Introduction

There are many different technologies that are emerging to help develop the future power infrastructure. The importance of these technologies is increasing the sustainability of how our society obtains and uses energy. Many studies have been proposed that suggest large-scale renewable energy plans in order to reduce the levels of CO_2 being emitted into the ozone layer [1].

A. Solar Walls

There is a large demand for green technologies that have minimal negative impact on the environment. These technologies can help make the way our society thrives more sustainably. One such green technology is solar walls. Buildings are responsible for nearly 33% of the world's greenhouse gases [2]. Solar walls can help reduce energy consumption in buildings by 30% [2]. These solar walls act as air conditioning (AC) systems that help ventilation, heating and cooling of buildings [2]. There are many different variations of solar walls. These variations are characterized by the wall's function and structure. These two characterizations place each solar wall into different groups. These groups range from the classic solar wall where an air space is created that heats the air using solar radiation and a photovoltaic wall that allows the cells that are embedded in the wall to perform better due to the AC function cooling the cells [2].

Solar Path, a start-up company located in Belmont, CA, has designed a solar wall that can be used in industrial and house hold buildings. The solar wall, designed by Doctor Narinder Singh Kapany, has progressed in its function and structure. Solar Path is currently testing its third prototype, where an array of solar panels has been imbedded into the solar wall to collect solar radiation, creating a more multifunctional wall. This prototype is a combination of a photovoltaic, classic and hybrid wall. Prototype III is being tested to analyze the efficiency level of the solar array by measuring the effects of the angle of incident the solar panels are facing the sun, the direction of the solar wall with respect to the sun and shadowing that might occur due to the structure of the solar array. The current prototype contains similar functions as the previous prototypes.

B. Prototype I

Prototype I was designed to test the abilities of the solar wall to heat the air inside the glass panels and to store the heat energy using a liquid. The dimensions of the wall include 39 ½" tall x 39$^{1/}$2" wide x41$^{/2}$" thick. The inside window is 37" tall x 37" Wide x4$^{1/2}$" thick which is the space for the conductive blinds. The blinds used in the window are coated with black conductive film that increases the absorption rate of solar radiation. The blinds used are standard office blinds with dimensions 10$^{3/4}$ x ½ inches and extend 34 inches. The first prototype can be seen in figure 1. This is similar to the methods implemented in most classic solar walls where the inside wall is coated black to absorb more solar radiation.

A

B

Figure 1 A.) 2-D model B.) Prototype I

Fans have been added to the top of the device in order to increase the circulation of air flow in the device. The fans are designed by Sunon and have an 80 x 50 mm dimensions. These fans have an optimal operation speed that is dependent on the resistance of the air flow generated by the fans. There are a couple of factors that dictate the air flow through the wall. One is the inlets and outlets of the air into and out of the wall. To allow no disruption in air flow the inlets and outlets should be made as wide as possible. The other factor is the resistance of the heat sink fins matching with the resistance of the fans speed. If these two resistances are matched it would provide the most optimal operation speed of the fans.

Imbedded around the panels of the wall are copper pipes that are designed to pump liquid around the window. The liquid collects the heat energy generated by the air. This liquid can then be stored in a water heater for later use. The actual heat transfer occurs at the top of the device. The heat exchanger can be seen in figure 2. Here most of the hot air is flowing out of the wall due to the density of the hot air and fans. The copper pipes near the top of the device are passed through cold plates. These cold plates are then attached with common heat sinks, made from Alpha, that gather the heat energy from the air inside the wall and transfer the energy to the liquid inside the copper pipes. Copper has a high thermal conductivity which makes it a good metal to use for transferring heat to the passing liquid.

Figure 2: Heat Exchange System.

The modeling of the heat exchange system required the use of fundamental equations. The maximum amount of heat exchange from air to liquid is a product of the mass rate transfer, the specific heat value for the substance and the temperature difference. To insure a good thermal connection silver paste is used to attach the copper pipes, heat sinks and cold plates. To help increase the heat exchange the space between the heat sink fins need to be minimized, the length of the heat collector needs to be maximized and the rate at which the liquid flows through the copper pipes needs to be optimized.

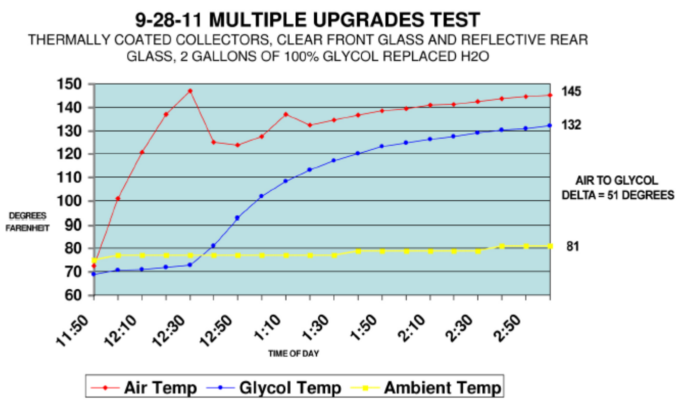


Figure 3: Prototype I, air and glycol temperature graph.

