energy flux is calculated first using equation # shown back in the *Method: Water Performance* section. The only difference is that the air system has a solid plate with a larger projected area for irradiation to hit an area of 1.08 m^2. Equation # shows the calculation for the temperature of the absorber plate assuming an absorptivity (α) of the absorber plate at 92%. The irradiation is, once again, based on the ASHRAE solar irradiation data.

$$T_{plate} = T_{in} + \frac{q}{h \cdot A_s} \tag{16}$$

The convective coefficient (h) is calculated the same way as water. The first step is to use the same Reynolds number calculation in equation # and determine a Nusselt number correlation, which in this case will be the same since we remain in fully developed laminar flow. The fluid temperature calculations are also able to skip the conduction aspect since there is no solid heat is required to travel through to get to the air. This means the calculation for the air temperature is simplified and shown in equation #.

$$T_{out} = T_{in} + \frac{q}{\dot{m} \cdot c_p} \tag{17}$$

Finally, the solar panel is broken up into sections so the temperature of the air can be plotted against the length of the pipe. This is to ensure that the chamber length used isn't too short, not allowing the air to heat up enough and not so long that the air is overheated for the building. This begins with equation # which nearly follows Newtons law of cooling energy equation exactly.

$$dq = h \cdot A_s \cdot dx \cdot (T_s - T_{fluid}) \tag{18}$$

The total energy transfer from the absorber plate to the fluid is then used to calculate the temperature of the fluid. Equation # shows the temperature calculation.

$$T_{fluid} = \frac{dq}{\dot{m} \cdot c_p} + T_{fluid(i-1)} \tag{19}$$

Results: Air Performance

The final plotted results of the air thermal performance analysis are known to be incorrect at this time; thus, this section will display the results and provide explanations as to what may have gone wrong within the analysis. Figure 4 shows the mean outlet temperature of the air and the temperature of the absorber plate using the average solar irradiation based on each month. The approximate outlet temperature of the air is being plotted at about 5,500℃ which would cause extreme overheating of the building and any piping or ducts. This error is believed to be caused by the energy absorbed by the absorber plate and the heat transfer, then caused by the forced internal convection of the air. Figure 5 shows the temperature of the air plotted against the length of an individual chamber. This plot looks like it is correct, but further validation will support this. Plotted during the month of February the maximum temperature of the air at the outlet is 206.8℃.

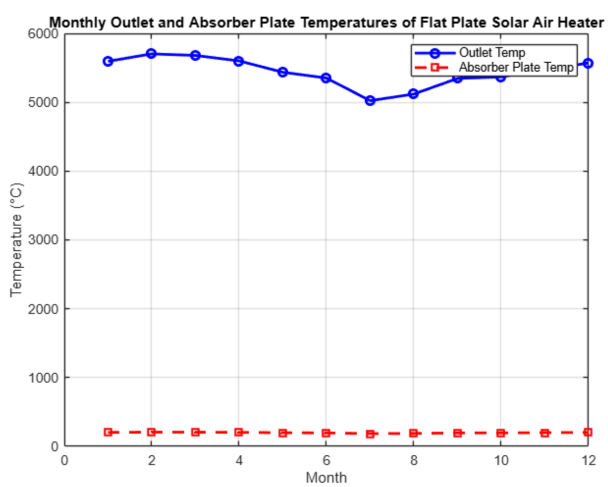


Figure 4: Monthly Air Temperature at Solar Noon

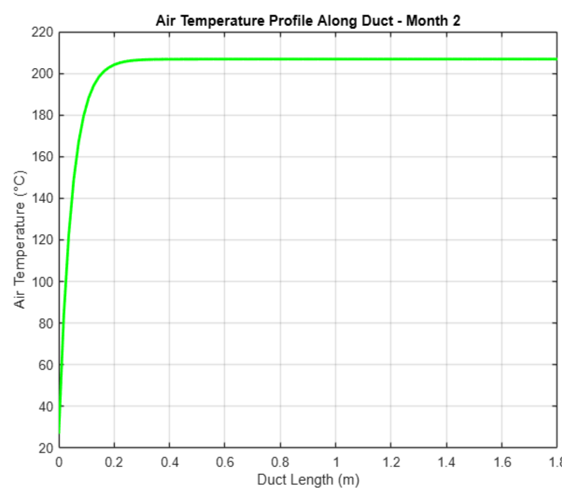


Figure 5: Air Temperature Throughout Chambers

3.3..3 Heat Exchanger Analysis – Tyler Hedgecock

For this analysis, it is essential to determine which device, the fan or pump, will be most efficient in supplying the building with heat during the winter months in the Renewable Energy building. Both devices will be modeled at steady state and will be attached by a heat exchanger to ensure that the building and the fan or pump won't overheat. Assumptions will be made, and calculations for both analyses will be performed based on said assumptions.

Fan analysis

To perform calculations for the fan, the schematic was modeled with the solar collector attached to the top of the heat exchanger to consider the heat collected by the sun's light transferring into the heat exchanger. From previous calculation for the heat transfer analysis on the solar collector, finding the rate of heat transfer is shown below with underlying assumptions:

$$\dot{Q}_{CV} = 152.14*1\text{m}*1.65\text{m}$$
$$= 251.031 \text{ W}$$

It was assumed that the dimensions of the solar collector were 1m by 1.65m and were multiplied to obtain the area of the solar collector. For the fan analysis, a MATLAB code was run for the solar collector analysis, and it was assumed that the solar panels would be at a 16.77-degree angle on top of the building's roof. Thus, the value was found to be 251.031$\frac{W}{m^2}$ at 16.77 degrees from previous calculations. By multiplying the area by the solar flux at 16.77 degrees, the rate of heat transfer could be obtained to perform thermodynamic analysis for the fan. In addition to assumptions, the inlet temperature for taking in the cold air within the building was set at 265.15K and a MATLAB code was run as shown in figure 5 below:

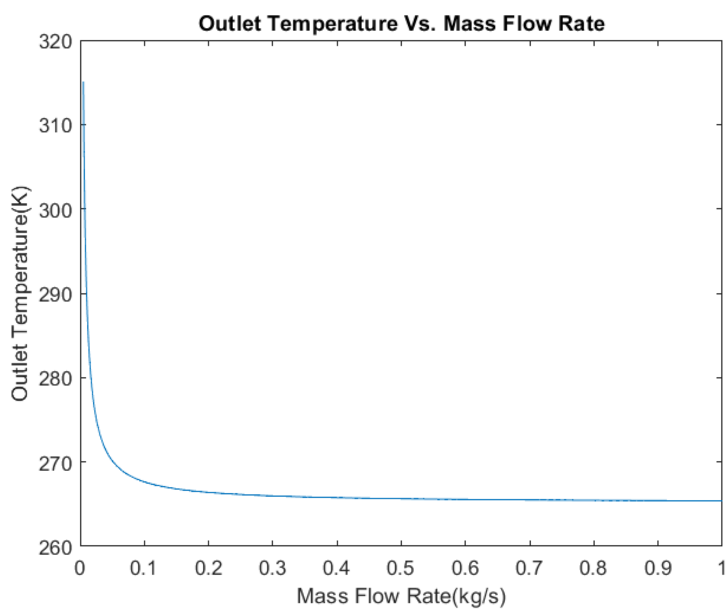


Figure 6: Outlet Temperature Vs. Mass Flow Rate

To perform calculations for MATLAB, the following equation was used to calculate the outlet temperature of the heat exchanger and the fan:

$$0 = \dot{Q}_{CV} - \dot{W}_{CV} + \Sigma_i \quad \dot{m}\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \Sigma_e \quad \dot{m}\left(h_e + \frac{V_e^2}{2} + gz_e\right) \quad (20)$$

The underlying assumptions for this equation was that no work was being done to the system ($\dot{W}_{CV}$=0), kinetic and potential effects could be ignored (KE=0 and PE=0), the air inside the building is an ideal gas model(c_p=1.005$\frac{kJ}{kg \cdot k}$), the system is at steady state, and heat losses can be ignored.

Pump Analysis

As with the fan analysis, the heat exchanger will be attached to the bottom of the solar panel although the pump will be attached to said heat exchanger. Assumptions from before will remain unchanged, except for work, which will be one of the factors calculated for the pump. Heat transfer can be assumed to be neglected when calculating the work for the heat pump. The equation used to perform calculations for the fan will remain unchanged.

Calculations:

When calculating the work for the pump, it was assumed that effects in kinetic and potential energy cannot be ignored along with pressure loss. It was also assumed that heat transfer could be neglected. Other assumptions were that water entering and exiting the heat pump was a saturated liquid. Calculations were performed as shown below:

$$V_2 = \frac{\dot{m}v}{A} \tag{21}$$

$$= \frac{\left(0.001827\frac{kg}{s} \cdot 1.0435x10^{-3}\frac{m^3}{kg}\right)}{0.001425m^2}$$

$$= 0.00134\frac{m}{s}$$

$$\dot{W}_{CV} = \dot{m}\left[(h_1 - h_2) - \left(\frac{V_1^2 - V_2^2}{2}\right) + g(z_1 - z_2)\right] \tag{22}$$

$$= 0.001827\frac{kg}{s}\left[\left(83.96\frac{kj}{kg} - 419.04\frac{kj}{kg}\right) - \left(\frac{\left(0.0012\frac{m}{s}\right)^2 - \left(0.00134\frac{m}{s}\right)^2}{2}\right) + 9.81\frac{m}{s^2}(0m - 2.7559m)\right]$$

$$= \mathbf{-612.2W}$$

After finding the work of the pump, it was required to calculate the temperature of the outlet heat exchanger and analyze if the pump system can fulfill client needs. Separate from the pump, assumptions made for the heat exchanger were that kinetic and potential effects could be ignored along with work. Calculations were made as shown below:

$$T_3 = \frac{\dot{Q}_{CV}}{\dot{m}c_p} + T_2 \tag{23}$$

$$= \frac{251.03W}{\left(0.001827\frac{kg}{s} \cdot 4184\ \frac{J}{Kg \cdot ℃}\right)} + 100℃$$

$$= \mathbf{232.84}℃$$

Results and decision:

After analyzing both results for the pump and the fan, it was deduced that the fan would be more appropriate for our solar system. When comparing the results between the fan and the pump, it shows that regardless of mass flow rate, the fan can maintain a stable temperature while for the pump, the system overheated when it passed through the heat exchanger. When at a higher flow rate, the fan demonstrated that it could maintain a stable temperature while for the pump after water passed through the heat exchanger it became much hotter, at a temperature of 232.84°C . Therefore, the team will design our solar system with a fan and ensure that the system can maintain a stable temperature for the client by the time winter arrives in Flagstaff.

