EVALUATION OF A PROTOTYPE SOLAR AWNING

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ABSTRACT

A prototype solar awning has been designed and installed on a University of Oregon campus building. The solar awning is composed of a light shelf with photovoltaic modules attached tilted 20° to the south. An interior light shelf and LED lights have been installed along with monitoring equipment to evaluate the total amount of energy produced by the system and saved by reducing the heat load of the building. The system has been extensively monitored and the analysis of this system will be used to evaluate the economics of solar awnings on campus buildings across the university system.

A kiosk in the hallway turns the system into a solar awning lab where students and faculty can perform tests and experiments on a real solar awning -- daylighting system. The data are also available over the internet.

The solar awning produces electricity, reduces heat buildup in the hallway, provides daylighting to reduce electrical load and heat associated with lighting, provides experience for future the installation of solar awnings, and offers educational opportunities.

1. INTRODUCTION

Climate change is currently a focal issue in higher education. University presidents, faculty, students and administrators are coordinating efforts and committing their institutions to environmental stewardship.

The approach of the Oregon University System (OUS) has been to complement the net zero climate initiative that each campus has made under the American College and University Presidents' Climate Commitment. Providing the leadership and the capital funding, OUS is able to advance sustainability best practices and policies to accelerate and strengthen Oregon's leadership aspirations.

The Solar Awning Project is one of several renewable energy demonstration projects that OUS has developed that can best leverage our institutions' unique research talents, Oregon's natural resources, and available funding opportunities to achieve the following:

- Reduce our carbon footprint
- Maintain our national leadership position in sustainability
- Allow student and faculty researchers to develop and test new technologies
- Increase the competitiveness of the university system's renewable energy curriculum
- Increase the value of the research, prior to commercialization
- Enhance the Oregon economy by creating both short and long term job opportunities in emerging renewable energy industries.

With support from the Governor and Legislature, many laws and policies have already been established to promote sustainable development. The Solar Awning Project will complement those efforts by combining renewable energy generation with energy conservation, which will contribute to our overall goal of carbon neutrality.

This paper is organized as follows. First, the system is described and the monitoring strategy is discussed. Set up of the Kiosk is also detailed. Data from the summer and winter will be analyzed and evaluated. Examples of the results found by monitoring the PV system performance and tem-

Fig. 1: Solar awning on the third floor of Pacific Hall. The modules are separated into two strings of six to minimize the shading problem on the whole system. The hallway on the second floor will be used as a control.

perature transducers will be presented. Next steps are then presented.

2. PROTOTYPE SOLAR AWNING

The prototype solar awning was located outside the third floor of a connecting bridge between two buildings. This connecting three-storey bridge building has a hallway with large windows on the south side and offices on the north side of the hallway (Fig. 1). The hallway often experiences excessive heat in the summer even with tinted film placed on the windows and air conditioning in adjacent wings of the building. The hallway on the floor below the awning has the exact physical attributes of the experimental third floor and will serve as a control when the awning cooling capacity system is tested this coming summer. The solar awning consists of 12 Sharp 80 Watt NE 80EJEA solar modules mounted in two strings of 6 modules each. Each string is

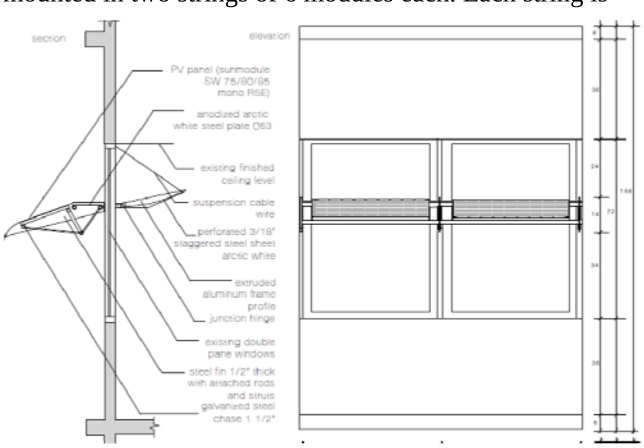

Fig. 3: Drawing for the prototype solar awning

Fig. 2: Light shelf inside the hallway reflects light to the ceiling and spreads the daylight further into the building. LED lighting can be seen on the outer edge of the light shelf. Florescent lighting on the ceiling will be removed when the LED lighting becomes operational.

connected to an SMA 700 inverter. Separate east and west arrays were necessary because severe shading problems were presented by walls on either side of the awning. The east half of the array is shaded in the morning and the west half is shaded in the afternoon.