Figure 3 shows the temperature levels for the ambient surrounding, glycol and air in prototype I with multiple upgrades. Prototype I included a clear front glass panel and a reflective glass used in the rear. The collectors were also coated to allow better thermal collection. The temperature readings were measured using thermocouples and each data point taken every 10 minutes as the position of the wall was changed every 40 minutes to track the position of the sun. The results show that the maximum temperature over a period of 3 hours was 148°F for the air inside the device and 132°F for the glycol. The solar wall took close to an hour to stabilize the internal temperature. The temperature difference, after the device stabilized, between the air and glycol in the system was about 13°F.

C. *Prototype II*

Prototype II shares similarities with the first prototype. The heat exchanger and liquid transport system are the same as well as the placement and use of fans to circulate the hot air. The wall has vents both at the top and bottom of the wall. Prototype II however is constructed to be larger and to be divided into three sections. The dimensions of the new prototype are 130x45$^{1/2}$x4$^{1/2}$ inches. Each window in the wall has dimensions of 39x38x4$^{1/2}$.

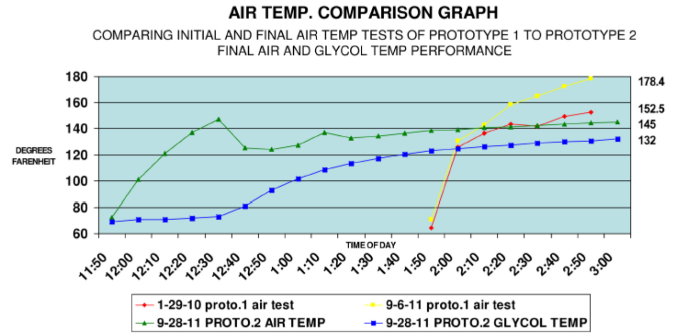


Figure 4: Prototype I and II air and glycol temperature graph.

Figure 5 shows the second prototype. The methods of collecting solar radiation are different. Instead of using conductive blinds, prototype II uses flexible sheets of copper to collect the solar radiation. This method of collecting heat is viable, but does not allow for a method of tracking the solar radiation at different times of the day. Figure 5 shows the temperature ratings for both prototypes I and II. Looking at the comparison for the Air temperature for Prototype I and II, clearly prototype I achieves higher level of air temperature. This is due to both the coated thermal collectors and the fact that the wall is moved to track the sun.

Figure 5: Prototype II

However the temperature levels obtained by prototype II are still relatively high reaching a maximum temperature of 148°F. The temperature values for prototype II can be seen in figure 5. The glycol solution in Prototype II reaches a temperature of 132°F. The difference in temperature between the air and glycol solution in Prototype is 13°F which is similar to what Prototype I reached in figure 3. These results show that there is no change in temperature levels from Prototype I to Prototype II.

D. Prototype III

The latest prototype is designed to contain a solar array, adding sustainable potential for the device. The structure of prototype III is similar to that of the second prototype. Prototype III can be seen in figure 6. It is large enough to be attached to a residential or industrial building. Prototype III was also made to be mobile. This allows the solar wall to change its position with respect to the sun. The solar array is located at the top portion of the wall. The latest Prototype is 115" tall, 36" wide and 4" thick. The bottom portion of the wall contains a single solar panel that is used to determine how much solar power can be obtained using a more efficient solar panel. This portion of the design would be utilized in an industrial environment.

Figure 6: Prototype III front view.

The solar panels that were used in the solar array are the Parallax Inc. XHHOO 1-4 rated at 6 volts and 123 mA. Each panel has the dimensions of 125 mm tall x 63 mm wide x 3 mm thick and contains 12 solar cells. The fill factor for each solar cell was calculated to be 82.125%. The fill factor equation was given by the photo voltaic education organization and can be seen in equation 1. Below, in figure 7, is a picture of the solar array.

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}} \quad (1)$$

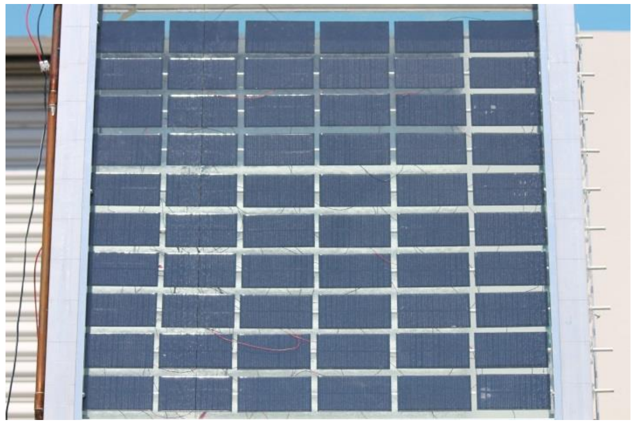


Figure 7: Solar Array located in Prototype III.

To control the angle of each row of the solar array a portion of the rod connecting the solar panels together is extruding from the left side of the wall. This can be seen in figure 8. To insure that each row is as close to the same angle of incident, small protractor templates were attached around each rod. The heat exchanger and structure of the fans is similar to the systems in prototype II. Glycol is also used in this prototype to collect the heat from the hot air and there are vents at the bottom and top of the wall.

Figure 8: Side view of rotating rods used to control each row in the solar array.

