FINAL REPORT

Provided by the University of Washington

PHOTO-VOLTAIC ALTERNATIVES FOR THE REHABILITATION OF THE WATCHMAN LOOKOUT

(Pkg. 404 Rehabilitate Watchman Lookout)

MARCH 1999

PREPARED FOR:

National Park Service

PREPARED BY:

Craig Connors and Philip C. Malte
MECHANICAL ENGINEERING DEPARTMENT
UNIVERSITY OF WASHINGTON
Box 352600
Seattle, WA 98195-2600

Phone: 206-543-5486
Fax: 206-685-8047
e-mail: malte@u.washington.edu

Photo-voltaic Alternatives for the Rehabilitation of the Watchman Lookout
(Pkg. 404 Rehabilitate Watchman Lookout)

report prepared for the

National Park Service

prepared by

Craig Connors and Philip C. Malte
University of Washington
Department of Mechanical Engineering
Box 352600
Seattle, WA 98195-2600
(malte@u.washington.edu)

March 1999

Executive Summary

A new photo-voltaic system for radio-repeater operation and lighting has been developed for the Watchman Lookout at Crater Lake National Park. Design of the new system has been guided by two primary requirements: 1) compatibility with the historic and scenic characteristics of the Watchman Lookout, and 2) reliability of the radio-repeater operation, which is essential for Crater Lake National Park. The study, conducted from September 1998 to March 1999, has involved three major phases, including:

- Analyzing the photo-voltaic and radio-repeater systems currently in place at the Watchman Lookout, which have functioned well for about ten years.
- Developing information on the improved photo-voltaic (PV) systems available today.
- Specifying and designing the new PV system recommended for the Watchman Lookout.

Solar flux data for Crater Lake National Park, available from measurements performed by Oregon State University, have been used in the study. The unique characteristics of this project have been carefully considered. This includes

minimizing the “visual pollution” of the photo-voltaic array by examining photo-voltaic modules (i.e., panels) of unobtrusive appearance and mounting the modules so they are essentially unseen. This approach proved more reasonable than trying to directly blend the photo-voltaic panels into the building materials of Watchman Lookout. Another unique characteristic of the project is the very low level of solar flux that can occur at Crater Lake National Park for periods of as long as one month in the wintertime. Any system selected must be able to function well year-in, year-out in spite of the large amounts of snow and the icing conditions that occur at Crater Lake National Park.

The photo-voltaic system presently in place has functioned well for about ten years. However, because of its age, its less-than-pleasing appearance, and the advent of new technology, it should be replaced. Further, the system may not be adequate for emergency situations once the new narrow-band, digital radio-repeater is installed at the Watchman Lookout. The new repeater will require about three times the standby current of the present repeater.

Various alternatives for the photo-voltaic panels have been considered, including asphalt shingle- and metal channel-type PV materials that can be blended in with a roof. However, Watchman Lookout has a wood shingle roof of rather shallow pitch, making it difficult to easily blend these PV materials into the structure. Construction of a PV tower located close to Watchman Lookout “in-the-trees” was also considered, though only briefly because other options showed more promise and have lower cost. A two-season approach was carefully examined. In summertime, the PV panels would lie flat on the roof, essentially unseen. In wintertime, the roof panels would be rotated to an angle of about 55 degrees, to effect snow and ice slide-off and optimize the solar gain. The present system has a permanent angle of about 45 degrees. A different approach would involve the placement of PV panels on the windows of the Watchman Lookout in wintertime. Both panels-outside-windows and panels-inside-windows options were considered. Uncertainty about window strength (i.e., the ability to withstand wintertime wind and snow loads) lead to limited attention to the panels-inside-windows option.

Upon consideration of the alternatives top priority has been assigned to the rotatable, roof mounted approach. During summertime, the PV panes would rest at the roof angle of about 20 degrees, close to optimal for Crater Lake. For wintertime, the panels would be rotated upward to about 55 degrees. Except for the incorporation of rotatability, this approach is very similar to the present design. Because the present system has functioned well, and because it appears to have been well engineered, we believed it important to design a new system with features close to those of the present system. Second priority is assigned to the approach using the summertime solar collection with panels mounted flat on the roof (i.e., at an angle of 20 degrees), and wintertime collection with panels hung vertically over the shuttered windows of the Watchman Lookout. This approach has two disadvantages, however, including the need to install and remove the panels each year, and the less-than-optimal angle for collection of wintertime solar radiation. During cloudy days, the vertically mounted panels would need to rely mainly on the reflection of solar radiation from the snow.

Several vendors of photo-voltaic systems and equipment components were contacted, discussions were held, and vendor literature was examined. Basic information was also examined. Analysis of the energy requirements was conducted. Based on these efforts, a new photo-voltaic system for the Watchman Lookout is specified. This system includes the following:

- Single-crystalline or advanced poly-crystalline PV panels of 240 to 270 watts rating in full sunlight. Full sunlight is defined as solar radiation of 1000 watts/meter^2 normal to the panel, further, the panel temperature is assumed to be 25 degrees C. Either two or three panels could be used, depending on the PV manufacturer chosen. Because of the significantly higher solar-to-electricity efficiency of the new panels, the total surface area of the new panels is only slightly larger than the present panels, which are rated at 120 watts total. The approximate doubling of the panel wattage should assure the ability to handle serious wintertime emergencies with the new radio-repeater, without unacceptably discharging the battery pack.

- Mountaintop, lead/calcium-acid, shallow-cycle batteries of about 300 amp-hours wintertime capacity. The batteries selected are similar to the batteries presently used at Watchman Lookout, though they have about 25% greater capacity. Because of the success of the present batteries for the Watchman Lookout, it has been decided best to stay with a proven technology. The increase in battery capacity will help prevent a large draw-down of the batteries in a serious wintertime emergency use of the radio-repeater, which can open up the possibility of battery freezing in very cold weather. The weight of the 300 amp-hour batteries is 58 pounds per cell. Lead/calcium batteries of 400 amp-hours wintertime capacity are also available. However, at 79 pounds weight per cell, these batteries may be too heavy to haul to the Watchman Lookout for maintenance-replacement.

  Serious consideration has also been given to nickel-cadmium batteries, because these can be deep-cycled, perform very well in cold weather, weigh about half as much as equivalent-capacity lead/calcium batteries, and have an estimated lifetime of 20-25 years. However, experience with nickel-cadmium batteries for this type of application is limited, there is uncertainty regarding the amount of distilled water that might need to be occasionally added to the batteries, recycling of the nickel and cadmium must be planned, and these batteries have a cost about twice that of the lead/calcium batteries. Thus, until more experience is gained with the nickel-cadmium batteries, it is thought best to continue to use the lead/calcium batteries for Watchman Lookout.

