Heat Collectors through Active Solar Energy

Heating Homes through Solar Energy

Allen S. Guinoo
Department of Engineering
University of Southern Maine
Gorham, ME, USA
Allen.Guinoo@maine.edu

Joshua A. Stewart
Department of Engineering
University of Southern Maine
Gorham, ME, USA
Joshua.Andrew.Stewart@maine.edu

Lin Lin
Department of Engineering
University of Southern Maine
Gorham, ME, USA
Llin@usm.maine.edu

Abstract - This project is designed to implement the use of active solar technologies via a solar hot air system to help reduce dependence on external energy sources to modern homes. Empty and plated solar hot air collectors were fabricated and tested in different operation conditions to determine the maximum effectiveness of the thermal solar energy absorption. A photovoltaic panel is utilized to provide power for the control unit and the fan in the exhaust vent of the collector. The photovoltaic cells are used to help reduce the amount of external energy the solar hot air system would need to run, ideally running with zero operating cost and even possibly providing additional electricity for the rest of the building or to be sold back to the grid. The entire system is governed by a control unit which will determine the operating mode in which the system will function, monitoring the temperature differential between external and internal temperatures. The control unit will help to increase the efficiency of the solar hot air system by regulating the rate at which the hot air will be injected into the home.

I. INTRODUCTION

The Sun is by far the most clean and powerful source energy generation that can be harnessed here on Earth. On average, the sun provides 1,360 watts per square meter to the Earth atmosphere, about 1,000 watts per square meter reaches the Earth's surface during peak conditions [1]. In 2012, solar power contributed to only 0.11% to the United States electricity generation while 67% was produced by fossil fuels. If solar energy was utilized to its full extent, the fossil fuel savings could be tremendous [2]. Harnessing one square meter of this free energy would provide approximately 4.2 kilowatt-hours of energy a day; enough energy to save almost one barrel of oil a year [3]. Figure 1 shows the potential for solar energy generation in the United States provided by National Renewable Energy Laboratory.

Fuel costs for heating homes have been on the rise. With certain fuels becoming scarcer, prices don't have intentions of plummeting anytime soon. States that rely heavily on heating fuel like Maine are affected heavily. With temperatures 9% colder than 2013 the Governor's Energy Office (GEO) reported that propane prices increased 23%, kerosene at 3%, and heating oil by 4% [4].These rising prices for fuel show the need to produce heat from alternate sources, such as solar energy.

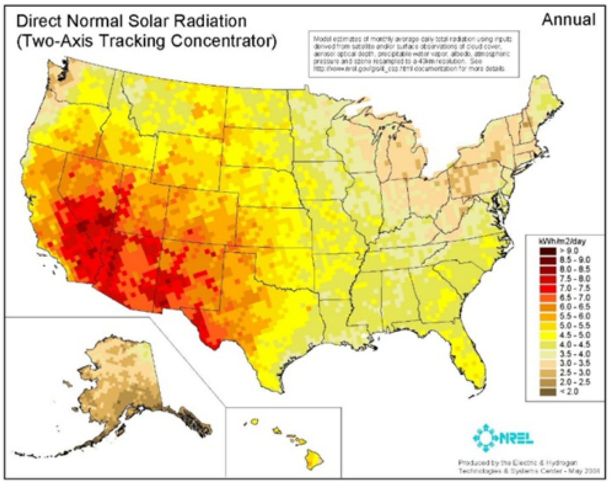


Figure 1: Monthly average daily total of solar radiation on the United States by NREL.

Solar hot air collectors utilize solar energy to heat homes or used as water heaters in the 1920's. However, the use of coal had taken over for water heating in boilers and space heating for domestic reasons in the U.S. But, in the 1960's, solar energy technology picked up again and became a popular interest internationally [5].

There are many different ways of constructing solar hot air collectors [6]. Generally a solar collector will have a layer of glazing, which creates the greenhouse effect. Different materials could be used as solar heat absorbers inside the collector such as aluminum soffits or aluminum cans. Most collectors also have an insulation layer. Some collectors are left empty inside. They are called flat collectors. Air flow through the collector to absorber the heat, Figure 2 shows the basic structure of a flat collector. Some collectors have plates to guide the air flow direction, and increase the time that air being heated in the collector. These plates also introduce flow resistance.