E. Goals

We hope to determine the optimal set up of the solar array to enable the most efficient design for the solar wall. Some of the factors that we will determine are first, if the solar array should be static or movable to track the sun which would insure the maximum gain of solar radiation. The second factor is the best installation direction for the wall on a building. Lastly, we want to optimize the structural form of the solar array to collect the most power per solar panel.

Methods

A. Analog Circuit Design

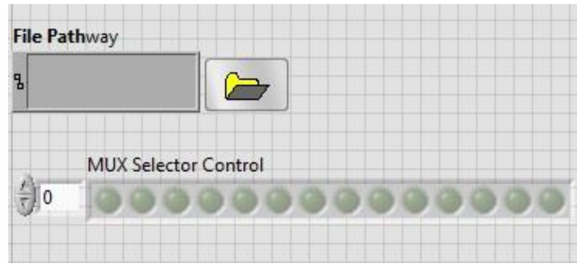
Eight 8-1 multiplexers where used to measure the voltage levels of each of the 60 solar panels in the solar wall array. The multiplexers are a MC14051B model made by Motorola. Referencing the LT spice circuit design in appendix A, the first port located on each multiplexer receives the first 8 solar panels located in the solar array, starting from the first row from the top of the window and the left most column. Each proceeding port in each multiplexer receives the next 8 solar panels following the direction from left to right and top to bottom. Two Arduino Uno R3 boards were used to control the values of the selector ports of each multiplexer and to record the voltage values of each solar panel. These two Uno boards where labeled as board A and board B. Looking again at the LT spice circuit design in appendix A, board A is responsible for collecting voltage values from the first four multiplexers and controlling the selector port values for all multiplexers. Board B collects the other four outputs from the remaining multiplexers. Due to the limitation of the voltage level of the Uno boards analog port inputs, a voltage divided was attached to the output of each multiplexer in order to make sure the voltage never surpassed 5V. The voltage divider used a 2/3 scaling factor for the input voltage from each solar panel. This voltage divider reduces the maximum voltage level of each panel from 6V to 4V.

B. LabView Programs

LabView was used to collect, sort and store the data collected from the solar array. LabView offers a VI package that allows the Uno board to interface with the LabView workbench. The Arduino boards are usually controlled using C programming software, but Labview was used because it provided a simpler interface for the user.

The first LabView program was created to collect the voltage values for each solar panel and store them in an array. The user control panel and program can be seen in figure 9. The program starts by initializing the port connection of both Uno boards to LabView. Then it sets the specific digital I/O pins, pins 2, 3, 4 on board A, as outputs. Next the specific value for each digital pin, either 1 or 0, is set with the indicator controlled by the user on the front panel of the program.

A



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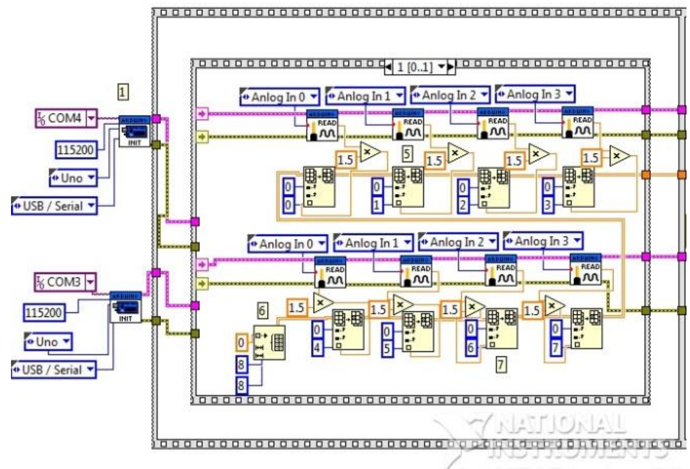
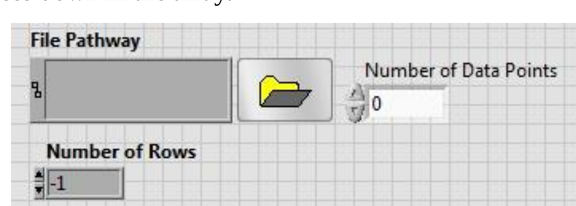


Figure 9 A.) Control Panel for collecting voltages B.) Program for collecting 8 solar panels

This signal is sent to each selector on all the multiplexer and determines which input the Uno board will receive. Each voltage value from the multiplexers is then stored in the main array created at the start of the program. The blank 8 by 8 array is filled with all the voltage values from each solar panel. Lastly the filled array is stored in a blank plain text file that is created by LabView.

The next program sorts the data collected into separate arrays specifically holding the voltage values for each solar panel at different angle of incidents facing the sun and at different times of the day. Figure 10 shows the control panel and program. This program first collects the data from the specified text file and stores it in an array. This array is then passed to three different for loops for each solar panel. Each for loop runs through the array and collects all the voltage values for each solar panel at both different times of the day and angle of incident. These three single dimension arrays are then combined together to make one array. This array is then stored in a separate plain text file. Referencing the LabView program in Figure 10, each row for each for loop is shifted 24 spaces down in the array.

