MEMO

To: Brent Nelson

From: Team 13: Saleh Alsadiq, Matt Beckham, Austin Chott, Thomas Griffin, Chris Heine

Date: 12/17/2013

Re: ULC Solar Water Heater Proposal

The attached proposal includes three designs for the Ultra-Low Cost Solar Water Heater. One each for three different applications: industrial, practical home use, and do-it-yourself. The commercial design is most applicable for an industrial use such as a factory or business where hot water is in high demand throughout the year. The practical home use design will be most applicable in a home where cost is important and the water demand is highest in the morning and the evening. We will be prototyping the do-it-yourself design which will include a circulation system. This design was chosen based on the cost per area per dollar analysis of our concept designs. Detailed analysis for these designs can be found in the attached proposal.

Commercial Design:

The commercial design will utilize a parabolic collector with black, painted, galvanized steel pipes and exclude any recirculation.

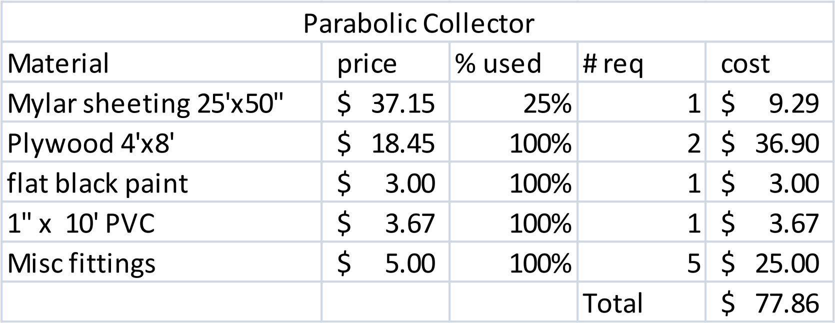
Practical Home Use Design:

The practical home use design will utilize a parabolic collector with black, painted, galvanized steel pipes and an active circulation system to maximize the hot water output of the system.

Do-It-Yourself:

The practical home use design will utilize a parabolic collector with black PVC and a passive circulation system to minimize cost while greatly increasing the absorption of the collector.

Estimated Prototype Cost:



Parabolic Collector				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	25%	1	$ 9.29
Plywood 4'x8'	$ 18.45	100%	2	$ 36.90
flat black paint	$ 3.00	100%	1	$ 3.00
1" x 10' PVC	$ 3.67	100%	1	$ 3.67
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 77.86

Ultra Low Cost Solar Water Heater

By
Austin Chott, Chris Heine, Matt Beckham, Saleh Alsadiq,
Thomas Griffin
Team 13

Final Proposal

Document

Submitted towards partial fulfillment of the requirements for
Mechanical Engineering Design I – Fall 2013

Department of Mechanical Engineering
Northern Arizona University
Flagstaff, AZ 86011

1. Introduction

1.1 Client's Point of View

In the United States, a high startup cost combined with a lack of knowledge about solar water heaters has contributed to low usage. Solar water heaters are a viable way of reducing energy consumption as well as reducing a household's carbon footprint. Solar energy is abundant and free which makes it the best option for a low cost energy source. Many factors must be considered when looking to reduce cost and improve or maintain efficiency of solar water heaters.

The U.S. Environmental Protection Agency (EPA) wants to change how solar water heaters are perceived which drove them to fund the project through the P3 – People, Prosperity, and the Planet Award Program. This program gives students the opportunity to research, develop, and design solutions to real world problems involving the sustainability of society as a whole. This program was developed in order to meet the technical needs of society in relation to a sustainable future. The following document contains all the information that has been gathered thus far and provides a final proposal solution to the overall problem.

1.2 Problem Statement

Current solar water heaters are too expensive and it takes a long period of use to make them financially sensible. Therefore, current solar water heater designs are financially impractical over a short period of use.

The solution to this need is to design a low cost solar water heater that is efficient enough to produce a quick financial return.

1.3 Objectives and Constraints

Below is a list of all the objectives and constraints. Our main operating environment will be outdoors and this will be reflected throughout all the descriptions.

- Heats Water: The objective of this project is to create a low cost solar water heater that heats water by solar convection.
    - Constraint: Potable Fluid Temperature (^{o}C): This solar water heater will maintain a specified temperature throughout a 24hr period.
- Weather Proof Design: The solar water heater must be weather proof since water heaters will typically be outside, either in a yard or mounted on a roof.
    - Constraint: Durability (Pa & Km/hr): The solar water heaters must be able to withstand high wind speeds; impact forces from hail, rain and debris; and in some cases, pressures from snow.
- Low Initial Cost: One significant problem with solar water heaters currently in the market is the initial cost of the heater is too expensive, and therefore requires the need of long-term use before there is a financial return.

  - Constraint: Break-Even Cost (USD): Things that influence the initial cost of the solar water heater are: materials used, complexity of the design, quantity of materials used, difficulty of manufacture and difficulty of production. As any of these cost multipliers increase, initial cost will increase.

- Low Maintenance Cost: The cost of maintenance should also be low to optimize break-even cost.

  - Constraint: Routine Maintenance Cost/Frequency (USD/Years): Frequency of maintenance should be at reasonable intervals varying slightly between geographical regions as well as daily use.

- Quick Financial Return: A solar water heater must show positive capital quickly in order for it to appeal to the general public.

  - Constraint: Break-Even Cost (Years): The solar water heater must conserve energy while maintaining a satisfactory working temperature of the potable fluid. Sacrifices in efficiency must be balanced with initial cost to obtain a quick financial return.

- Implemented into Current Water Heating Systems: A high percentage of houses in the world have an existing water heating system currently installed. Many systems which use solar heat also use gas or electricity for times when solar energy is not available.

  - Constraint: Able to be integrated into Current Systems (yes/no): To maintain marketability and appeal it is crucial for the solar water heater to be easily integrated into current water heating systems. The ease of installation will be measured with a yes/no metric based on surveyed data.

- Safe Operation: Operating the solar water heater should be safe under all condition.

  - Constraint: Safety (yes/no & ^{o}C): Safety and energy conservation are factors to be considered when selecting the water temperature setting of a water heater. High water temperatures can cause severe burns or death from scalding. The solar water heater design should meet all government safety standards and regulations.

- Sensible System Size: A properly sized water heater system will provide a significant portion of a home's hot water.

  - Constraint: Size (m^3): A water heater should be easily contained inside a house or apartment. The system size should not be a restraining factor.

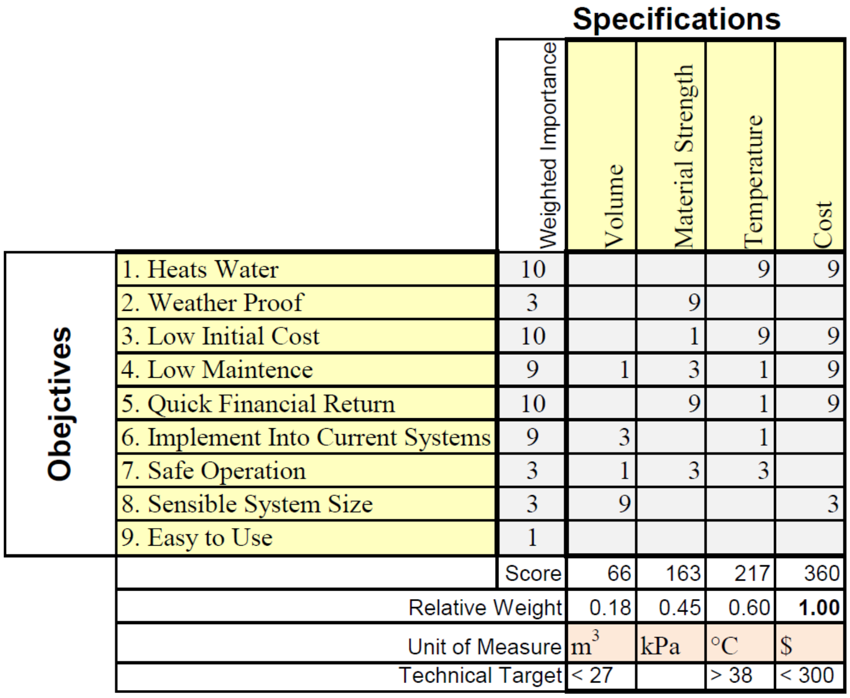
Table 1: Objectives and Constraints

Objective	Constraint	Units
Heats Water	Potable Fluid Temperature	degrees C
Weather Proof	Durability	Pa
Low Initial Cost	Break Even Cost	USD
Low Maintenance Cost	Maintenance Cost	USD
Quick Financial Return	Break Even Cost	Years
Implementation	Able to be Integrated	yes/no
Safe Operation	Safety	yes/no
Sensible System Size	Size	m^3

1.4 QFD

The Quality Function Deployment matrix (QFD) is used to break the project down to find what the most important specifications are for the given problem. It is used to help engineers focus in on viewpoints of the company, marketing, and technological needs of a given project. The QFD below goes over the objectives and constraints in designing a low cost solar water heater.