The solar modules are tilted 20 degrees to provide optimum shading in the summer and are mounted in front of 30.5 cm-wide (12”) exterior light shelves. A gap between the photovoltaic (PV) module and the light shelf was provided to enhance the air flow around the PV modules.

The supports holding the modules are bolted through the frames around the window to ensure a solid structure. Light shelves inside the hall are aligned with the light shelves outside and help reflect the light farther into the building. The PV modules are mounted on tubes that run the entire length of the awning and house the wiring from the modules. This avoids the unaesthetic appearance of wires hanging from the array and helps protect the wires from the elements.

The inside edge of the interior light shelf is constructed so that the wires for the LED lighting can run along the edge of the light shelf (Fig. 2). The LED lighting will replace the florescent tubes that currently illuminate the hallway. Daylighting controls will be included in the circuit for the LED lighting to further minimize the use of electricity and to help designers and facility managers gain experience with daylighting controls and LED lighting.

The walls and ceilings of the hallway have been painted with average reflectance of 90% for the ceiling and 75% for the walls. The floor reflectance is 55%. This ensured a good

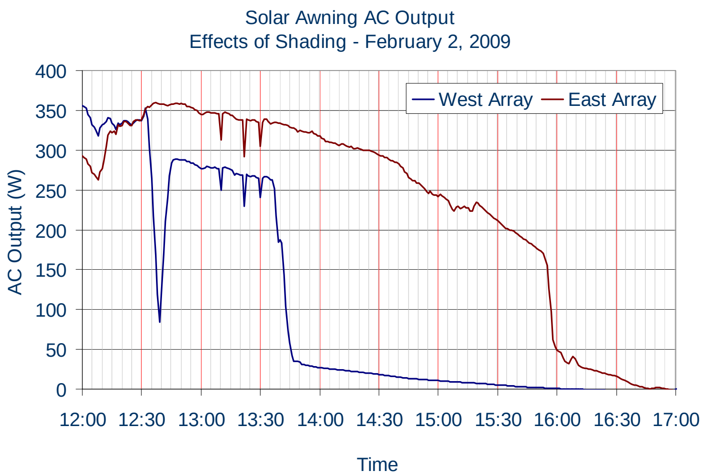

Fig. 4: AC Output of shaded verse unshaded array. The west array, lower trace, is shaded.

Fig. 5: Shading at 12:35

Fig. 6: Shading at 12:50

Fig. 7: Shading at 13:35

indoor room reflectance value to help reflect the light in the hallway. Already the hallway is more comfortable and painting the walls a brighter color makes a stark contrast to the dark halls that existed prior to the experimental intervention. The drawing for the solar awning is shown in Fig. 3.

3. MONITORING OF THE SOLAR AWNING

Extensive monitoring of the solar awning has been initiated to accurately study the performance of the system and to verify the expected energy savings. A Campbell Scientific data logger is used to collect averaged data in one minute intervals. Data are downloaded and sent to a database on a web server for display on the kiosk and are also incorporated in files that are available on the SRML Website at http://solardata.uoregon.edu. The DC current and voltage, and AC power output are measured for each array, along with incident solar radiation and module temperature. One temperature strip (a resistance temperature detector or (RTD)) is on the back of the first module of the east array and a second RTD is mounted on the back of the last (6^{th}) module in the string. The AC power to the LED lighting will be monitored when the lighting is installed.

A Kipp and Zonen SP-Lite pyranometer is mounted in the plane of the solar awning between the sixth and seventh module. This location is not easily accessible, and so the SP -Lite pyranometer and other outside sensors cannot be regularly cleaned. However, global, beam, and diffuse irradiance and meteorological data, such as ambient temperature, are measured at the main solar monitoring station on the adjacent roof. These instruments are maintained five days a week and can be used to check on the soiling of the solar awning pyranometer.

In addition to the PV system monitoring, four LiCor photometers (light sensors) are mounted to test daylight performance of the combined exterior/interior light shelf and shading system. One Li-Cor photometer is mounted on the light shelf outside the window, the second is mounted on the light shelf inside the window, a third is mounted on the shelf below the below the window, and a fourth is mounted horizontally on the back wall. Two temperature strips are mounted on the window. One is above the light shelf and the other is below the light shelf. The pyranometer and photometer on the exterior of the building will not be cleaned on a regular basis.