A



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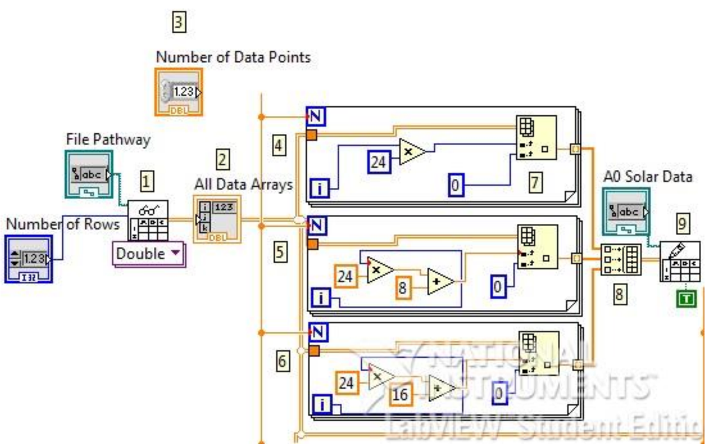

Figure 10 A.) Control Panel for Sorting data B.) Program for one solar panel.

The number 24 is chosen due to three arrays of data stored in the file referencing 0, 10 and 20 degree angle of incident for each time period throughout each trial. Each array is 8 rows long which mean that the next data point for each solar panel at a specific angle of incident is 24 rows away from the previous point. This number can be changed based on the number of angle of incidents that are taken into account for each trial.

C. Temperature Collection

The new prototype not only needed to be able to collect solar energy from the sun efficiently, but also needed to retain its ability as an AC system. During each trial the temperature was monitored to ensure that the air inside the window was consistent and reached the appropriate levels. The temperature level is also important to identify the efficiency of each solar panel throughout the temperature range. In order to collect the temperature level two thermocouples are set on both edges at the top and bottom of the window. This configuration can record the temperature difference across the entire window. Each thermocouple was attached to a thermometer in order to display the value of the temperature.

The temperature of the glycol was also needed in order to identify if the latest prototype can store the heat energy efficiently from the hot air. Like the previous prototypes the liquid collects the heat from the top of the device, using heat sinks, and circulates it through the device. The temperature in the container that holds the glycol was measured after being mixed using a digital temperature gauge.

D. Solar Radiance

A solar meter was used to collect the power output from the sun. The solar meter is a TM-206 made by Ambient Weather. Measurements of the suns power output in W/m^2 where taken with each measurement of the solar array. The solar radiance measurements were taken at chest level. The measurements weren't taken at the same height of the solar array, but there aren't any significant changes to the solar radiant measurements from the solar arrays height and the height of the actual measurements.

E. Solar Array Measurements

Collecting the measurements for the solar array at different angle of incidents and direction of the wall measurements were taken every 20 minutes. The temperature of both the air and glycol for each data point was also taken at the end of each measurement of the solar array at different angle of incident.

Results

A. Efficiency of Solar Panel vs. Temperature

The first aspect of prototype III was to test how the efficiency of each solar panel changed with respect to the internal air temperature. This is important because if the efficiency of each solar panel decreased dramatically when the temperature increased, then the overall function of the AC aspect of the wall would be jeopardized. The efficiency of each solar panel can be calculated using the equation 2 below [3].

$$\eta = \frac{VocIscFF}{P\,in} \qquad (2)$$

From this equation the only quantity that changes is the input power from the solar panel. Since the resistance of the solar panel is constant the only factor that is varying is the input voltage. Thus by showing how the input voltage level changes at different temperatures will show how the efficiency of the solar panel changes. Figure 11 shows the change of voltage of 4 different solar panels at different positions in the solar array.

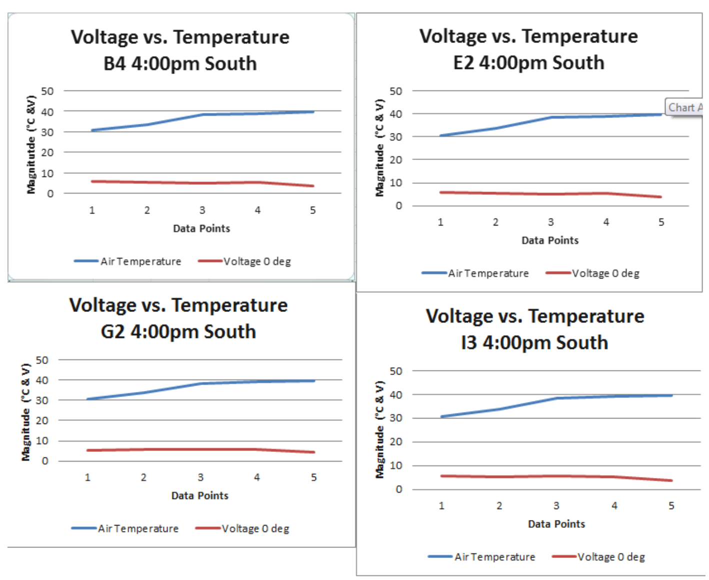

Figure 11: Four solar panels efficiency rating based on temperature change.

The four solar panels are B4, E2, G2, and I3. Each graph shows the change of input voltage for each solar panel at 4:00pm as the solar wall faces south. All four graphs in figure 11 show that as the temperature surpasses 40^0 C the voltage level starts to decrease almost by 50%.

