Red Feather Solar Furnace

Preliminary Proposal

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Mechanical Engineering

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DISCLAIMER

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1 BACKGROUND

1.1 Introduction

The team is partnered with Red Feather, a non-profit organization, to create a heating solution for the Native American people on the reservation. Red Feather is a non-profit organization that develops sustainable solutions for the housing needs of the Navajo and Hopi Tribes such as repairing and renovating homes for the members of the Native American community. They also organize professionals, volunteers, and materials to address the needs of the Native American community.

The Native American people used to receive coal from a coal power plant to heat their homes, the Navajo Generating Station. The coal plant closed in November of 2019 making heating homes more expensive. In addition, burning coal increases respiratory health risks. Other forms of heat such as space heaters are not practical due to the risk of fires. Solar heaters are a good option for being renewable and inexpensive long term [1].

1.2 Project Description

Following is the original project description provided by the sponsor.

> Red Feather Development Group, a non-profit in Flagstaff, works with the Navajo and Hopi Tribes to develop and implement sustainable solutions to their housing needs. Currently, the majority of these two Nations use coal and or wood to heat their homes during the extremely cold winters. Wood and coal smoke is one of the leading contributors to the higher respiratory disease rates on American Indian Reservations (5 times higher). With the pending closure of a coal-fired electricity plant and the mine that supplies it, coal is expected to become very scarce over the next couple years. It is expected that the majority of households using primarily coal to heat their homes will switch to wood, since it can be burned in the same stove, and historically has been reasonably abundant. Tribal officials expect this increase demand for wood will strain local woodlands and rapidly create a similar scarcity for both fuels. The remaining fuel choices are electricity and propane, as only a very limited number of families have access to Natural Gas. Propane has a number of risks, including CO poisoning and risk of explosion, as well as being cost prohibitive for most families. Electricity is not available for thousands of Navajo and Hopi families, and when it is available, space heaters are the most common appliance used for heating. Not only are space heaters the most expensive way to heat a home but they are the number one cause of home fire deaths in the United States.[REDFETAHER]
>
> This capstone project will task a team of students to research and develop sustainable and lasting solutions to the different heating problems on the reservations. This is the second year NAU ME capstone has partnered with Red Feather and this year's team may work off of the results of last year to create a more economical solution to the last solution. This project will begin as an analytical project where the team's final deliverables are in-depth theoretical models of the proposed solutions, thoroughly backed by analyses. However, there is a strong potential to procure extra sponsorship during the semester to provide resources for prototyping and testing. Red Feather may also provide additional solar furnaces for the team to do a comparative study on the Return-On- Investment (ROI) of the currently marketed products versus the team's solution [1].

1.3 Original System

The use of solar energy for heat is not necessarily ground-breaking technology. Although its applications are not as common as standard gas and electrical heating systems, solar furnaces and other similar devices are in use today both commercially and in homes. The basis of this furnace design is to create a heating device that can compete with commercial options, for a fraction of the price. There are two original systems that have been reviewed. Both systems are manufactured commercially, one by Your Solar Home and the other by Arctica Solar. Solar furnaces of this design are suitable for homes, but both brands offer the ability to be installed in series for larger scale applications.

1.3.1 Original System Structure

The basic design of a solar furnace is simple. There is overall structure, usually square, that encases some area of varying geometry that is black in color and accepts solar heat. That heat is transferred from the black surface to air forced over it. A fan in the back of the device pushes the heated air into the home through ducting, and hole on the front accepts new air to be heated by the black inner material. All three models rely on a small photovoltaic panel to power the fan. The main design difference between manufacturers is the geometry of the inside.

The inner geometry is usually not flat, as to create the largest amount of surface area, increasing heat acceptance. An image of Your Solar Home's corrugated inner sheet can be seen below in figure 1. This specific design is made entirely of aluminum, including the casing. The heat absorbing plate is not exposed directly to the environment however and is covered by tempered glass [2]. This brands design is scalable, and the manufacturer recommends use both on homes, and in some industrial applications. The Solarsheat 1500GS, seen below, is 7.25ft by 3.6ft.

Figure 1: Your Solar Home Inner Geometry (Solarsheet 1500GS) [2].

The Solar Arctica system is somewhat similar, however the corrugations of the plate are designed in a different pattern. The application of their system is intended purely for home use and thus is slightly smaller (images are not to scale) but the manufacturer states that they can be installed in series for larger scale use. The Arctica solar model is also an aluminum design with a tempered glass heating window. The system is powered by a 10W photovoltaic panel [3]. An image of the Solar Arctica model, which is 3.2 ft by 5.4 ft, can be seen below in figure 2.

Figure 2: Arctica Solar Design (1500 series) [3]

1.3.2 Original System Operation

The overall operation of a solar furnace is very simple. The systems are automated, requiring no user input. Both the Your Solar Home and the Arctica Solar system are controlled by a thermally activated DC fan. That fan forces heated air into the home and cycles ambient air back into the furnace from the house. The temperature at which the fan is activated is determined by a simple thermostat [2, 3].

1.3.3 Original System Performance

The following values were obtained from datasheets provided by the manufacturers. The Your Solar Home furnace is larger in size and thus is rated to heat a larger space than the Arctica Solar furnace. The datasheet for Your Solar Home's Solarsheat 1500GS states that on a "clear sunny day" their system provides 20,400 Btu/day, or just under 250 Watts. They claim that this can heat between 500 and 1000 sqaure feet [2]. According to the Arctica Solar data sheet, their 1500 Series furnace is capable of heating a 150 square foot space. Arctica Solar did not provide a Btu output but said that the furnace was equivalent to a 1500-watt space heater in terms of capability [3]. These values are most likely for ideal operating conditions prompting a need for further testing of both systems in real life applications.

1.3.4 Original System Deficiencies

Both commercial options meet performance needs. The main deficiency in the original systems, is the cost. Red Feather is a non-profit organization, attempting to affordably heat the homes of residents of the Native American Reservation who are financially insecure. The Your Solar Home option that Red Feather currently utilizes retails at $1780 [2]. The Arctica Solar option retails at $899. Red Feather is hoping to manufacture a new design for under $500.

2 REQUIREMENTS

2.1 Customer Requirements (CRs)

The customer requirements are listed below.

1) Low cost
2) Heat a home
3) Store heat
4) Durable
5) Low weight
6) Easy to build

The team met with the client who is a leader at Red Feather to gather customer needs and find more about the conditions on the reservations. The solar furnace must have a low cost, able to heat an entire home, and scalable for different size homes. The homes on the reservations range from 200 square feet to about 1500 square feet. In addition, the solar furnace must be able to be built with standard power tools and welding equipment so that volunteers or residents would be able to manufacture it. It also must have a low weight so that it could be installed by two people or less. The solar furnace must also be durable so that it can last a long time. It must have a low noise level, be wall or roof mountable, and have a heat storage capability.