- Rotatable, roof-mounted panels. Both simple manual mounts and commercial motorized mounts have been examined. Both would probably work, though the motorized system has yet to be evaluated for twice-a-year functioning, year-in, year-out, in the adverse weather conditions of Crater Lake. Thus, manual mounts are preferred. These could be designed in an addendum to the present study.

- Lighting system of 120 watts capacity for summertime use. Because of the over-capacity of the PV system during the summertime, energy is sufficient for operating lighting in the summer and early autumn, up to about October 1st. The lighting energy would be drawn from the same battery pack used to operate the radio-repeater. A separate battery-pack for the lighting system could be installed, though our analysis indicates this is unnecessary. Further, because a separate battery pack would essentially be bypassed during the wintertime, lack of charging during the wintertime could cause frequent failure and replacement of a second battery pack.

- Additional components of the system include the controller, wiring, and lightning arrestor. A system monitor or "meter" is recommended to collect data on this installation. Such a datum base could prove quite useful for the design and engineering of other all-year PV systems used by the National Park Service in severe wintertime climates.

Cost of the new system is expected to be about US$5000. Cost of the panels will be about US$1600. The battery pack will cost about US$2200, and is the highest cost component. The cost estimate does not include cost of the personnel, including travel and per diem, for installation.

Our study indicates the new photo-voltaic system is compatible with the rehabilitation of the Watchman Lookout.

TABLE OF CONTENTS

PHOTO-VOLTAIC ALTERNATIVES FOR THE REHABILITATION OF THE WATCHMAN LOOKOUT
(Pkg. 404 Rehabilitate Watchman Lookout)

report prepared for the

NATIONAL PARK SERVICE

prepared by

Craig Connors and Philip C. Malte
University of Washington
Department of Mechanical Engineering
Box 352600
Seattle, WA 98195-2600
(malte@u.washington.edu)

INTRODUCTION

The purpose of this study is to examine alternatives for the photo-voltaic (PV) system used for the Watchman Lookout at Crater Lake National Park (CRLA). The PV system provides electricity for the radio-repeater, and in the future will provide electricity for lighting in addition to the radio-repeater. It is important to employ a photo-voltaic system for Watchman Lookout that meets operational needs and is compatible with the historic character of the site and structure. In this study, the placement and selection of PV collector panels for best compatibility are addressed, and the main features of the full PV system are provided.

BACKGROUND

History of Watchman Lookout

The history of Watchman Lookout has been provided by the National Park Service [Todd, 1998; based on text by McCelland]:

> "Construction of the Watchman Lookout began in 1931, incorporating a fire lookout and exhibit room open to the public. In the 1950s radio equipment was installed. In the 1980s a solar-powered radio repeater was installed. The Watchman was listed on the National Register of Historic Places in 1988. It continues to be seasonally staffed during the day in high fire season, with occasional overnight use.

> The design used stone and timber materials fashioned into functional two-story structures that included a large viewing platform on the upper story entirely surrounded and enclosed by large windows and an outside balcony. The fire lookout posed a dilemma for designers: in order to perform their essential function, these structures needed to be situated on prominent peaks; they needed to provide visibility in 360 degrees; and they could not be concealed or screened by vegetation. The use of native stone and timber and the simple, rectangular form with hipped roof contributed greatly to the ability of these structures to blend inconspicuously into their settings, even when viewed from a neighboring peak or nearby trail. Towers such as the Watchman not only helped detect fires in remote areas but also were open to visitors for the enjoyment of scenic views. These basic designs would be repeated in appropriate local materials in many variations throughout the parks in the 1930s."

Watchman Lookout at Present

Photographs of Watchman Lookout are shown. Photograph 1 shows Watchman Lookout atop the mountain. The photograph was taken from the start of the trail, which runs about 0.75 mile from the parking lot located north of Watchman Lookout to the lookout. The photograph was taken in early October 1998, about one day after the initial snowfall of the autumn. Shown in Photograph 2 is Watchman Lookout as approached on the trail. The time of day is about 2PM (daylight saving time). Note the full sunlight on the southwest facing windows, and the high elevation of the windows about the ground. Photograph 3 shows the entrance to the upper room, i.e., the enclosed viewing platform or observatory room of Watchman Lookout. The PV collector panels are mounted above the entrance, and the radio antenna (not seen in Photograph 3) is located to the right of the entrance. This side of the lookout faces southeast. Photograph 4 is a view from Watchman Lookout looking south. Note the road. This runs north from Rim Village along the west side of the rim. From points along this road, reflection of sunlight from the PV panels can be seen. The four photographs discussed are shown below.

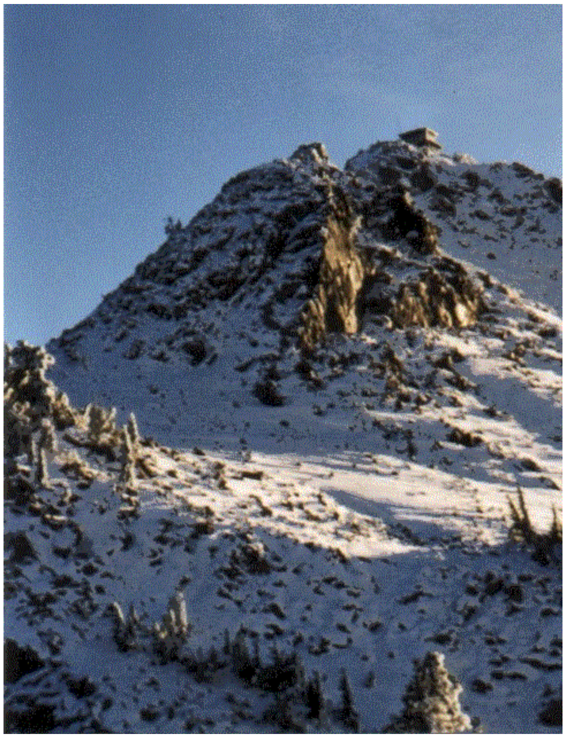


Photo 1: View of Watchman from distance.

Photo 2: View of Watchman as seen from approach by trail.

Photo 3: Enclosed observatory room at Watchman.

Photo 4: View from Watchman looking south (notice road).

