ME 476C Capstone Project

Summer 2025

RE Lab Solar Heater

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Project Description

Primary Goal

- Implement a solar water or air heater to provide heat to the Renewable Energy Lab to offset the current, nonrenewable, method of heating.

Technical Components

- Thermal performance analysis on solar air and water heaters
- Thermal energy storage that can be used at night and in winter months
- Building heat load analysis

Figure 1: Solar Thermal System [8]

Brendan Frazier

Background and Benchmarking

1. Furnace – converts fuel into heat for your building
2. Boiler (radiators) - heats water to produce steam or hot water for heating purposes
3. Baseboard heater – heats elements in baseboard to generate heat

Figure 2: Furnace [1]

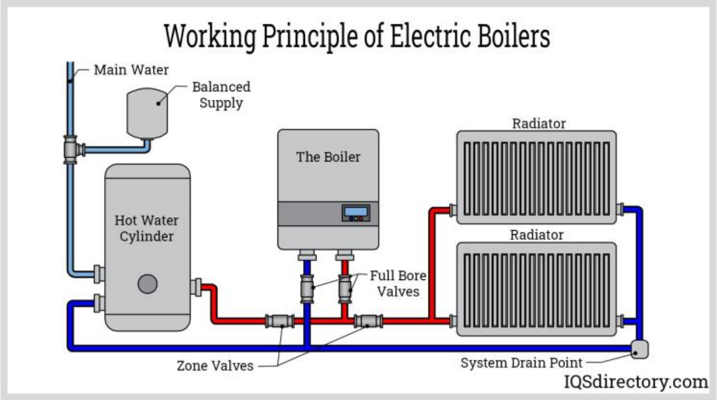

Figure 3: Boiler/Radiator [2]

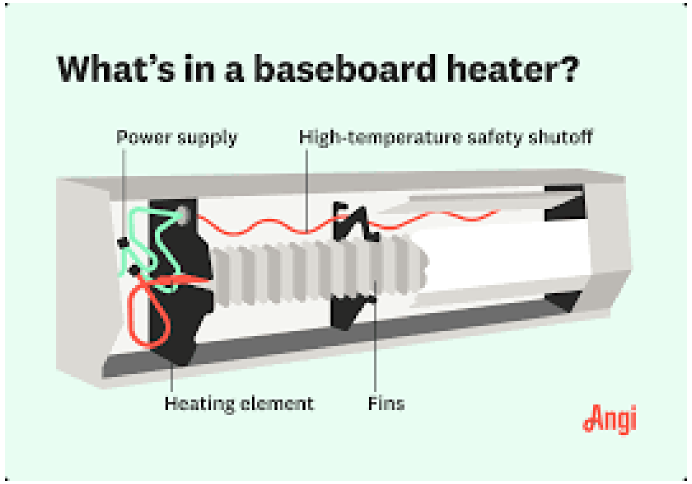

Figure 4: Baseboard Heater [3]

Jacob Apodaca

Customer Requirements

1. System must reduce building heating load by at least 30% during the worst case months
2. System must operate in winter climate conditions and should work when the sun is out.
3. System must use renewable solar energy as primary input
4. Installation must not require any major structural mods to the building
5. System must be safe and comply with relevant codes.
6. System must have minimal maintenance (<4 hrs/year)
7. Payback period must be under 10 years
8. System must have a visual indicator of operation status
9. System must have ability to include temperature and performance monitoring
10. System must not overheat or cause interior overheating (i.e. thermostat regulated)

Jacob Apodaca

Engineering Requirements

1. Solar battery to store energy
2. Efficient insulation
3. Smart System
4. Reliable
5. Pump / Fan
6. Heat exchanger
7. Life expectancy
8. Cost
9. Complexity

Tyler Hedgecock

Quality Function Deployment

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

	Solar Battery to store energy	Efficient Insulation	Smart system	Reliable	Pump / Fan	Heat exchanger	Life expectancy	Cost	Complexity
	0								
	0	0							
	+	0	0						
	+	+	0	0					
	+	+	+	0	0				
	+	+	+	+	0	0			
	+	+	+	+	+	0	0		
	+	+	+	+	+	+	0	-	
Desired direction of improvement (↑,0,↓)	↑	↑	↑	↑	↑	↑	↑	↓	↓

1: low, 5: high — Competitive evaluation (1: low, 5: high)