2.2 Engineering Requirements (ERs)

Table 1: Engineering Requirements

Technical Requirement	Technical Requirement Goal
Cost	$350
Heat Generation	1500 W
Heat Capacity	2 hours
Weight	45 kg
Durability	20 years
Noise Level	40 dBa
Install Time	3 hours

Based on the customer needs, engineering requirements were made. Red Feather currently pays $750 for their solar furnaces. From speaking with the client, the goal cost would be $350 so the solar furnaces would be affordable to a larger amount of people. The heat generation would be 1500 W because that is what is needed to comfortably heat a home and is also comparable to what space heaters produce. The heat capacity would be 2 hours because the home will continue to stay warm for a while after the solar has been shut off. The weight of the solar furnace would be 45 kg so that it could be installable by only one or two people. The durability of the solar furnace would be 20 years because it is important for the consumers to have a return on investment. The noise level would be under 40 dBa so it would not interfere with the consumers lives such as not allowing them to sleep. The install time would be under 3 hours so that it would take less people and resources to install the solar furnace.

2.3 House of Quality (HoQ)

After generating the engineering requirements and customer needs for the Solar Furnace project, the team placed them into a house of quality, HoQ, that established their rank of importance. The HoQ is shown in figure 3.

		Cost	Heat generation	Heat Capacity	Weight	Durability	Noise level
1	Cost						
2	Heat generation	9					
3	Heat Capacity	9	3				
4	Weight	9	9	9			
5	Durability	9	9	9	9		
6	Noise level	9	3	1	1	1	
7	Install Time	9	1	3	9	1	1

Legend	
A	Your Solar Home
B	SolarArctica
C	Previous Capstone Team

	Customer Needs	Customer Weights	Technical Requirements: Cost	Heat generation	Heat Capacity	Weight	Durability	Noise level	Install Time	Customer Opinion Survey: 1 Poor	2	3 Acceptable	4	5 Excellent
1	Low cost	5	9	9	9	9	9	9	9		A	B	C	
2	Heat a home	5	9	9	9	1	3	1	3			BC	A	
3	Low noise	4	9	3	1	1	1	9	1		AC	B		
4	Store Heat	3	9	3	9	9	3	1	3	ABC				
5	Durable	4	9	3	3	3	9	1	3		C		AB	
6	Low weight	5	9	9	9	9	9	1	9		B	C		A
7	Easy to build	4	9	1	3	9	9	1	9		A	C	B	
	Technical Requirement Units		$	W	hr	kg	Year	dBa	hr					
	Technical Requirement Targets		$350	1500	2	45	20	40	3					
	Absolute Technical Importance		270	172	190	174	190	102	166					
	Relative Technical Importance		1	5	2	4	3	7	6					

Figure 3: House of Quality

In the HoQ the customer needs were first correlated to the engineering requirements as shown in the center of the figure. These correlations were then multiplied against the customer weight for their respective category and added for each engineering requirement to determine the Absolute Technical importance. The rankings of these numbers were determined and then ranked to find the Relative Technical Importance. The Relative Technical Importance shows the team which engineering requirements are the most important to focus on to best meet the customer needs of the project. The most important engineering requirement was the cost of the Furnace as price reduction is the primary goal of the project. The next is the heat capacity of the design which tells the team the furnace must still be able to produce enough heat compared to commercial options despite a reduced price. The third most important engineering requirement is durability. This is important for the design as commercial solar furnaces are long lasting and require little to no maintenance. To be competitive the team's prototype must accomplish the same goals. From the HoQ the team was able to infer that other engineering requirements such as install time and noise level are less important to the success of the design. They will still be considered when making decisions but will not be the primary deciding factor.

In the HoQ the team also benchmarked two commercial options by Your Solar Home and Arctica Solar as well as the design of the previous Red Feather Capstone team. This benchmarking is shown on the right of the HoQ. These models are further discussed in section 3.2.

2.4 Functional Decomposition

The team made a black box model and functional model to analyze the different signal, materials, and energy in a solar furnace system. The functional model shows the different subfunctions of the system.

2.4.1 Black Box Model

The black box model is shown in figure 4. This shows the inputs and outputs of various data to heat a home. This helps the team visualize the project because it breaks down the different materials, energy, and signals to better understand a solar furnace.

Material in	Cold air		Heated air	Material out
Energy in	Solar Energy	Heat Home	Energy Transfer as heat	Energy out
Signal in	Setting thermostat		Change in temperature in home	Signal out

Figure 4: Black Box Model

2.4.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional models help break down subfunctions of a device and the different energy flows. The function model is shown below in figure 5 for a device with a solar furnace, solar panel, fan, and battery system.

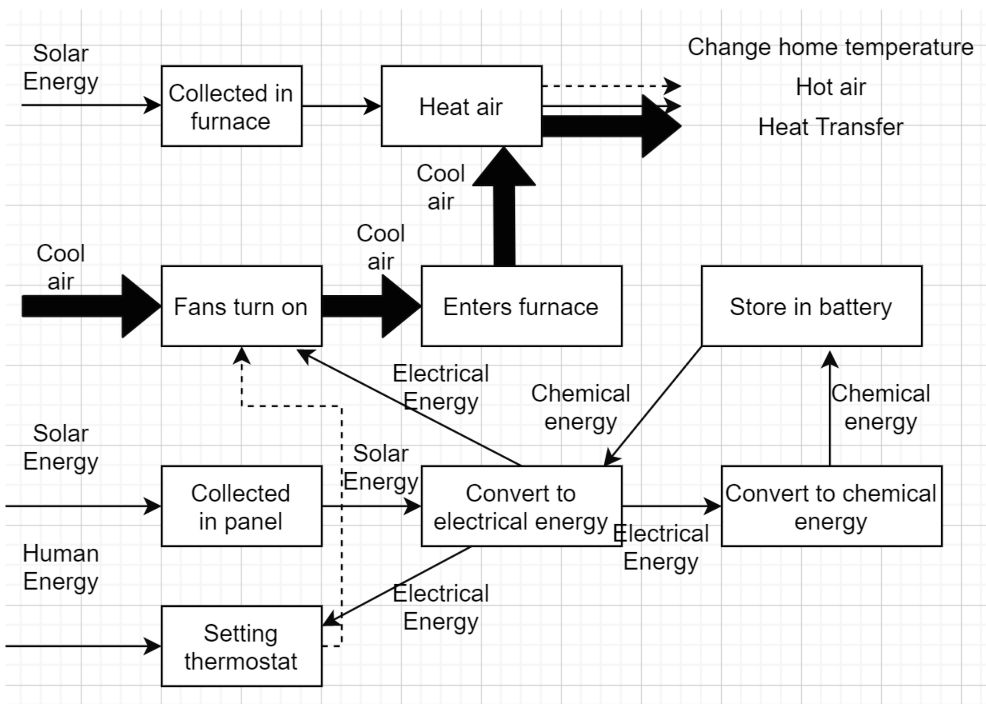


Figure 5: Functional Flow Diagram of Solar Furnace, Solar Panel, Fan, and Battery System

3 DESIGN SPACE RESEARCH

3.1 Literature Review

Each team member conducted a literature review to learn more about their designated topic. Topics of material/emissivity, solar technology, and thermal storage was researched.