B. Shading Effect of Solar Array Construction

The next issue that was analyzed was shading that occurs due to the structure surrounding the solar array and shading that each row cast on one another. Below in figure 12 there are six grey scale representations that show each solar panel, in the solar array, voltage level with respect to each other. Each rectangle from left to right and top to bottom represents the solar array at 1 hour intervals from 1-6 pm at 0˚.

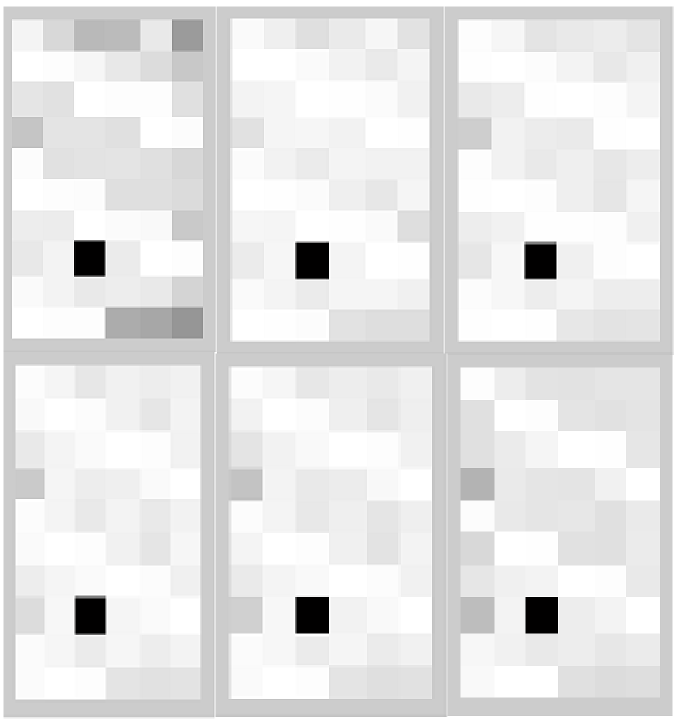

Figure 12: Grey scale for solar array based on voltage levels change over time.

The most shading occurs in the graph at 1pm. The shading digresses to a minimum point at 4pm. The major portions of the solar array that are affected by shadowing are the top and bottom rows of the array and the right most columns. These areas are affected because of the structure of the housing unit for the solar array. The housing unit surrounds the array and casts shadows on the solar panels around the perimeter. The next aspect is the analysis of the shadows that occur from each row. Figure 13 has three grey scale graphs of the solar array at different angle of incidents at 3pm. The three graphs from left to right represent $0 – 20^0$ respectively. Looking at figure 13 there isn't any significant changes in any of the solar panels voltage due to the angle of incident of the solar array.

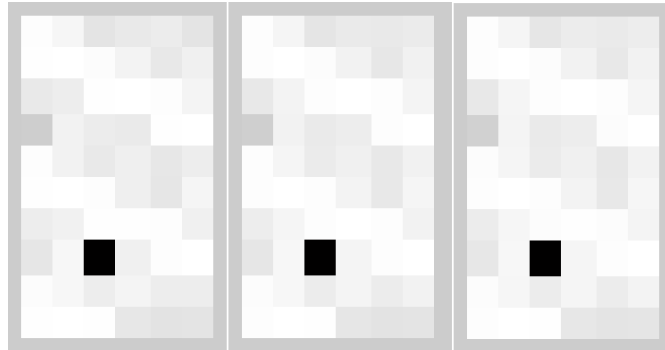

Figure 13: Grey scale for solar array based on voltage levels change at different angle of incident.

C. Voltage Level vs. Angle Incident of Solar Array

The angle of incident of the solar array will help determine if the solar array should track the movement of the sun or should have a static position that is an optimal configuration. Below in figure 14 are three graphs for the average power for three different solar panels at different positions in the solar array. The graph for each solar panel displays the average power for the three different angles of