	Customer importance rating	Engineering Requirements (How's) → / Customer Requirements - (What's) ↓	Solar Battery to store energy	Efficient Insulation	Smart system	Reliable	Pump / Fan	Heat exchanger	Life expectancy	Cost	Complexity	Weighted Score	Solar Water Rating	Solar Air Rating	Furnace rating	Boiler rating	Baseboard Heater rating
1	5	System must reduce heating load by 30% during worst case months (compared to baseline method)	5	5	0	3	3	5	0	0	1	55	4	3	5	5	4
2	5	System must operate in winter conditions	5	5	0	5	3	3	1	0	3	55	3	3	5	5	5
3	5	System must use RE solar as primary input	5	5	3	3	1	3	0	0	5	80	5	5	1	1	1
4	3	Installation must not require major mods to building	0	1	0	1	1	0	0	3	3	18	2	3	2	3	4
5	5	System must be safe and comply with codes	3	3	0	5	3	3	3	0	1	35	5	5	5	5	1
6	3	System must have minimal maintenence	1	1	5	5	3	5	5	1	5	51	3	4	4	4	4
7	3	Payback period must be under 10 yrs	5	5	0	1	5	5	3	5	0	45	5	5	1	1	1
8	1	System must have ability to include temp. and performance monitoring and visual indicator of operation status	3	0	5	5	3	3	0	0	5	16	5	5	4	4	3
9	3	System must not overheat or cause interior overheating	5	0	5	5	5	3	0	0	0	39	5	5	5	5	5
		Technical importance score	126	111	50	121	95	112	44	27	79	765					
		Importance %	16%	15%	7%	16%	12%	15%	6%	4%	10%	100%					
		Priorities rank	**1**	**4**	**7**	**2**	**5**	**3**	**8**	**9**	**6**						
		Units	Joules	R Value	N/A	N/A	Watts	Joules	Years	$	N/A						
		Target															
		Benchmark															
		Difficulty										1: very easy, 5: very difficult					
		Cost and time										1: low, 5: high					
		Priority to improve	**1**	**4**	**7**	**2**	**5**	**3**	**8**	**9**	**6**						

Figure 5: QFD [2]

Calvin Schenkenberger

Literature Review

- Brendan: “Thermal performance improvement method for air-based solar heating systems,” *Solar Energy*, vol. 186, pp. 277–290 [7]
- Jacob: Fundamentals of Heat and Mass Transfer 8th edition (Chapter 6) [5]
- Tyler: Fundamentals of Heat and Mass Transfer 8th edition (Chapter 13) [5]
- Calvin: “ThermoPowerTM 30 Tube Evacuated Tube Solar Collector,” SunMaxx Solar - Solar Hot Water Systems, Aug. 22, 2023. [6]
- Joseph: *Solar water heaters*. Energy.gov. (2025, March 27). [12]

Time Required to Heat Up Building

Assumptions:

- No Insulation
- Table A-4: density and heat capacity @ T = 250 K (Worst/coldest day)

Estimations:

Vol. of building = 3079.5 ft^3 or 87.2 m^3

P = 11.7 kWh/day

ΔT = 27.59° C

C_p = 1.006 kJ/kg*K

ρ = 1.3947 kg/m^3

Q = 3375.1 kJ

t = 115.4 min

Jacob Apodaca

Solar Air Heater Analysis

Assumptions and Conditions

- Temperature boundary condition with 5m pipe length

Pros and Cons

- Low specific heat capacity
  - Easy to heat up
  - Very little storage capabilities