3.1.1 Student 1 (Nathan Fisher-Materials/emissivity)

A crucial design component of a functioning solar furnace is the materials with which it is built. Different casing and heat absorber design materials, as well as material finishes (colors) will affect the efficiency of the system. The casing material, being the overall structure, influences the durability of the design as well as increases or decreases its efficiency. The material choice for the inner geometry (heat absorber) will change the heat generation and transfer ability depending on thermal conductivity of the material. The finish, or color, of the heat absorber will also affect the generation of the system. Black has a low emissivity but, certain shades can be more reflective than others.

For the outer casing there are basically two options, wood or some type of metal (usually aluminum). The thermal conductivity of these two materials are drastically different. Balsa wood, for example, has a thermal conductivity of 0.048 W/mK [4]. Aluminum on the other hand has a thermal conductivity value of approximately 237 W/mK [4]. Similar to the principle of electrical conductivity, this means that heat will transfer much faster through aluminum than through wood. Even small layers of low thermal conductivity materials can significantly improve the insulation of a design [5]. For this reason, wood makes a good casing material, since it basically self insulates. However, problems arise with the use of wood in terms of longevity, as it is less resistant to harsh weather. Aluminum, though it transmits heat very quickly, would make a good casing material because it's durable and light. Use of aluminum would require the design to include some amount of insulation, either an air gap or solid insulation.

As for the inner geometry, the material must be a metal. The material must have a high thermal conductivity as to absorb as much heat as possible. The heat absorber also needs to transfer that heat to the air at a relatively quick pace. With a high thermal conductivity value, heat will be transmitted into the air at much higher rate, functioning as very simple heat exchanger. The choice now, is what metal to use. The two viable options are steel and aluminum. Steel is much cheaper however, its thermal conductivity is approximately 54 W/mK, much lower than that of aluminum [4]. Steel is also much denser, so its use would greatly increase the weight of the system. Despite aluminum's higher cost, its lower weight and higher thermal conductivity makes it a more viable material.

In addition to the material of the heat absorber, the finish of it is important as well. The absorber needs to reflect as little light as possible, absorbing as much solar radiation. The emissivity of the material is affected by both the way it was refined as well as any coating applied to it (i.e. paint, polish, etc.). Emissivity values range from 0 to 1 and are a measure of a surfaces heat radiation ability [5]. An emissivity value of 1 corresponds to what is called a black body and is the ideal value for max solar irradiance [6]. To increase light and heat absorption, the finish of the heat absorber should have as high of an emissivity as possible. This allows for heat to be absorbed and released at a faster pace. Uncoated aluminum only has an emissivity of 0.1, however many black paints have emissivity values ranging from 0.8 to 0.9 [7]. By coating the heat absorber in a black paint, the emissivity can be greatly increased.

3.1.2 Student 2 (Leann Hernandez, Solar Technology)

There are many ways for people to obtain power such as burning fossil fuels and wind power. Solar energy is a great way for people to power their homes due to the carbon-free and renewable energy produced. Photovoltaic cells convert radiation from the sun into electricity. [9] Radiation is defined as energy transfer through electromagnetic waves. [5] The heat must be absorbed through an absorber material such as aluminum covered with a kynar layer which produces a solar absorbance of 91.5%. [8]

Solar power allows people who live off the electricity grid to have power. For people who live on the power grid, the excess energy flows back into the power grid. Photovoltaic cells are made of semi-conducting material such as silicon and establish an electric field. Phosphorous is also added to the silicon for more electrons to add more negative charge. The element boron is added to the bottom layer of a solar panel to create more positive charge. This configuration is the main way that solar panels conduct electricity. In addition, conductive plates made from metal collect the electrons to move them through the wires.

Solar thermal power plants generate electricity like photovoltaic panels. Concentrating solar thermal technology is used by solar power plants. Solar power plants produce a much larger scale of energy. The power plants use the solar power to heat a fluid which then produces steam that produces electricity. [9] In solar thermal technology, energy from the sun is used to heat an engine, which then powers a generator that makes electricity. [10] Solar thermal energy is different from photovoltaic because solar thermal involves heating a fluid while photovoltaic directly changes the sun's energy to electricity. The advantage of using solar thermal energy versus photovoltaic energy is that storage of energy is possible. The heat is stored in a working fluid. The advantage of photovoltaic energy is that it is simpler for small scale houses, easier to manufacture, and is much cheaper. The team's main goal is to heat a home as shown in the black box diagram. After analyzing both solar thermal and photovoltaic, it was feasible to go with photovoltaic and not store any heat. Photovoltaic would be the cheaper and more realistic option [10].

It is also important to consider how heat is produced and lost in a typical home. This includes analyzing the heat in situations such as how many people are in the home and their activities that make them produce more heat. According to Egan, in his work of "Concepts of Thermal Comfort", walking upstairs produces 4400 BtuH of body heat versus only 300 BtuH of body heat while sleeping. A more thorough analysis will give the team a better idea of how much power the solar furnace would have to produce to comfortably heat a home.[11]

3.1.3 Student 3 (Trevor Scott, Thermal Storage)

Thermal storage is a potential option for the solar furnace redesign. The inclusion of a solar battery would allow the system to function past daylight hours by storing heat throughout the day to be dispersed once the sun sets and the solar furnace no longer functions. The concept of a thermal battery for use in heating applications is a popular one, with several examples existing.

There are several strange mediums used in thermal battery applications. Low maintenance solids such as rock, sand, and even soil, are used when cost and simplicity are desired [12]. However, solids like rock have lower specific heats compared to many liquids including water, glycol, and antifreeze. These fluids should be considered when heating is more critical and higher temperatures are desired [13]. Passive heating and cooling systems such as those in Earthships use the passive heat storage of rock and soil to regulate fluctuations in temperature but are not ideal when high heat is desired, typically relying on the earth to act as an insulator and using another method to generate heat [14]. Water is the most popular medium for residential thermal storage applications with antifreeze (Ethelene glycol) second [13]. Ethelene glycol has better thermal storage capabilities than water but is toxic when consumed and more expensive than water [12]. Some high efficiency heating systems in industrial and commercial buildings take advantage of Ethelene glycol, but for home applications water is preferred to protect children and pets and simplify maintenance [13].