3.3..4 Thermal Battery Analysis – Joseph Meza

In the solar energy heating project part of the calculation necessary to allow the system to be reliable would be the thermal battery. It is a key component that allows for stored thermal energy to be used when solar input is not available, referring to during nighttime or overcast winter days. Flagstaff typically snows over the wintertime and has cloudy days, so it is essential to get the calculations correct. My analysis focused on estimating the thermal energy storage capacity of the battery, evaluating how much energy it could hold, and for how long it could supply usable heat. The thermal battery uses water as the storage medium due to its high specific heat capacity, affordability, and ease of integration into closed-loop systems.

This analysis focuses on determining the energy storage potential of the battery system and predicting thermal losses over time due to imperfect insulation. The thermal battery will be modeled as a large, insulated water tank with copper coil heat exchangers embedded within it. Stored heat is transferred through the coils to supply warm water to the building as needed. MATLAB is used to perform a simplified heat balance over time and determine both energy retention and the duration of usable stored heat.

Method: Thermal Battery Performance

- The modeling begins by estimating the total heat that can be stored in the water tank using the equation:

$$Q = m \cdot C_p \cdot \Delta T \tag{24}$$

Where:

- Q is the amount of thermal energy stored in joules (or converted to megajoules),
- m is the mass of the storage medium (water) in kilograms,
- C_p is the specific heat capacity of water, which is approximately 4.186 kJ/kg
- ΔT is the temperature change in the water between its starting (cold) and ending (heated) states in degrees Celsius.

The tank will be well-insulated with a heat exchanger coil running through it to transfer heat. However, thermal losses through the insulation are estimated using Fourier's Law of conduction:

Where:

$$Q_{loss} = \frac{k \cdot A \cdot \Delta T}{x} \tag{25}$$

- k is the thermal conductivity of the insulation,
- A is the surface area of the tank,

- ΔT is the temperature difference between tank and ambient,
- x is the insulation thickness.

This loss is integrated over time to find out how long the tank will maintain usable thermal energy before reheating is needed.

Results: Thermal Battery Performance

The simulation modeled a 300-liter (0.3 m^3) water tank with a maximum internal temperature of 60°C and a surrounding ambient of 20°C. Assuming the tank is well-insulated with polyurethane foam (k = 0.03 W/m·K) and 5 cm thick walls, the theoretical energy stored is approximately 50.2 MJ. Thermal losses are then calculated, and it is determined that the tank can provide useful heating (above 30°C outlet) for approximately 6–7 hours without additional input.

The simulation suggests that proper insulation is critical for winter performance. To extend thermal retention, phase change materials (PCMs) or increasing wall thickness may be implemented. Experimental validation is recommended to refine model assumptions and confirm theoretical values before physical integration.

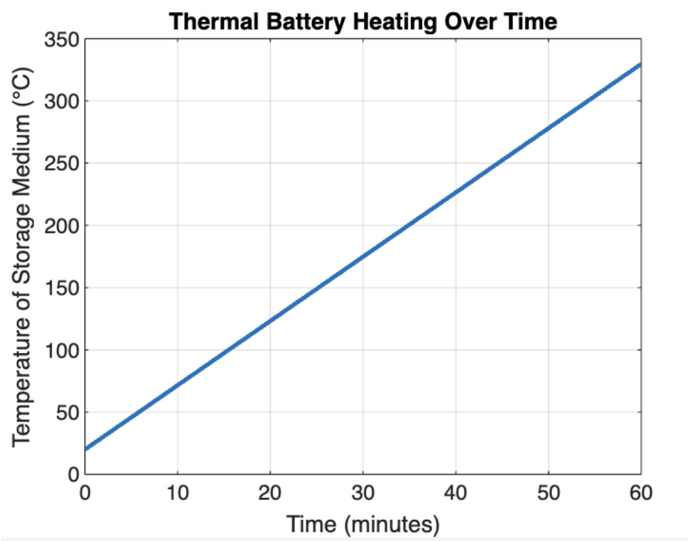


Figure 7: Thermal Battery Heating over one hour graph

Code: Fourier's Law of Conduction

For the thermal conductivity storage material (k) I used .6 since this is the approximate value for liquid water at room temperature. Water has relatively high thermal conductivity for a liquid and is the medium in the thermal battery. Furthermore, the heat transfer area is .05 m^2 since it is more likely this would be the contact surface area between the heating elements (copper coil) and that water inside the thermal battery. For the thickness of the thermal path .1 was used for the 10 cm wall or layer that heat must travel through for the distance between a coil and the outer edge of the tank. The initial temperature of the water would be 20 degrees Celsius because that is the standard room temperature representing the cold starting point of water before any solar heat has been applied. The temperature of the heat source in degrees Celsius is 80 degrees. The reason I utilized this variable was because it simulates solar heated water temperature which is considered to be most efficient between 70 and 90 degrees. 80 degrees is safe, so the water won't boil. The specific heat capacity of water (J/kgK) is 4186, which is the universal unit. The mass flow rate is equivalent to 3 liters per minute and the time is 3600 seconds, which is used to simulate how the water heats over a1-hourr period. The formula heat transfer rate into the tank, based on Fourier's law, is used to model conduction throughout the tank with the coil or heating wall. This code also includes the temperature of water over time, when rearranging the total heat equation.

Results and Discussion: Thermal Battery Simulation

The MATLAB simulation for thermal battery performance is very important in providing insight into how the storage medium heats over time when subjected to a constant external heat source. When using Fourier's Law, the heat transfer into the medium was calculated and used to estimate the temperature rise across a 60-minute period. The plot reveals a steady and linear increase in temperature, with the storage medium heating from an initial 20°C to approximately 330°C within one hour. The reason this rises so much is due to the constant heat input, which is a small thermal mass, based on mass flow rate, and ideal assumptions such as perfect conduction and no heat losses. These assumptions make it easier to understand the modeling; however, the numbers may need tweaking when accounting for thermal losses and material output. The calculations, however, show that the system can achieve a high storage temperature in a quick amount of time, essential for delivering consistent heat throughout the colder months.

3.3..5 Building Heat Load Analysis – Calvin Schenkenberger

<u>Method: eQUEST</u>

Heat load analyses are tedious and intense calculations to perform by hand, so the use of software is vital. Version 3.65 of eQUEST was released in October 2018, and it is widely considered to be the best free method of performing heat load analysis. It supports several different codes, such as ASHRAE 90.1, and the implementation of their Building Creation Wizard makes the software widely accessible for amateur engineers. Users are prompted with up to 43 pages of questions to fill out regarding the specifications of their building, and at the end the software provides an in-depth, year-round estimate of the total energy consumption of the building. This consumption is broken down into months and categories such as lighting load and heating load. The software is also smart, and it adapts during the creation wizard process. For example, if the building does not have a domestic water heater, the related pages will be skipped, and the process will be sped along. Figure 8 below shows the first page of the schematic design wizard, which asks for basic information such as the location of the building, square footage, jurisdiction, and heating equipment.

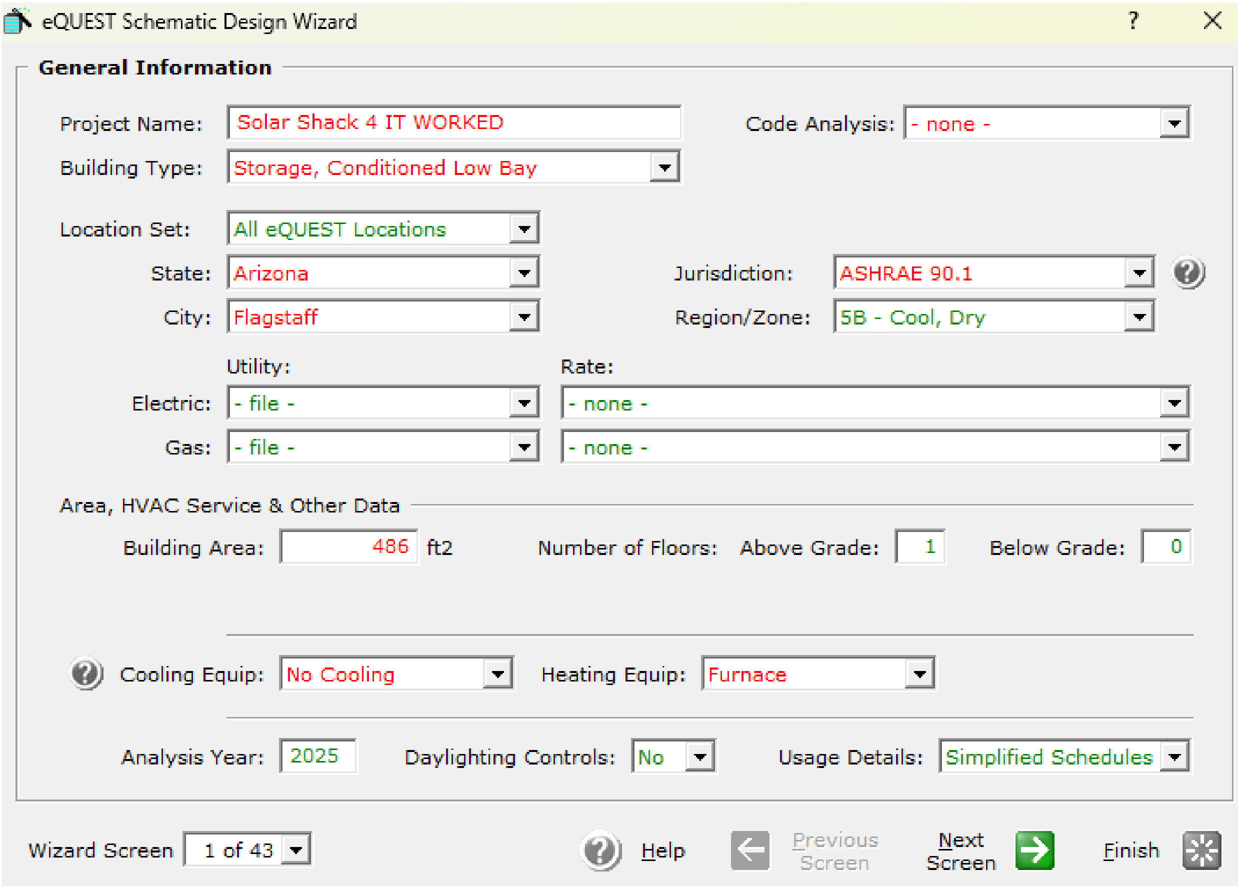


Figure 8: Page 1 of the Schematic Design Wizard with User Inputs in Red

For the purposes of this simulation, we used "Furnace" as the heating equipment, even though in reality we would be using a system of solar air panels, ducts, and fans. Ideally, we would have picked "Solar Air Heater," but the options were severely limited. We decided that the assumption of "Furnace" was reasonable because both systems use hot air as their medium of heating, and both use fans and air ducts.