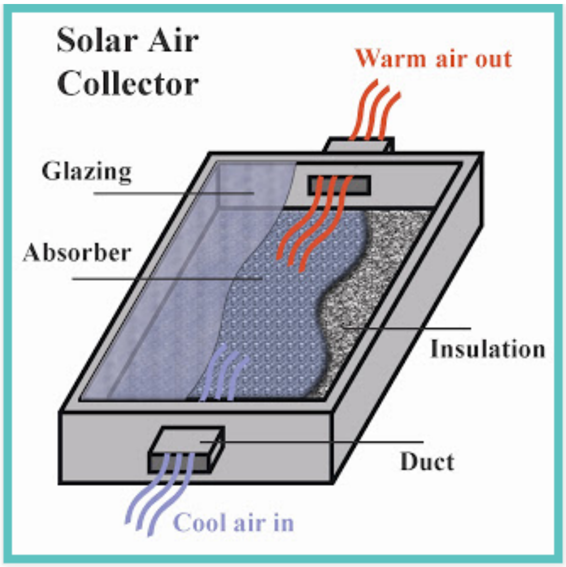


Figure 2: Flat Solar Hot Air Collector [7]

Another variation of solar hot air collectors uses evacuated tubes. There are different variations of evacuated tubes for heat collection although they all operate under the same premise. The fundamental design for the evacuated tube heat pipe (ETHP) collectors' use multiple tubes aligned next to each other. Each tube is comprised of two sealed glass tubes, one inside the other. The first tube has a layer of coating that is designed to absorb the solar radiation; this tube is placed inside the second outer tube. The gap between the two glass tubes contains a vacuum, which greatly aids in the prevention heat loss through conduction and convection allowing for greater efficiencies. A transfer fluid or gas then passes over the top of the tube and collects the thermal energy. Condensation then forces the cooled absorber fluid to return towards the bottom of the pipe [8, 9].

Flat collectors and ETHP collectors are considered stationary collectors because they do not move in respect to the sun. Tracking solar collectors are another variation of heat collectors that are more efficient because they orient themselves with respect to sunlight, therefore, having optimal sunlight contact much longer during the day than stationary collectors In tracking solar collectors, mirrors are used to create a focal point for the sunlight to heat an absorber tube [10]. The absorber tube then heats up the media inside and transfers the media to a thermal storage trough, where it can then be dispersed to the place desired. This is also used in photovoltaic cell panels. A motor that is connected to the fixture of the panel is programmed to track the sun and will automatically shift the fixture in order to have more sunlight contact during the day.

This project focuses on comparing the performance of a flat collector to plated collector at different operation conditions, and developing a control system to monitor and regulate the airflow and self-efficient power system. A microcontroller will be used to monitor the temperature in the testing unit and collector, and coded to control the air flow based on the temperature difference between collector and inside of house. All of the electronic components of the system will be powered by photovoltaic cells.

II. DESIGN AND CONSTRUCTION OF SOLAR COLLECTOR

All three modes of heat transfer present in solar collectors. Many factors affect the efficiency of a solar collector, such as weather condition, time of day, direction. Etc. In order to compare the performance of different solar collector, a testing unit and a reference unit were designed and constructed. Both units resemble the average home and are identical to keep a uniform controlled volume. Both roofs were constructed at a forty-five degree angle. Constructed at a half home scale to save materials and space, both units were also constructed on individual platforms to be moved around easier. The testing unit has a computer fan mounted on the inside of the roof to draw the heated air through the collector into the testing unit. Holes were made through the collectors and the roof of the testing unit to help air flow circulation as well as recycling hot air. Both testing and reference unit were built of MDF board as shown in figure 3.

Figure 3: Finished model of the reference unit

The solar heat collectors were designed with interchangeable parts to save time, money, labor, and materials. With interchangeable parts, a variety of systems can be created inexpensively. Empty collector is an empty system with a black back plate and black MDF board frame. A plated collector has black plates that placed inside of the collector and normal to the black back plate. These plates are used to regulate the air flow path to the inside of the house. The plated solar collector allows the air to have more contact time to absorb solar thermal energy before entering to the house. Plexiglass (Acrylic sheet) is used for the cover. Both collectors have air vents on the bottom of the frame that can be closed or opened. This allows testing with a closed system or an open system with the environment air. Figure 4 shows the side by side comparison of the collector's design

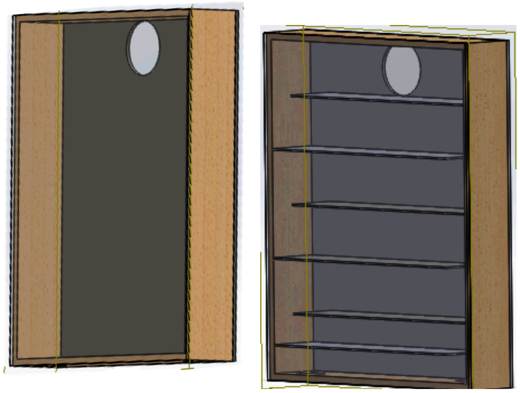

(a) (b)

Figure 4: collector design (a) Empty collector with plexiglass cover. (b) plated collector with plexiglass cover.