Water storage systems vary in size depending on the needs of the space being heated. The average furnace in a home outputs around 100,000 Btu/hr to heat a home [15], but how long and often the furnace turns on will depend on the heating need. A 600 square foot home in Northern Arizona is expected to require around 35,000 Btu/hr to heat in the winter to maintain a temperature of 70 degrees Fahrenheit [16]. This is assuming average insulation, so homes on the reservation may require more heat. Not accounting for losses in the system, a thermal battery would need to store 35,000 Btu per hour heating desired. Depending on insulation efficiency, a water heater tank offers between 15,000 to 60,000 Btu of storage per 50 gallons [15]. This means to heat the 600 square foot home for 3 hours with a high would require a 105,000 Btu, which with a high efficiency tank would take 100 gallons with a low efficiency tank requiring up to 4 times as much water. This would also require the solar furnace to produce the extra heat to heat the water with. Based on this analysis, unless the team can find used water heaters for free or a very low cost, the system would out of budget. Another option would be to heat water for use rather than heating which requires far less heat. A small home that uses hot water conservatively could use around 50 to 100 gallons of hot water which would require between 35,000 to 70,000 Btu per day depending on use [17]. Depending on water heating method, either natural gas or electric, this could save families between 20-60 dollars a month for energy [17]. If the families current water heater tank was used and one did not have to be bought, the ROI for the project could be fast and high.

3.2 State of the Art - Benchmarking

3.2.1 System Level State of the Art - Benchmarking

Three existing designed were analyzed to better understand solar furnaces. The subsystems of each design are also shown. The existing designs analyzed were Your Solar Home, Arctica Solar, and NAU Capstone 2018-2019 team.

3.2.1.1 Existing Design #1: Your Solar Home

The Your Solar Home 1500 GS has been the main design used by Red Feather to date. The design is a large 87" x 43.15" x 3.8" panel that uses a photovoltaic panel or standard AC outlet (with inverter) to run a DC fan. It weighs 82 pounds and is made of an aluminum shell, glazed tempered glass, and is insulated with Polyisocyanurate R4 insulation. The panel has a max flow rate of 150 CFM and runs at a temperature of about 120 degrees Fahrenheit. It claims to put on an average of 20,400 BTU/day or about 6000W/hr./day. The advertised price at the time of this report is $1,780. [2]. The testing method to determine these outputs is unavailable from Your Solar Home, but the team hopes to test the actual output in the future. An image of the Your Solar Home 1500GS model can be seen below in figure 6.

Figure 6: Your Solar Home 1500 GS [2]

3.2.1.2 Existing Design #2: Arctica Solar

Arctica Solar's 1500 series panel is newer model being implemented by Red Feather. It is a smaller panel than the 1500GS by Your Solar Home, making it more modular and better able to accommodate the small size of many homes on the reservation. It is made of an aluminum housing with a tempered glass and "high R-value insulation" [3]. The panel weighs 50 pounds and uses a 10 W photovoltaic solar panel to run a small DC fan. It claims an output of 1500W/hr./day by heating the air to 75 degrees above ambient Fahrenheit with a flow rate of 65 CFM. The advertised price at the time of this report is $899 [3]. An image of the Arctica Solar 1500 Series model can be seen below in figure 7.

Figure 7: Arctica Solar 1500 Series [3]

3.2.1.3 Existing Design #3: NAU Capstone 2018-2019

The 2018-2019 Red Feather Capstone team developed an alternative to commercial alternatives above. Their scale prototype is shown in figure 8 and produces 1296.8 BTU/day. They estimated that a full size 4' x 8' model would be capable of 20,748 BTU/day at a price of around $900 [18]. This outcompeted commercial options but left Red Feather with further questions of longevity and manufacturing procedures. The prototype uses steel fins in a wooden housing with a small computer fan to be run by a battery [18].

Figure 8: Red Feather 2018-2019 Capstone Prototype [18]

3.2.2 Subsystem Level State of the Art Benchmarking

Each existing design from Your Solar Home, Solar Arctica, and the NAU Capstone Team 2018-2019 has been broken into their subsystems to better analyze their designs. This helped the team develop a better design by individualizing analyzing the subsystems. The subsystems analyzed are the heat absorber, heat transfer mechanism, front panel design/material, and the casing design/material. How a home is heated using a solar panel system is shown in figure 9.

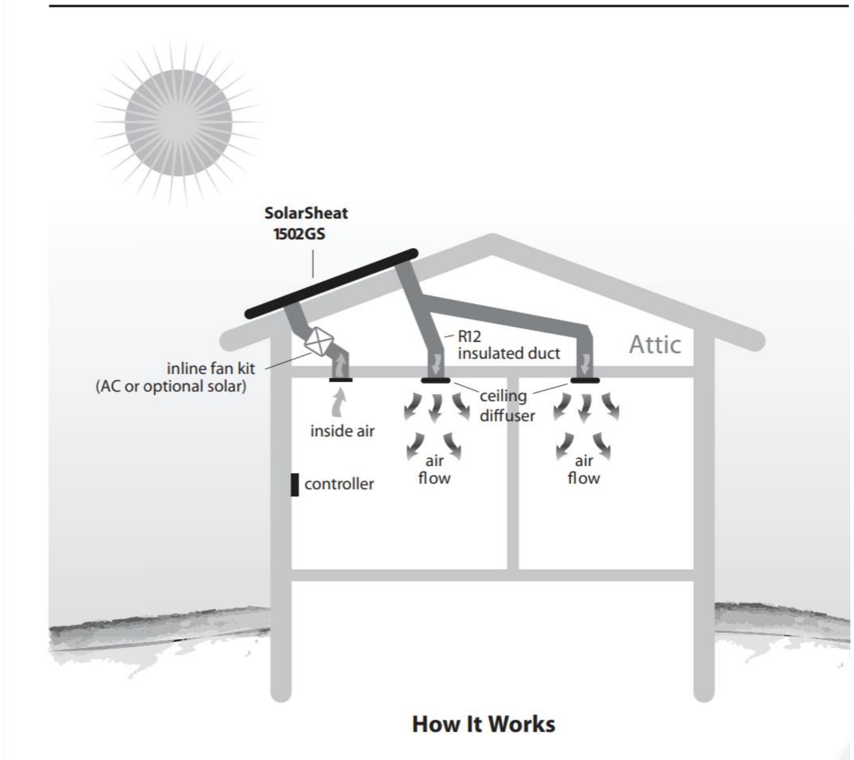


Figure 9: How a Solar Panel System Heats a Home [2]

3.2.2.1 Subsystem #1: Heat Absorber

Solar heating is captured by photovoltaic cells converting the radiation from the sun to electricity. An inverter will convert DC electricity to AC electricity which powers appliances in a typical home. The conversion of energy can heat a home. If too much electricity is made, then the electricity flows back into an electric grid. Solar panels are great for people who do not have access to be connected to typical electricity systems. [19] This relates to the team's engineering requirements because the team must produce a certain heat output. Different materials can be used for the heat absorber. This is important because different materials will have a different emissivity.