4. EVALUATION OF THE PV SYSTEM

The 960 $Watt_{DC}$ photovoltaic system has generated over 800 kWhrs during the first year. Shading problem reduce the AC output by between 20-25%.

The solar awning is located outside a connecting corridor between two buildings that are subject to severe shading conditions. The two identical systems provide an ideal opportunity to evaluate the effects of shading on PV systems. Since only half of the array is shaded at a time, it is necessary to combine the output of the west side array in the morning with the output of the east side array in the afternoon to evaluate the performance of an unshaded array of equivalent size. While initially viewed as an inconvenience, this happenstance offered an excellent chance to evaluate the shading effects on PV array performance (Figures 4-7).

Monitoring of the PV system reveled two phenomena. First, there is a large drop in output from the West array when the shading first starts. This may be related to the max power

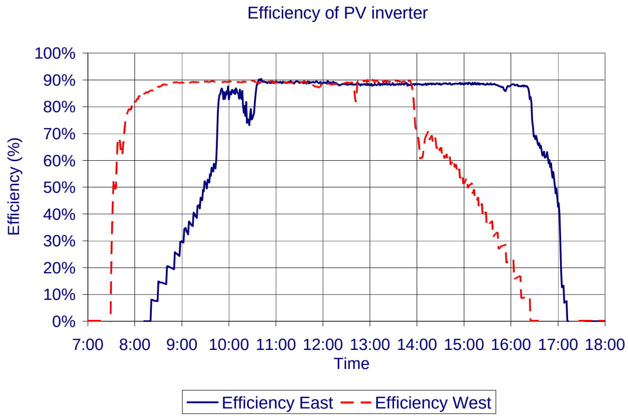

Fig. 8: Inverter efficiency drops when shadow first affects AC output. February 21, 2010. See drop at about 12:40.

point tracker in the inverter trying to adjust when the shading is reducing the output of the PV module and the bypass diode in the module is starting to divert the current around the poorly performing module. The efficiency of the inverter drops briefly from 90% to 80% (Fig. 8).

When one module is bypassed, the performance drops by about 17% because 1 of the 6 modules is not contributing to the output. The max point tracker shifts the operating DC voltage from 96 to 77 volts (Fig. 10). When two modules are shaded and bypassed, one would a reduction in max power point voltage to be in the mid-60 volt range and another 17% drop in output. However, the production of the array drops precipitously. The SMA 700 inverter has a max power point range of 77 to 120 volts in the mode of operation chosen for this array. It appears as if the max power point tracker starts to drop the current downward to keep within its voltage specifications and as is does so, the current approaches that of the shaded arrays. With the lower

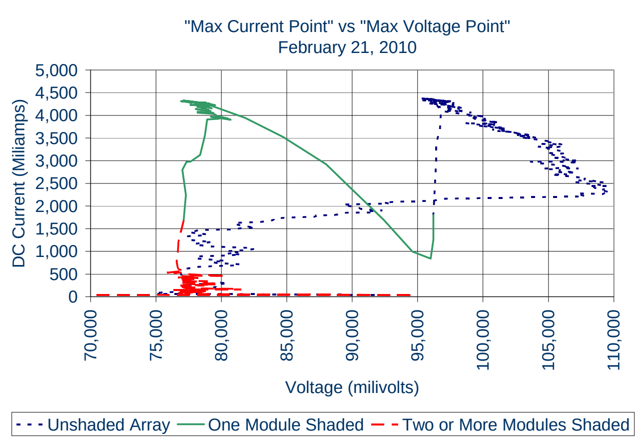

Fig. 10: Plot of DC current and voltage on a clear day when 0, 1, and 2 or more modules are shaded. The max power point tracker operates in the 77 to 120 volt range.

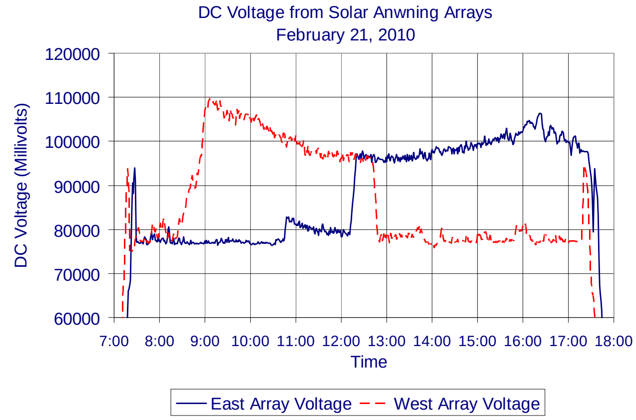

Fig. 9: DC voltage for the east and west arrays.

current, the bypass diodes let the current flow through the shaded modules and the minimum voltage can be maintained. The PV system now behaves as if the whole array is shaded.