Table2: Quality Function Deployment Matrix



Specifications

Obejctives	Weighted Importance	Volume	Material Strength	Temperature	Cost
1. Heats Water	10			9	9
2. Weather Proof	3		9		
3. Low Initial Cost	10		1	9	9
4. Low Maintence	9	1	3	1	9
5. Quick Financial Return	10		9	1	9
6. Implement Into Current Systems	9	3		1	
7. Safe Operation	3	1	3	3	
8. Sensible System Size	3	9			3
9. Easy to Use	1				
	Score	66	163	217	360
	Relative Weight	0.18	0.45	0.60	**1.00**
	Unit of Measure	m^3	kPa	°C	$
	Technical Target	< 27		> 38	< 300

1.5 State of the Art Research

Based on prior research it was found that current Solar water heaters in the US cost 5,000 to 10,000 USD which presents the problem and our needs for our team. Our analysis considers this high price for a commercial solar water heater sold in the US and reduces the cost by using parts found from local hardware stores that are significantly cheaper. Our research shows that there is also the possibility of scavenging our systems parts because it has been done in other cheap solar water heater designs and because most parts of our system can be found in construction scrap piles.

2. Original Concepts for Consideration

The main specification evaluated in this section while determining possible solutions was absorption per cost per area. Designs that did not show promise of optimal absorption per cost per area were discarded. Multiple concepts are considered for this project. Collector and circulations systems are the main aspects in the solar heater. Several options for both systems are briefly described in this section.

2.1 Collector Systems

2.1.1 Involute Curve Solar Collector

An involute curve solar water heater consists of a system of one or more stationary parabolic or involute collectors focused on a cylindrical absorber as shown in Figure 1. The involute curve allows for nearly all the radiation energy from the sun to be directed to the absorber and subsequently absorbed and transferred to the fluid. Through the geometry of the involute curve the solar rays will bounce off the reflectors any number of times always being directed to the absorber. What makes this collector unique is the placement of the absorber. A hot air trap is created by placing insulation above the absorber so the heat cannot escape easily. By retaining more heat in proximity to the absorber the fluid stays at a higher temperature. A study done by Smyth in 1989 showed that involute solar water heaters retained 60% of the collected solar energy for a 16 hour non-solar period.

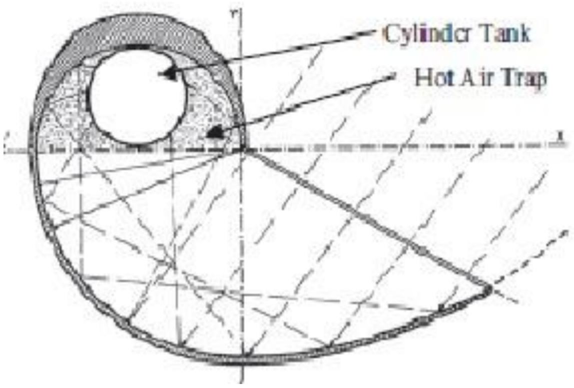


Figure 1: Involute Curve Collector

- Variations of this design include: a system of multiple absorber tubes housed in parabolic crescents, double parabolic curves with an absorber placed in the center, and two absorbers stored in an involute curve. Figures 2 and 3 below show diagrams of the various designs.

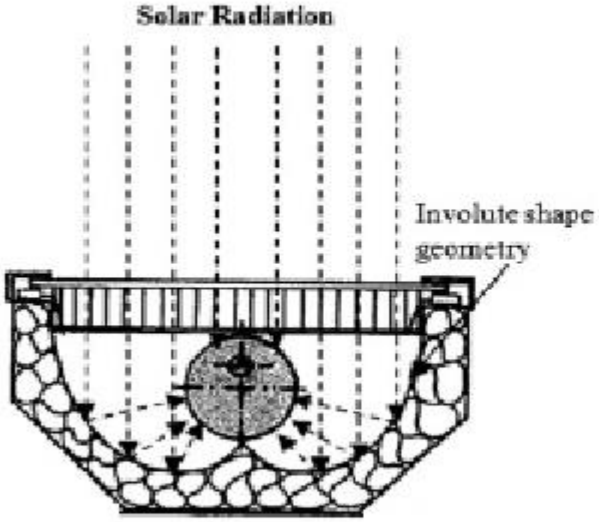


Figure 2: Tank Centered Between Two Involute Curves

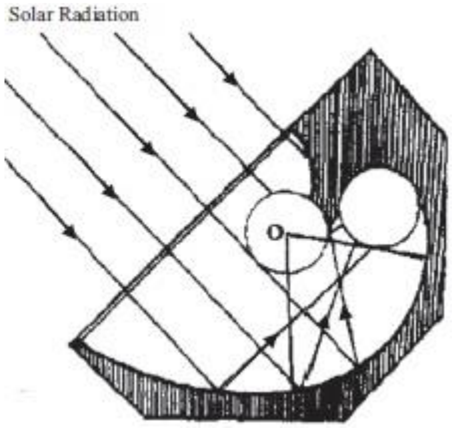


Figure 3: Involute Curve Collector with Two Tanks

- The involute solar water collector paired with a passive circulation system provides a very high absorption per cost per area ratio. The biggest benefit of passive circulation is the high ratio of absorption per cost.

- (Note: The involute concept was later changed to a similar parabolic concept, and that will be explained and reflected in the engineering analysis section.)

2.1.2 Flat Plate Solar Water Heating System Utilizing Passive Circulation

The solar radiation is absorbed by Flat Plate Collectors which consist of an insulated outer metallic box covered on the top with glass sheet as shown in Figure 5. Inside there are blackened metallic absorber sheets with built in channels or riser tubes to carry water. The absorber absorbs the solar radiation and transfers the heat to the flowing water. The water passing through the collector is then delivered to an insulated storage tank. The insulated box provides structure and reduces heat loss from the back or sides of the collector. The absorber plate surface is painted or coated to maximize radiant energy absorption. Absorber plates are usually made of high-thermal-conductivity metals. Choice of materials and design aspects can greatly affect not only the solar thermal performance but most importantly the overall cost of the system. High-temperature rigid-foam insulation, low-iron tempered glass, and aluminum frames are the most common materials.

The main advantage of flat plate solar collectors over other designs is their price. Even though recent trends in collector's technology closed part of the gap, flat-plate solar collectors are still a cheaper solution. However, freezing conditions may limit the efficiency of a flat plate collector because flat plate collectors are subject to a high heat loss factor. Because of this it is mostly used in warm and mild climates.

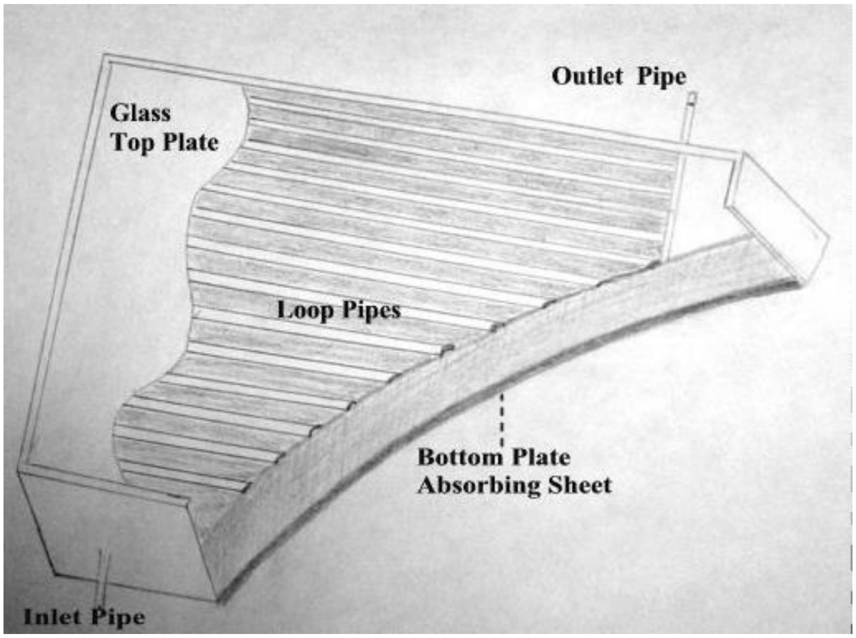


Figure 4: Flat plate collector

2.1.3 Breadbox Solar Water Heater Utilizing Active Circulation

The bread box solar water heater design utilizes a large frontal area of capture so that a large amount of solar radiation can be absorbed and stored. The basic concept is that a stripped black tank is mounted inside some kind of box and tilted towards the sun. A piece of dual pane glass is placed on top of the box so that the solar radiation can move into the box with the tank, but it cannot escape. The goal is to trap as much heat inside the box as possible without letting any of that heat out. This trapped heat moves through the tank and into the tank where the water is stored. Angled light reflectors will be connected to three of the four sides to direct as much light as possible into the area where the tank of water sits.

The main advantage of this design is its simplicity and the ability to store and heat water at the same time. The bread box design is something that almost anyone can build and utilize with simple knowledge and materials. This simplicity allows for a low initial cost of building but it may not be as efficient as some of the other proposed designs. The other advantage is the ability to heat and circulate water in the same vessel. There is no need for a storage tank to keep the water warm. This helps the user because he or she can just take from the hot water supply as needed. This advantage greatly reduces overall cost compared to the other proposed systems. If the cost of materials can be severely minimized and the efficiency can get to a moderate level, than the bread box design shows the most promise for a final concept.

The bread box design must utilize an active system of circulation. Although the active system is less cost effective, this concept can use the pressure provided by the city to pump the cold water to the home. This lowers cost because the user doesn’t have use an outside pump to move the water through the system. The water is going to move as fast as the pressure the city provides moves it. This allows for the cold water to be heated up longer because it is going to sit in the tank a little longer than if you pump the water in and out of the tank. Below is a simple graphic of the structure of a bread box designed solar water heater.