3.2.2.1.1 Existing Design #1: Your Solar Home

In some products by Your Solar Home has a Kynar on a corrugated aluminum plate as the heat absorber. Kynar is often used to coat steel roofing panels. According to NREL, a 22.9-27.9 micrometer coat of kynar which produces a 91.5% absorptance when painted onto aluminum absorber plates. Your Solar Home also mentions that they use a high temperature foam to provide insulation for the SolarSheat collector [2].

3.2.2.1.2 Existing Design #2: Solar Arctica

Arctica Solar has high performance absorber material. It is a metal substrate with a high absorptivity, a low emissivity coating. It has 1500 W heating capacity. Arctica Solar does not require any assembly [3].

3.2.2.1.3 Existing Design #3: NAU Capstone 2018-2019

The NAU Capstone team used steel with a black coating for their heat absorber. They estimated that a full size 4' x 8' model would be capable of 20,748 BTU/day at a price of around $900 [18].

3.2.2.2 Subsystem#2: Heat Transfer Mechanism

Fans are used to blow the inside air through a duct. An attic fan is used to exhaust hot air out of the home. The attic fan makes sure the home does not get too hot. They regulate the temperature better than regular vents do. Attic fans allow moisture to escape [20]. Excess moisture in a home can lead to mold and bacteria growth in an attic which could spread to different parts of the home. The team will need to select a fan for their solar furnace design.

3.2.2.2.1 Existing Design #1: Your Solar Home

The Your Solar Home has a DC fan with ball bearing built in. The fan has solar electric power with 14.5 watts and a fan service life of 70,000 hours. The flow rate is 151 CFM [2].

3.2.2.2.2 Existing design 2: Solar Arctica

They also have a 4" air outlet and 4" air inlet on the back of the PV panel. The fan is powered through the solar panels so electrical wiring is not needed. Air comes in form the bottom of the heater and flows out of the exhaust located at the top of the heater [3].

3.2.2.2.3 Existing Design #3: NAU Capstone 2018-2019

The NAU Capstone 2018-2019 team used a small computer fan in their solar furnace design. This fan was used to regulate the air flow around the solar furnace [18].

3.2.2.3 Subsystem#3: Front Panel Design/Material

The front panel design is important because the inner parts of the solar panel must be enclosed by a material. Glass such as polycarbonate or plexiglass is commonly used in solar furnace designs. The price of the material used is important because a highly important customer need is lowering the overall price of the solar furnace.

3.2.2.3.1 Existing Design #1: Your Solar Home

The front panel is protected with tempered glass and has polyisocyanurate and R4 insulation. This is a great R-value for conducting heat transfer. The higher the R-value then the better the insulation is. The frame material is an aluminum extrusion. The team must choose a higher R-value for their solar furnace design [2].

3.2.2.3.2 Existing Design #2: Solar Arctica

The PV panel is 383.379" by 64.950." Arctica Solar claims this is designed for 1500 W/hr/day which would heat about 150ft^2 of living space. On a sunny day, temperature can be heated 75° F higher than the ambient air temperature. The PV panel is about 50 lbs which is much lighter than the team's current engineering requirement. It is made of an aluminum housing with a tempered glass and "high R-value insulation" [3].

3.2.2.3.3 Existing Design #3: NAU Capstone Team 2018-2019

The NAU Capstone Team 2018-2019 used polycarbonate to protect their solar furnace. They used wood to enclose their design due to price. The longevity of the choice of using wood is questionable because they have not built a full-scale model but only a prototype [18].

3.2.3 Subsystem #4: Casing Design & Material

3.2.3.1.1 Existing Design #1 Your Solar Home

The Your Solar Home model has a metal casing. The frame material is an aluminum extrusion, manufactured to be highly durable [2].

3.2.3.1.2 Existing Design #2 Solar Arctica

The Arctica Solar design is made of an aluminum housing with a tempered glass and "high R-value insulation" to reduce heat loss through the boundaries of the system [3].

3.2.3.1.3 Existing Design #3 NAU Capstone 2018-2019

The NAU Capstone Team 2018-2019 used wood as their enclosing to contain the insides of the solar furnace. Wood was used for the cheap price and the availability of the item such as a Home Depot [18].

4 CONCEPT GENERATION

Generating concepts is one of the most important stages of design, as it is the foundation for a feasible design in the future. In order to create the designs that will discussed below, the Red Feather capstone team utilized a morph matrix. This morph matrix contained five distinct design features that contributed to twenty concept variants. A decision matrix was then employed to evaluate these designs, resulting in the three full system concepts that will be discussed below. The morph matrix and decision matrix can be seen in figures A-1 and A-2 of appendix A and will be discussed in more detail in the following Full System and Subsystem Concept sections of the report.

4.1 Full System Concepts

Using the morph matrix, discussed in detail later in this report, 20 unique concepts were generated. In order to determine the most suitable designs, a decision matrix was utilized. Using this decision matrix, seen in figure A-1 of appendix A, the 20 concepts were narrowed down to the three highest scoring designs. The criteria for the decision matrix are explained in section 5 of this report. Those three full system designs are described in detail below.

4.1.1 Full System Design #1: Wood Casing/Air Gap/Corrugated Fins/Plexi Glass

Developed using the morph matrix, this design is cheap, durable, and partially insulated. This design utilizes an entirely wooden casing, with in air gap between the inner geometry and an extra outer shell. The air gap will insulate the heat absorbing portion of the system. To transfer the heat into the home, a low power DC fan will be utilized. Corrugated fins increase the surface area of the heat absorbing geometry. This design can be seen below in figure 10.