This is shown in Figures 8, 9 and 10 when the second panel is shaded at around 14:00 and the DC voltage is maintained at about 77 volts. When the third, fourth, and other panels are shaded there is little change as the PV system is already operating as if the whole array was shaded (Fig. 4).

Shading of the modules also affects their temperature as shown in Fig. 11. As expected, modules in direct sunlight heat up faster than those in the shade. The two temperature measurements were taken on the back of the first and sixth module of the east array. Module 6 is located in the east wall and therefore has poor circulation while also receiving reflected light from the east wall. This might result in higher temperatures observed for module 6 in the afternoon after 14:00.

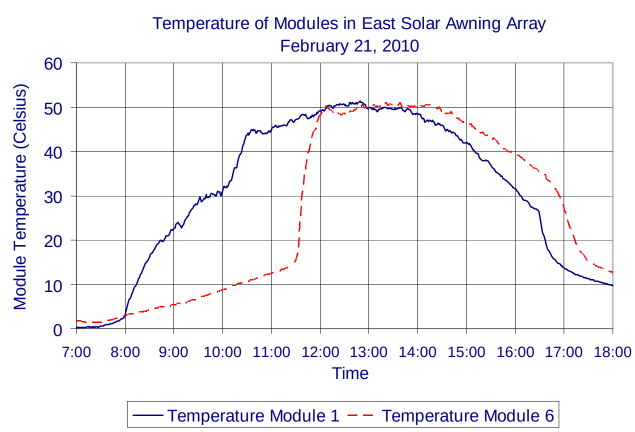

Fig. 11: Effect of shading on PV module temperature. Modules 6 is shaded until 11:30 and while module 1 is free of shade by 8:00 am.

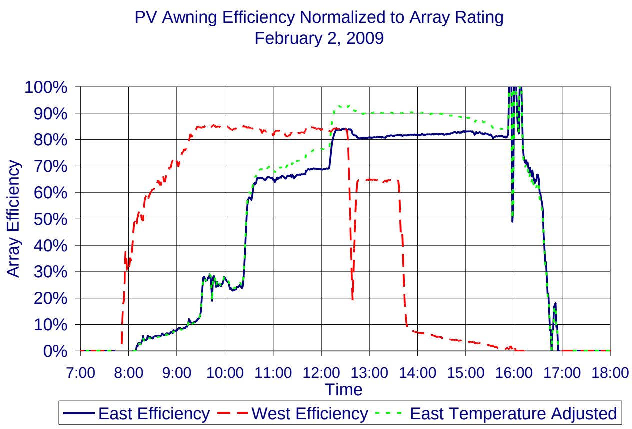

Fig. 12: February 2009—PV AC Output divided by system DC rating. The dotted line is the normalized ratio adjusted for a temperature of 25 Celsius.

4.1 <u>PV Performance over Time</u>

Of considerable interest is the decrease in performance of PV systems over time. Soiling is the main problem here, as the awning is on the third floor and this location makes cleaning difficult. This soiling reduces the amount of solar radiation that can penetrate through the glazing to enable the solar cells to produce electricity. By comparing the system performance on clear days, a year apart, an rough estimate can be made of the decrease in performance.

A good method for comparing the system performance is to divide the AC output by the incident energy and normalizing the output by dividing by the DC rating of the array. This normalized performance ratio is show in Figs. 12-13.

Temperature also affects the performance of the solar module. To obtain an accurate comparison, the module temperature should be normalized to 25 °C. For this example, it is assumed that the performance decreases -0.485%/°C as stated on the spec sheet. The exact coefficient of decrease depends on a number of conditions, but the two days should be similar enough so that the decrease in performance verses temperature should be similar.

The correction was only made for the East array because the temperature strips were attached to the back of the modules on the east side. When the solar awning was first installed, the normalized temperature adjusted PV performance was about 90% (Fig. 12). Notice that normalized array efficiency, normalized to a constant temperature, is nearly constant from 13:00 to nearly 15:00 while plot for array efficiency without the temperature normalization increases. As expected, PV efficiency increases as module temperature decreases and when comparing PV efficiency it is important to specify the temperature or normalize it to a reference temperature.