To use eQUEST, one needs extensive knowledge of the building they are analyzing. We took many pictures and measurements of the solar shack. The creation wizard needs to know the exact dimensions of the building as well as what materials were used for construction. Thankfully, the construction of the solar shack was not difficult to interpret due to the attic and roof access, and the exposed, unfinished surfaces. We know that the walls are a combination of wood studs and masonry brick, and that they are insulated with R-13. We know that the attic uses 2x12 joists, and from that and the relative size of the insulation we can deduce that the attic is insulated with R-30. The foundation is exposed, and we can see that it raises the building 6 inches off earth contact. Below, in Figure 9, is another example of the information the Schematic Design Wizard requires.

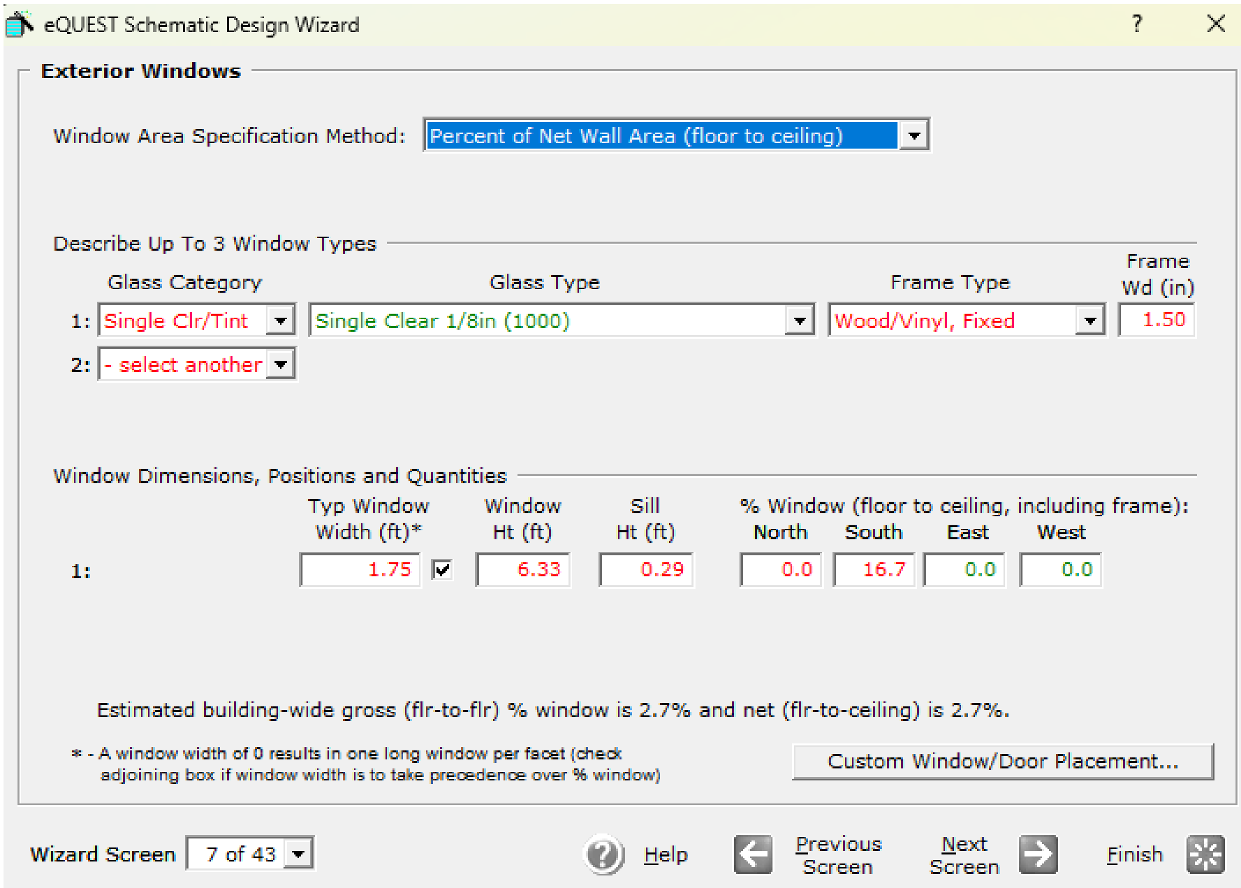


Figure 9: Page 7 of the Schematic Design Wizard – Window Specifications

This process of inputting dimensions and material types continued for all parts of the building, from the foundation and walls to the attic and roof.

Results: Energy consumption and Heat Load Analysis

After inputting all the necessary information, eQUEST generated a 3D model of the building. This is the layout that software uses to simulate heating and electrical loads year-round. The 3D model also serves as a visual verification for the user that their inputs will generate the proper results.

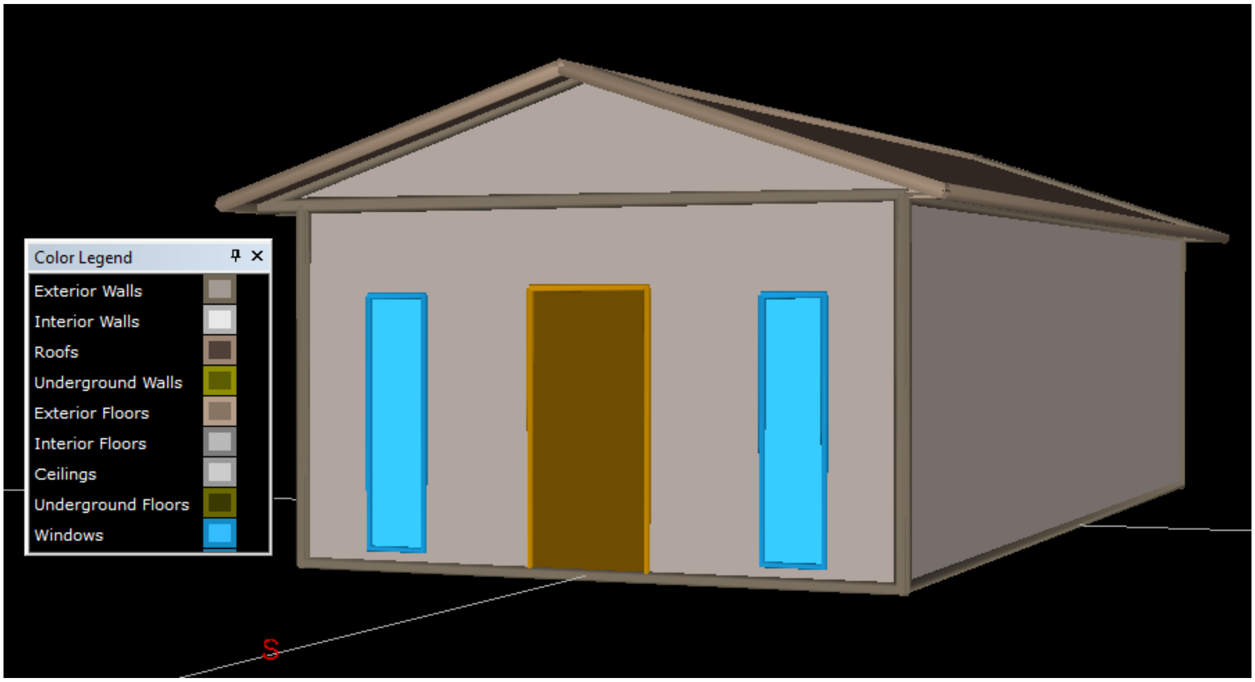
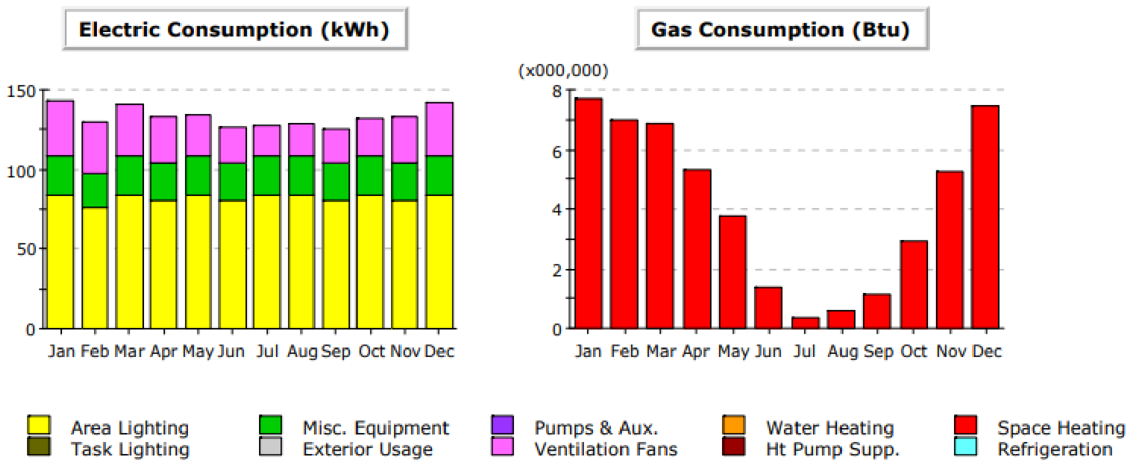


Figure 10: Final 3D Model of the Solar Shack Generated by User Inputs in eQUEST

It took much trial and error to get eQUEST to generate a proper 3D model and simulation. There were many error codes that were hard to decipher, but finally it generated a model that was accurate enough to run simulations on. Running the simulation was as simple as pressing the button labeled "Perform Simulation." After a few seconds, the software outputs an intuitive summary table of the building's yearly energy consumption. This table is shown below in figure 11.