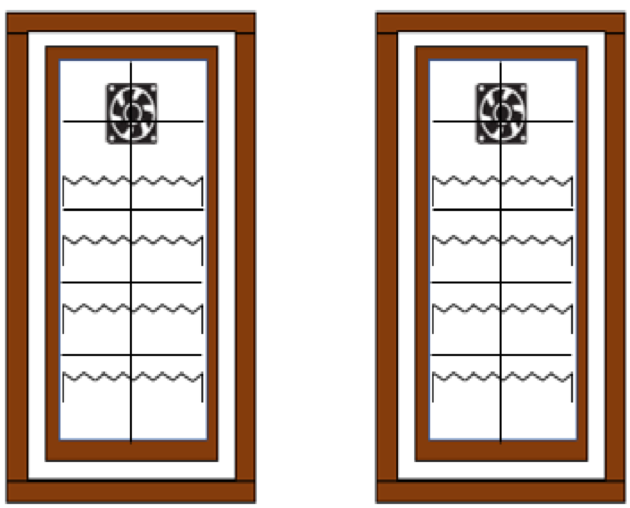


Figure 10: Corrugated Fins + Fan + Composite Plexi Glass + Air Gap

4.1.2 System Design #2: Wood & Metal Casing/Corrugated Fins/Plexi Glass

Developed using the morph matrix, this design is also cheap, and durable, and slightly insulated. This design utilizes a metal casing around the inner heat absorbing geometry, with a thin wood outer casing to increase insulation. To transfer the heat into the home, a low power DC fan will be utilized. Corrugated fins increase the surface area of the heat absorbing geometry. This design can be seen below in figure 11.

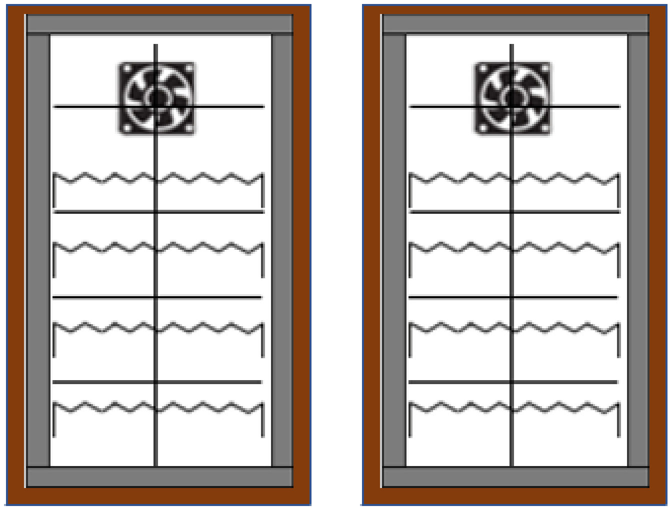


Figure 11: Corrugated Fins + Fan + Composite Plexi Glass + Metal/Wood Casing

4.1.3 Full System Design #3: Wood Casing/Corrugated Fins/Plexi Glass

Developed using the morph matrix, this design is also cheap, and durable, though it lacks insulation. This design utilizes a single wood outer casing. This design would be the most cost effective, but would be the least insulated, though wood does have a low thermal conductivity compared to most metals. To transfer the heat into the home, a low power DC fan will be utilized. Corrugated fins increase the surface area of the heat absorbing geometry. This design can be seen below in figure 12.

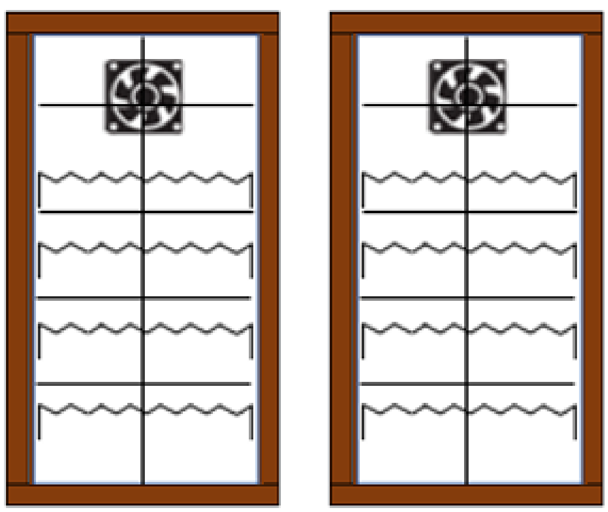


Figure 12: Corrugated Fins + Fan + Composite Plexi Glass + Metal/Wood Casing

4.2 Subsystem Concepts

In order to develop the three designs discussed above, a much larger pool of concept variants was first created. This was accomplished using a morph matrix seen in figure A-2 of appendix A. Mentioned above, there were five separate design components included in the morph matrix: The heat absorber (inner geometry), the heat transfer mechanism, the front panel design (heat window), the front panel material, and the case design/material. Possible concepts for all five of these subsystems will be discussed below. The front panel design and material will be discussed in the same section (4.2.3).

4.2.1 Subsystem #1: Heat Absorber (Inner Geometry)

The heat absorber generates heat by exposing a metal surface to sunlight to generate heat from the solar radiation. The heat generated is then transferred to the air inside the box and conveyed into the space to be heated. A higher thermal conductivity material and higher surface generally creates more heat.

4.2.1.1 Design #1: Flat Plate

The flat plate designs utilize a simple sheet of metal painted black to generate heat. It has a relatively low surface area compared to the other designs but is simple and cheap to implement.

4.2.1.2 Design #2: Corrugated Plate

The corrugated plate design uses a corrugated sheet of steel to generate heat. It would be as simple as the flat plate to install but has a slightly higher surface area to generate heat with.

4.2.1.3 Design #3: Fins with a Flat Plate

The design uses fins paired with a flat back plate to generate heat. This was the design used by the last capstone team. It creates more surface area for heat generation at the expense of increased complexity and cost.

4.2.1.4 Design #4: Corrugated Fins with a Flat Plate

This design uses fins made from corrugated sheet metal to generate heat. It is the same design as #3 but uses corrugated metal to increase the surface area of the fins and generate more heat.

4.2.2 Subsystem #2: Heat Transfer Mechanism

In order to heat the home, hot air needs to be forced into the desired room, and room temperature air needs to be drawn back into the furnace. This is accomplished by a low power DC fan that forces the circulation of air.

4.2.2.1 Design #1: DC Fan

The DC fan will use a simple DC electric fan powered by a small photovoltaic solar panel to force air through the system. The forced air increases convection and a heat transfer into the home. The photovoltaic can be moderately expensive (~$50) and the fan will need to be long lasting and able to withstand the heat of the air.

4.2.2.2 Design #2: Passive Air Flow

The passive airflow design uses the temperature potential created by the heat difference between the interior of the solar furnace and the home to move heat. It is very inexpensive to implement but reduces the amount of convection and airflow into the home.

4.2.3 Subsystem #3: Front Panel Design & Material

The way solar energy enters the furnace is through a translucent panel on the front of the furnace. This "window" needs to be resistant to long term sun exposure, as well as natural weather variations. This front panel also needs to withstand any possible vandalization (i.e. rocks, bb guns, etc.).

4.2.3.1 Design #1: Composite Window

The composite window design will use multiple pieces of material glued together. This creates cheaper prices for window material and allows individual panes to be replaced should one be damaged. The main con is that the pieces will need to be fixed together which could block some light.