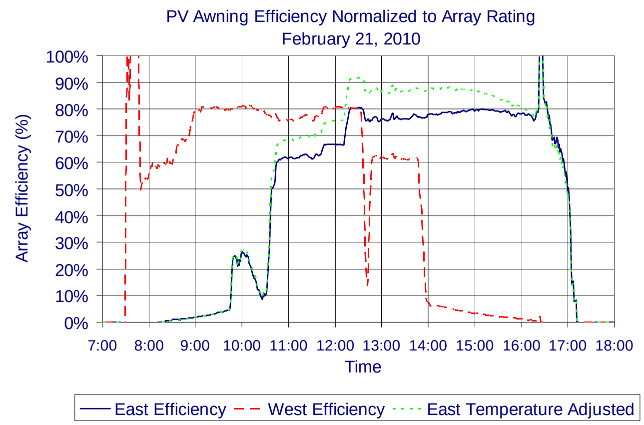

Fig. 13: February 2010—PV AC Output divided by system DC rating. The dotted line is the normalized ratio adjusted for a temperature of 25 Celsius.

When similar information is plotted for February 2010, the average array efficiency decreases by about 2%. Two days is a very limited sample. In addition, the uncertainty in the irradiance measurements has absolute uncertainties of about 5% and relative uncertainties of a percent or two. It is likely that the responsivity of the pyranometer decreases over time and the irradiance on the second period a year later should be increased by the proportion the responsivity of the pyranometer decreased. Therefore, the decrease in system performance degradation might be slight greater than the 2% observed without adjusting for pyranometer calibration change. Of course, comparisons on many more than two days are needed to ascertain the true decrease in performance with any level of confidence. It should be noted that there is a decrease in measured tilted irradiance around noon. The cause of this phenomenon is unknown, but it has been observed at the same time in data taken one year apart.

These data are available on the UO Solar Radiation Monitoring Laboratory Website at http://solardata.uoregon.edu for those interested in evaluating this or other issues.

5. <u>COOLING BY THE SOLAR AWNING</u>

Cooling of the hallway by the solar awning is significant. A more detailed analysis of this cooling will commence once the LED lighting has been installed and permission is granted to isolate the hallways from the adjoining buildings. This should be completed in the summer of 2010.

While a full-scale evaluation is anticipated later this year, the effects of shading can be seen by looking at the temperature measurements made for the inside of the window. The window has two temperature sensors, one above and one below the light shelf. Therefore, a quick way to look at the

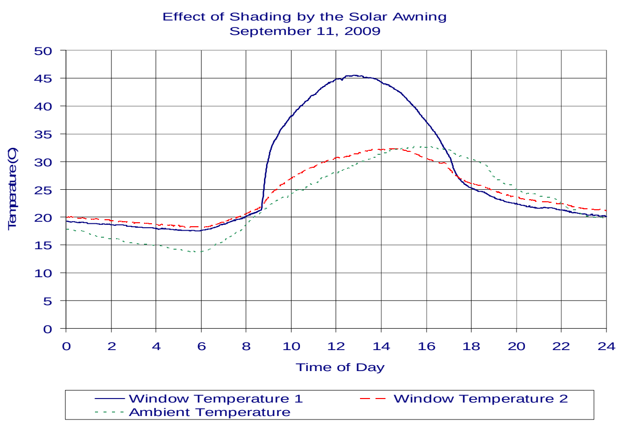

Fig. 14: Temperature of the window above and below the solar awning. Ambient temperature is also included. Air conditioning in the building affects the window temperatures as does the incident solar radiation and ambient temperature.

cooling effect of the awning blocking the direct sunlight is to examine the temperature difference between the shaded window area and the window area exposed to the direct sunlight. The temperature of the area exposed to direct sunlight is up to 15°C higher than that of the area in the shade (Fig. 14).

The air conditioning in the building clearly affects the temperature of the window pane and during much of the night the two temperatures are about equal. Note that in the morning the window temperature is above the ambient temperature and in the evening, the window temperature is below the ambient temperature. The ambient temperature certainly affects the temperature of the single pane window, but this is moderated by the temperature inside the building. Since this is one pane of glass, the conduction of heat from above the light shelf does have some affect on the pane temperature below the light shelf. However, the 15 °C temperature difference between the two areas shows significant cooling effect of being in the shade.