The Photo-voltaic and Radio-repeater Systems at Watchman Lookout

The characteristics and history of the photo-voltaic and radio-repeater systems used at Watchman Lookout have been provided by the National Park Service [Kossen, 1998; and Dunstan, 1998]. Additional informational has been provided by the manufacturer of the battery system used [C&D Technologies, Inc., 1998]. The information is summarized as follows:

- The PV collector panels were originally installed flat on the roof of the Watchman Lookout in 1983. This installation is pictured in Photograph 5 (see below). Automotive-size gel cell batteries provided electrical energy storage.

- Snow and ice build-up significantly reduced the electrical output of the PV system to the point that the system was unacceptable in wintertime. Further, the gel cell battery system failed at least twice.

- Because of the unreliable working of the PV system at Watchman Lookout (as well as that of a similar system at the Scott Lookout, Crater Lake National Park) the radio-repeater was moved to the attic of the Crater Lake lodge in 1988. Although this location of the radio repeater did not provide full coverage of the park, the coverage was adequate for the rim area.

- In 1989, the PV installation at Watchman Lookout (as well as at Scott Lookout) was rebuilt. The PV collector panels were moved close to the edge of the roof and tilted upward at an angle of about 45 degrees. The tilt angle is similar to the latitude of Crater Lake (43 degrees), the angle recommended for best year-round performance of fixed solar collector panels. This angle allows for slide-off of snow and ice. With the new installation, electrical output was acceptable year-round. The PV collector system, mounted on the roof, is pictured in Photograph 6 (see below). The system “looks” to the southeast.

Photo 5: View of “flat” panels.

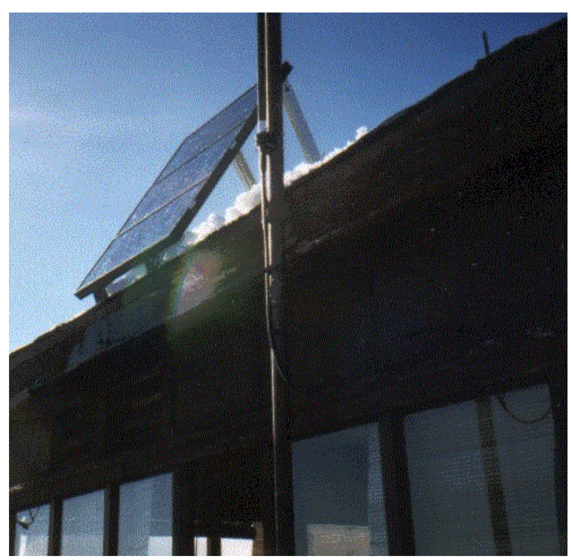


Photo 6: View of raised panels.

- In 1989, new lead/calcium batteries were also installed. The addition of calcium to the lead structure significantly reduces self-discharge and thus significantly improves battery charge-life. However, because calcium is brittle, and thus does not respond well to the temperature-induced expansions associated with deep-cycle operation, lead/calcium batteries are used for shallow-cycle operation. Such batteries are recommended for communication systems. According to C&D Technologies (1998), shallow-cycle batteries can be discharged to 20% of their rated capacity on a daily basis, and can occasionally be deep-discharged to 80% of their rated capacity.

- The system as installed in 1989 has worked well, and essentially is the system currently in use at Watchman Lookout.

- Three PV panels, of poly-crystalline silicon, are connected in parallel. Each panel is rated at 40 watts in full sunlight (i.e., the solar flux normal to the collector is 1000 watts/meter^2 and the temperature of the panel is assumed standard, 25 degrees C). Voltage is 17.5 v, and amperage is 2.3 a. Each panel consists of 40 elements connected in series. Thus, the voltage of each element is 0.44 v, and the electrical power output of each element (in full sunlight) is 1 watt. The 40 elements per panel can be seen in Photograph 3. The size of a panel is 17.5 inches by 42 inches, for an area of 5.1 feet^2 (0.47 meter^2). Efficiency is about 8.5% based on total panel area [i.e., 40 watts / (1000 watts/meter^2 x 0.47 meter^2)]. The three-panel system provides an electrical output of 120 watts, 17.5 v, 6.9 amps in full sunlight, and has an area of 1.4 meter^2. The panel manufacturer is Solarex, and the model number is SX120.

- The battery cells are of either KCPSA-5 or KCPSA-7 type, manufactured by C&D Technologies. These are “mountaintop” batteries, with a sulfuric acid specific gravity of 1.300. The high value of specific gravity helps prevent freezing of the sulfuric acid electrolyte. Charge capacity of the batteries is about 240 to 320 amp-hours, over a temperature range of 0 to 80°F, assuming steady discharge over 20 days. The 240-320 amp-hour charge capacity of the batteries corresponds to about a 20% de-rating from the charge capacity of new KCPSA-7 batteries. Cell voltage varies from about 2.5 v at full charge to 1.9 v as the recommended maximum discharged is approached. However, in cold weather, over-charging to 2.9 v per cell is recommended in order to provide gas for stirring to overcome stratification of the sulfuric acid electrolyte. Thus, the nominal cell voltage, averaging over all charge and weather conditions, is about 2.25 v. The six-pack of cells, with cells connected in series, has a nominal voltage of 13.5 v.

- Additional components of the system are the lightening arrestor, charge controller, and battery saver. The charge controller prevents over-charging of the batteries, and is located between the PV panels and the batteries. The unit is a standard battery charge regulator for PV systems, manufactured by

ASC (Specialty Concepts, Inc.). Maximum voltage is set at about 14 v. Energy not sent to the batteries as electricity is dissipated as heat from the PV panels. Originally, the system had a battery saver unit. Now, however, the battery saver function is performed by the radio-repeater. That is, in order to prevent excessive draw-down of the battery system, the radio-repeater shuts off at about 10.5 v.

- At least two radio-repeaters have been used at the Watchman Lookout. Originally, a GE MASTRII radio-repeater was used. This drew about 200 ma (milliamps) in standby mode. In 1991 or 1992, the GE unit was replaced with a Daniels MT2 series mountaintop radio-repeater. This draws only about 60 ma in standby mode. Current draw in receiving mode is about 300 ma, and in transmitting mode it is about 5 a. The nominal voltage is 12 v. Kossen (1998) recommends a nominal duty cycle of 90/5/5 for standby/ receiving/transmitting. With the nominal duty cycle applied to the Daniels radio-repeater, the daily charge draw is 7.7 amp-hours, and the daily energy draw is 92 watt-hours (assuming 12 v). In order to maintain constant battery charge, the photo-voltaic panels must receive a daily solar flux of at least 775 watt-hours/meter^2/day (based on 8.5% efficiency and 1.4 meter^2 area).