4.2.3.2 Design #2: Single Sheet

The single sheet design uses one sheet of material to create a window. This window would allow the most light through but increases cost. Furthermore, if the window were damaged or broken the entire thing would need to be replaced.

4.2.3.3 Design #3: Plexi-Glass

Plexi-Glass is made from acrylic and offers a strong, clear window that is more affordable than glass. It is shatterproof, light, and easy to cut. It also does not degrade in sun and remains clear for decades.

4.2.3.4 Design #4: Tempered Glass

Tempered glass is extremely clear and allows a large amount of light through. It is the preferred material in commercial designs due to its high performance. It is expensive and can be shattered.

4.2.3.5 Design #5: Polycarbonate

Polycarbonate is a cheap plastic material that is resistant to impact and damage. The plastic degrades with exposure to the sun and clouds over time, reducing its ability to let light through.

4.2.4 Subsystem #4: Furnace Casing

All of the subsystems discussed above need to be contained within the same system. This outer casing can be made of a range of materials, though for affordability, they are usually constructed with wood or a cheap metal (steel/aluminum).

4.2.4.1 Design #1: Wood

A wood casing is a viable option for two main reasons. First, wood is cheap and widely available. Second, wood has a low thermal conductivity, so it is basically self-insulated. Wood, however, can be heavy depending on the amount used, and is not always weather resistant.

4.2.4.2 Design #2: Polymer

The idea of a polymer casing was discussed purely for weight measures. Unfortunately, a design made of polymer would be expensive to custom manufacture, and most likely would not hold up to durability standards. Most designs utilizing this concept did not score well in the evaluation stage.

4.2.4.3 Design #4: Metal

Metal is a possible casing material since it will increase heat absorption within the inner geometry. Unfortunately, due to its high thermal conductivity there will be a higher heat loss associated with a metal case. Depending on the metal, the system could be lighter if something like aluminum is utilized however, some metals can be somewhat expensive to obtain.

4.2.4.4 Design #5: Insulation

Any heat lost during generation relates directly to a necessary increase in overall generation. Use of some type of insulation would theoretically reduce this heat loss by a significant amount. Insulation however can be unhealthy if inhaled, and somewhat difficult to work with.

4.2.4.5 Design #6: Air Gap

This idea is very similar to insulation concept above. In order to reduce heat loss during generation, an air gap will be used as an insulator. Air is an affordable, and fairly effective insulator.

5 DESIGNS SELECTED – First Semester

After creating the final designs using the morph matrix, the team evaluated them against selection criteria based on their engineering requirements. These selection criteria were used to create a decision matrix where each of the designs were evaluated. The final three designs were presented to the client for their input and a final design was chosen.

5.1 Technical Selection Criteria

As discussed, a decision matrix as shown in figure A1, was used to evaluate all twenty concept variants. These variants were assessed on four distinct criteria of different weighting: cost (35%), heat Generation (35%), manufacturability (15%), and durability (15%). Cost is weighted highly due to the client's specification that the model needed to be as affordable as possible, and much lower in price than current commercial options. Heat generation is also weighted at 35% because the ultimate purpose of the device is to generate heat. Manufacturability was included, but weighted much lower, because Red Feather Development Group volunteers need to be able to construct the device themselves, as a cost saving measure. The fourth criterion was durability, the device needs to be reliable to function for as long as mechanically possible. This was weighted at 15% because although being a very necessary engineering requirement, all evaluated designs were considered to meet minimum durability. This criterion was intended to slightly boost the scores of designs constructed from materials such as metal instead of wood.

5.2 Rationale for Design Selection

All designs were evaluated using the criteria defined above and the two best design selections were the concepts that scored the highest. The two top designs were the metal and wood cased furnace, and the wood cased furnace with an air gap. These designs can be seen below in figure 13.

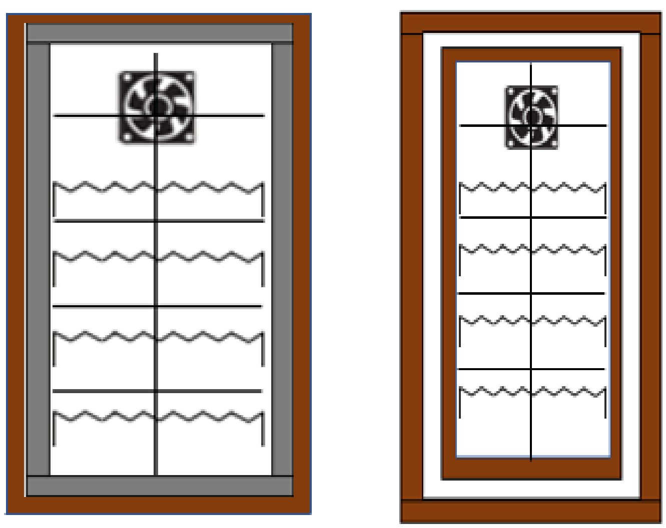


Figure 13: Final Design Choices

6 REFERENCES

[1] "Red Feather Solar Furnace 2," *Northern Arizona University*, Jan-2020. .

[2] *SolarSheat 1500GS*. Your Solar Home Inc. 2019. [Online]. Available:https://static1.squarespace.com/static/5272dc2ce4b0793e8f87f40d/t/528cc5cfe4b06e6e83ebe65d/1384957391688/1500GSSpecs.pdf. [Accessed: 2 February 2020].

[3] *Arctica Solar Fully Integrated Solar Air Heater - 1500 Series*. Arctica Solar, 2019. [Online]. Available: http://www.arcticasolar.com/product/1500_series_datasheet_v2.pdf. [Accessed: 2 February 2020]

[4] Thermal Conductivity of Metals, Metallic Elements and Alloys. Engineeringtoolbox.com, 2020. [Online] Available: https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html [Accessed 13 March 2020].

[5] T. L. Bergman, A. Lavine, and F. P. Incropera, *Fundamentals of heat and mass transfer*. Hoboken, NJ: John Wiley & Sons, Inc., 2019.

[6] *The Efficient Use of Energy*, 1982. Electrical heating fundamentals. pp.94-114. [Online]. Available: https://doi.org/10.1016/B978-0-408-01250-8.50016-7. [Accessed: 13 March 2020]

[7] *Table of Emissivity of Various Surfaces*. Mikron Instrument Company, Inc, 2020. [Online] Available at: http://wwweng.lbl.gov/~dw/projects/DW4229_LHC_detector_analysis/calculations/emissivity2.pdf. [Accessed 13 March 2020].