6. DAYLIGHTING AND THE SOLAR AWNING

A unique feature of this solar awning is the addition of a light shelf. The light shelf produces an interesting pattern of light in the hall (Fig. 2). Before the solar awning was installed the walls were painted pastel yellow with a 1.2 m (4 ft) high blue trim and the ceilings were off white for an average light reflectance of 40% and 70% respectively. To increase the indoor reflectance ratios for maximum daylighting and a reduction in glare index ratio of the windows to walls, a light yellow and pale green was used around the frames to increase the hallway's reflectance to 75%. The ceiling tiles were painted white to increase the reflectance to 90%. The new paint certainly brightened the hallway and increased the daylight efficacy. When the solar awning was installed, the lighting level did increase because of the light self, but the glare was reduced because the awning blocked the direct sunlight at eye level.

Fig. 15 provides the illuminance distribution levels (isolux) comparison of the daylight factor (%) distribution of the experimental floor on the far right after the implementation of the solar awning and the internal light shelf. The control

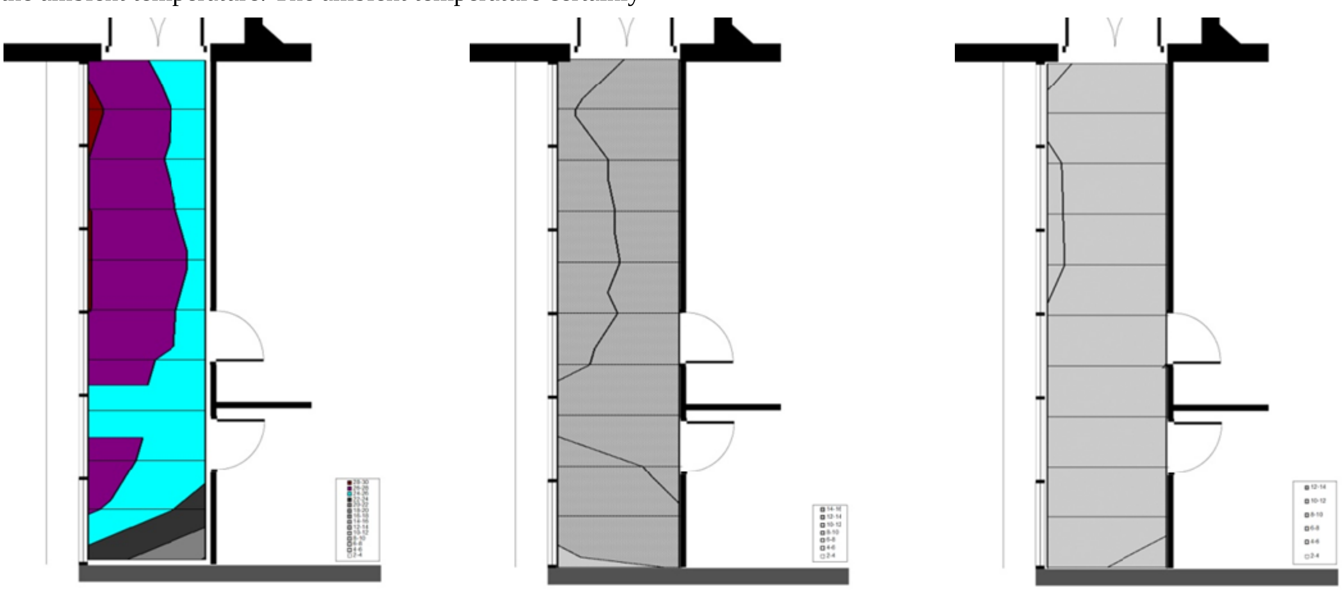

Fig. 15: Isolux distribution levels in 1/2 the hallway outside the offices. South is to the left. The distribution on the right is without the solar awning and light shelf. The distribution in the middle is for the solar awning with only the exterior light shelf. The distribution on the right is for the solar awning and the exterior and interior light shelves.