Figure 5 demonstrates the placement of the collectors on the testing unit. Although the collectors have interchangeable parts, the main focus in our testing is the difference between the empty collector and the plated collector. There are four conditions have been tested in this project:

- Plated with plexiglass cover closed vents
- Plated with plexiglass cover open vents
- Empty with plexiglass cover closed vents
- Empty with plexiglass cover open vents

Figure 5: Testing unit with the plated collector placed on top.

III. DESIGN AND CONSTRUCTION OF MICROPROCESSOR CONTROL SYSTEM

The objective of control theory is to monitor the output of a system and manipulate the inputs to obtain a desired output. This is typically done through the use of a controller and multiple sensors as shown in Figure 6. In this project the input and output variables are temperatures. The input variable is the temperature of the hot air collector and the output variable is the temperature inside the testing unit. These temperatures are measured by two separate thermocouples and read by the controller. The controller then makes the determination whether to run the exhaust fan to push more hot air into the testing unit and raise the internal temperature.

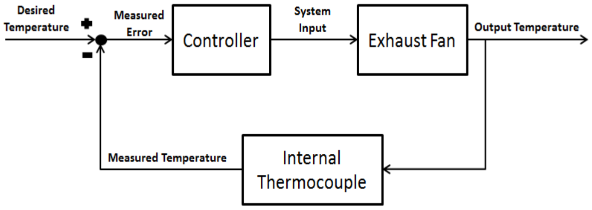


Figure 6: Diagram of the control theory used.

The major factor of the control system was to design it to operate within the capabilities of the photovoltaic cell (SPE-500, SolarMade, CO), providing a maximum power that the system would draw. There were three steps that had to be taken in order to obtain the desired functionality for the microprocessor. The first step was to measure the temperatures in both the collector and testing unit using two K-type thermocouples (Adafruit Industries, NY). The intrinsic voltage generated by the thermocouples is then amplified using a MAX31855 amplifier (Adafruit Industries, NY), to a range that the Arduino Uno microprocessor (R3, Arduino, Italy), is able to read. A thermocouple to digital convertor, operating with cold-junction temperature compensation, would read the voltages produced by the thermocouple and send out a digital signal to the microprocessor. Through the use of two thermocouples and amplifier breakout boards the microprocessor is able to read the temperatures at both thermocouple locations. The difference between the two temperatures could then be easily determined using a logic statement. The microprocessor would then output a High or Low (5V or 0V) signal, depending on the voltage differences, to a reed relay (W107DIP-5, Mangecraft, IL) to operate the exhaust fan. The exhaust fan operates at a rated voltage and current that is beyond the output capabilities of the microprocessor, the relay allowed the voltage produced from the photovoltaic cell to go directly through the fan. A full diagram of this circuit is shown in Figure 7.

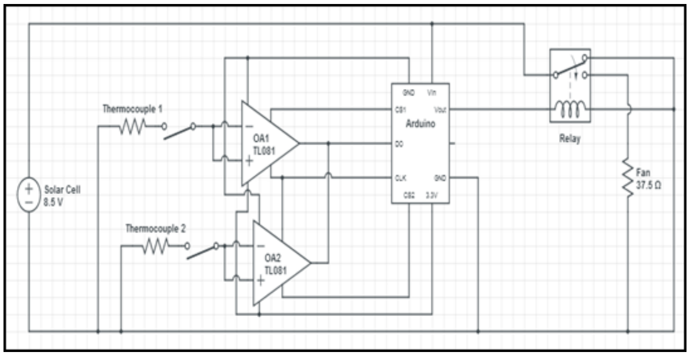
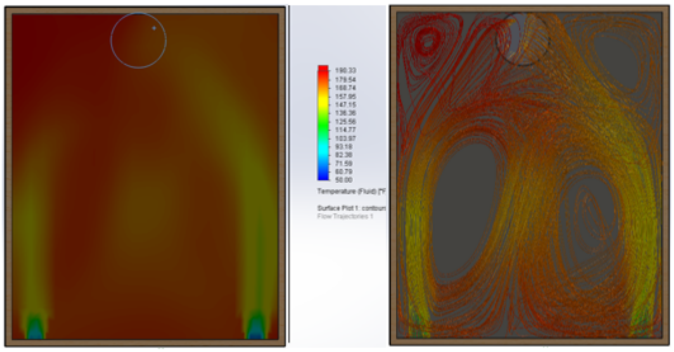