$$T_{mo} = T_s - (T_s - T_{mi}) * e^{\frac{-h*P*L}{\dot{m}*c_p}}$$

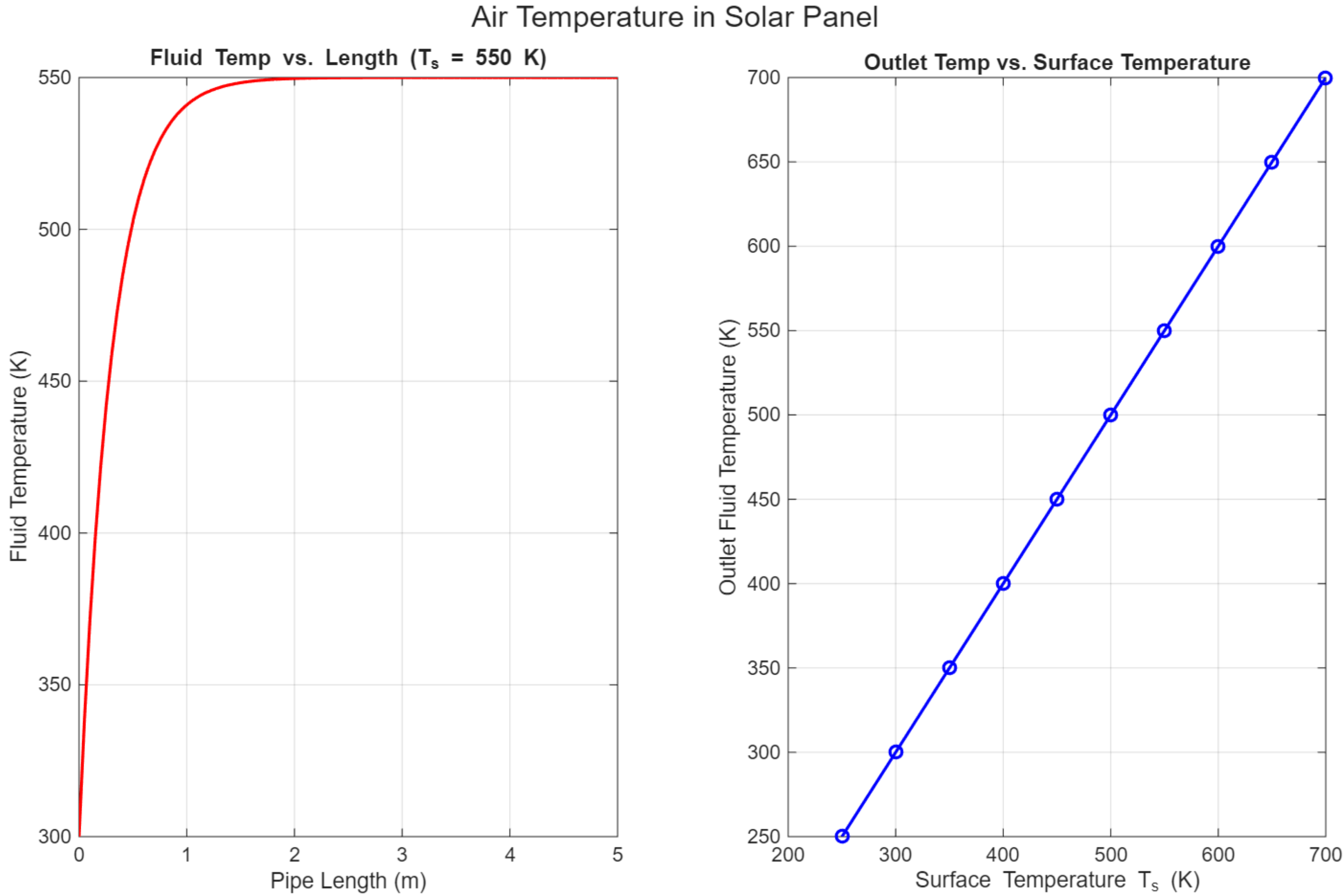

Figure 6: MATLAB Air Temperature Calculations [4]

Brendan Frazier

Solar Energy Absorbed

Assumptions:

- G=950 W/m^2 [10]
- Neglect convection
- Sun's temperature at 5800K [5]
- Black surface for solar panels: α=0.9 [11]

$$\alpha = \frac{\int_0^\infty \alpha_\lambda(\lambda)\, G_\lambda(\lambda)\, d\lambda}{\int_0^\infty G_\lambda(\lambda)\, d\lambda} \quad [5]$$

Gabs=αGcos(90-θ)

Gabs = rate of solar radiation absorbed per unit area
α = absorptivity
G = Solar flux incident on the surface
θ = angle of the solar panels