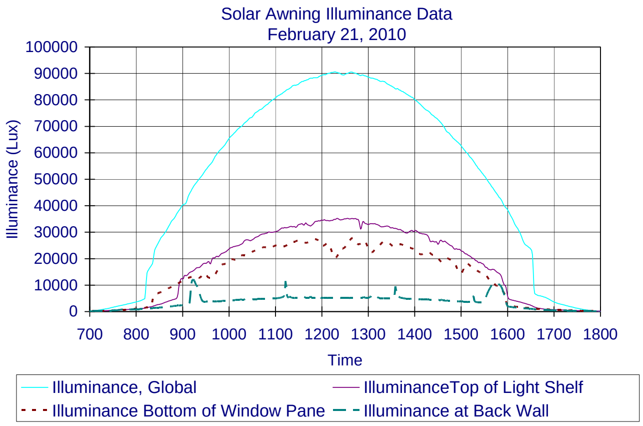

Fig. 16: Illuminance measurements on a clear day. Top solid line is on the light shelf outside the window. Second solid line is on the light shelf in the hallway. Dotted line is on the bottom window frame in the hallway. Dashed line is from the horizontal instrument on the back wall.

floor is illustrated on the far left without the awning or the light shelf. The middle isolux plot compares the implementation of the awning without the addition of the internal light shelf. The elimination of hot spots and glare from the excessive daylight is reduced tremendously in the proposed system with average ambient illumination of 6-8% daylight factor. These levels exceeds the recommended minimum daylight factor levels for a corridor space of (1%), and are within the range for offices and galleries (4-6%). This will provide evidence-based support that the proposed awning system would meet or exceed the recommended daylight factor levels for most common commercial space types (1-6%).

A sample of the illuminance readings on a clear day in February is shown in Fig. 16. There is a significant difference between the illuminance inside and outside the window because of the film on the window to reduce heat loss. The illuminance is down by a factor of nearly 3. The roughness of the illuminance on the bottom of the window sill results from shading by trees or other objects. The illuminance measured on the back wall is reduced by a factor of nearly 7. The spikes in the data from the back wall result from the light passing between gaps in the light shelf. Fig. 2 shows the pattern of the gaps that can move up and down or across the back wall as the sun moves across the sky.

LED lighting will eventually replace the fluorescent lighting in the hallway. There are twelve LED lights, each about 30 cm (one foot) wide and mounted on the end of the light shelf aimed at the middle of the ceiling. The lights are connected in series and the wire runs down the outside conduit at the end of the light shelf.

A daylight sensor will be mounted on the ceiling to control the LED lights. This is not standard equipment for these lights, but monitoring the AC power to the lights will show how much energy could be saved with daylight controlled LEDs.

7. KIOSK AND SOLAR AWNING LAB

The interactive kiosk display is designed to be used by students who will conduct measurements and tests of the performance of the solar awning. While this is a learning tool for classes studying the solar awning, it is also used to showcase the solar awning and to familiarize students, faculty, and staff about an actual energy component of the building and get them interested in building energy use. At the top of the display are graphic meters that show the instantaneous output of the arrays and incident solar radiation. The total amount of energy produced is also displayed (Fig. 17).

A graph of the AC power produced is also shown in the display below the gauges (Fig. 17). Tabs allow views of AC power minute by minute, hourly, daily, weekly, and monthly. The data are updated every minute. Other pages, yet to be constructed, will enable those at the kiosk to view the readings of the other instruments. Another page will allow the view to select between a combination of measurements and compare and contrast the results. The final page discusses the project.

The kiosk pages are also viewable on the internet at http://solarawning.uoregon.edu. The data from the solar awning will be available at the SRML Website at http://solardata.uoregon.edu.

8. SUMMARY

The prototype solar awning project was initiated to evaluate of the performance of this building integrated photovoltaic (BIPV) system. Adding daylighting and controlled LED lighting provided the opportunity to test new ideas. The need to have comprehensive monitoring and the desire to install a real-time interactive kiosk further expanded the project and enable the creation of a laboratory for students to see, feel, touch, and explore the energy productions and savings from a photovoltaic system, an awning, light shelves and daylighting, and LED lighting with daylight controls. These concepts now become real and not something that is read about in a textbook.

The solar awning project tests:

- Output of the PV arrays
- Effects of shading on PV system performance
- Effects of long-term soiling on PV output

- Cooling produced and energy saved by the awning
- Electricity saved by use of daylighting
- Electricity saved by using LED lighting
- Use of daylighting controls

In addition, the solar awning projects

- Enables an economic study of the total energy saving from a solar awning
- Provides a lab where students can study how solar awnings, daylight, and PV systems work
- Gives a visible example of solar at work in a corridor frequented by students, faculty, and facility managers.
- Shows the university's commitment to solar energy

Once the project evaluations are complete, the findings will be used to assess the installations of solar awning across the university system.