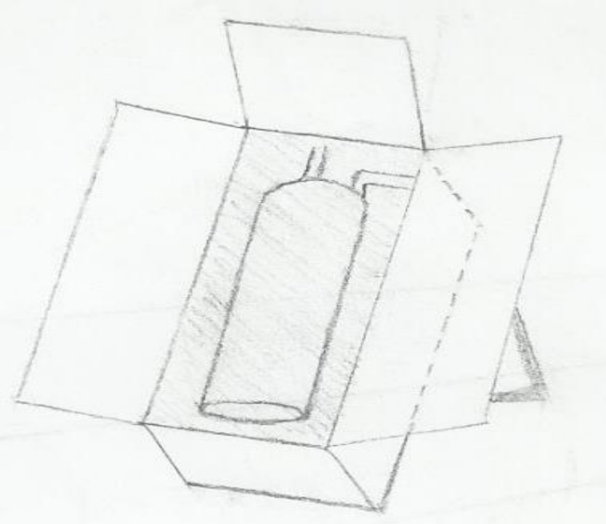


Figure 5: Bread Box Solar Water Heater

2.2 Implementation and Circulation

Our SWH will be integrated through the cold water inlet to an existing water heater. There will be a simple valve system shown in Figure 6 which will allow the homeowner or tenant to shut off water flow to the SWH and use the existing water directly from the source. It will require two T joints to be installed directly above the cold water inlet to the existing water heater. The pre-heated water from the solar water heater will return back to the original inlet allowing the existing water heater to function as originally intended.

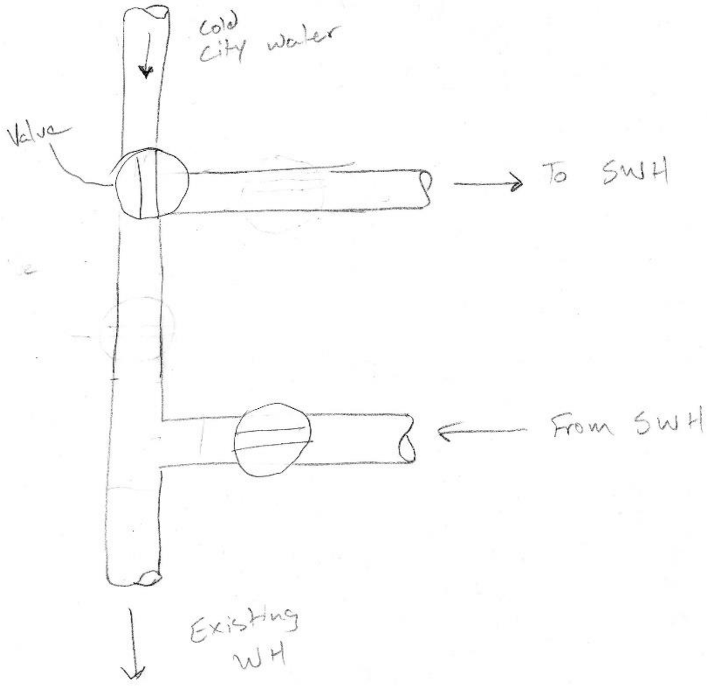


Figure 6: Integration schematic

2.2.1 Active Circulation System

In the active system concept, water is drawn from the original source and fed into a secondary storage tank. From there, a pump draws the water out of the tank and feeds it to the collector at an efficient rate. The water is heated in the collector and flows back into the tank. This process gradually raises the average temperature of the tank. When the existing water heater draws water, it is taken from this tank. It is important to note that a pressure release valve must be placed in the secondary storage tank to avoid a dangerous buildup of gasses.

2.2.1.1 Advantages and Disadvantages

There are several advantages to using an active circulation system. First, an active system allows more freedom in implementation. This system makes the position of the collector irrelevant to the position of the secondary storage tank. Second, this system may yield much higher system efficiencies by allowing much more control of the flow rate of fluid through the collector. Third, this system can much more easily control when, and how much, water is drawn from the SWH.

There are also some disadvantages to this type of system, most importantly, being its cost. This type of system requires a possibly expensive secondary pump to be installed within the SWH system. Also, it is much more difficult to build and maintain, especially for the average homeowner.

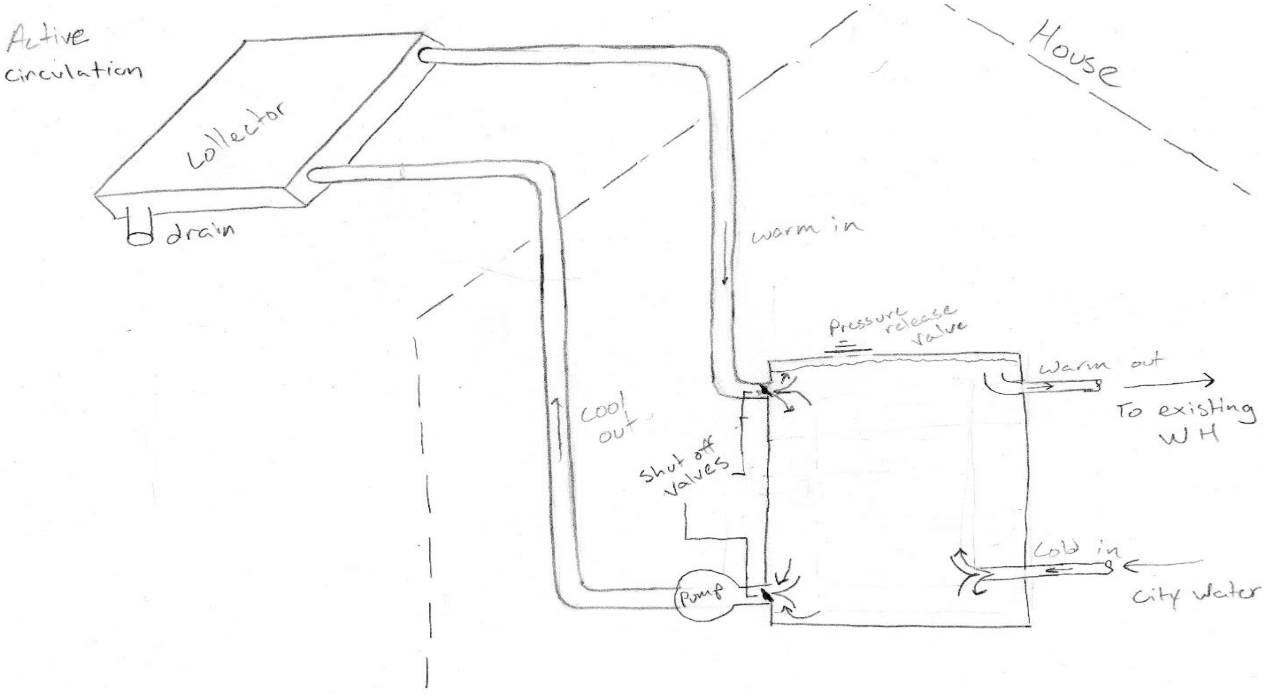


Figure 7: Active circulation system

2.2.2 Passive Circulation

In the passive system concept, water is drawn from the original source and fed into a secondary storage tank. The entire system must be filled for flow to start. This system relies entirely on a thermosyphon to move water through the collector. The collector must be placed below the storage tank in order for the thermosyphon to work. When water is heated in the collector, the resulting pressure difference causes it to rise and flow into the storage tank. A one way valve is place near the collector to ensure the flow continues to circulate. This process gradually raises the average temperature of the tank. When the existing water heater draws water, it is taken from this tank. It is important to note that a pressure release valve must be placed in the secondary storage tank to avoid a dangerous buildup of gasses.

2.2.2.1 Advantages and Disadvantages

A thermosyphon circulation system is much cheaper than an active system. This is because it does not require a secondary pump. However, the circulation is entirely dependent on solar energy. This means two things. First, without maximum solar radiation on the collector, possible on a cloudy day, the circulation is severely hindered. Second, this means that the efficiency of the SWH will be notably less than a SWH with an active system.

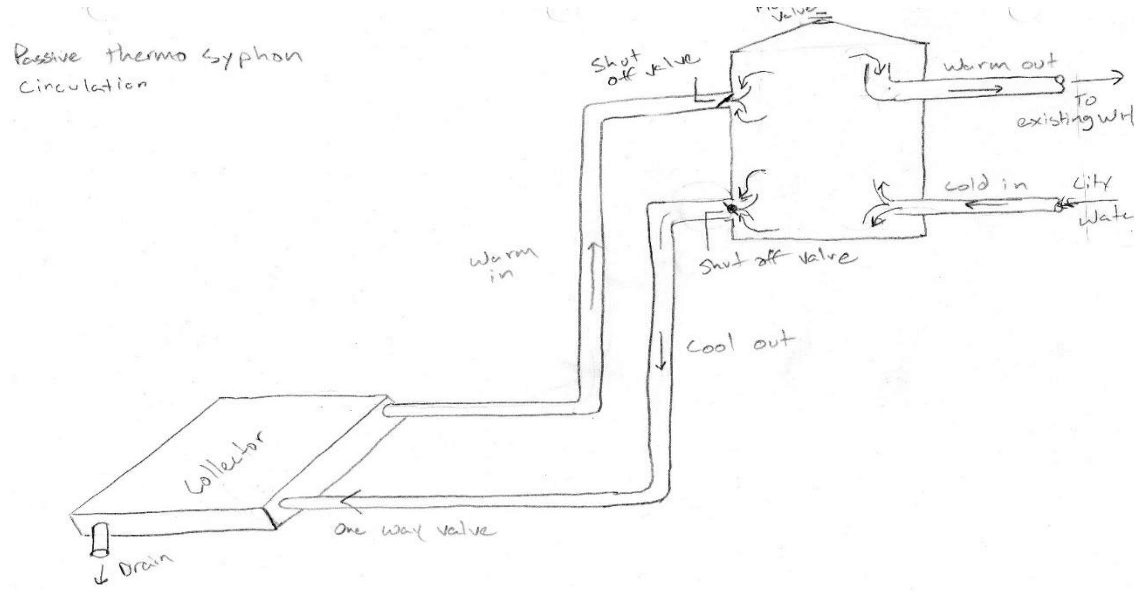


Figure 8: Passive circulation system

2.2.3 Bread Box Circulation System

The bread box collector system requires a unique, but simple, circulation system. The flow through this system is entirely dependent on the rate at which the existing water heater uses water. This is because the secondary storage tank in this SWH is also the collector. It is connected so that water flows freely through the collector at the same rate it is used in the existing water heater.