- The GE and Daniels radio-repeaters are of analog-type. Within one-to-a-few years, a digital radio-repeater with a new APCO narrow-band 25 compliant system will be installed at the Watchman Lookout. With this unit, the standby current will return to about 200 ma. For planning purposes, Kossen (1998) recommends assuming 200 ma standby-mode current, 300 ma receiving-mode current, and 5 amp transmitting-mode current. With the nominal duty cycle applied to the 24-hour period, the daily charge draw will be about 10.8 amp-hours, and the daily energy draw will be about 130 watt-hours (assuming 12 v). In order to maintain constant battery charge, the photo-voltaic panels will need to receive a daily solar flux of at least 1090 watt-hours/meter^2/day (based on 8.5% efficiency and 1.4 meter^2 area).

- Major emergency use of the radio-repeater will have significantly greater receiving and transmitting percentages than assumed by the nominal duty cycle. If an emergency duty cycle with 6 hours per day of transmission is assumed, the daily charge and energy draws of the new digital radio-repeater would be about 35 amp-hours and 420 watt-hours, respectively. The minimum daily solar flux to maintain constant battery charge would need to be about 3530 watt-hours/meter^2/day (based on 8.5% efficiency and 1.4 meter^2 area). The 6 hours per day of transmission appears to be more than adequate (Kossen, 1998).

SOLAR ENERGY FLUX AT CRATER LAKE

Solar energy flux at Crater Lake has been measured by Oregon State University (Crawford, 1998). The measurement site is located on the southwestern part of the rim, west of the Rim Village. Table 1 lists monthly-average daily energy fluxes for the December 1991 to June 1994 period. The values listed represent the average amount of solar energy received by a flat horizontal surface over 24 hours. No special precautions were taken to prevent snow and ice buildup on the instrumentation. In particular, ice could have influenced some of the wintertime readings (Crawford, 1998). The energy is expressed as watt-hours. Wintertime average is about 1000 watt-hours/meter^2/day, and summertime average is about 6000 watt-hours/meter^2/day.

Table 1
Monthly-average daily energy flux for Crater Lake (watt-hours/meter^2/day)
Measurements performed by Oregon State University.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1991												1049
1992	1195	1784	3810	3807	6604	5853	6145	5940	4446	2496	1578	964
1993	1350	1493	3353	4364	4104			6311	4174	2666	1024	811
1994	724	1893	2803	4032	5391	5650						
Average	1090	1723	3322	4068	5367	5752	6145	6125	4310	2581	1301	941

Daily energy fluxes for the autumn and winter months are plotted in Figures 1 through 4:

- Figure 1 shows the situation for the Dec-11-91 to Feb-29-92 period.
- Figures 2 and 3 show the daily fluxes for the Oct-1-92 to Mar-15-93 period.
- Figure 4 contains the data for Nov-1-93 to Feb-15-94.

The important features of Figures 1 through 4 are discussed below.

Spring and summer solar fluxes are shown below in Figures 5 and 6. Maximum summertime flux is almost 8000 watt-hours/meter^2/day, and minimum summertime flux lies in the range of 2500 to 3000 watt-hours/meter^2/day.

Figure 7 graphically displays the monthly energy flux averages listed in Table 1.

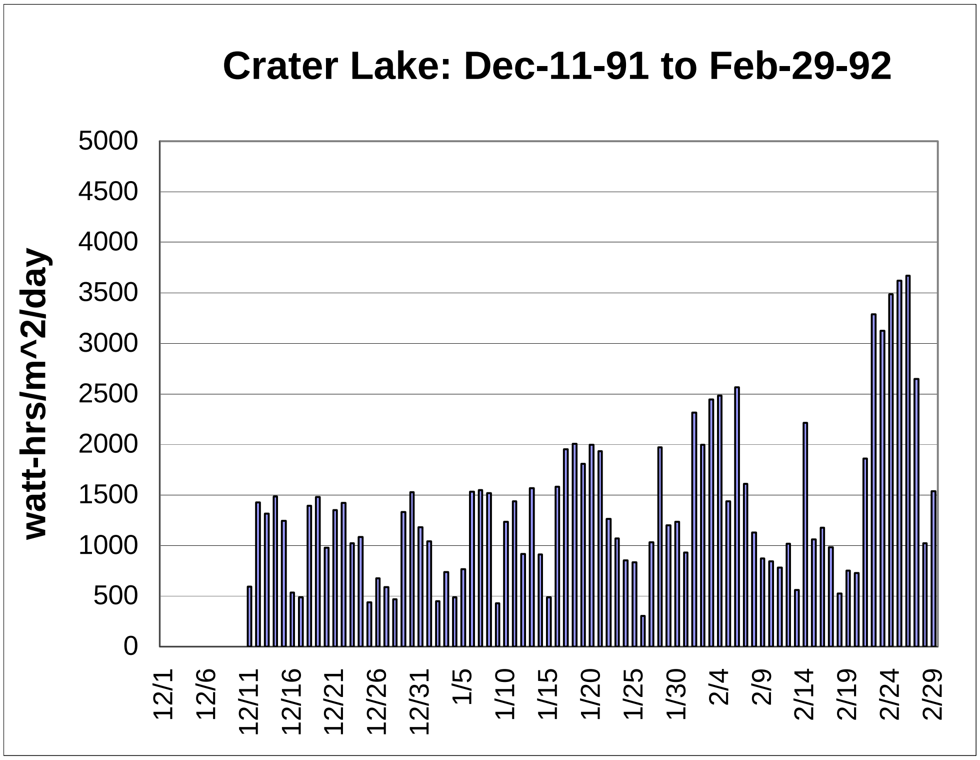


Figure 1. Solar Flux at Crater Lake. Winter 91-92.