Figure 7. A circuit diagram of the control system operating off of the photovoltaic cells. The two thermocouples are represented as a resistor due to the lacking of a thermocouple in the part library. The thermocouples to digital converters are represented as Op-Amps.

IV. TESTING AND RESULTS

A. *Simulations*

Simulations for both the empty and plated collectors were done using Solidworks. Boundary conditions are set with the testing fluid selected as air with a temperature of -0.56°C which is the average temperature in Maine in the month of November. Because of the software restrictions, only the opened systems (fresh air added in system) were able to be simulated. However, the software demonstrates the thermal characteristics and flow trajectories of both the empty and plated collector design. Refer to Figure 8 for Simulations of Empty Collector and Figure 9 for Simulations of Plate Collector.



(a) (b)

Figure 8. Simulations of Empty Collector with open vents.
(a) temperature contours. (b) flow trajectories.

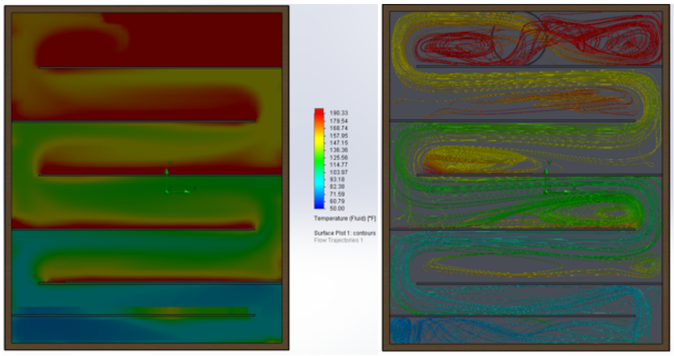


Figure 9. Simulations of Plated Collector with open vents.
(a) temperature contours (b) flow trajectories.

Simulation results showed that the empty collector has a larger dead zone, which helps the collector reaching uniform temperature. Variation of temperature in the plated collector is larger, and it provides higher temperature output through the area of the fan.

B. *Control Unit Testing*

In order to verify that the control system would operate correctly once implemented into the testing unit. An outdoor test needed to be conducted prior to installation into the testing unit. This was done by operating the entire system off of the photovoltaic cell. The temperatures of the two thermocouples were then raised and lowered independently.

For testing purposes, the control unit was set to record and display the temperatures of both the collector, and inside of the house. It was set that the fan would run when the temperature differential between the inside of the house and collector reached a preset value, and it would stop when that differential became too low or the desired internal temperature was reached. This verified the system, proving that it could then be used for the testing unit.

C. *Indoor Testing*

The indoor testing provided a controlled environment to determine which collector was most effective. The reference unit and each variation of collector were tested under the same conditions. For each test, the units were subjected to thirty minutes under a heat lamp. Measurements of temperature at the thermocouple locations were recorded every minute for the duration of the test. The testing unit and collectors were allowed to cool to room temperature between each test. The testing of the reference unit established a baseline for the rest of the testing showing a change in temperature of 1.25°C, seen in Table 1, over the thirty minute period.

Table 1: Temperature change during 30 minutes period for the reference unit

Reference House	
Outside Temp = 19.44 ^{o}C	
Time (minutes)	Inside Temperature (Degrees ^{o}C)
0	19.5
5	19.5
10	19.5
15	19.75
20	20.25
25	20.5
30	20.75
ΔT	1.25

Figures 10 and 11 show the results collected from the indoor testing. The ambient temperature of the testing area ranged from 20.6^{o}C to 22.2^{o}C throughout testing, which had an effect on the initial temperatures of the testing unit. Although the major numbers to be considered were not the max temperatures but rather the greatest change in temperature over the thirty minute period.