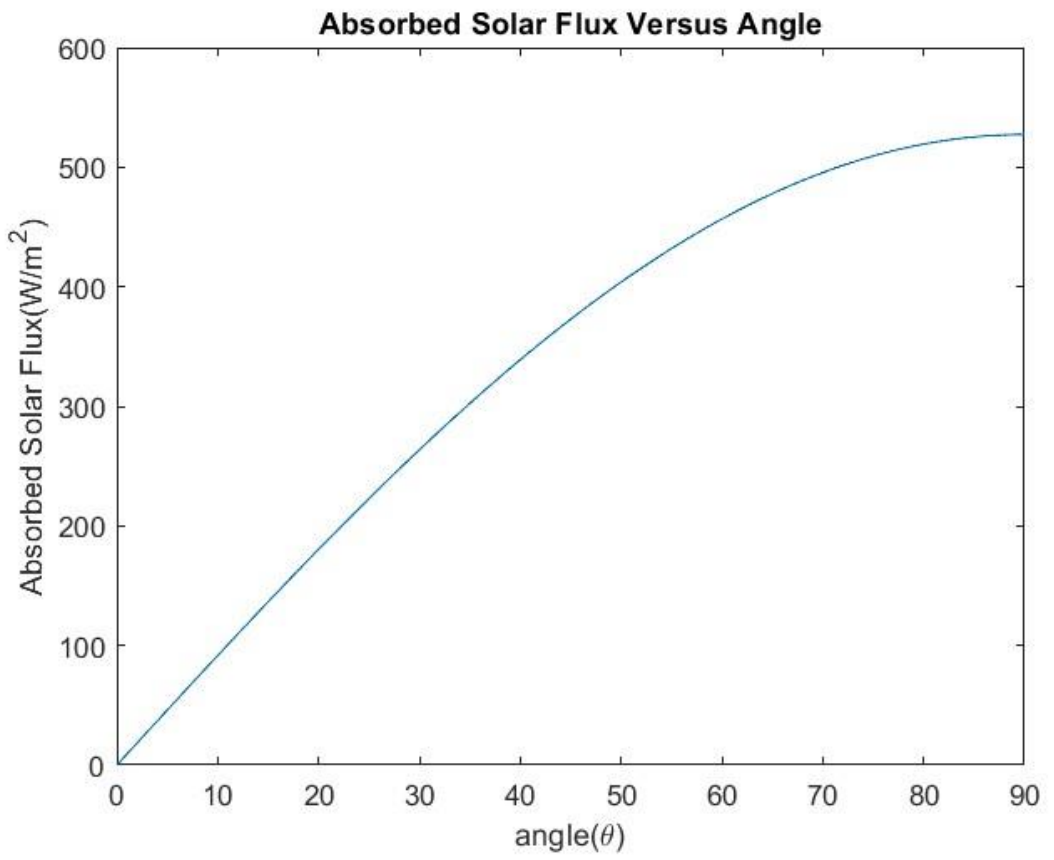

Figure 7: solar energy absorbed vs the angle of the solar panels

Tyler Hedgecock

Thermal Storage Capacity and Heat Loss Modeling

$$Q_{\text{stored}} = m \cdot c \cdot \Delta T$$

Q stored - total thermal energy stored (joules)
M – mass of the storage (water) (kg)
C – specific heat capacity
Delta T – change in temperatures (c)

- Flagstaff air density @ 12degrees is 1.183 kg/m^3
- Estimated floor area and height is 69.73m (assumed building is 300sqrft
- Mass of air in building with assumptions is 82.45 kg (mass)
- Stored heat calculation Flagstaff worse day to best (-20degrees to 55 degrees)
- Specific Heat of air = 1.005 J/kg degree c

Qstored =82.45 * 1.005 J/kg degree c * 75 ≈ 6.22mJ stored heat in air

$$Q_{\text{loss}} = U \cdot A \cdot \Delta T \cdot t$$

Q loss - total heat loss over time (joules)
U – overall heat transfer coefficient (insulation)
A– surface area of the storage tank (m^2)
Delta T – difference in temperature between inside and outside(c
T – time period for the loss (s)

- Inside temperature of 20 degrees.
- Outside temperature of -20 degrees
- U-value is insulation 1.5W/m^2*C
- Surface are of walls 100m^2
- 10 hours over night or 36,000 seconds

Qloss = 1.5 W/m^2*C *100m^2 *40 * 36,000≈ 216mj

Joseph Meza

Daily Power Output of Evacuated Tube Heater

Calculate the average daily power output in KWh/day of the evacuated tube solar thermal heater during the coldest and least sunny month.