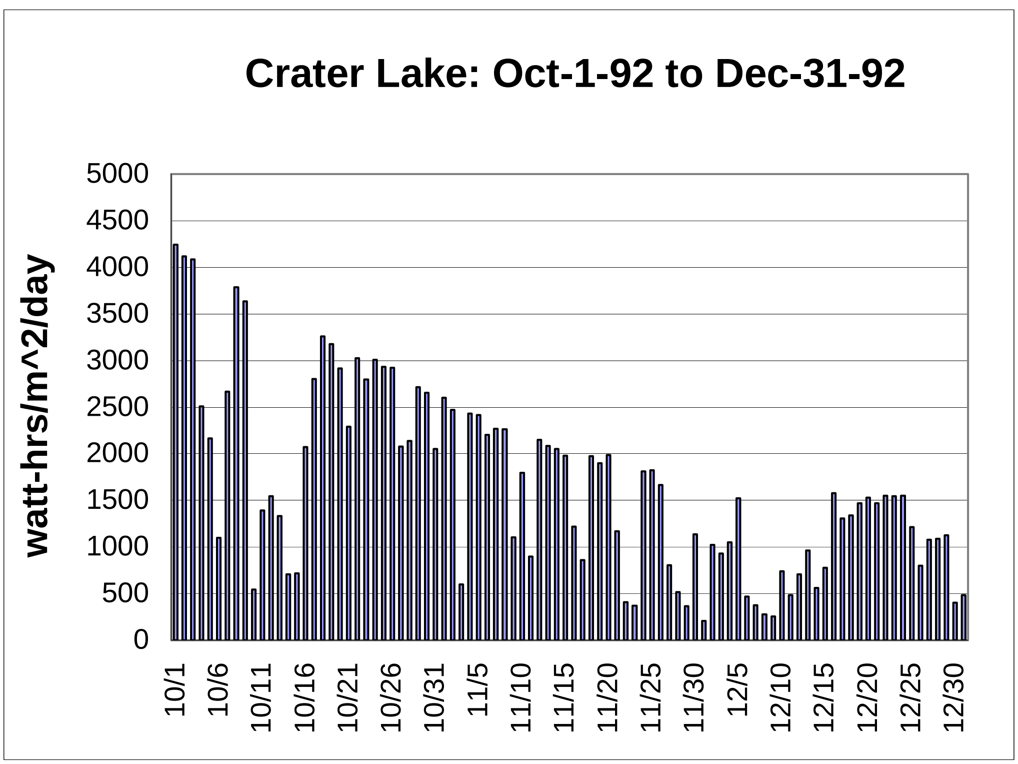


Figure 2. Solar Flux at Crater Lake. Autumn 92 and Early Winter 92-93.

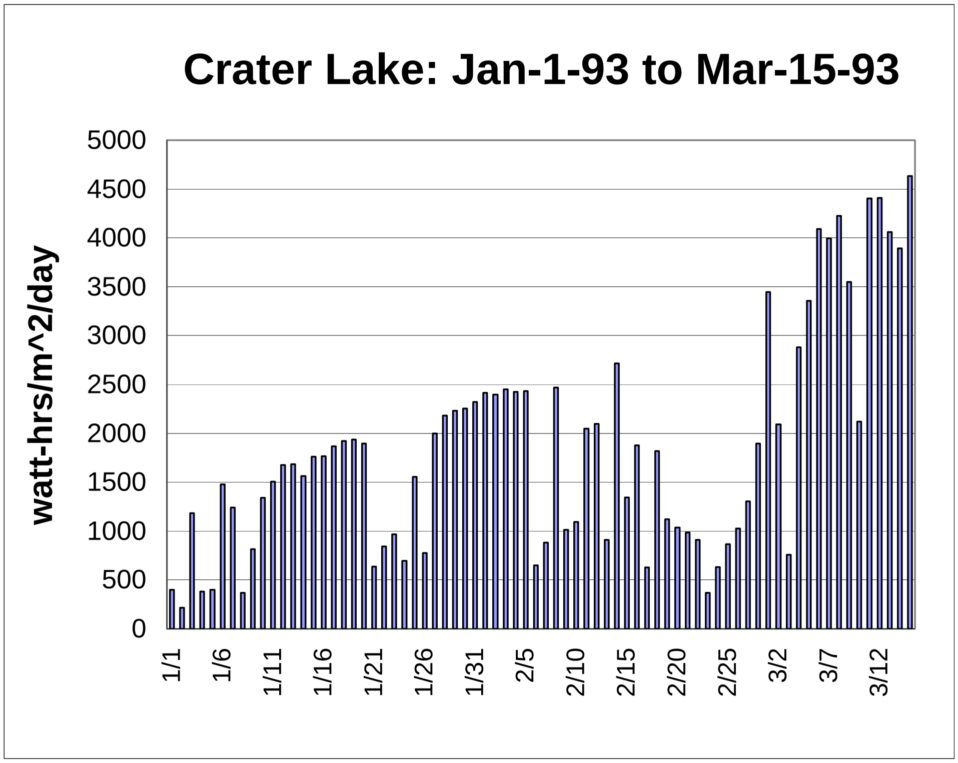


Figure 3. Solar Flux at Crater Lake. Late Winter 92-93.

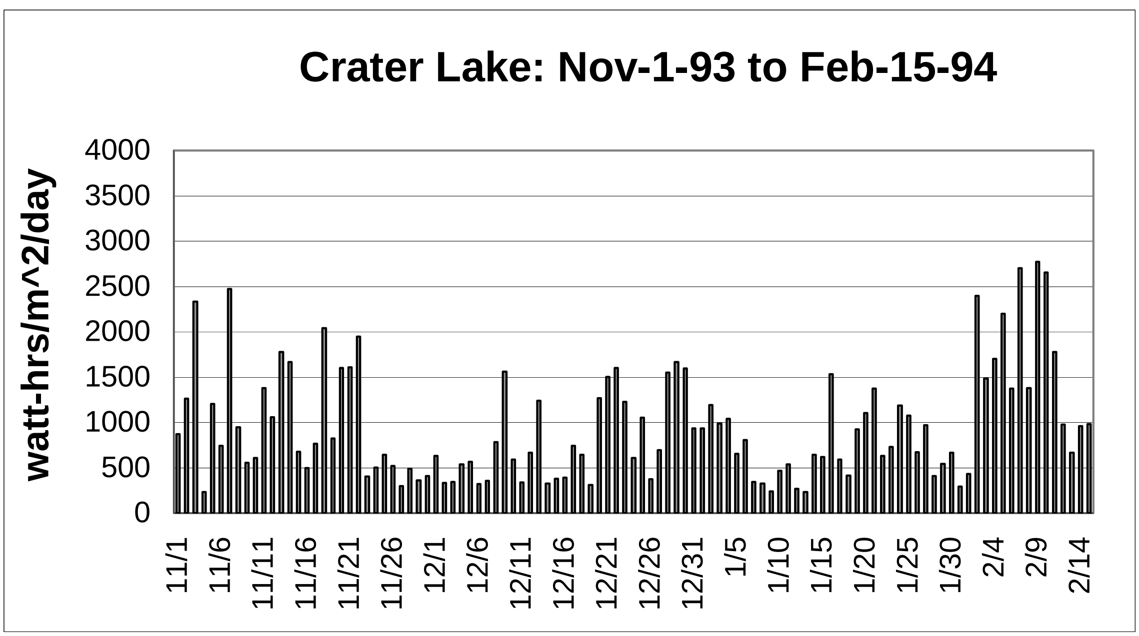


Figure 4. Solar Flux at Crater Lake. Winter 93-94.