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	35.4	32.1	33.1	29.1	26.6	21.4	20.0	20.2	20.5	24.2	28.9	34.6	326.0
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	24.4	22.0	24.4	23.6	24.4	23.6	24.4	24.4	23.6	24.4	23.6	24.4	287.0
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	83.7	75.6	83.7	81.0	83.7	81.0	83.7	83.7	81.0	83.7	81.0	83.7	985.2
Total	143.4	129.7	141.1	133.6	134.7	125.9	128.0	128.2	125.1	132.3	133.5	142.7	1,598.1

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	7.68	7.00	6.89	5.34	3.76	1.36	0.38	0.62	1.12	2.92	5.23	7.44	49.74
HP Supp.	-	-	-	-	-	-	-	-	-	-	-	-	-
Hot Water	-	-	-	-	-	-	-	-	-	-	-	-	-
Vent. Fans	-	-	-	-	-	-	-	-	-	-	-	-	-
Pumps & Aux.	-	-	-	-	-	-	-	-	-	-	-	-	-
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	-	-	-	-	-	-	-	-	-	-	-	-	-
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	7.68	7.00	6.89	5.34	3.76	1.36	0.38	0.62	1.12	2.92	5.23	7.44	49.74

Figure 11: eQUEST Simulation Summary

Consumption is divided into two categories: Electric consumption and Gas consumption. For our purposes, we are mostly interested in gas consumption. Although the final model will not use a gas furnace, it is still the closest thing to the solar air heater as explained earlier. As you can see, gas consumption peaks during the cold month of January at 7.68 MMBtu. Considering that there are 744 hours in January, consumption is on average 10.32 KBtu/h. This value is highly attainable using the solar air heater design while the sun is out.

Since there are approximately 10 hours of sunlight each day during the month of January, 41.67% of the day is spent in sunlight. Even without an energy storage system for heating overnight, since the solar air system operates above the heating requirement, it could decrease heating loads by 41.67%, which is more than the 30% required by the client. It is important to note that this simulation was run with a default design temperature of 72 °F, rather than the minimum of 40 °F. This is because one of the main design options discussed later involves heating the building in excess and allowing some heat to dissipate overnight without employing the use of a solar battery. A battery-free system like this would reduce heat loads by even more than 41.67% since the building would not instantly drop to 40 °F once daylight is gone. At the client's request, we may re-run the simulation at the bare minimum design temperature of 40 °F, but this is not necessary. This simulation already shows that solar air systems are viable options for heating the building.

4 Design Concepts

4.1 Functional Decomposition

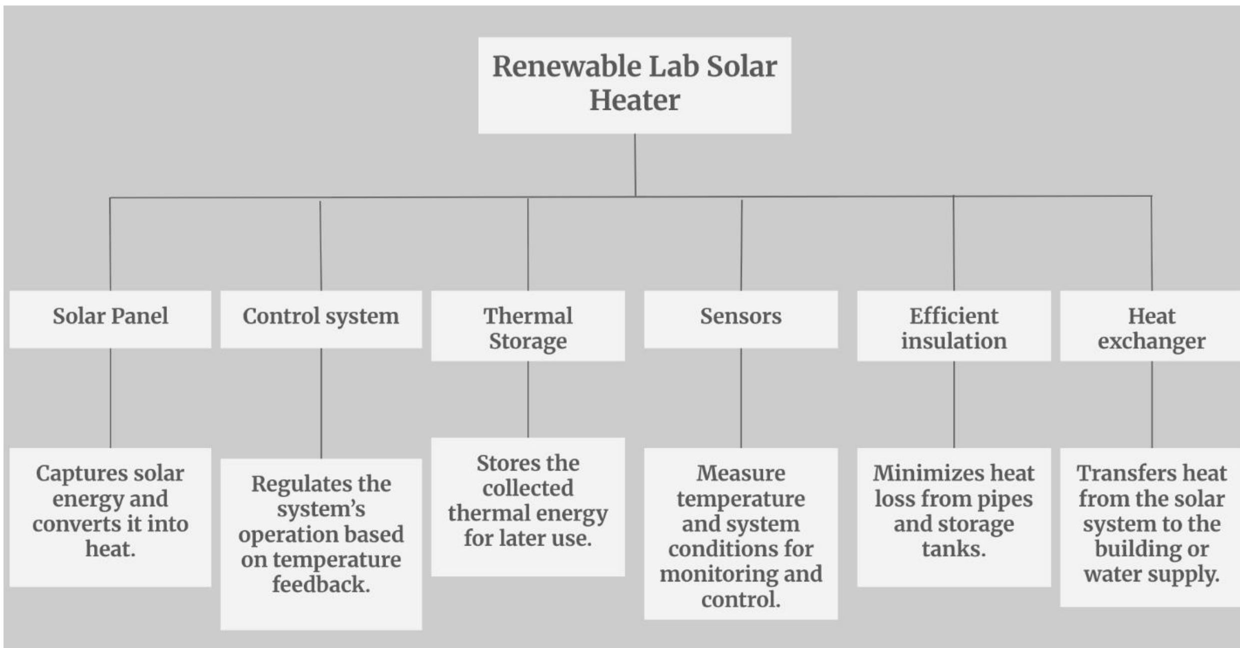


Figure 12: Decomposition Chart

The Functional decomposition of the renewable lab solar heater (figure blank) shows how the system has 6 critical components being the: Solar panel, control system, thermal storage, sensors, efficient insulation, and heat exchanger. Each of the components and functions plays an important role in the overall performance and reliability of the heater. The solar panel is used to capture energy from the sun and convert it into heat. The control system is used to navigate the system using real-time temperature feedback. Thermal storage stores collect heat for use during low sunlight hours, while sensors monitor temperatures and system conditions to ensure efficiency and safety. Efficient insulation is used to bring down heat loss within the system, and the heat exchanger will transfer stored thermal energy to the building or tank. The functional decomposition clarifies each of the components' contributions to the purpose of the system. This helps design decisions, troubleshooting, and structure throughout the project.

4.2 Concept Generation

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

1) Solar Panel

- This entails the style of solar panel including the orientation/position and the fluid medium that is used to transfer heat to the building.

2) Control System
   - This component will determine when and for how long the system is operating. The time aspect will be determined by the total amount of temperature increase needed within the building. The control system will also have integrated ties with any sensors being used.

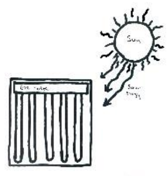
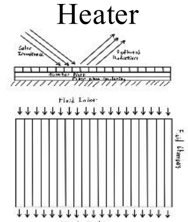
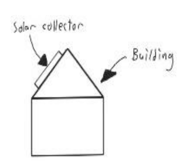
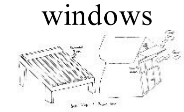
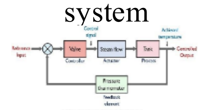
3) Thermal Storage
   - This is how the system will save some of the solar energy collected to be used for a later time. This aspect is specifically applicable to winter months when solar energy and temperature decrease, but the building still needs to remain heated.

4) Sensors
   - Multiple sensors can be used for this project. This includes but is not limited to temperature sensors to determine if the system is worth turning on, photovoltaic or light sensors to determine if the solar panel pump or fan should be turned on, and tracking sensors to optimize the direction the solar panel is facing.

5) Thermal Insulation
   - To minimize heat losses throughout the system, thermal insulation will be used throughout. This will consist of building insulation, back-side solar panel insulation, and piping insulation as the fluid is in transit to the building or radiator.

6) Heat Exchanger
   - Each system will integrate a heat exchanger with some assisting with the overall heat transfer into the building and others helping with thermal storage capabilities of the system.

Table 1: Concept Generation Table

	Jacob	**Brendan**	**Tyler**	**Joseph**	**Calvin**
Subsystems	**1**	**2**	**3**	**4**	**5**
Solar Panel (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 

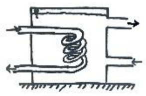
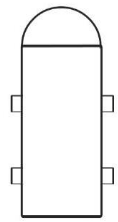
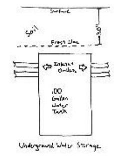
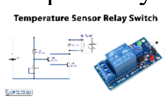
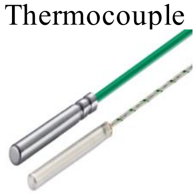
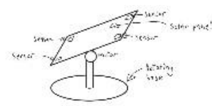
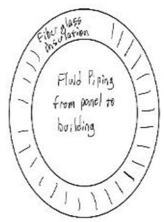
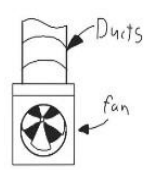
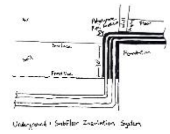
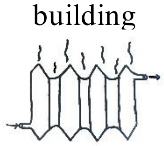
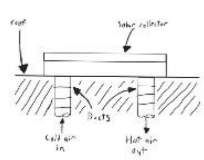
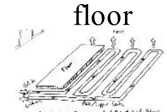
					
Thermal Storage (C)	Storage tank with CFWH 	Building Insulation 	Compressed air tank 	Insulated cylindrical tank for thermal 	Underground storage tank with OFWH 
Sensors (D)	Arduino, sensor inside building with simple relays 	186K-type Thermocouple 	Solar tracking sensors 	Digital temperature sensors 	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 (F)	Radiator inside of building 	Silica Fire Bricks 	Direct contact heat exchanger 	Copper coils submerged in storage tank 	Hot coils under floor 

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

4.3 Selection Criteria

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

Solar Panel:
The solar collection component was selected based on its ability to absorb solar energy and convert it into usable heat effectively, even during colder periods with limited sunlight. The performance was chosen by using the energy capture equation $\mathbf{Q = A \cdot G \cdot \eta}$, where **A** represents the collector area, **G** is the solar irradiance, and $\boldsymbol{\eta}$ is the efficiency of the collector. This allowed us to choose a better product using these variables to achieve greater heat gain potential, guiding the choice towards collectors with large surface area and strong thermal efficiencies.