9. ACKNOWLEDGEMENTS

The prototype solar awning project is made possible by funding from the Oregon University System, the University of Oregon Facilities, the University of Oregon, Department of Architecture and High-Performance Environments Lab (HiPE), as well as the Energy Trust of Oregon. Additional support for the University of Oregon Solar Radiation Monitoring Laboratory comes from the Bonneville Power Administration, Eugene Water and Electric Board, the National Renewable Energy Laboratory Subcontract No. NFE-8-88401-01, Emerald People's Utility District, Salmon River Electric Cooperative, and Benton County Public Utility District. The solar awning and kiosk were fabricated and installed by Image King Signs of Eugene, Oregon.

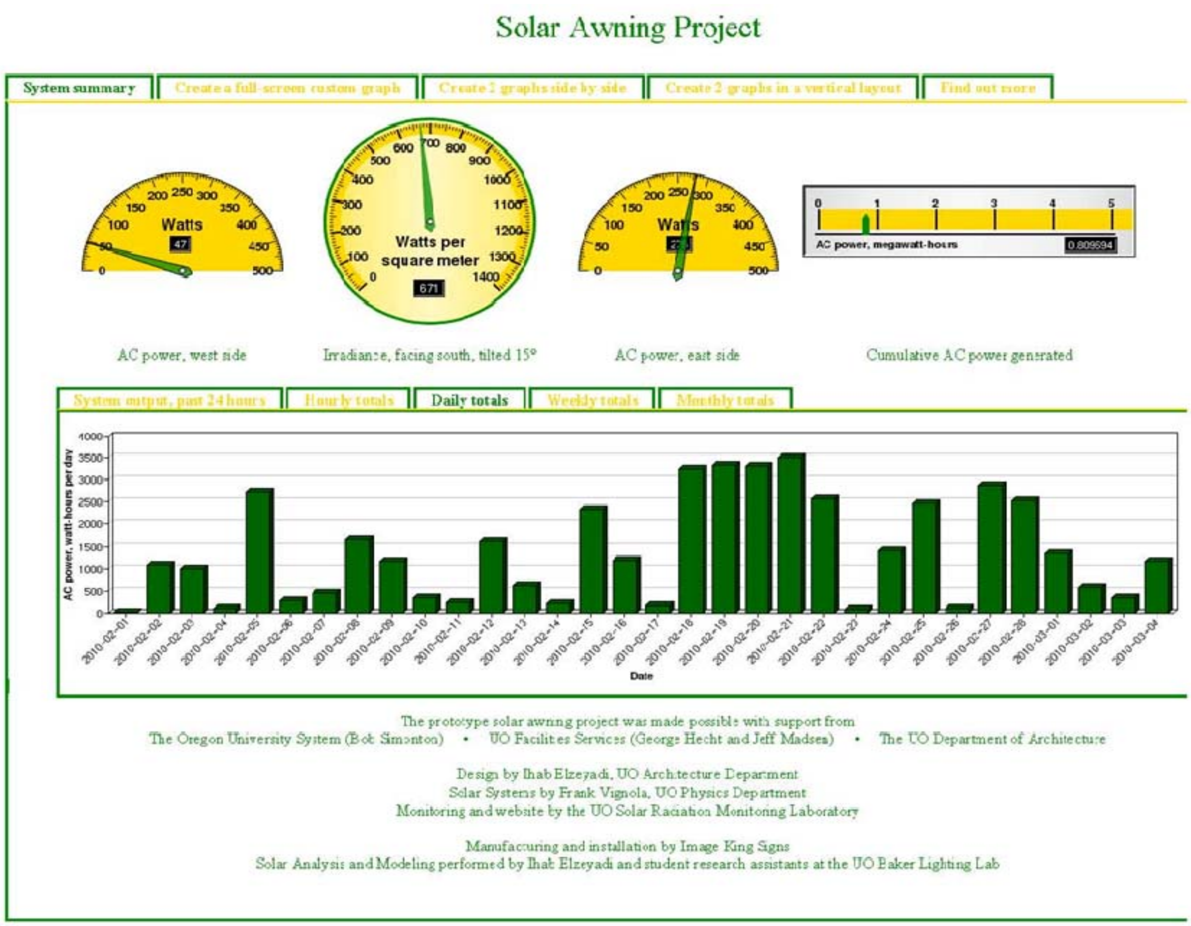

Fig. 17: Display on kiosk's home page. Meters for instantaneous display are on the top row along with one showing the cumulative AC output. Plots of one-minute, hourly, daily, weekly, and monthly AC output can be chosen by selecting taps above the plot. Example is for daily totals.