3. Decision Matrix

The decision Matrix below shows the different concepts chosen and their evaluating objectives. The main aspects of our decision matrix are absorption, area and cost. Three collector with different circulation systems options are included in the matrix. One through nine ranking scale is used to get the heights rank.

	Weight	**Involute (Active)**	**Involute (passive)**	**Parabolic (Active)**	**Parabolic (passive)**	**Flat plate (open /active)**	**Flat plate (closed /active)**	**Flat plate (open /passive)**	**Flat plate (closed /passive)**	**Bread Box**
Absorbtion	9	9	9	3	3	3	9	3	3	9
Area	9	9	9	9	9	3	3	3	3	3
Cost	9	3	3	3	3	1	1	9	3	3
Buildable	5	1	1	3	3	9	3	9	3	9
System Size	3	9	9	9	9	3	3	3	3	1
	Raw	221	221	177	177	117	141	189	105	183
	Rank	**1**	**1**	**5**	**5**	**8**	**7**	**3**	**9**	**4**

4. Engineering Analysis

The engineering analysis of the solar collectors included three different designs: Bread Box, Parabolic, and Flat Plate collector. This analysis focuses in the collectors' solar absorption per its area per its cost. Several assumptions were made to perform this analysis. Balance equation and heat transfer equations were used to obtain most of our results. Equations were conducted from the heat transfer book. We based our cost analysis of the whole system off of local hardware stores. We based our area of the systems off of the concept design of each specific collection system.

4.1 Bread Box Collector Analysis

The following will describe an analysis process designed to calculate the amount of heat transfer that can move into the water of a "bread box" style solar water heater. Figure 1 shows the layout of the physical design aspect of the bread box. It is important to note that the heat flux that hits the collector surface has been previously calculated through Excel spreadsheets. The q” value for a bread box with an area of $18m^2$ is 1309.83. Some temperature values were also properly assumed. Most values were chosen due to similar experiments that have been done on the materials used in our analysis. An engineering drawing of this design can be seen in the Appendix Figure 1.

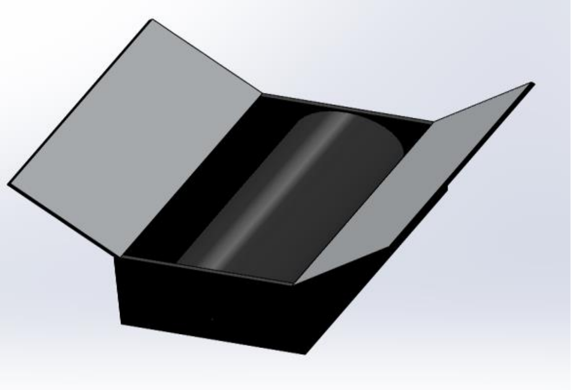


Figure 9: Bread Box Solar Water Heater

The entire analysis relies on a simple energy balance that allows you to solve for the q_{in} value. This q_{in} is the ultimate goal because it tells us how much heat transfer is making it to the water in our system. The energy balance can be seen below in. This equation stems off the fact that heat flows into the system as well as out of the system through radiation, convection, and conduction.

$$q_{solar} = q_{radiation} + q_{losses} + q_{in}$$

Where:

q_{solar} = the heat flux that hits the collector
$q_{radiation}$ = the q loss due to radiation
q_{losses} = any losses due to convection or conduction
q_{in} = heat transfer into the water

The equation that governs the losses due to radiation can be seen directly below. This equation is assuming that the medium in not inside an enclosure.

$$q_{radiation} = A_s \varepsilon \sigma (T_{s,o}^4 - T_\infty)$$

To calculate the losses due to convection and conduction, a thermal resistance network must be built. The governing equations for resistances due to convection and conduction can be seen below in the R values seen below. The resistance to convection has an h value and this value can either be assumed to be free convection of air or can be calculated. For this analysis, the h value was logically assumed and its value was made arbitrary so different scenarios could be tested.

$$R_{cond} = \frac{L}{kA}$$

$$R_{conv} = \frac{1}{hA_c}$$

$$R_{cond} = \frac{{r_o}/{r_i}}{2\pi kL}$$

Once all the resistances are known, it is possible to find the losses from ambient air to inside the bread box, and then subsequently from the inside of the box into the water. The governing equation for the losses into the box can be seen below.

$$q_{conv,air} = \frac{T_{air,i} - T_{air,o}}{R_{conv,o} + R_{cond,glass} + R_{conv,i}}$$

$$q_{cond,pipe} = \frac{T_s - T_{air,i}}{R_{pipe}}$$

By simply summing up the two above equations, we can figure out all the losses due to conduction and convection in the system. The equation below shows this relationship.

$$q_{losses} = q_{conv,air} + q_{cond,pipe}$$

The only value left to calculate is the q_{in} value. This value is governed by the q_{in} equation below.

$$q_{in} = \frac{T_{s,o} - T_{s,i}}{R_{pipe}}$$

This equation leaves us with two unknowns but if we use the energy balance, a value for $T_{s,i}$ can be easily calculated. When calculated, the $T_{s,i}$ value was 0.4K less than $T_{s,o}$. The final calculation was done to get a final value of a q_{in} = 776.7 W. This value is the amount of heat that is actually getting from the sun into the water that sits in the collector. If we know the amount of heat, a full absorption/area/cost analysis can be completed.

4.2 Parabolic Collector Analysis

During the brainstorming process our team originally thought that an involute collector would be much easier to construct accurately. This still holds true, however, using a 1 inch pipe we determined the collector would have a very small collection area. As a result, we decided to use a parabolic shape, despite the difficulties that may arise during construction. The following analysis determines the total heat transfer in to the water of a parabolic concentration collector. Figure 2 below shows the basic structure to the parabolic collector design. An engineering drawing of this collector can be seen in the Appendix Figure 2.

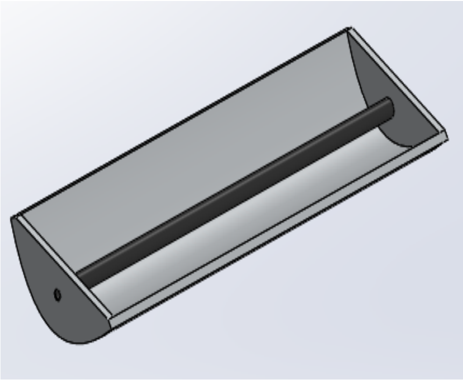


Figure 10: Parabolic Collector

From the previous methodology used to determine the total heat flow q_{solar} into the system, an energy balance must be created. Heat flows out of the system through convection and radiation, and continues to the water as q_{in}.

$$q_{solar} = q_{radiation} + q_{losses} + q_{in}$$

The heat out through radiation is determined by the following equation which assumes a small object in large surroundings.

$$q_{radiation} = A_s \varepsilon \sigma \left(T_{s,o}^4 - T_\infty\right)$$

Where A_s is the surface area of the object, in this case the pipe which the solar energy is concentrated. The emissivity $\varepsilon = .97$ for a flat black painted surface or $\varepsilon = .13$ for the surface of galvanized steel, is the emissivity of the pipe. The Stefan-Boltzmann constant $\sigma = 5.67 * 10^{-8}$. Also, $T_{s,o}$ is the outside temperature of the pipe, and T_∞ is the temperature of the outside air assumed to be 20° C. The q_{losses} also denoted $q_{conv,o}$ is the heat loss through convection on the outside of the pipe.

$$q_{conv,o} = \frac{(T_{s,o} - T_\infty)}{R_{conv,o}}$$

Where,

$$R_{conv,o} = \frac{1}{\bar{h} 2\pi r_o L}$$

is the convective resistance on the outside of the pipe. In this equation r_o is the outside diameter of the pipe, and L is the length of the pipe. In our design $r_o = .0142$ meters for a 1 in galvanized steel pipe and $L = 5$ meters. The convection coefficient $\bar{h}$ is determined by the Nusselt Number $\overline{Nu_d}$. The equation for $\overline{Nu_D}$ depends on the Reynolds Number Re_D defined by:

$$Re_D = \frac{VD}{v}$$

where V is the velocity of the outside air assumed to be 8 mph for the average wind speed in flagstaff. $D = D_o = 2r_o$ (the outside diameter of the pipe). The kinematic viscosity $v = 1.53 * 10^{-5}$ for air at an assumed 20° C. This yield a $Re_D = 6670.85$. The Prandtl Number for air at the same temperature: $Pr_o = .709$. Based on Re_D and Pr_o, the equation for Nusselt Number is:

$$\overline{Nu_D} = \frac{\overline{h_o} D_o}{k_{air}} = C Re_D^m Pr_o^{1/3}$$

Where $k_{air} = 0.0257$ is the thermal conductivity of air at 20° C, and $C = 0.193$ and $m = 0.618$ are determined by tables based on the Reynolds number. This yields an outside convection coefficient $\overline{h_o} = 35.39$ [W/m^2-K]. Substituting that into the outside convection resistance yields $R_{conv,o} = 0.06225$.