Control System:
Our objective for the control system is to manage heat flow by activating pumps or valves based on real-time temperature data. One key goal was for a component that could quickly make the system respond to thermal changes, modeled using $\mathbf{t = \Delta T / (R \cdot C)}$, where $\mathbf{\Delta T}$ is the change in temperature, **R** is the thermal resistance, and **C** is the thermal capacitance. If the response time is fast then there is better regulation, which helps in narrowing down options with minimal lag and reliable performance in low-power environments.

Thermal Storage:
For thermal storage, it needs to retain heat over time. Thermal storage options were judged based on energy capacity. The formula $\mathbf{Q = m \cdot c \cdot \Delta T}$ was applied, where **m** is the mass of the storage material, **c** is its specific heat, and $\mathbf{\Delta T}$ is the change in temperature. When having a higher heat capacity indicated a greater ability to store solar energy for delayed use. The calculation is used for evaluating the different materials and storage volumes so we can expect what to happen without physical testing.

Sensors:
The objectives for sensors that we used to measure the performance was evaluated based on sensitivity, accuracy, and output clarity. The equation used is a simplified sensor output model, $\mathbf{V = \boldsymbol{\alpha} \cdot T}$, used to determine how much voltage **V** the sensor produces per degree of temperature **T**, with $\boldsymbol{\alpha}$ being the sensor's

sensitivity constant. We chose based on the sensors that delivered reliable voltage signals over the expected temperature range.

Thermal Insulation:
Insulation selection focused on minimizing heat loss from tanks, pipes, and storage units. The equation Fourier's law for conduction: $\mathbf{Q = (k \cdot A \cdot \Delta T) / d}$, was used for calculating the rate of heat loss. In the equation, it was modeled using where **k** is the insulation's thermal conductivity, **A** is the surface area, **ΔT** is the temperature difference across the insulation, and **d** is its thickness. Materials with lower **k**-values and feasible installation thicknesses were prioritized to ensure energy retention over time.

Heat Exchanger:
The heat exchanger component was looked at based on its ability to transfer thermal energy from the storage medium to the building interior. This can show the effectiveness of this exchange by looking at the equation $\mathbf{Q = U \cdot A \cdot \Delta T_{lm}}$, where **U** is the overall heat transfer coefficient, **A** is the contact surface area, and $\mathbf{\Delta T_{lm}}$ is the log mean temperature difference between fluids. This efficiency exchangers that have a greater surface area and level thermal gradients were used for the best heat deliv ery.

4.4 Concept Selection

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

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

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

Concept:

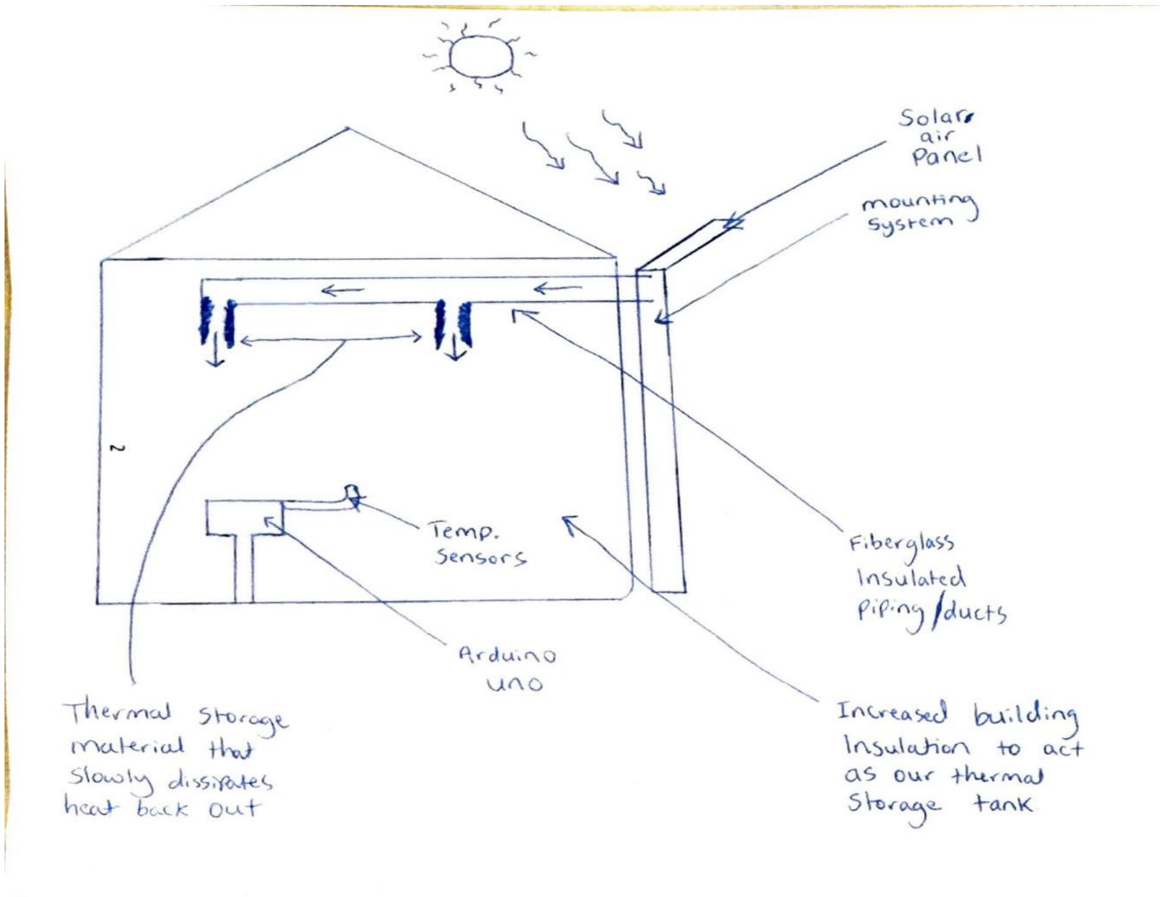


Figure 13: Concept Design #1

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 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:

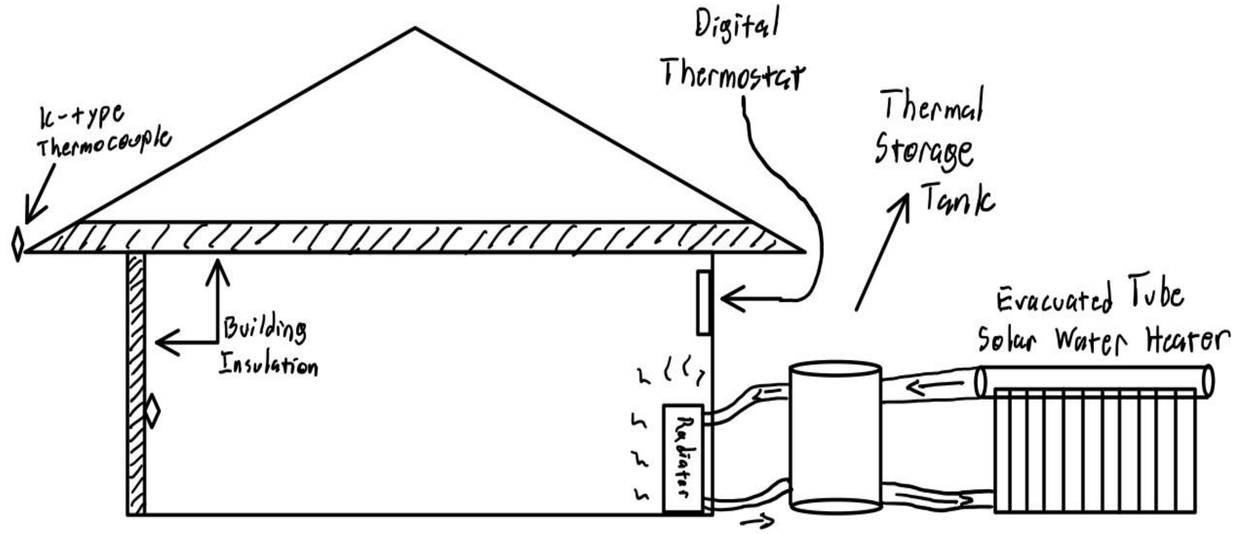


Figure 14: Concept Design #2

Solar Panel: The panel selected for the design is an evacuated tube solar water heater with the primary advantage to this design being that freezing temperatures will not affect the system's operation (i.e. no freezing water blocking pipes).

Control System: To control the operation of the system, this concept design uses a smart digital thermostat. Using a smart thermostat will allow for custom programming of the preferred building temperature. This will also allow for manual changes of the temperature settings within the building.