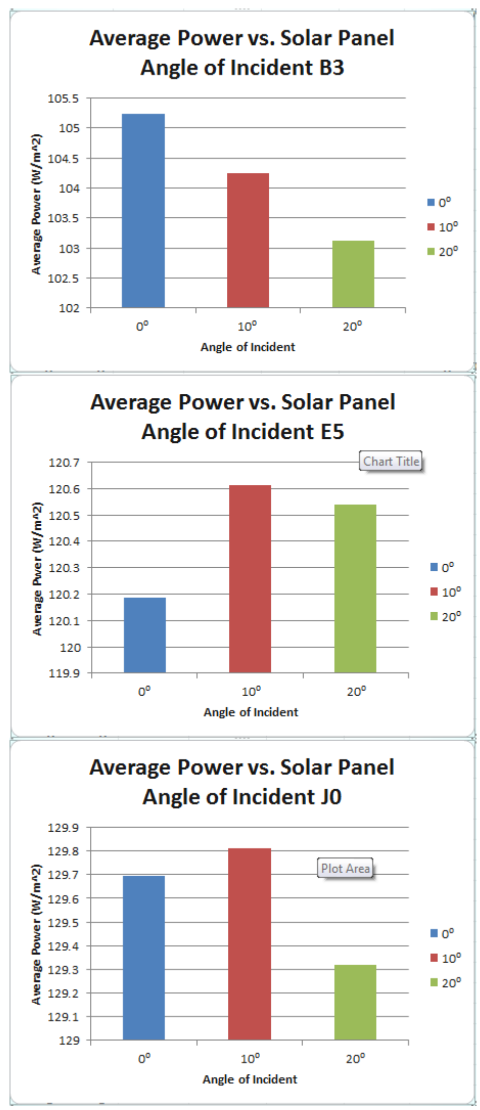

Figure 14: Average power for three solar panels vs. angle of incident

incident. Looking at how the power changes for each angle of incident can give more insight on the best configuration for the solar array. The solar panel E5 and J0 reach a maximum average power at 10^0. However solar panel B3 had a maximum average power at 0^0. The shading issues that mostly affected the outer rim of the solar array could be affecting the average power for solar panel B3.

D. Average Power vs. Direction of Solar Wall Installation

Another issue that solar path wants to test is the optimal direction of installation for the solar wall. Testing the average power will indicate the impact the direction of installation has on the efficiency of the solar wall. In figure 15 the four graphs represent four solar panels in the solar array and their

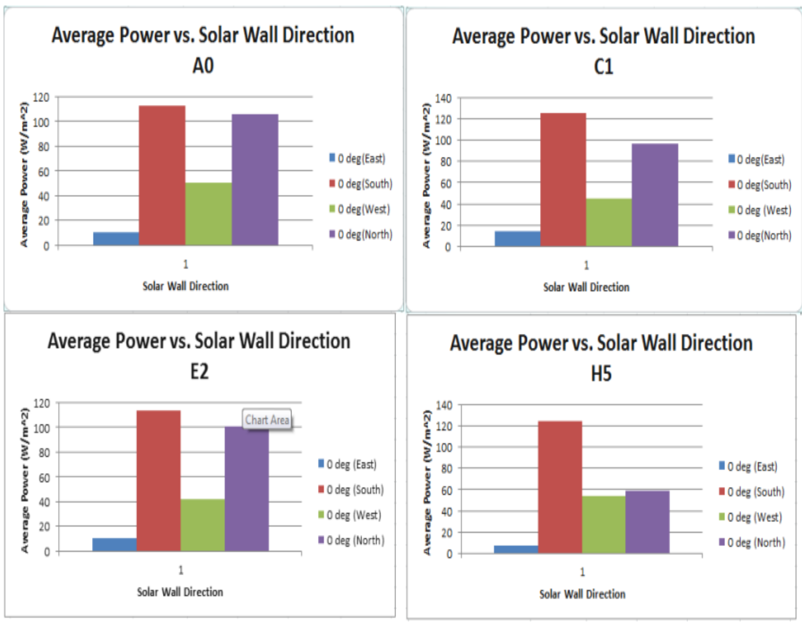

Figure 15: Average power for four solar panels vs. direction of installation.

average power for each direction of installation. The angle of incident for each solar panel was analyzed at 0º to reduce the shading effects due to the structure of the solar array and casing. The graphs show that for each solar panel in different position in the solar array the most optimal direction of installation is south. The trends for the other direction of incidents are the same for all four solar panels.

E. Average Power Per Hour for angle of incident and installation direction

The final aspect of the new prototype is to determine the amount of power per hour the solar wall can obtain. First the maximum amount of power per meters square hours needed to be calculated. In order to accomplish these calculations the average power for the solar array per hour needed to be calculated. In order for the data not to be screwed due to weather, the amount of solar energy that is emitted by the sun is determined and used to normalize the values from the solar

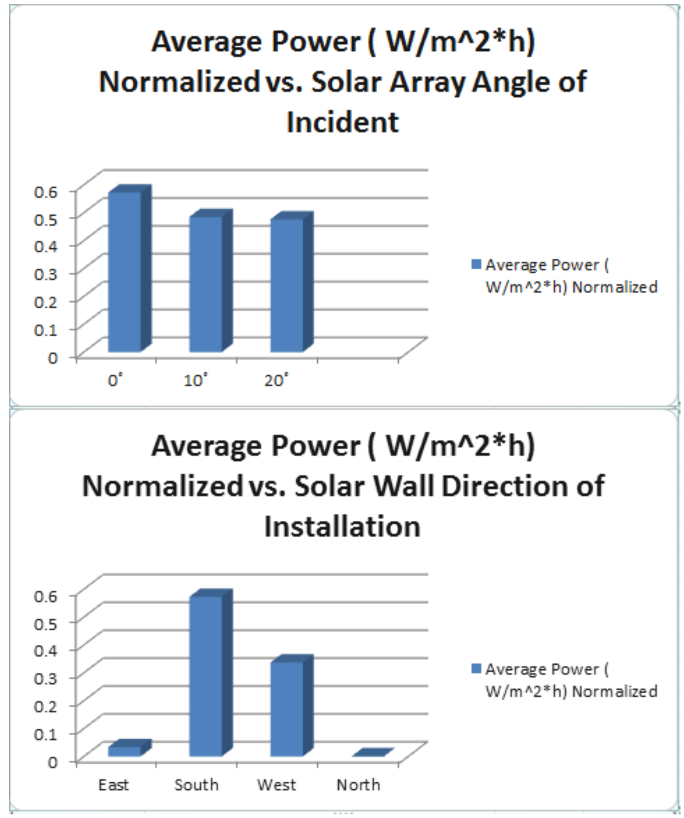

Figure 16: Average normalized power per hour for angle of incident and direction of installation.