Using r_o, $r_i = 0.0217$, $k_{steel} = 54$, and L;

$$R_{cond} = \frac{\ln(\frac{r_o}{r_i})}{2\pi k_{steel} L} = 6.68 * 10^{-5}$$

Where

$$q_{cond} = \frac{(T_{s,o} - T_{s,i})}{R_{cond}}$$

$T_{s,i}$ is the inside surface temperature of the pipe.

Assuming an inside water temperature, $T_w = 293$ K a Reynolds Number must be calculated to find the inside convection coefficient $\overline{h_i}$. The Reynolds Number $Re_D = 504.27$ indicates laminar flow on the inside of the pipe. Based on the Reynolds Number, the equation:

$$Nu_D = \frac{hD_i}{k_{water}}$$

and assuming a small change in water temperature along the pipe yields $\overline{h_i} = 103.47$.

$$R_{conv,i} = \frac{1}{\overline{h_i} 2\pi r_i L} = 0.024223$$

$$q_{conv,i} = \frac{(T_{s,i} - T_{water})}{R_{conv,i}}$$

Using a thermal circuit it can be concluded that,

$$q_{in} = \frac{(T_{s,o} - T_{water})}{R_{conv,i} + R_{cond}}$$

Substituting into the energy balance equation:

$$q_{solar} = A_s \varepsilon \sigma \left(T_{s,o}^4 - T_\infty\right) + \frac{(T_{s,o} - T_\infty)}{R_{conv,o}} + \frac{(T_{s,o} - T_{water})}{R_{conv,i} + R_{cond}}$$

And solving for $T_{s,o}$, yields $T_{s,o} = 31.853$. Substituting that value into q_{in} gives the absorption of the parabolic collector,

$$q_{in} = 737.0396 \text{ W}$$

The same steps were repeated using an unpainted galvanized pipe, which gave a slightly lower $q_{in} = 514$ W.

4.3 Flat Plate Collector Analysis

The flat plate collector is the most commonly used solar collector in industrial and commercial applications which was a contributing factor to why it was chosen for analysis. A simple structure of the flat plate collector can be seen below in Figure 3. The following analysis determines the total heat transfer in to the water of a flat plate collector made from common materials. An engineering drawing of this collector can be seen in the Appendix Figure 3.

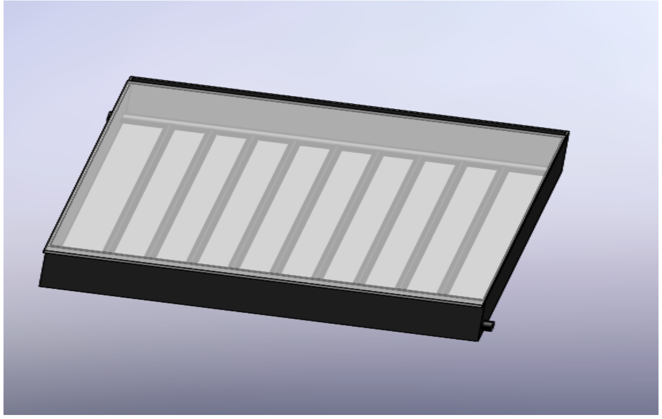


Figure 11: Flat Plate Collector

The goal of the analysis is to determine the amount of heat flux transferred into the water. To start this calculation the total amount of absorbed radiation must be calculated using the equation below. Table 1 provides typical material properties for reflectivity, absorptivity, and transmissivity.

$$q_{solar} = q_{radiation} A_s \rho \alpha \tau$$

Where:

q_{solar} = Solar irradiance at pipe surface

$q_{radiation}$ = Solar irradiance

ρ = Reflectivity

α = Absorptivity

τ = Transmissivity

Table 1: Material Properties

Material	**Reflectivity**	**Absorptivity**	**Transmissivity**
PVC		0.94	
Galvanized Metal		0.65	0.94
Mylar			0.95
Glass	0.85		
Plexiglass	0.75		
Plastic Sheeting	0.65		
Flat Black Paint		0.97	
Lava Rock		0.75	

The q_{solar} can then be used to calculate the total useful heat flux based on the equation below.

$$q_{solar} = q_{radiation} + q_{losses} + q_{in}$$

Where:

$q_{radiation}$ = Radiation heat loss

q_{losses} = Losses from convection and conduction

q_{in} = Heat flux into the water

The heat out through radiation is determined by the following equation which assumes a small object in large surroundings.

$$q_{radiation} = A_s \varepsilon \sigma \left(T_{s,o}^4 - T_\infty\right)$$

Where:

$\varepsilon =$ Emissivity of surface

σ= Stefan-Boltzman constant

T_s= Surface temperature

T_∞= Ambient temperature of surroundings

q_{losses} can be calculated, which is the change in temperature divided by the resistance of the medium through which it must travel.

$$q_{losses} = \frac{(T_s - T_\infty)}{R_{conv,air} + R_{cond,glass} + R_{cond,air}}$$

Where:

$$R_{convenction,a} = \frac{1}{h_{air} A_s} = \frac{K}{L}$$

$$R_{conduction,g} = \frac{L}{K_{glass}A_s}$$

$$R_{conduction,a} = \frac{L}{K_{air}A_s}$$

The convection resistance is calculated using the Reynolds number for forced convection assuming there is wind blowing over the outside surface of the glass. The Reynolds number is calculated using the equation below. The convection off the glass accounts for the largest heat loss from the system.

$$Re_D = \frac{VL}{v}$$

Where:

V= Velocity of the wind

L= Length to the from the farthest edge

v= viscosity of the air

The convective resistance of the air can be considered as conduction due to the fact that the Rayleigh number was calculated to be 671 which is less than 1708. The Rayleigh number compares the ratio of buoyancy forces to viscous forces. By definition of an enclosure, the viscous forces overcome the buoyancy forces and do not allow air to circulate. This allows the convection resistance inside the enclosure to be calculated using the method of conduction.

$$Ra_L = \frac{g\beta(T_1 - T_2)L^3}{\alpha v}$$

Where:

g= Gravity

β= Expansion coefficient

T_1= Hot surface

T_2= Cold surface

L= Distance from glass to pipe

α= Thermal diffusivity

The basic equation for conduction can be used to calculate the conductive resistance of the glass based on the thickness and thermal conductivity of glass.

Summing the losses and subtracting them from the useable solar heat flux gives the heat flux $q_{in}^{"}$ into the water. Assuming the water from the city comes in at roughly 283 degrees kelvin, the temperature of the water after passing through the solar collector can be obtained.

$$T_{mo} = T_{mi} + \frac{q_{in} P L_{pipe}}{\dot{m} C_p}$$

Where:

T_{mo}= Fluid temperature at outlet

T_{mi}= Fluid temperature at inlet

P= Perimeter

L_{pipe}= Length of pipe

$\dot{m}$= Mass flow rate of fluid

C_p= Specific heat

Table 3 provides data on inlet temperature of city supplied water in cities across the nation. Calculated values for different collector styles can be seen in Table 3 below. The data displayed in Table 4 is given assuming an average inlet temperate of 283^{o}K.

Table 3: Water Inlet Temperatures

Location	**Average Inlet Temperature (^{o}F)**	**Location**	**Average Inlet Temperature (^{o}F)**
Phoenix, AZ	82.3	Denver, CO	61.3
Detroit, MI	49.9	Boston, MA	59.3
St. Louis, MO	61.3	Milwaukee, WI	46.0
Dallas, TX	68.3	New Orleans, LA	64.9

Table 4: Heat Flux Values for Different Materials

		$q_{in}^{"}$ $(\frac{W}{m^2})$	T_{mo} (^{o}K)
Materials 1	PVC	714.776	284.628
	Glass		
Materials 2	Galvanized Pipe	714.784	284.615
	Glass		
Materials 3	PVC	558.235	284.272
	Plastic		
Materials 4	Galvanized Pipe	558.243	284.262
	Plastic		

From the results in Table 4 it is determined that there is very little difference in performance between the different configurations. Material selection will be determined by the cost of the material in order to optimize the absorption per cost per area metric.

5. Results

5.1 Area/$

5.1.1 Bread box collector and circulation system

- With an area of 4.6 m^2 and a cost of $201.82 the area per cost of the bread box collector with plastic covering is .02256, giving it the highest area per cost value out of all of the other collector designs.
- With an area of 4.6 m^2 and a cost of $279.80 the area per cost of the bread box collector with glass covering is .01627.

5.1.2 Parabolic collector and circulation system

- Using an area of 1.16 m^2 and a cost of $255.64 the area per cost of the parabolic collector with galvanized, unpainted piping is .01194.
- Using an area of 1.16 m^2 and a cost of $260.23 the area per cost of the parabolic collector with galvanized, black painted piping is .01140.