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:

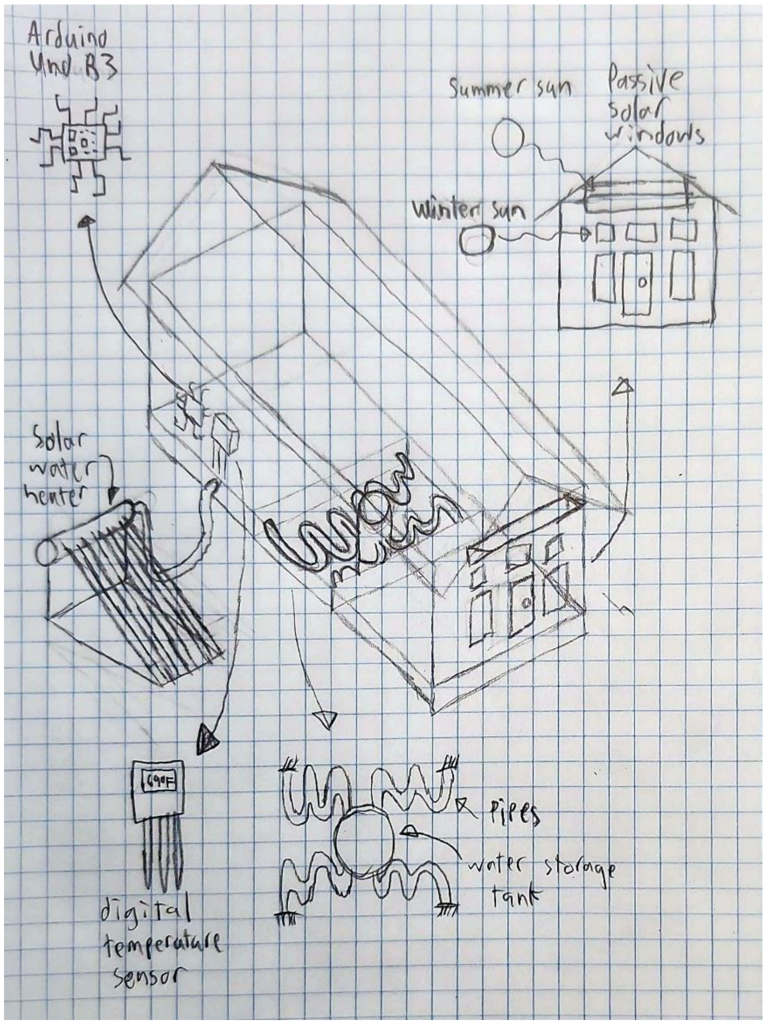


Figure 15: Full Concept Design #3

Solar panel: for this component of the system, it uses a combination of a solar water heater and a passive solar window. The solar water heater is a solar collector with evacuated tubes while the passive solar windows are responsible for collecting, storing, and reflecting solar energy for the building.

Control system: for this design, it utilizes an Arduino Uno R3, a microcontroller board designed to be simplistic in terms of coding and electronics. It is affordable, replaceable, and useful in terms of controlling the system.

Thermal storage: underground water storage was the component selected for this design. The purpose of underground water storage is to store heat stored generated by the solar panels and have it evenly distributed throughout the renewable energy building.

Sensors: to establish the temperature within the building, this design utilizes a digital temperature sensor. Its functionality is to provide accurate and reliable temperature readings so the client can understand the building's temperature and adjust it as needed.

Thermal insulation: the component selected for thermal insulation is insulated piping and storage tank. The purpose of the insulated piping and storage tank is to ensure that the heat carried by the working fluid won't escape the system and will provide sufficient heating to the building during the colder months.

Heat Exchanger: for this design, the heat exchanger is conceptualized to be a single Loop that exchanges heat directly with the floor. The objective of this component is to distribute heat throughout the building, ensure that the system won't overheat, and that temperatures within the building are evenly distributed.

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

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

Concept:

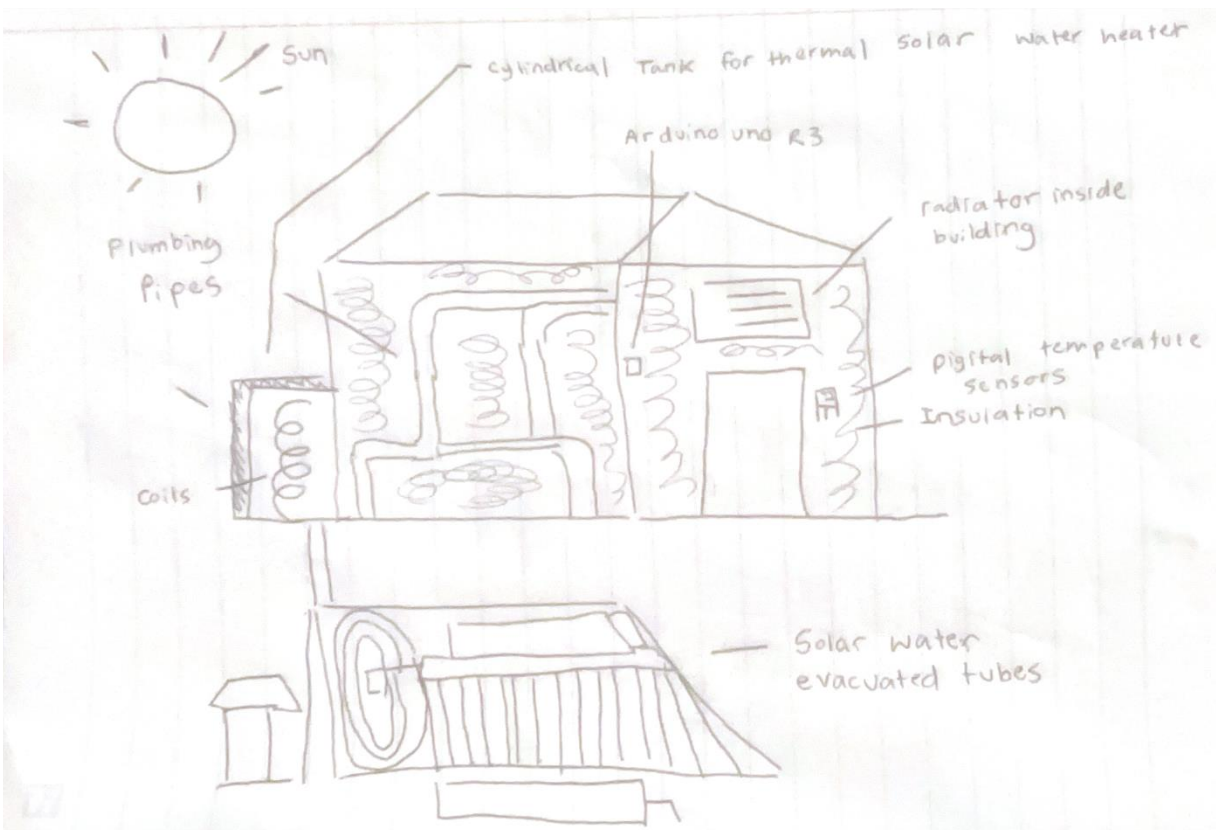


Figure 16: Full Concept Design #4

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

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

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

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

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

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

Design 5 (Calvin):

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

Concept:

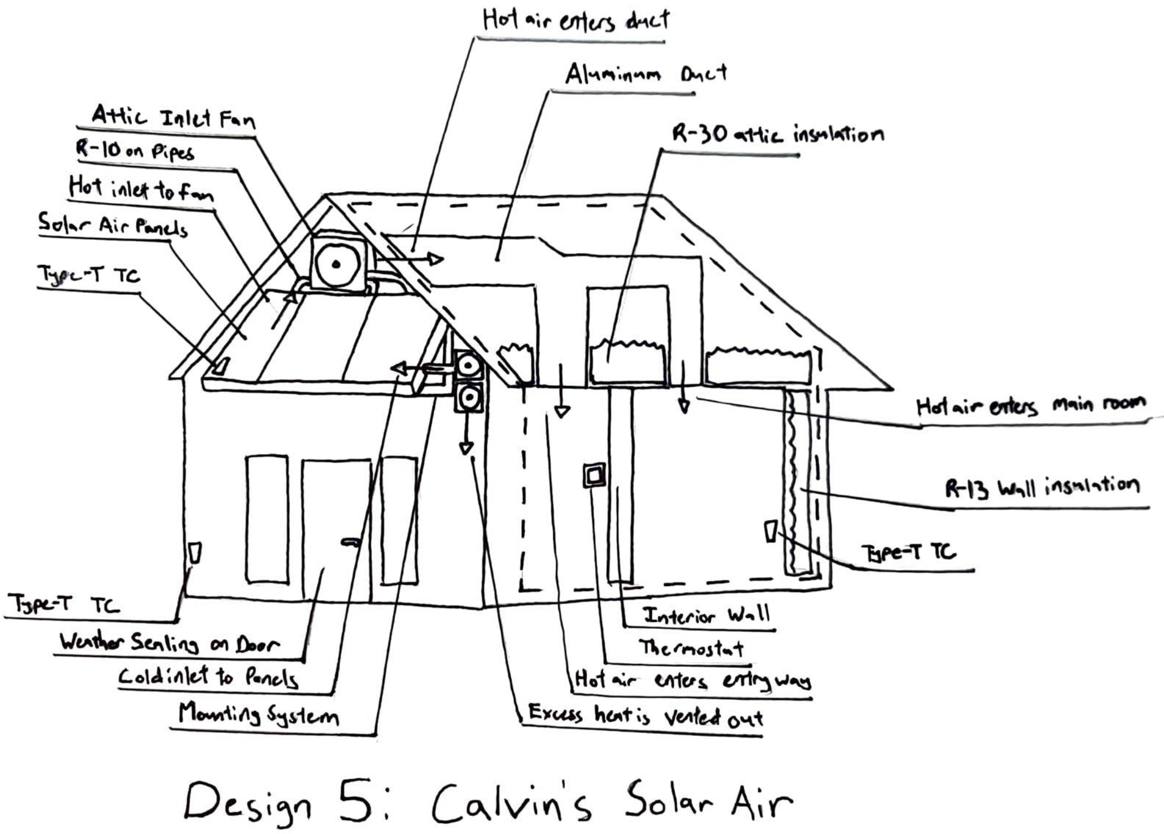


Figure 17: Full Concept Design #5

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℃. 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