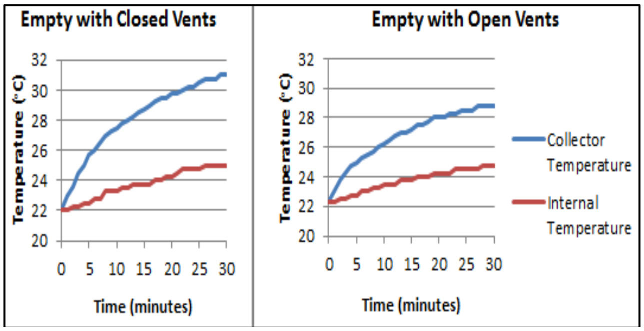


Figure 10 : Empty Collector data with open and closed vents.

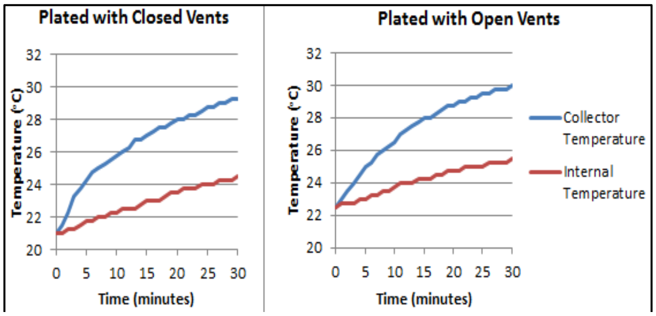


Figure 11: Plated Collector data with open and closed vents.

From the figure, it is clear that the temperatures in both the collector and inside of the house all increase. Table 2 shows the indoor testing data, change of temperature for these four different cases are calculated and listed in the table.

Table 2: Number comparisons of Figures 10 and 11.

Indoor Testing	Sensor Location	Initial temp (˚C)	Final temp (˚C)	ΔT (˚C)
Plate with Open Vents	Collector	22.5	30	7.5
	Internal	22.5	25.5	3
Plated with Closed Vents	Collector	21	29.25	8.25
	Internal	21	24.44	3.44
Empty with Open Vents	Collector	22.25	28.75	6.5
	Internal	22.25	24.75	2.5
Empty with Closed Vents	Collector	22	31	9
	Internal	22	25	3

To compare these two collectors with four different operation conditions, Figure 12 is generated to indicate the temperature change in the house. Percentage of increase in temperature is calculated and plotted. Temperature change of the reference unit is also plotted for comparison.

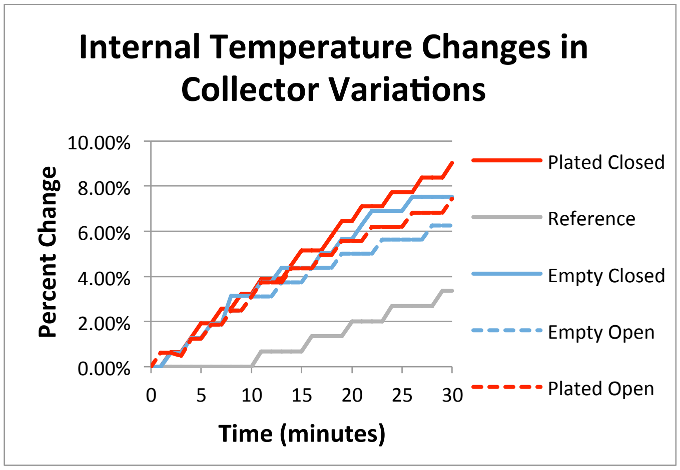


Figure 12: Percentage increase in temperature increase in internal temperature for all collector variations and reference.

Obviously, all four cases provide extra heat to the house. Closed vent (recirculate the interior air) cases have better performance than the open vent (fresh air) cases. For both operation conditions, the plated collector provides more heat to the house than an empty collector. Between testing each variation of collector, the testing unit was allowed to cool down to the baseline temperature.

D. *Outdoor Testing*

Both the testing unit and reference unit were subjected to real life winter temperature conditions. The roofs of the units were set side by side facing to the sun, for maximum radiation exposure. The environment temperature was 6.1°C with a 1.1°C wind-chill factor. The photovoltaic cell panel powered both the fan and microcontroller, allowing for complete independence from external power sources. There were two thermocouples placed inside the testing unit: one by the exhaust fan of the collector and one inside the testing unit. This allowed temperature data to be collected for inside the collector and inside the testing unit, concurrently. Another thermocouple was placed inside the reference unit to compare the difference between the testing unit and the reference unit. The temperature inside the reference unit remained around 14.7 ±0.2°C, giving the baseline. Each collector remained outside until their temperatures reached a plateau; at that point their temperatures were recorded seen in Table 3.