Assumptions:
Radiation measured using ATaL
Q= 5.49 kwh/m^2/day [9]
Using lowest monthly average temperature
Ta = -10.722 °C

Q= Solar Radiation (kwh/m^2/day)
T = Temperature Gradient Ti-Ta (°C)
Ti = Internal Temperature (°C)
Ta = Ambient Temperature (°C)
P = Power Output (kwh/day)
α = Absorbtivity
A = absorber area

Table 1: Interpolated Data from Manufacturer's OG-100

Interpolated OG-100 Table				
		Climate (kWh/m^2*day)		
		6.3	5.49	4.7
Temp Gradient (°C)	5	13.6	12.3	11.1
	9.45	13.2	11.7	10.4
	20	12.1	10.3	8.6

P = 11.7 kWh/day

Validation:
P = Q*A*α
P = 5.49 kWh/m^2*day * 2.563 m^2
P = 12.945 kWh/day

Calvin Schenkenberger

WBS: Gantt Chart

Capstone 2025 Project Schedule

Gantt Chart Template © 2006-2025 by Vertex42.com.

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Project Start Date	6/2/2025 (Monday)	**Display Week**	1
Project Team	RE Lab Solar Heater		

WBS	TASK	LEAD	START	END	DAYS	% DONE	WORK DAYS
1	[Task Category]			-			-
1.1	Team Charter	All	Tue 6/03/25	Fri 6/06/25	3	100%	4
1.2	Presentation #1	All	Sun 6/08/25	Thu 6/19/25	11	100%	9
1.3	Team Analysis Memo	All	Tue 6/17/25	Thu 6/26/25	10	10%	8
1.4	Report #1	All	Tue 6/17/25	Tue 7/08/25	22	5%	16
1.5	Presentation #2	All	Thu 6/19/25	Thu 7/10/25	22	5%	16
1.6	1st Prototype Demo	All	Thu 7/17/25	Thu 7/24/25	7	0%	6
1.7	2nd Prototype Demo	All	Thu 7/24/25	Wed 7/30/25	6	0%	5
1.8	Presentation 3	All	Fri 7/18/25	Thu 7/31/25	13	0%	10
1.9	Project Management (	All	Tue 7/15/25	Fri 8/01/25	17	0%	14
1.1	Report 2 (Final Report)		Tue 7/15/25	Fri 8/01/25	17	0%	14
1.11	Final CAD & Final BOM		Tue 7/15/25	Thu 8/5/2025	21	0%	17