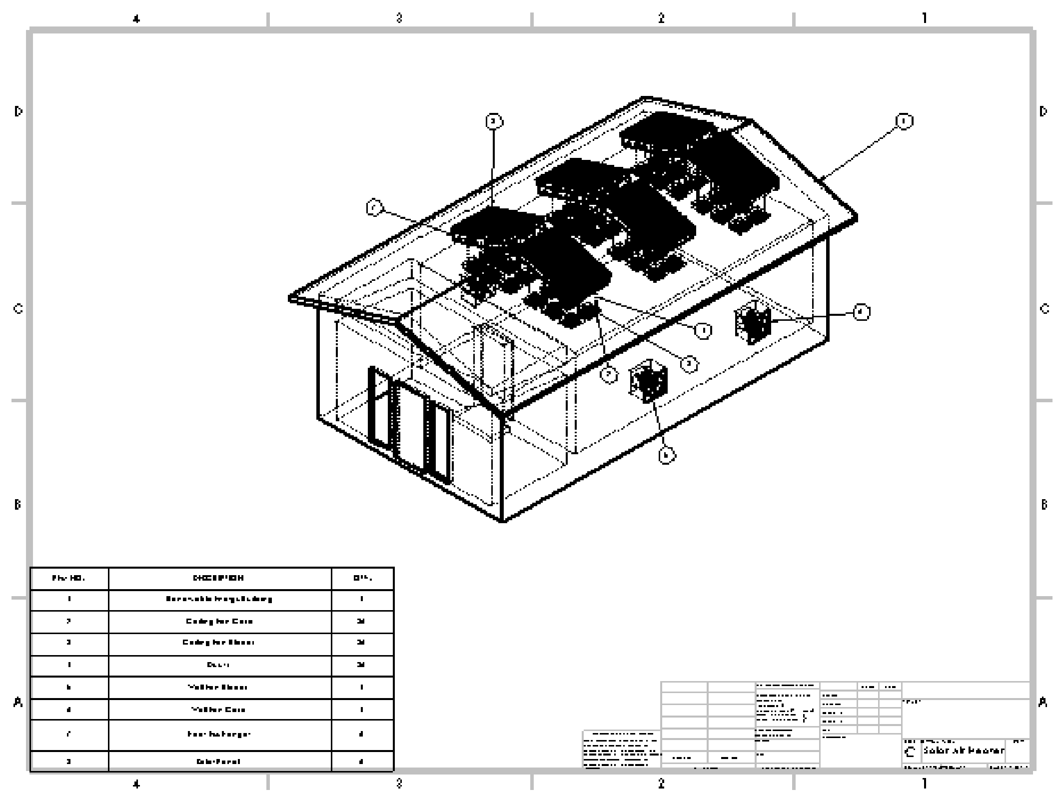


Figure 18: CAD Drawing

5 CONCLUSIONS

The goal for this project is to install a solar water or air heater into the renewable energy lab located above the engineering building. The heater system is used strictly for heating the air within the building. This goal is important to help Northern Arizona University achieve their cardon neutrality goal by 2030. This project is merely microscopic in the grand scheme of all that must happen to achieve this goal but is still a step in the right direction for the university. The system in total must reduce the building heat load requirements by 30% during winter months when heating is most required. The system must also be able to operate mostly autonomously through light and temperature sensors, but thermostats may be used for manual control of the heating. After creating 6 subsystems and 30 concept variants a series of full concept designs were graded through a Pugh Chart and Decision Matrix to determine the most viable option. The result of these designs produced an air-based solar thermal system that implements a digital thermostat to allow for customizable options. The thermal storage is the building itself and will be slightly overheated and with improved insulation should be able to retain enough heat to meet the 30% reduction requirement. There will also be increased weather sealing around windows and doors to ensure maximum heat retention. The temperature sensors that are used for this system will be the T-type thermocouples to determine if the temperature should be turned on at all. That is if the outside temepratture is so low that the air going into the building will be lower in temperature than the internal temperature the fans will not be able to turn on.

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

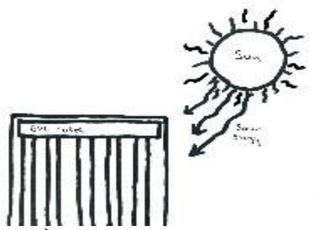
[36] ASHRAE Handbook & Product Directory, 1980 Systems. 1980.

[37] "4000 Series Solar Air Heater," Arctica Solar, 2022. https://www.arcticasolar.com/products/4000-series-solar-air-heater-gen-1 (accessed Jul. 14, 2025).

7 APPENDICES

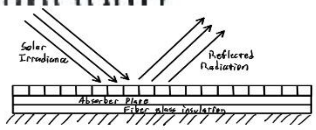
[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report.]

7.1 Appendix A: Concept Variant Descriptions



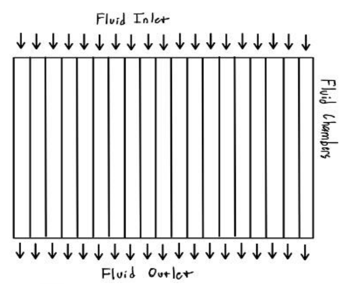
This water-based solar thermal system is an evacuated tube setup. The water flows through the tubes and achieves a phase change since the water is static and absorbs all the solar energy. The non-changing water flows over the top retaining the rising superheated fluid.

Figure 19 – 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 20 – A2

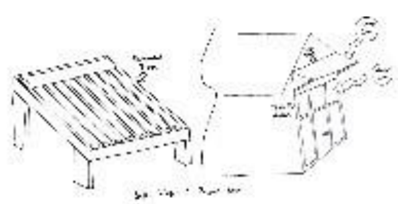


From Figure 25 on the left, it shows a design idea of implementing a solar panel on the roof of the renewable energy building.

Figure 21 – 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 22 – 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.

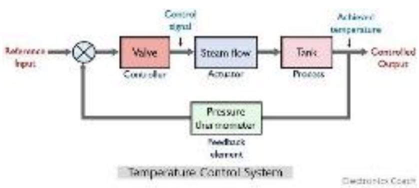
Figure 23 – A5

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 24 – 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.

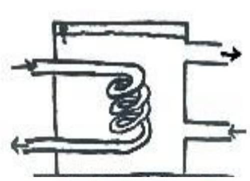
Figure 25 - B2



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 26 – 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 27 – B4

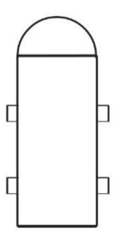
A Raspberry Pi can be programmed to turn fans or pumps on or off given certain triggering conditions. When connected to Wi-Fi, remote monitoring would still be possible.
Figure 28 – B5



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 29 – 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.

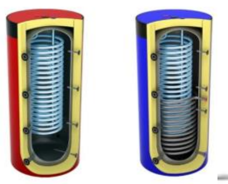
Figure 30 - C2



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.

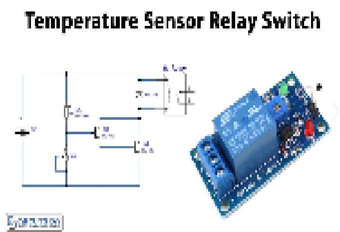
Figure 31 – C3

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



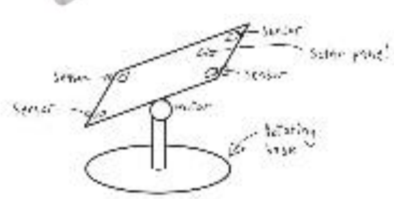
improve overall energy efficiency.
Figure 32 – C4

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 33 – 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 34 – 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 35 – D2



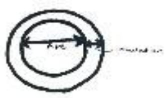
For one of the sensors concepts, solar tracking was one of the ideas proposed to the team. The Senors, as shown in figure 28, would be attached to the solar panels themselves and would send signals to the motor so it can move the solar panels around to effectively collect solar energy.

Figure 36 – D3

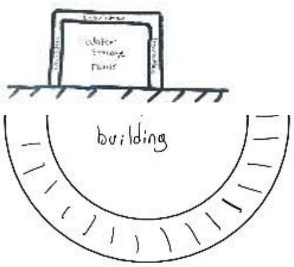
Figure 37 – D4

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 38 – 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 39 – 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 40 - 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.

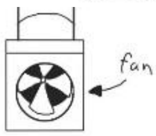
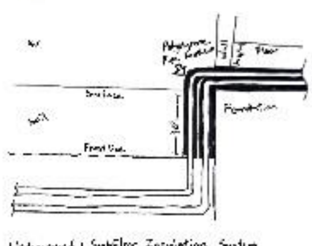
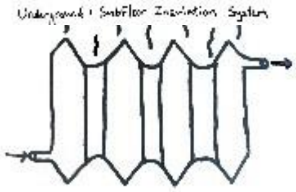


Figure 41 – E3

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 42 – E4

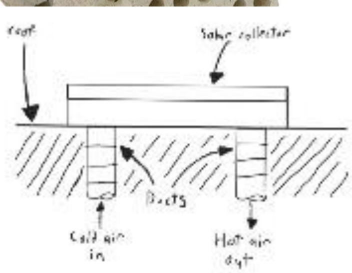


Keeping pipes buried under the frost line would keep them insulated from the freezing winter temperatures. Similarly, pipes could be run underneath the floor when inside the building.
Figure 43 – E5



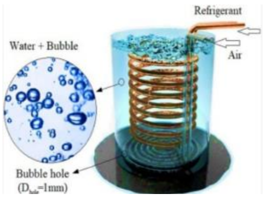
This concept uses a radiator located inside the building. Not only will the natural convection heat up the building but providing fans around the radiator the forced convection will provide additional heat if needed.
Figure 44 – F1

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 45 – F2



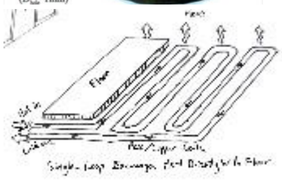
For the heat exchanger concept, one of the concepts was to design it as direct contact and would heat the cool air in the building from the solar panels attached to the top of it.