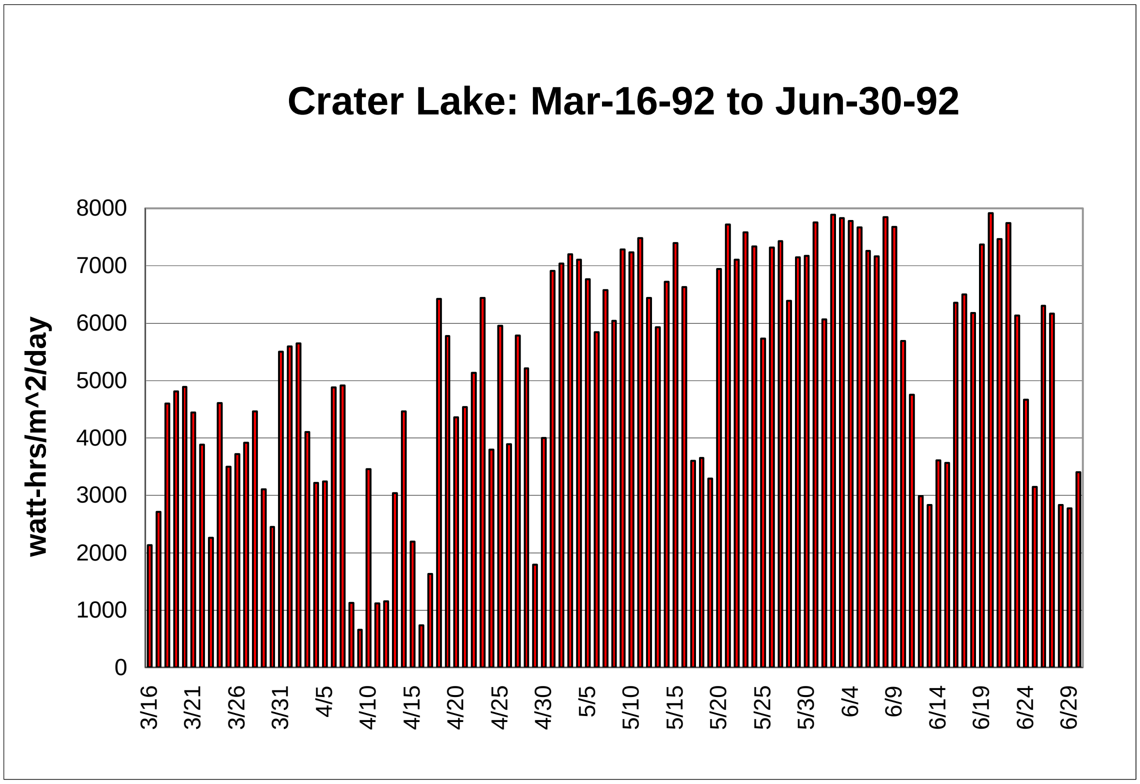


Figure 5. Solar Flux at Crater Lake. Spring and Early Summer 92.

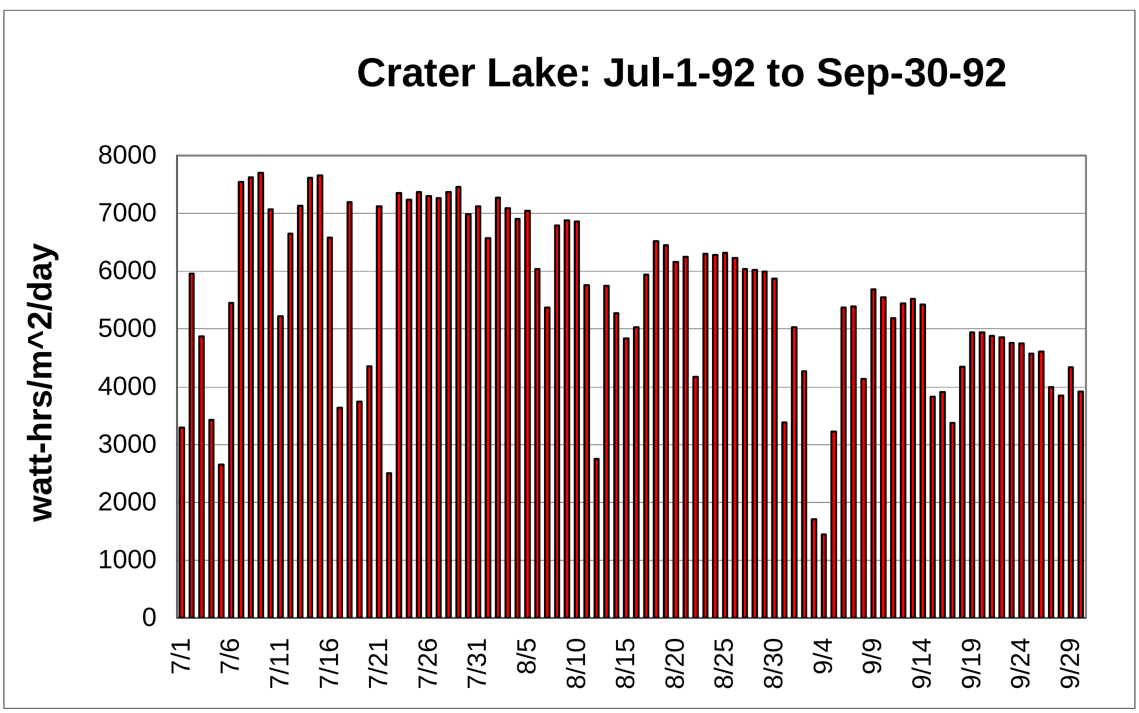


Figure 6. Solar Flux at Crater Lake. Summer and Early Autumn 92.