Table 3: Maximum recorded collector and internal temperatures for the respective collectors. Temperature inside of the reference unit is 14.7 °C.

Collector Type	Collector (Degrees °C)	Internal (Degrees °C)
Plated Closed	32.5	19.5
Plated Open	32.5	18.44
Empty Closed	32.25	19.5
Empty Open	23.25	16.5

E. Discussion of Results

The testing of the control system showed that the microcontroller could accurately read the temperatures at the location of the thermocouples through a digital converter. The microcontroller also was able to switch the reed relay and operate the exhaust fan dependent on the difference between collector and internal temperatures.

An observation based off the data collected is that the plated collector worked better than the empty collector, causing a higher change in temperature inside the house. The testing unit with any variation of the collectors caused a faster rise in temperature than the reference unit without a collector. This shows that the collectors work as designed, which is to heat a home while being self-efficient based off solar energy.

V. CONCLUSION

Solar energy technology is becoming an evolutionary field and with an ever-growing interest in the industry. Collecting solar energy and converting it to thermal energy through a hot air collector while converting electrical power through a PV cell simultaneously is a good way to utilize solar energy.

By designing and constructing different variations of solar hot air collectors, this project showed that the plated collector regulated the air flow inside which creates more time for the heat transfer through radiation. This has a greater effect on the temperature of the air by the time it is drawn through the fan and into the house. Although the empty collector had a higher uniform temperature in dead space areas, the plated collector utilized more air affected by thermal radiation and reduced the affected dead space areas. The plated collector induced a higher percent change in temperature inside the house of 9.03%, compared to the empty collector which caused a change in temperature of 7.54%. With the comparison of testing the empty collector and the plated collector, it is evident that the plated collector was more effective, showing that it would be a greater benefit for modern home integration.

With the many options to harnessing solar energy, such as active solar hot air collectors, solar energy should be explored and considered more as an alternative energy than it is today. Seeking an alternative energy that is reliable, safe, and effective provides a cleaner today and a better tomorrow.

VI. FUTURE WORK

In order to increase efficiency of the design, a heat trough that acts as thermal energy storage should be incorporated to preserve the heat that is gained during operations and used later on when needed. The structure of the collector being made of MDF board serves great insulation properties; however, construction qualities could be better with harder wood. More Solidworks simulation is needed to investigate the optimal number of plates in the collector and distances between the plates. On behalf of the control system, developing a program or system to be integrated into the control system to improve data acquisition and in turn the accuracy of results. The addition of variable fan speeds would allow for greater control over the air flow through the system, allowing the air to stay in the collector longer if needed.

REFERENCES

[1] Przyborski, Paul and Ichoku Charles. “Climate and Earth’s Energy Budget.” NASA Earth Observatory. 2009.

[2] “What is U.S electrcity generation by energy source?” U.S Department of Energy. U.S Energy Information Administration. May 9, 2013.

[3] “How much solar energy is available?” The George Washington Solar Institute. The George Washington University. 2009.

[4] Smith, Lisa J. and Woodcock, Patrick. “Current heating fuel prices.” InforME. January 24, 2014.

[5] Islam, M. Raisul, Sumathy, K., and Khan, Sarnee Ullah. Solar water heating systems and their market trends Renewable and Sustainable Energy Reviews. Volume 17, 2013, Pages 1–25

[6] W.B.Stine and R.W.Harrigan. Solar Energy Systems Design. John Wiley and Sons, Inc. 1986.

[7] Cole, Jonathon R. Light on earth: the solar option. BookSurge Publishing. 2010.

[8] Walker, Andy, Fariborz Mahjouri, and Robert Stiteler. Evacuated-Tube Heat-Pipe Solar Collectors Applied to the Recirculation Loop in a Federal Building. Rep. no. NREL/CP-710-36149. National Renewable Energy Laboratory, 14 July 2014. Web. 25 Jan. 2014.

[9] Kalogirou, Soteris A. Solar Thermal Collectors and Applications. Progress in Energy and Combustion Science 30 (2004) 231–295.

[10] Quaschning, Volker. Solar thermal power plants. Renewable energy world. Routledge. June 2003.