array. In figure 16 are the graphs for the average power per hour against the angle of incident of the solar array and the direction of installation. Looking at these two graphs the maximum amount of power per hour occurs at 0˚ and the best direction of installation is south. The northern direction data was set at 0 because the normalized data for the solar array was above 1. This could occur due to the difference in the amount of sunlight the solar cells absorbed from the reflected light from the solar path building and the light obtained from the solar meter. This data shows more information about these two aspects of the new prototype because it includes the overall performance of the solar wall throughout the day.

Discussion

A. Optimization of solar Array Area in Solar Wall

The first aspect of the solar wall to analyze is the most optimal area for the solar array. Looking at figure 12 the most optimal areas in the array is in the white three diagonals that run across the middle of the window. These three diagonals show up no matter the change in angle of incident and the time of day. The areas of the window that are affected by shading again are the solar panels that line the rim of the solar window either in the wall. In order to improve the area of the window either the solar panels around the rim of the array need to be removed or the structure of the window needs to be changed to reduce the amount of shading that occurs due to the housing container of the wall.

B. Analysis of Automatic Traction of the Sun vs. Optimal Static Design

To determine what is the best functional configuration for the solar wall the impact that the change in power due to the change in the angle of incident of the solar array needs to be analyzed. Looking at figure 16 the most optimal angle of incident for a static solar array would be at 0˚. At this angle the solar array can reach the highest average power for each day. Comparing the static power and tracking power for the solar array in figure 16, the difference from the other angle of incidents only vary at most by 2 W/m^2. This is a change of 1.5% in power consumption. Based on those statistics it is better to have a static design for the solar array then to construct a system that tracks the optimal position of the sun. Since the change in power absorption from each angle changes by such a small margin, this allows the user to change the position of the solar array at any time of the day and not have to worry about a large decrease in performance.

C. Alternate solar panels for solar array

In order to improve the system of the solar array better solar panels could replace the current solar panels. Having thinner solar panels can decrease the effect of shading that occurs from each solar row. Thinner solar panels will also make the design of the solar array cleaner and more visually appealing.

Conclusions

A. Overall Temperature Efficiency of Solar Wall

One of the main concerns for the new prototype was to maintain the ability to reach the same level of temperature difference inside the windows environment. The new temperature ranges for prototype III can be seen in figure 17. This figure shows three different testing days where the solar window was tested at three different directions (east, south and west) facing the sun. The direction of the solar wall changed every 5 minutes during the 20 minute interval for each data point for the data set. The three graphs represent the solar walls temperature when it faced the southern direction.

The maximum temperatures that the air and glycol reach based on these three graphs are 109˚F and 105˚F respectively. The difference between prototype III maximum temperature and the previous prototypes is 39˚F for the air inside the window and 27˚F for the glycol solution. The change in temperature can be due to the different method in which the solar wall temperature was obtained. The temperature values for the first two prototypes where obtained by tracking the sun. While the values for the last prototype did not track the

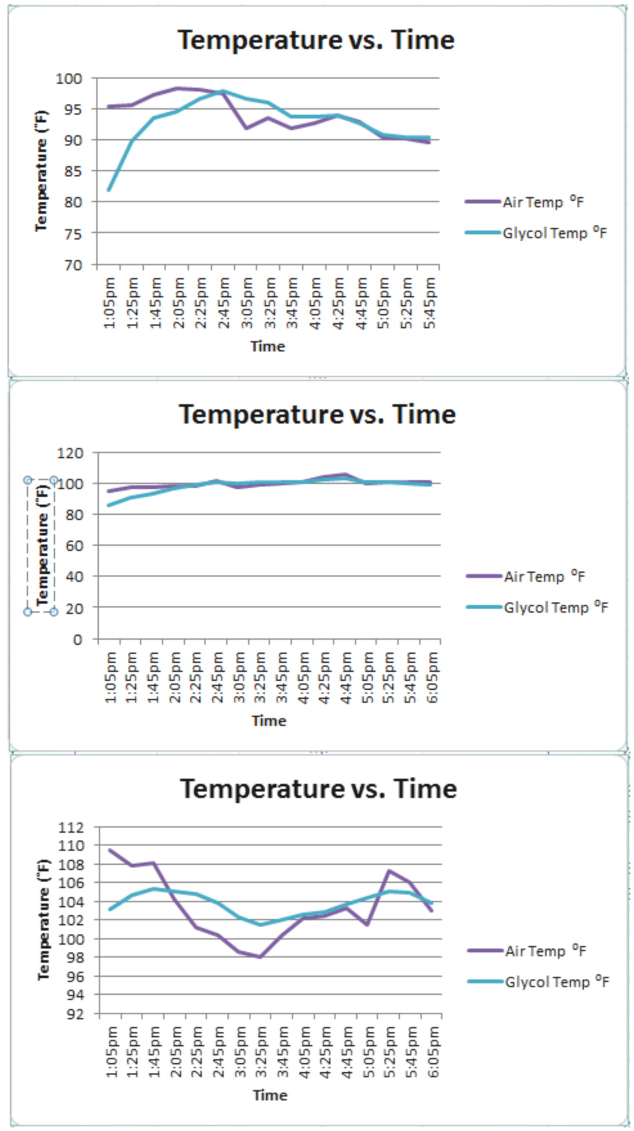

Figure 17: Temperature vs. Time for solar array for three different data sets with the solar wall facing the southern direction.