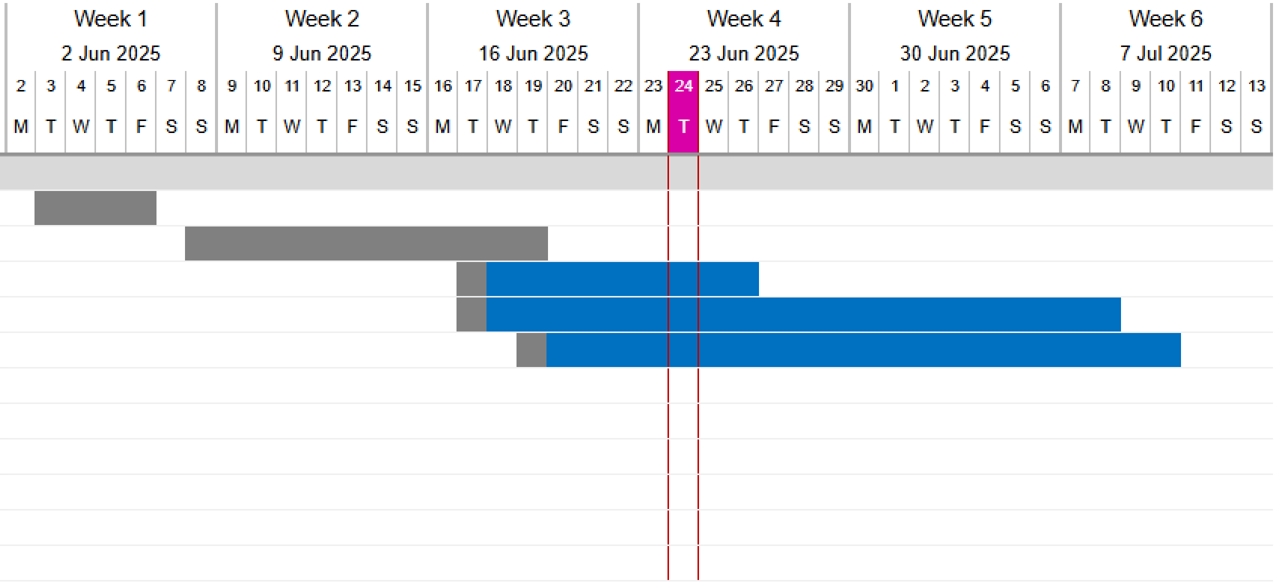

Figure 8: Gantt Chart

Calvin Schenkenberger

References

- [1] FurnaceFinancing. ca Staff, “What are the different types of furnaces for your home? -,” Furnace Financing, https://furnacefinancing.ca/2021/12/06/what-are-the-different-types-of-furnaces-for-your-home/ (accessed Jun. 17, 2025).
- [2] “Electric boilers manufacturers, suppliers and industry information,” Electric Boiler Manufacturers | Electric Boiler Suppliers, https://industrial-boilers.com/electric-boilers/ (accessed Jun. 17, 2025).
- [3] T. Lacoma, “How to install Baseboard Heater,” Angi, https://www.angi.com/articles/how-to-install-baseboard-heater.htm (accessed Jun. 17, 2025).
- [4] “Digital Design & Operation | IES Virtual Environment,” *www.iesve.com*. https://www.iesve.com/software/digital-design-and-operation
- [5] T. L. Bergman, *Fundamentals of Heat and Mass Transfer, 8th Edition*. New York: John Wiley & Sons, Incorporated, 2016.
- [6] “ThermoPower™ 30 Tube Evacuated Tube Solar Collector,” *SunMaxx Solar - Solar Hot Water Systems*, Aug. 22, 2023. https://www.sunmaxxsolar.com/product/30-evacuated-tube-collector/?srsltid=AfmBOopmOyTZ4_WJKAmUMHG1tdiKVZ-1GyjoKz3r5CHg0Qu_inw2yz631oM&gQT=1 (accessed Jun. 18, 2025).
- [7] Y. Choi, M. Mae, and H. Bae Kim, “Thermal performance improvement method for air-based solar heating systems,” *Solar Energy*, vol. 186, pp. 277–290, Jul. 2019, doi: https://doi.org/10.1016/j.solener.2019.04.061.
- [8] "Solar Thermal Collector Design of Experiment for the NAU Renewable Energy Laboratory", Former NAU Capstone project
- [9] “Solar Energy and Solar Power in Flagstaff, AZ,” *Solar Energy Local*, 2025. https://www.solarenergylocal.com/states/arizona/flagstaff/ (accessed Jun. 18, 2025).
- [10] A. G. Safitra, L. Diana, F. H. Sholihah and C. P. Rahayu, "Experimental Analysis of Artificial Equilateral Triangle Solar Air Heater Using Zig-zag Channel," 2021 International Electronics Symposium (IES), Surabaya, Indonesia, 2021, pp. 494-498, doi: 10.1109/IES53407.2021.9593967. keywords: {Fluids;Shape;Solar radiation;Solar heating;Sun;Thermal energy;solar air heater;zig-zag;temperature;absorber;efficiency},
- [11] E. Engineeringtoolbox, “Absorbed solar radiation,” Engineering ToolBox, https://www.engineeringtoolbox.com/solar-radiation-absorbed-materials-d_1568.html (accessed Jun. 18, 2025).
- [12] “Solar water heaters,” Energy.gov, https://www.energy.gov/energysaver/solar-water-heaters (accessed Jun. 17, 2025).

Project Budget and Overview

Total Budget Available: $1,000 total

- $500 provided by the Renewable Energy Lab
- $500 required to be raised by the team to cover unexpected purchases and extra materials
  - Potential Leads: Nau department of Engineering recycle material

Joseph Meza

Anticipated Expenses

- Solar collector materials (pipes, glazing, absorber plate): **$250**
- Insulated water storage tank or thermal mass unit: **$150**
- Pump, valves, and circulation hardware: **$150**
- Structural support and mounting materials: **$100**
- Insulation and sealing supplies: **$100**
- Sensors, controls, and temperature gauges: **$75**
- Miscellaneous/contingency: **$175**
- **Total Estimated Expenses: ~$1,000**

Joseph Meza

Fundraising

- **Department Outreach:** Ask the RE Lab and ME department for any available leftover materials or internal funding.
- **Business Sponsorship:** Approach local hardware or plumbing supply stores in Flagstaff for material donations or small sponsorships.
- **Team Contributions:** Each team member will be prepared to contribute a small amount if needed to close any funding gap.

Joseph Meza

Thank You
Questions?