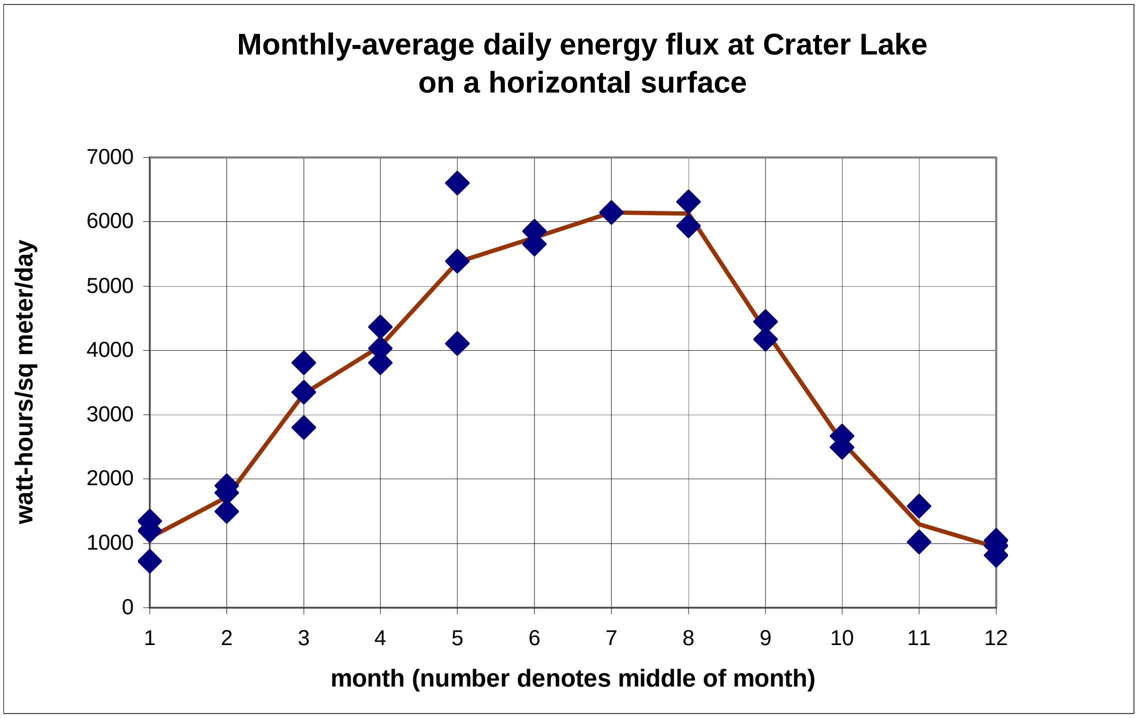


Figure 7. Solar Flux at Crater Lake. Monthly-Average Daily Amounts.

The wintertime period is of primary importance, because of the low solar flux. From Figures 1 through 4, the following may be deduced:

- The monthly-average daily flux during December and January is about 1000 watt-hours/meter^2/day.

- The maximum daily flux during December and January is about 1500 watt-hours/meter^2/day.

- The minimum daily flux during December and January is about 200 watt-hours/meter^2/day.

- Of the three wintertime periods shown in the figures, the winter of 1993-94 is a “worst case.” This is noted in Figure 4. It is also noted by the Nov-93, Dec-93, and Jan-94 averages given in Table 1.

  Several days of very low solar flux occurred, including Nov-4-93 (233 watt-hr/m^2/day) and Jan-13-94 (235 watt-hr/m^2/day). [The day of lowest solar flux in the database is Dec-1-92 (205 watt-hr/m^2/day).]

  The week (7 consecutive days) of lowest solar flux occurred from 7-Jan-94 to 13-Jan-94 (average of 346 watt-hr/m^2/day).

Two weeks (15 consecutive days) of lowest solar flux occurred from 23-Nov-93 to 7-Dec-93 (average of 449 watt-hr/m^2/day).

Four weeks (27 consecutive days) of lowest solar flux occurred from 23-Nov-93 to 19-Dec-93 (average of 545 watt-hr/m^2/day). Only twice during this period did the daily solar flux exceed 1000 watt-hours/$meter^2$/day. A second four week period (28 consecutive days) of low solar flux occurred between Jan-5-94 and Feb-1-94 (average of 668 watt-hr/m^2/day).

These results – both the nominal and worst-case wintertime solar fluxes – are used below to examine the PV panel performance and storage battery capacity required to meet the electrical requirements of Watchman Lookout. Plots of results are presented. This is preceded, however, by a discussion of the alternatives for placement of the PV panels on Watchman Lookout – the next section.

Modification of the Photo-voltaic System at Watchman Lookout

As part of the rehabilitation of the Watchman Lookout, it is desired to minimize the “visual pollution” of the PV collector panels, and as much as practical, to blend the solar collection system into the structure of Watchman Lookout. The other requirement is to provide a PV system that will meet the demands of the new narrow-band radio-repeater, and function well over the wintertime of minimal sunlight.

<u>Minimizing Visual Pollution</u>
Several approaches could be taken to minimizing the visual pollution of the PV panels. The possibilities are discussed as follows:

1. Select PV panels of pleasant appearance. The PV panels presently in place were conventionally made of poly-crystalline silicon. Such panels are not favored from the appearance standpoint, because of the many grain boundaries and grain colors prominently seen. On the other hand, some of the new multi-layer, amorphous-silicon panels rate high in appearance because of their uniform color and texture. Although these products have an efficiency of almost as much as that of the PV panels currently installed at Watchman Lookout, their efficiency is not as great as that of some of the new single-crystalline silicon panels. [Maximum efficiency of a single-crystalline panel is about 14% based on total panel area (and assuming standard temperature, 25 degrees C)]. Additionally, the multi-layer, amorphous-silicon panels have not gained as much experience as the single-crystalline and poly-crystalline silicon panels. Thus, they carry a somewhat higher risk regarding longevity and resistance to weathering.

2. Select PV panels of roofing-type. At least two roofing-type PV panels are commercially available. One type simulates asphalt singles, and the other type simulates channeled metal roofing. These panels are attractive, and blend in well with the building structure. However, as above, their efficiency is about one-half that of the best single-crystalline silicon panels and their experience is limited. Further, because the Watchman Lookout has a wood shingle roof of modest slope, these PV panels appear poorly suited to the architecture of the Watchman Lookout.

3. Mount the PV panels “flat” on the roof of Watchman Lookout (i.e., at an angle of about 20 degrees to the horizontal). In this position, the panels will not reflect light into surrounding areas of the park, and they will be little noticed by visitors to the Watchman Lookout. High-efficiency single-crystalline silicon or poly-crystalline silicon panels could be used. Of course, based on the experience gained early with PV at Watchman Lookout, this configuration will not be reliable for wintertime. Thus, for wintertime an alternative configuration

will be required. That is, a two-season approach will be required. At least two alternatives exist for the wintertime:

a. Rotate the PV panels upward for wintertime to provide for slide-off of snow and ice.
b. Mount separate panels for wintertime. An obvious possibility in this regard is mounting the panels over the windows of the observatory room.