Figure 46 – 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 47 – 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 48 - F5

7.2 Appendix B: Analysis Code

B.1 Thermal Battery Storage

```
% Thermal Battery Heat Transfer Modeling
clc; clear;

% Given / Assumed values
k = 0.6;            % Thermal conductivity of material (W/m·K) - e.g., wate
A = 0.05;           % Cross-sectional area for heat transfer (m²)
L = 0.1;            % Thickness/distance of heat path (m)
Ti = 20;            % Initial temperature of storage medium (°C)
Tsource = 80;       % Temperature of heat source (°C)
cp = 4186;          % Specific heat capacity (J/kg·K) - water
m_dot = 0.05;       % Mass flow rate (kg/s)
t = linspace(0, 3600, 100); % Time in seconds (e.g., 1 hour span)

% Fourier's Law - Heat transfer rate into the storage medium
q = (k * A * (Tsource - Ti)) / L;  % W (Joules/second)

% Temperature of storage medium over time
T = Ti + (q ./ (m_dot * cp)) .* t;

% Plotting results
plot(t/60, T, 'LineWidth', 2);
xlabel('Time (minutes)');
ylabel('Temperature of Storage Medium (°C)');
title('Thermal Battery Heating Over Time');
grid on;
```

B.2 Water Thermal Performance Analysis

```matlab
% Program: Capstone Analysis
% Course: ME476C
% Programmer: Brendan Frazier
% Date: 06/17/2025
clc; clear; close all
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Constants and Solar Properties
sigma = 5.67e-8;           % Stefan-Boltzmann constant (W/m^2-K^4)

% Monthly average solar irradiance (W/m^2)
G = [983, 1002, 998, 984, 955, 940, 882, 899, 939, 943, 960, 979];

%% Water Solar Panel Geometry
N_w = 30;                        % Number of tubes
D_ow = 0.058;                    % Outer diameter (m)
D_iw = 0.043;                    % Inner diameter (m)
L_w = 1.8;                       % Length of tubes (m)
t_w = D_ow - D_iw;               % Tube wall thickness (m)
alpha_w = 0.92;                  % Absorptivity
k_t = 401;                       % Thermal conductivity of tube material (W/m-K)
V_dot = 0.00015;                   % Volumetric flow rate (m^3/s)

%% Water Properties
T_wi = 300;                      % Inlet temp (K)
rho_w = 999;                     % Density (kg/m^3)
cp_w = 4179;                     % Specific heat capacity (J/kg-K)
mu_w = 0.000855;                 % Dynamic viscosity (Pa-s)
k_w = 0.613;                     % Thermal conductivity (W/m-K)

%% Derived Geometry & Flow Properties
A_proj = N_w * D_ow * L_w;                              % Projected area
A_inner = pi * D_iw * L_w * N_w;                        % Total inner area
m_dot = rho_w * V_dot;                                  % Mass flow rate (kg/s)
A_cross = N_w * (pi * (D_iw/2)^2);                      % Flow cross-section
v = V_dot / A_cross;                                    % Velocity of water (m/s)
Re = (rho_w * v * D_iw) / mu_w;                         % Reynolds number
Pr = (cp_w * mu_w) / k_w;                               % Prandtl number
Nu = 0.023 * Re^0.8 * Pr^0.4;                           % Dittus-Boelter for heating
h = Nu * k_w / D_iw;                                    % Convective heat transfer coeff

%% Initialize Results
T_out = zeros(size(G));         % Preallocate output temp array
T_surface = zeros(size(G));     % Preallocate surface temp

%% Iterate over each month
for i = 1:length(G)
    q_dot_total = alpha_w * G(i) * A_proj; % Total absorbed solar energy (W)

    % First guess for surface temperature
    T_s = T_wi + 10;  % Initial surface temp guess [K]
    T_tol = 0.01;
    max_iter = 100;
    err = 1;
    iter = 0;

    while err > T_tol && iter < max_iter
        q_flux = alpha_w * G(i);  % Heat flux per unit area (W/m^2)

        % Inner tube wall temperature using Fourier's Law
        T_inner = T_s - (q_flux * t_w / k_t);

        % Estimate bulk outlet temp
        T_bulk = T_wi + (h * A_inner * (T_inner - T_wi)) / (m_dot * cp_w);

        % Update surface temp estimate
        q_est = h * A_inner * (T_inner - T_wi);
        T_s_new = T_inner + (q_est * t_w / k_t);

        err = abs(T_s_new - T_s);
        T_s = T_s_new;
        iter = iter + 1;
    end

    T_out(i) = T_bulk;           % Save outlet temperature
    T_surface(i) = T_s;          % Save surface temperature
end

%% Plot Monthly Outlet and Surface Temperatures
months = 1:12;
figure
plot(months, T_out - 273.15, 'b-o', 'LineWidth', 2); hold on
plot(months, T_surface - 273.15, 'r--s', 'LineWidth', 2);
xlabel('Month'); ylabel('Temperature (°C)');
title('Monthly Outlet and Surface Temperatures of Solar Water Heater');
legend('Outlet Temp', 'Surface Temp');
grid on

%% Plot Temperature Along a Pipe for Representative Month
% Choose month with highest irradiance
[~, month_max] = max(G);        % Month with max solar irradiance
G_sample = G(month_max);        % Irradiance for selected month

% Recalculate absorbed flux and surface temp for chosen month
q_flux = alpha_w * G_sample;
T_s = T_wi + 10;
T_tol = 0.01;
err = 1; iter = 0;

while err > T_tol && iter < max_iter
    T_inner = T_s - (q_flux * t_w / k_t);
    T_bulk = T_wi + (h * A_inner * (T_inner - T_wi)) / (m_dot * cp_w);
    q_est = h * A_inner * (T_inner - T_wi);
    T_s_new = T_inner + (q_est * t_w / k_t);
    err = abs(T_s_new - T_s);
    T_s = T_s_new;
    iter = iter + 1;
end

% Discretize pipe length
N_seg = 100;                    % Number of segments
dx = L_w / N_seg;               % Segment length
T_fluid = zeros(1, N_seg+1);    % Fluid temperature at each segment
T_fluid(1) = T_wi;              % Inlet temp

% Per-pipe surface area and flow
A_inner_pipe = pi * D_iw * L_w;
m_dot_pipe = m_dot / N_w;

% Compute fluid temp along pipe
for j = 1:N_seg
    T_local_inner = T_s - (q_flux * t_w / k_t); % Assume constant along pipe
    dQ = h * pi * D_iw * dx * (T_local_inner - T_fluid(j));
    dT = dQ / (m_dot_pipe * cp_w);
    T_fluid(j+1) = T_fluid(j) + dT;
end

% Plot temperature along pipe
x_pos = linspace(0, L_w, N_seg+1);
figure
plot(x_pos, T_fluid - 273.15, 'g-', 'LineWidth', 2)
xlabel('Pipe Length (m)')
ylabel('Fluid Temperature (°C)')
title(['Temperature Profile Along Pipe - Month ', num2str(month_max)])
```

B.3 Air Thermal Performance Analysis

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Program: Capstone Analysis - Flat Plate Solar Air Heater
% Course: ME476C
% Programmer: Brendan Frazier
% Date: 07/08/2025
clc; clear; close all
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Constants and Solar Properties
sigma = 5.67e-8;          % Stefan-Boltzmann constant (W/m^2·K^4)
alpha = 0.92;             % Absorptivity of absorber plate

% Monthly average solar irradiance (W/m^2)
G = [983, 1002, 998, 984, 955, 940, 882, 899, 939, 943, 960, 979];

%% Geometry of Flat Plate Air Heater
W = 0.6;                  % Width of the collector (m)
L = 1.8;                  % Length of the collector (m)
H = 0.02;                 % Height of the air channel (m)

A_proj = W * L;                     % Projected absorber area (m^2)
A_cross = W * H;                    % Air flow cross-sectional area (m^2)
P = 2 * (W + H);                    % Wetted perimeter (m)
D_h = 4 * A_cross / P;              % Hydraulic diameter (m)

%% Air Properties (at ~27°C or 300K)
T_in = 300;                         % Inlet air temperature (K)
rho = 1.1614;                       % Density (kg/m^3)
cp = 1007;                          % Specific heat capacity (J/kg·K)
mu = 1.846e-5;                      % Dynamic viscosity (Pa·s)
k = 0.0263;                         % Thermal conductivity (W/m·K)

V_dot = 0.00015;                    % Volumetric flow rate (m^3/s)
m_dot = rho * V_dot;               % Mass flow rate (kg/s)
v = V_dot / A_cross;               % Average flow velocity (m/s)

%% Heat Transfer Coefficient Setup
Re = (rho * v * D_h) / mu;         % Reynolds number
Pr = (cp * mu) / k;                % Prandtl number

if Re > 2300
    Nu = 0.023 * Re^0.8 * Pr^0.4;    % Turbulent duct flow
else
    Nu = 7.54;                       % Laminar flow between parallel plates
end

h = Nu * k / D_h;                  % Convective heat transfer coefficient (W/m^2·K)

%% Initialize Results
T_out = zeros(size(G));           % Outlet air temperature (K)
T_plate = zeros(size(G));         % Absorber plate surface temp (K)

%% Compute for Each Month
for i = 1:length(G)
    q_abs = alpha * G(i) * A_proj;           % Solar power absorbed (W)

    T_plate(i) = T_in + q_abs / (h * A_proj); % Absorber plate temp
    T_out(i) = T_in + q_abs / (m_dot * cp);   % Outlet air temp
end

%% Plot Monthly Temperatures
months = 1:12;
figure
plot(months, T_out - 273.15, 'b-o', 'LineWidth', 2); hold on
plot(months, T_plate - 273.15, 'r--s', 'LineWidth', 2);
xlabel('Month'); ylabel('Temperature (°C)');
title('Monthly Outlet and Absorber Plate Temperatures of Flat Plate Solar Air Heater');
legend('Outlet Temp', 'Absorber Plate Temp');
grid on

%% Plot Temperature Profile Along Duct for Max Month
[~, month_max] = max(G);
q_abs = alpha * G(month_max) * A_proj;
T_s = T_in + q_abs / (h * A_proj);      % Absorber plate temperature

N_seg = 100;                            % Number of segments
dx = L / N_seg;
T_fluid = zeros(1, N_seg+1);
T_fluid(1) = T_in;

for j = 1:N_seg
    dQ = h * W * dx * (T_s - T_fluid(j));      % Heat transferred in this segment
    dT = dQ / (m_dot * cp);                    % Temperature increase
    T_fluid(j+1) = T_fluid(j) + dT;
end

x_pos = linspace(0, L, N_seg+1);
figure
plot(x_pos, T_fluid - 273.15, 'g-', 'LineWidth', 2)
xlabel('Duct Length (m)')
ylabel('Air Temperature (°C)')
title(['Air Temperature Profile Along Duct - Month ', num2str(month_max)])
grid on
```