5.1.3 Flat plate collector and circulation system:

- With an area of .93 m^2 and a cost of $488.42 the area per cost of the flat plate collector with galvanized pipe with no spacing in between each pipe is .00282, giving is the lowest area per cost value out of all the other collector designs.
- With an area of .93 m^2 and a cost of $234.9 the area per cost of the flat plate collector with a rock bed as a thermal reservoir is .01214.

5.2 Area/$ conclusion:

It is obvious from this analysis that the bread box collector and circulation system utilizing a plastic cover is the most affordable per its area.

5.3 Absorption/area/$

5.3.1 Bread box collector and circulation system

- With an absorption of 654.32 W for plastic covering, an area of 1.67 m^2, and a cost of $181.31 the absorption per area per cost is 2.16.
- With an absorption of 776.6 W for glass covering, an area of 1.67 m^2, and a cost of $201.36 the absorption per area per cost is 2.31.

5.3.2 Parabolic collector and circulation system

- Using an absorption of 514.07 W for galvanized, unpainted piping, an area of 1.16 m^2, and a cost of $255.64 the absorption per area per cost is 1.73.
- Using an absorption of 737.04 W for galvanized, black painted piping, an area of 1.16 m^2, and a cost of $260.23 the absorption per area per cost is 2.44.

5.3.3 Flat plate collector and circulation system:

- Using an absorption of 738.48 W for galvanized pipes with no spacing, an area of .93 m^2, and a cost of $488.41 the absorption per area per cost is 1.63.

5.4 Absorption/area/$ conclusion

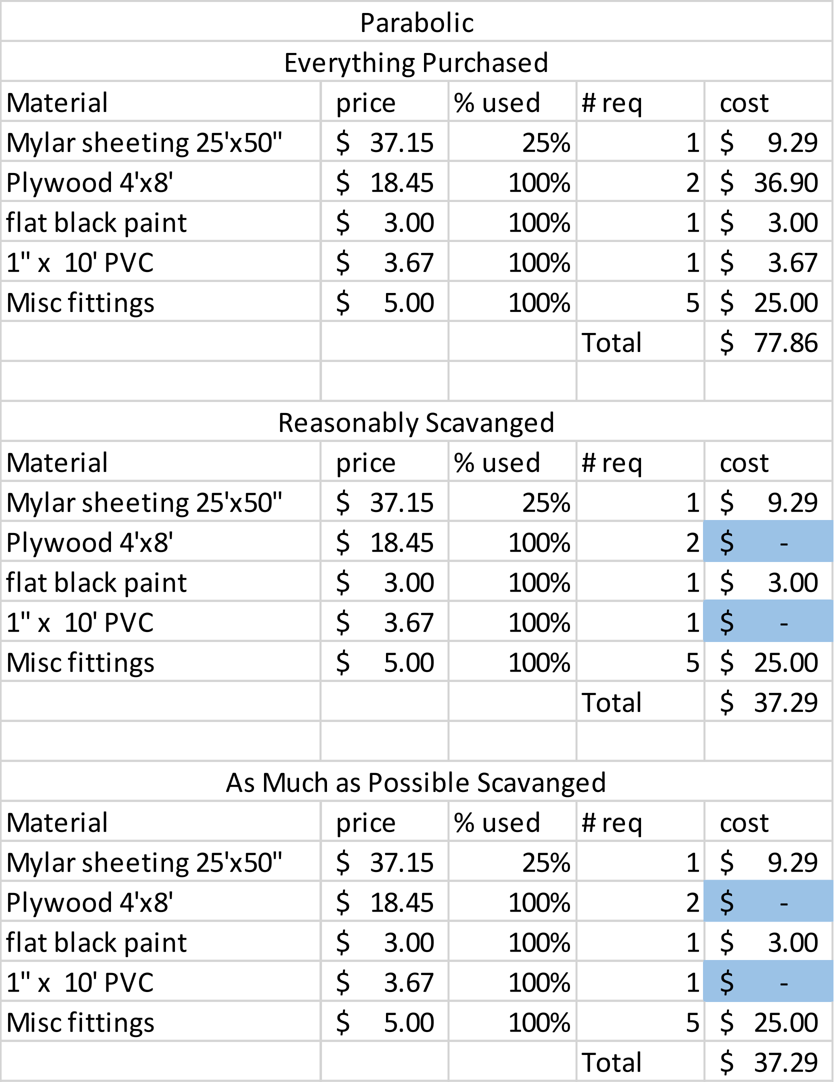
It is obvious from this analysis that the parabolic collector and circulation system utilizing galvanized, black painted pipe is the most affordable per its absorption per area and will be the design that team 13 will use as a final concept.

6. Cost analysis

The cost of each considered design is analyzed based on three categories: each part purchased, some parts scavenged, everything possible scavenged. First, the cost was analyzed based on each part being scavenged. The main application of our design is a do-it-yourself solar water heater, which the return is greater than the cost to build in less than two years. As a result the team also analyzed the cost based on what parts are reasonably scavenged, and what parts can be scavenged with considerable effort. The cost of these scavenged parts then goes to zero, significantly reducing the total cost of each design. In Tables 5-7 the blue cells indicate scavenged items for their respective categories.

6.1 Parabolic Cost Analysis

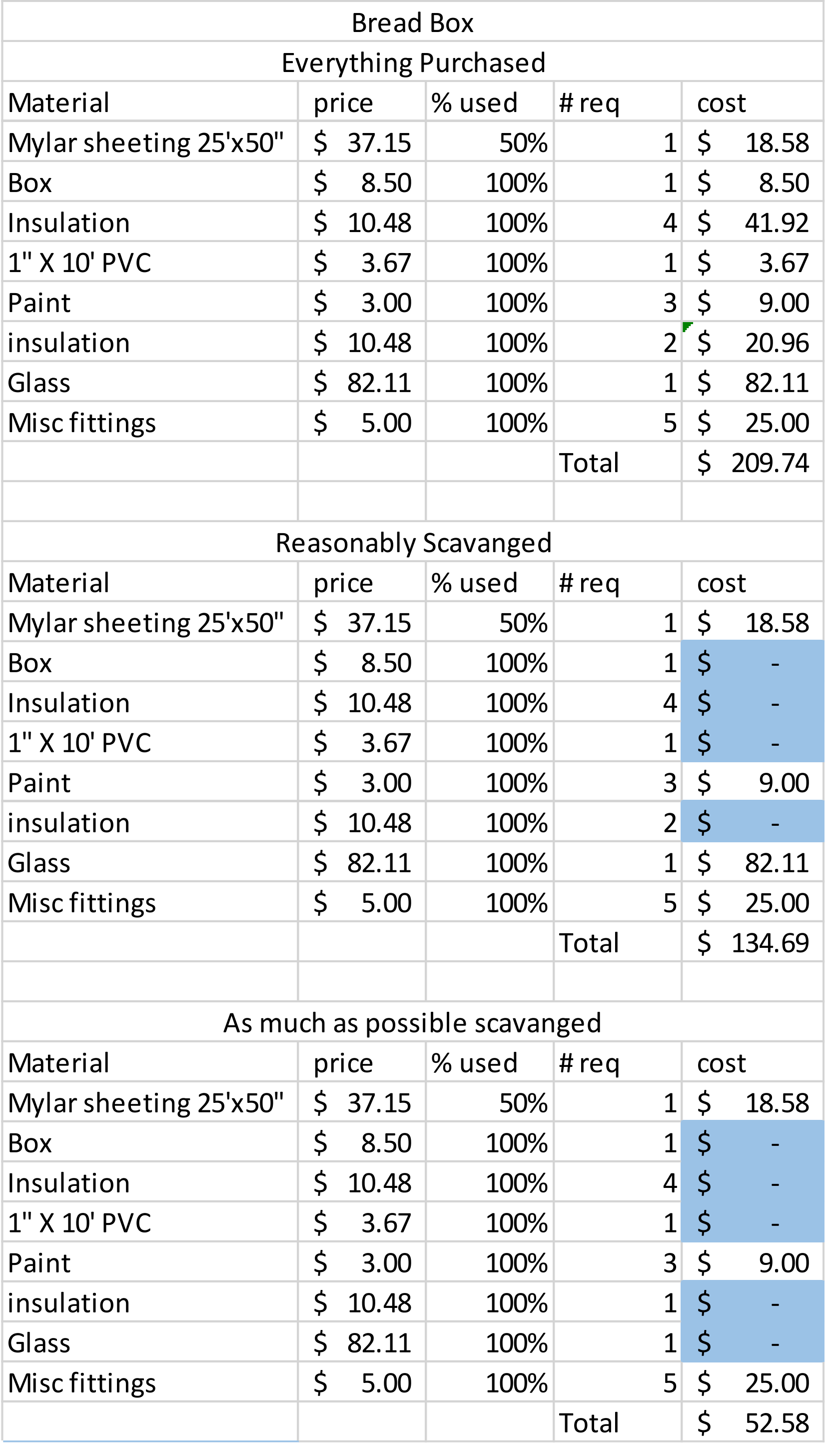
Table 5: Parabolic Cost Analysis



Parabolic				
Everything Purchased				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	25%	1	$ 9.29
Plywood 4'x8'	$ 18.45	100%	2	$ 36.90
flat black paint	$ 3.00	100%	1	$ 3.00
1" x 10' PVC	$ 3.67	100%	1	$ 3.67
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 77.86
Reasonably Scavanged				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	25%	1	$ 9.29
Plywood 4'x8'	$ 18.45	100%	2	$ -
flat black paint	$ 3.00	100%	1	$ 3.00
1" x 10' PVC	$ 3.67	100%	1	$ -
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 37.29
As Much as Possible Scavanged				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	25%	1	$ 9.29
Plywood 4'x8'	$ 18.45	100%	2	$ -
flat black paint	$ 3.00	100%	1	$ 3.00
1" x 10' PVC	$ 3.67	100%	1	$ -
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 37.29