[8] C. J. Colon and T. Merrigan, "Roof Integrated Solar Absorbers: The Measured Performance of 'Invisible' Solar Collectors," *National Renewable Energy Laboratory*, 21-Apr-2001. . DOI: https://www.nrel.gov/docs/fy01osti/30848.pdf

[9] M. Trimarchi, "How Solar Thermal Power Works," *HowStuffWorks Science*, 27-Jan-2020. [Online]. Available: https://science.howstuffworks.com/environmental/green-tech/energy-production/solar-thermal-power.htm. [Accessed: 12-Mar-2020].

[10] "Solar Thermal vs. Photovoltaic," *Solar Thermal Energy: Solar Thermal vs. Photovoltaic*. [Online]. Available: http://www.solar-thermal.com/solar_vs_pv.html. [Accessed: 12-Mar-2020]. DOI: http://www.solar-thermal.com/solar_vs_pv.html

[11] M. D. Egan, *Concepts in thermal comfort*. Englewood Cliffs, NJ: Prentice-Hall, 1975.

[12] I. Dincer and S. Dost, "A perspective on thermal energy storage systems for solar energy applications," *International Journal of Energy Research*, vol. 20, no. 6, pp. 547–557, 1996.

[13] I. Dincer, "On thermal energy storage systems and applications in buildings," *Energy and Buildings*, vol. 34, no. 4, pp. 377–388, 2002.

[14] M. Grimwood, "Earthships: DIY Fully Sustainable Off-Grid Living: A 2020 Guide," *Renewable Resources Coalition*, 02-Dec-2019. [Online]. Available: https://www.renewableresourcescoalition.org/earthships/. [Accessed: 11-Mar-2020].

[15] "PA Solar," *Lesson 3: Solar Water-Heating Systems; Siting and Sizing | Pennsylvania SolarCourse*. [Online]. Available: https://pasolar.ncat.org/lesson03.php#volume. [Accessed: 11-Mar-2020].

[16] "Calculate How Many BTUs are Needed to Heat Home," *Inch Calculator*. [Online]. Available: https://www.[15]ulator.com/calculate-btus-to-heat-home/. [Accessed: 11-Mar-2020].

[17] M. Sadiq, “Solar water heating system for residential consumers of Islamabad, Pakistan: A cost benefit analysis,” *Journal of Cleaner Production*, vol. 172, pp. 2443–2453, 2018.

[18] *Red Feather Thermal Energy for Homes*. Northern Arizona University College of Engineering, Informatics, and Applied Sciences, 2019. [Online]. Available: https://www.cefns.nau.edu/capstone/projects/ME/2019/19S1_RedFeather/files/Final%20Poster.pdf

[19] L. Richardson, “How Do Solar Panels Work? Step by Step Guide: EnergySage,” *Solar News*, 18-Feb-2020. [Online]. Available: https://news.energysage.com/solar-panels-work/. [Accessed: 14-Mar-2020].

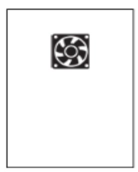
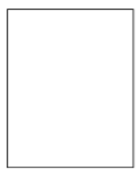
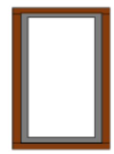
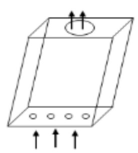
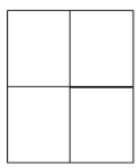
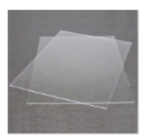
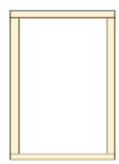
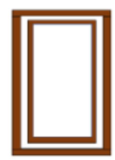
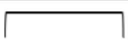
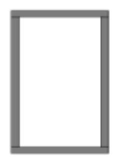
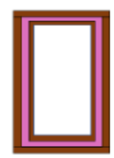
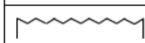
[20] Sierra Pacific. 2020. *Solar Attic Fans And Impact On Home*. [online] Available at: <https://www.pacifichome.com/blog/solar-energy/solar-attic-fans-impact-your-home/> [Accessed 8 March 2020].

7 APPENDICES

7.1 Appendix A: Concept Generation and Selection Tools

Redesign																					
Criteria	**Weight**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Cost	**0.35**	3	2	3.5	2	3	2	4	3	3.5	4	3	2.5	2.5	4	3	3	3	4.5	4	5
Heat Gen	**0.35**	4.5	4.5	4	4	3.5	3.5	3	3	2.5	2.5	2.5	3	3.5	2	3	3.5	2	2.25	2.5	1.5
Manufacturability	**0.15**	4	4	4.25	3	3.5	3	4	4	4	3.5	3.5	3	2.5	4	3	4	4	3.5	3.5	4
Durability	**0.15**	4	4.5	4	4.5	4	3.5	3	3	4.5	3	3	2	3	2.5	2	2	4	4	4	2
Sum (out of 5)	1	**3.83**	**3.55**	**3.86**	**3.23**	**3.40**	**2.90**	**3.50**	**3.15**	**3.38**	**3.25**	**2.90**	**2.68**	**2.93**	**3.08**	**2.85**	**3.18**	**2.95**	**3.49**	**3.40**	**3.18**

Figure A1: Decision Matrix

Heat Generation	Heat Transfer (to home)	Front Panel Design	Front Panel Material	Case	Case Cont.
 Flat plate	 Forced air (fan)	 Single sheet	 Tempered Glass	 Wood	 Wood/Metal
 Corrugated plate	 Passive air flow	 Composite	 Plexi-glass (Acrylic)	 Polymer	 Air Gap
 Fins			 Polycarbonate	 Metal	 Insulated
 Corrugated Fins					

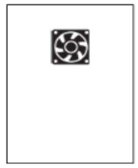
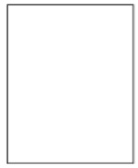
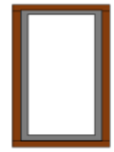
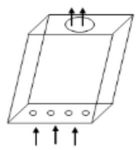
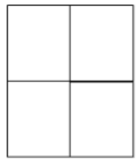
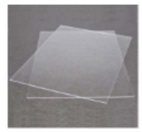
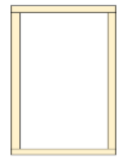
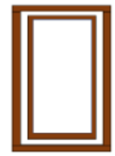
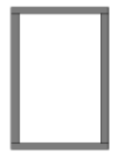
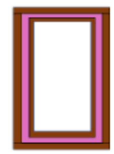
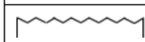
Heat Generation	Heat Transfer (to home)	Front Panel Design	Front Panel Material	Case	Case Cont.
 Flat plate	 Forced air (fan)	 Single sheet	 Tempered Glass	 Wood	 Wood/Metal
 Corrugated plate	 Passive air flow	 Composite	 Plexi-glass (Acrylic)	 Polymer	 Air Gap
 Fins			 Polycarbonate	 Metal	 Insulated
 Corrugated Fins					

Figure A-2: Morph Matrix