sun. The only consistent temperature graph in figure 17 is the second graph. The major variations that occur in the other two graphs can be due to the thermocouples position on the solar wall. The thermocouples are located at the outside the solar wall near the top vent. Due to their location the temperature of the air taken by the thermocouples can be affected by the wind throughout the day. In order to increase the reliability for the temperature readings on prototype III the thermocouples should be placed inside the top vent to prevent distortion from change in wind speeds. In order to verify, more precisely, the temperature the same process that was used for the first two prototypes needs to be implemented on the prototype III.

B. Improving Data Collection Methods

Due to the longevity of testing done for the solar wall, automating the testing system can improve the amount of data collected for each trial. In order to automate the testing procedures, the program that was created using LabView needs to change to allow the program to choose the run through the selector values for the multiplexers. The program should also store and sort the values of the voltage from the solar array in all the different ways that the user desires to analyze the system.

Another physical aspect that could improve the data collection methods is to create a way to rotate each row in the solar array at the same angle simultaneously. This would improve the reliability of the data collected when testing the difference in power of the solar array at different angle of incidents. Each row would need to be set at the same angle of rotation, and then connected together. The connection between all the rows could be very similar to the connection to a traditional set of blinds.

C. Review of Prototype III and Future Works

Prototype III solar array was able to produce a maximum watt/m^2*hrs of about 67% of the maximum power that could be obtained by the solar window. Again the best configuration for the solar wall is to be installed facing south with the solar array angled at 0˚. The overall performance of the window decreases by 15% when the angle of incident of the solar array is changed to either 10˚ or 20˚. The temperature range of the new prototype reached values 90˚F up to 109˚F. This is not as high as the first two prototypes, but might be due to the method of heating up the air inside the wall and the placement of the thermocouples that are collecting the temperature readings. The methods for collecting data from the solar array need to be more automated in order to collect more data. In order to optimize the amount of power to cost ratio of the solar wall the area of the solar array needs to be changed in order to cut out solar panels that don't obtain as much power as the rest of the array or the structure of the solar wall that holds the solar array needs to be changed.

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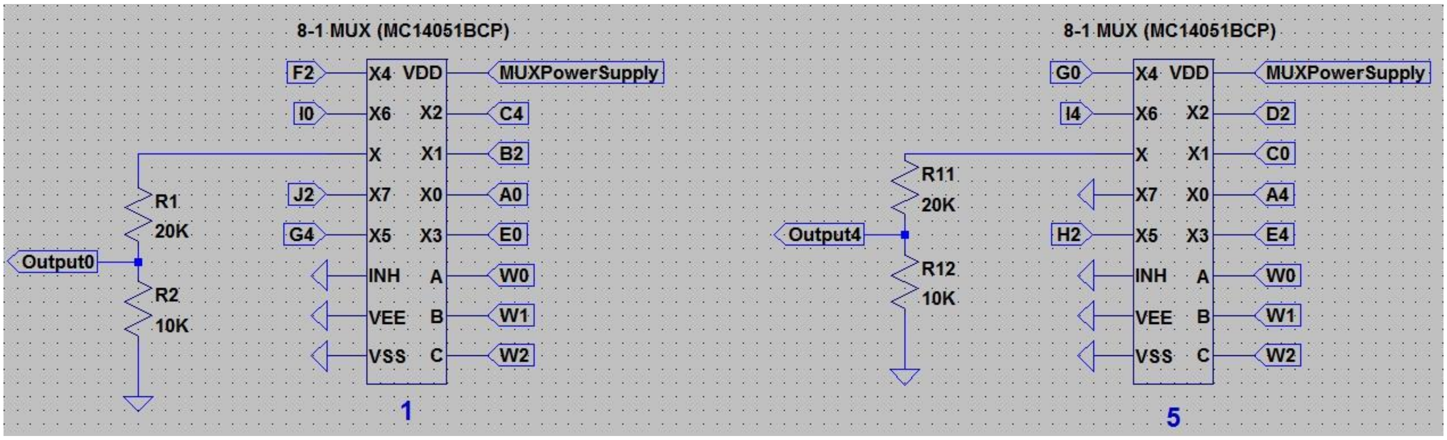
[2] Saadatian, Omidreza. "A state of the art review of solar walls: Concepts and applications."*Building Physics*: 55-79. Print.

[3] *PVeducation*. N.p., n.d. Web. 15 Aug. 2013. <http://pveducation.org/pvcdrom/solar-cell-operation/efficiency>.

Appendix A

MUX Connection (MUX 1 and MUX 5)



Arduino Connections and Power Supply