6.2 Bread Box Cost Analysis

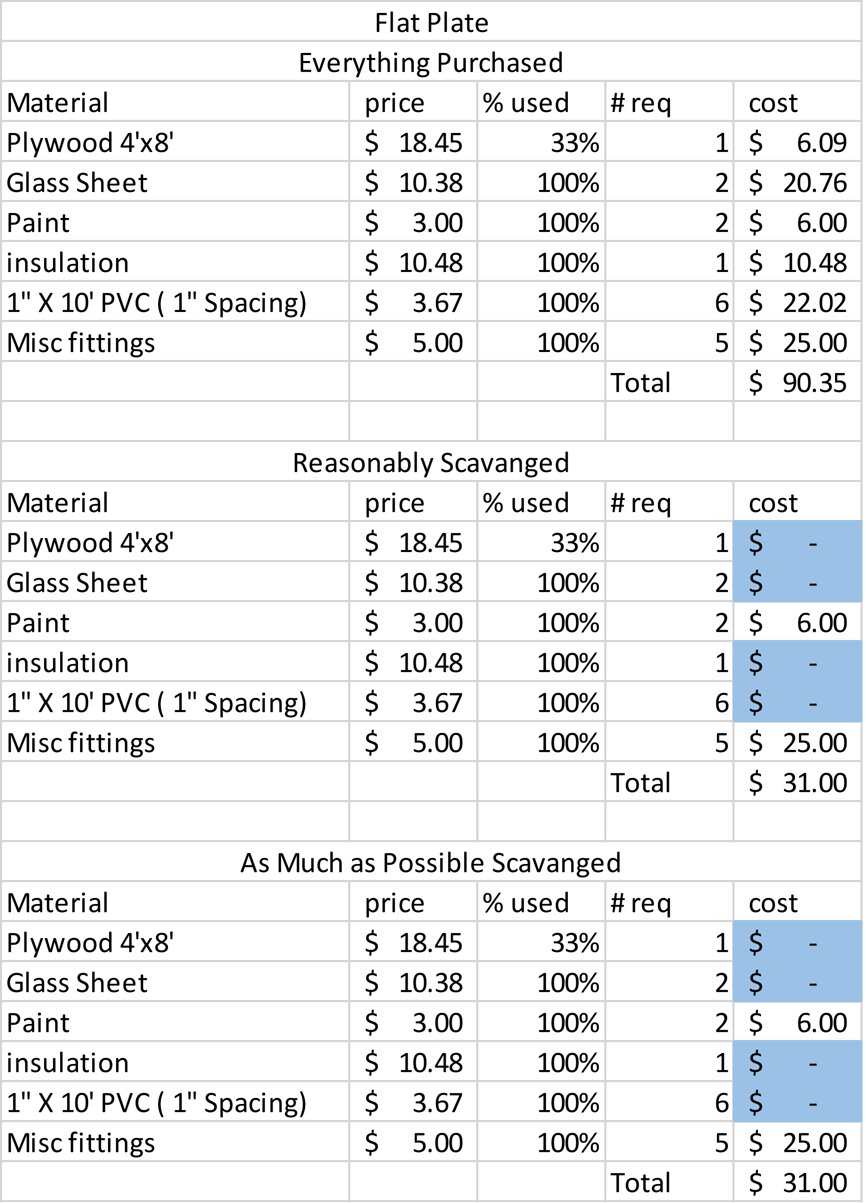
Table 6: Bread Box Cost Analysis



Bread Box				
Everything Purchased				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	50%	1	$ 18.58
Box	$ 8.50	100%	1	$ 8.50
Insulation	$ 10.48	100%	4	$ 41.92
1" X 10' PVC	$ 3.67	100%	1	$ 3.67
Paint	$ 3.00	100%	3	$ 9.00
insulation	$ 10.48	100%	2	$ 20.96
Glass	$ 82.11	100%	1	$ 82.11
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 209.74
Reasonably Scavanged				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	50%	1	$ 18.58
Box	$ 8.50	100%	1	$ -
Insulation	$ 10.48	100%	4	$ -
1" X 10' PVC	$ 3.67	100%	1	$ -
Paint	$ 3.00	100%	3	$ 9.00
insulation	$ 10.48	100%	2	$ -
Glass	$ 82.11	100%	1	$ 82.11
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 134.69
As much as possible scavanged				
Material	price	% used	# req	cost
Mylar sheeting 25'x50"	$ 37.15	50%	1	$ 18.58
Box	$ 8.50	100%	1	$ -
Insulation	$ 10.48	100%	4	$ -
1" X 10' PVC	$ 3.67	100%	1	$ -
Paint	$ 3.00	100%	3	$ 9.00
insulation	$ 10.48	100%	1	$ -
Glass	$ 82.11	100%	1	$ -
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 52.58

6.3 Flat Plate Cost Analysis

Table 7: Flat Plate Cost Analysis



Flat Plate				
Everything Purchased				
Material	price	% used	# req	cost
Plywood 4'x8'	$ 18.45	33%	1	$ 6.09
Glass Sheet	$ 10.38	100%	2	$ 20.76
Paint	$ 3.00	100%	2	$ 6.00
insulation	$ 10.48	100%	1	$ 10.48
1" X 10' PVC (1" Spacing)	$ 3.67	100%	6	$ 22.02
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 90.35
Reasonably Scavanged				
Material	price	% used	# req	cost
Plywood 4'x8'	$ 18.45	33%	1	$ -
Glass Sheet	$ 10.38	100%	2	$ -
Paint	$ 3.00	100%	2	$ 6.00
insulation	$ 10.48	100%	1	$ -
1" X 10' PVC (1" Spacing)	$ 3.67	100%	6	$ -
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 31.00
As Much as Possible Scavanged				
Material	price	% used	# req	cost
Plywood 4'x8'	$ 18.45	33%	1	$ -
Glass Sheet	$ 10.38	100%	2	$ -
Paint	$ 3.00	100%	2	$ 6.00
insulation	$ 10.48	100%	1	$ -
1" X 10' PVC (1" Spacing)	$ 3.67	100%	6	$ -
Misc fittings	$ 5.00	100%	5	$ 25.00
			Total	$ 31.00

6.4 Cost Analysis Conclusion

All three designs, when scavenged, have very competitive costs. The bread box has the highest cost at $52.58. However, this is only $15.29 more expensive than the parabolic collector which costs $37.29. The least expensive is the flat plate at $31.00. It should be noted the cost is in no way a direct indicator of the best design.

7. Conclusion

Based on the engineering analysis and cost analysis above, it is apparent that the parabolic collector with a passive circulation system has the best absorption/area/dollar ratio. This design also has a high likely hood be able to be built by an average person that has an average knowledge of tools and building skills. This will be our final design and next semester (starting 13 JAN 2014) we plan to build several variations of this parabolic collector designs, such as a parabolic collector using black PVC piping, using galvanized steel piping and using black galvanized steel piping. For other applications, it would be more beneficial to use other variations of this collector. In a commercial application where water is in extremely high demand throughout the day, the circulation system should be bypassed entirely. This type of system would serve as quick way to pre-heat the water. In a practical in home use application, an active circulation system with a parabolic collector should be considered. This design would maximize the hot water output of the solar water heater.

8. Appendix

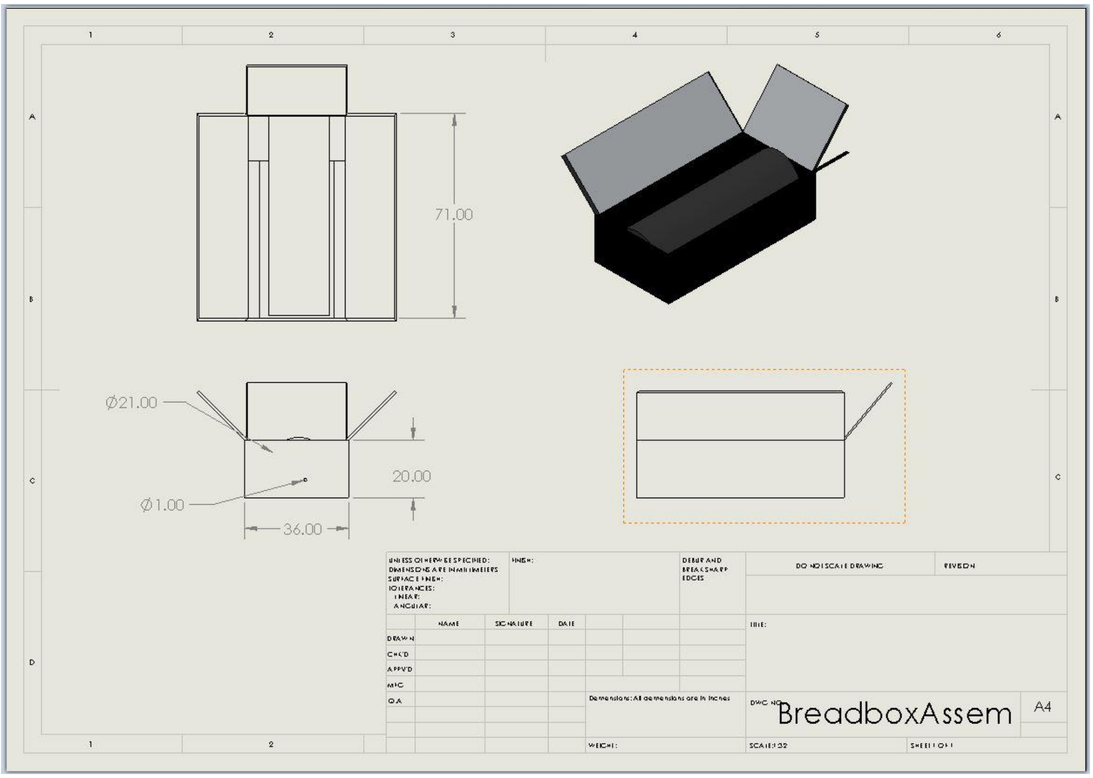


Figure 1: Bread box collector engineering drawing.

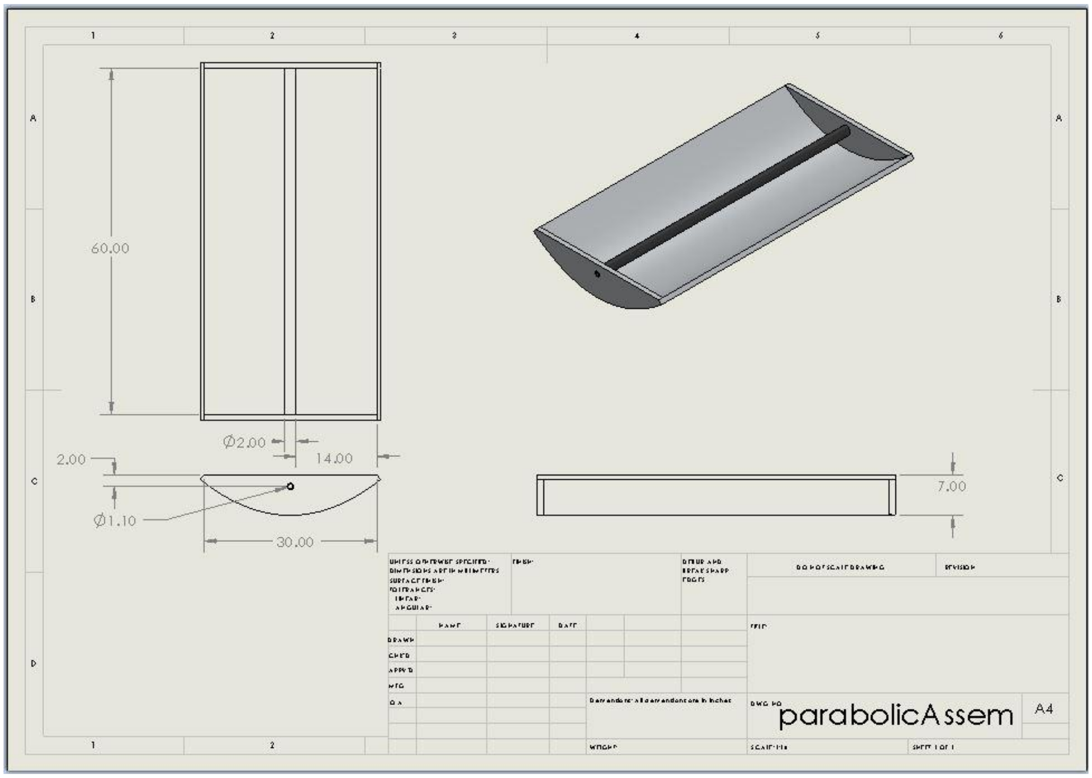


Figure 2: Parabolic collector engineering drawing.

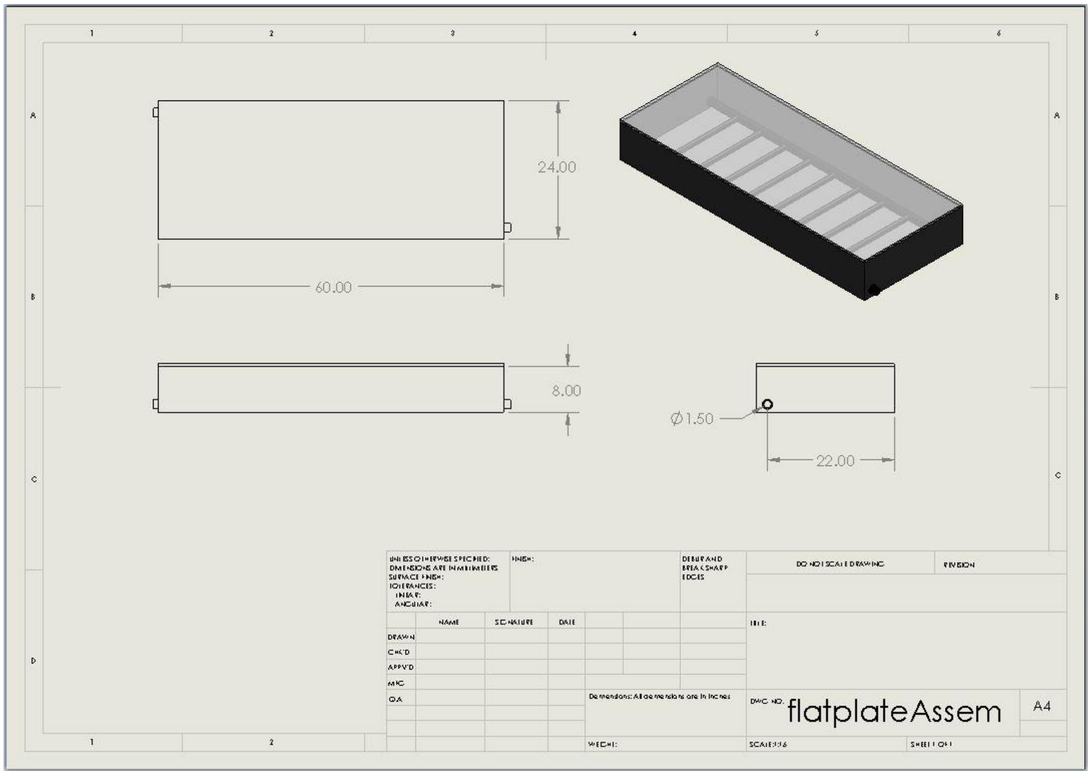


Figure 3: Flat plate collector engineering drawing.

References

- Energy Protection Agency (EPA). (2013). *P3:People, Prosperity, and the Planet Student Design Competition for Sustainability* . Washington, DC: EPA. http://www.epa.gov/P3/. Accessed October 2013
- U.S. Department of Energy (DOE). (2012). *Building Energy Codes Program*. Washington, DC:
- U.S. Department of Energy. http://www.energycodes.gov/adoption/states/. Accessed October 2013.
- Raisul Islam, K. Sumathy and S. Ullah Khan, "Solar water heating systems and their market trends," *Renewable and Sustainable Energy Reviews*, vol. 17, pp. 1-25, 1, 2013.
- U.S. Department of Energy (DOE). (2005). *Residential Energy Consumption Survey 2005*. Washington, DC: Energy Information Administration. http://www.eia.doe.gov/emeu/recs/. Accessed October 2013.
- Energy Information Administration (EIA). (2005). *Office of Energy Markets and End Use, Forms EIA-457 A-G of the 2005 Residential Energy Consumption Survey.* Washington, DC: EIA.
- American Society of Heating and Air-Conditioning Engineers (ASHRAE). (1987). *Methods of Testing TO DETERMINE THE SOLAR PERFORMANCE OF SOLAR DOMESTIC WATER HEATING SYSTEMS*. Atlanta, GA: ASHREA Standard- 95.

- American Society of Heating and Air-Conditioning Engineers (ASHRAE). (1987). *Methods of Testing to Determine the Performance of Solar Collectors*. Atlanta, GA: ASHREA Standard-93.
- M. Raisul Islam, K. Sumathy, Samee Ullah Kahn. (2012). *Solar water heating systems and their market trends*. Atlanta, GA: Renewable and Sustainable Energy Reviews. http://www.elsevier.com/locate/rser/. Accessed October 2013.
- Database of State Incentives for Renewables and Efficiency (DSIRE). (2012). *Arizona Incentives/Policies for Renewables and Efficiency*. Raleigh, NC: North Carolina State University.
- http://www.dsireusa.org/incentives/index.cfm?re=0&ee=0&spv=0&st=0&srp=1&state=AZ/. Accessed October 2013.
- U.S. Department of Energy (DOE). (2012). *Building Codes and Regulations for Solar Water Heaters*. Washington, DC: U.S. Department of Energy. http://energy.gov/energysaver/articles/building-codes-and-regulations-solar-water-heating-systems/. Accessed October 2013.
- U.S. Department of Energy (DOE). (2012). *Building Energy Codes Program*. Washington, DC: U.S. Department of Energy. http://www.energycodes.gov/adoption/states/. Accessed October 2013.
- Energy Protection Agency (EPA). (2013). *P3:People, Prosperity, and the Planet Student Design Competition for Sustainability* . Washington, DC: EPA. http://www.epa.gov/P3/. Accessed October 2013