4. Mount the PV panels on a structure separate from Watchman Lookout. This would require the construction of a tower close to the Watchman Lookout, but unseen by visitors to the lookout. This approach is significantly more expensive than the other alternatives, and is not as straightforward as mounting the panels on the Watchman Lookout. It has not been seriously explored in this study.

Roof-Mounted-Rotatable PV Panels

The approach recommended for the PV panels is the roof-mounted-rotatable system of #3a. The backup approach recommended is the panels-outside-windows system of #3b. Both approaches involve separate configurations for summertime and wintertime. Highest priority is given to #3a for several reasons:

- The wintertime configuration is essentially identical to the present installation, which has functioned well for approximately ten years.

- The summertime configuration, “flat” on the roof, will essentially eliminate visual pollution. The PV panels will be nearly unseen. The summertime configuration was used several years ago at Watchman Lookout, and worked well during the non-snow period of the year.

- The summertime angle of the PV panels will be much closer to the optimal angle than the 45 degrees currently used. For summer solstice, the angle of the collector should be about 20 degrees to the horizontal. Twenty degrees is essentially the angle of the hip roof of the Watchman Lookout. For winter solstice, the angle should be about 66 degrees, in order for the panels to collect the greatest amount of direct sunlight (i.e., beam radiation). However, this angle is not optimal for capturing the greatest amount of diffuse radiation from a very cloudy sky – the prevalent situation at Crater Lake in the wintertime. In order to capture maximum diffuse radiation, the collector should “see” as much of the sky as possible – that is, the collector should be horizontal, provided it could be kept free of snow and ice. Solar flux calculations we have performed indicate the PV panels should be set at an angle of at least 60 degrees for maximum collection of the mix of beam and diffuse radiation (and radiation reflected from the snow) expected at the Watchman Lookout in December and January. However, the PV panels will be in wintertime position for a period much longer than December and January, about nine months, from late September/ early October to late June. Over this nine-month period, the optimal angle is about 50 degrees. As a compromise between 50 and 60 degrees, 55 degrees is selected as the angle for the Watchman PV panels for the late September/ early October to late June period. The nominal summertime angle (from late June to late September/ early October) is 20 degrees.

- Only one new feature will be required for the panel mounting system. The mount will need to be designed to permit rotation in late June and late September/ early October. A manual system would be easiest to design and probably most reliable to employ, but might require work on the roof two days per year. An electric motor driven system would be easiest to use, but would require additional design or evaluation of a commercial mount to ensure weatherproofing and would draw energy from the batteries. The task would be to design or select a motorized system that would operate reliability twice a year, over many years. Our recommendation, based on consultation with the National Park Service, is a manual system, custom-designed for this application. The design of this could be undertaken in a follow-on task to the present study.

<u>PV Panels Mounted on Windows</u>
Another viable approach is #3b. This is assigned backup priority, and is described as follows.

- The summertime component of this approach would be similar to that of approach #3a discussed above. That is, the summertime collector would be mounted "flat" on the roof. This would be a fixed system. During the wintertime, this system would not be used.

- For the wintertime, PV panels mounted over the windows of the observatory room of Watchman Lookout would be relied upon. During wintertime, wood shutters are placed over the windows in order to prevent damage to the windows by wind and snow. The PV panels would be placed over the outside of the shutters, on the sides of Watchman Lookout facing southeast or southwest. Since the window area is substantially greater than the PV panel area required, the PV panels would be mounted only over the upper part of the shutters – as high above the snow as possible.

- An alternative approach could involve mounting the PV panels inside the windows of Watchman Lookout. Panels could be hung from the ceiling, and rotated down during the wintertime to collect solar radiation. However, in order for viability of this system, several steps would have to be taken, including reinforcement of the windows to prevent wintertime damage, and switching to low reflectivity glazing for the windows. Windows in the museum room might be more amenable to reinforcement than the windows of the observatory room. However, the museum room, being one level below the observatory room, might be more susceptible to snow cover than the observatory room. Because of the uncertainties and potential difficulties associated with the panels-inside-windows alternative, it is not regarded as a viable approach compared to the panels-outside-windows alternative. New knowledge of snow patterns around Watchman Lookout could change this assessment. For the present report, further study has not been conducted on the panels-inside-windows alternative.

- Although the panels-outside-windows approach is viable, it carries some concerns, and accordingly, is assigned backup priority. The concerns are listed as follows:

  - The PV panels will need to be handled twice a year, once for installation in the early autumn, and once for removal and storage in the early summer.

  - Upon installation in the early autumn, the system will need to be checked for electrical continuity and battery charging. Upon summertime changeover to the roof-mounted PV panels, system checks will need to be performed again.

  - Weatherproof electrical plugs will need to be specified and installed for easy connection of the PV panels to the electrical system.

  - Although snow is unlikely to cause failure of PV panels mounted high on the window shutters, snow patterns at Watchman Lookout are not well known.

  - Vertical placement of PV panels is not optimal for capture of wintertime solar radiation. Optimal angle has been discussed above.

ANALYSIS OF ELECTRICAL ENERGY

The amount of electrical energy generated, expressed as monthly-average daily watt-hours (watt-hr), is determined for PV installation at the Watchman Lookout and compared to the electrical energy required.

The starting point for the analysis is the monthly-average daily solar flux data of Table 1 (i.e., the row of data termed “average”) and Figure 7 (i.e., the curve). The following procedure is used to determine the solar energy received by a PV panel in one day:

- The monthly-average daily energy flux data of Table 1 (and Figure 7) for a horizontal surface are split into a beam radiation fraction and a diffuse radiation fraction. During wintertime, the diffusive fraction is predominant. The diffuse fraction assumed for each month is listed in Table 2 below. The beam fraction is equal to one minus the diffuse fraction. The diffuse fraction listed in Table 2 follows the trend recorded for Medford, Oregon (www.rredc.nrel.gov), though with 0.08 added to account for cloud cover at Crater Lake. The reflectively assumed for the surface forward of the PV panels is also listed in Table 2. High reflectivity (0.75) is associated with a snow surface, low reflectivity is associated with a nominal ground surface (Kreith and Kreider, 1978).

- The instantaneous solar flux (watts/meter^2) incident on a horizontal surface is assumed to obey a “sin” function. For example, see Equation 4.12, page 75, text by Twidell and Weir (1986):

  $$\textit{Instantaneous solar flux } (w/m^2) = \textit{Solar flux at true noon } (w/m^2) \times \sin(\pi \times \textit{time / hours of sunlight})$$

  Integration of this equation over the day gives the daily solar energy flux as:

  $$\textit{Daily solar energy flux } (w\text{-}hr/m^2) = 0.637 \times \textit{Hours of sunlight (hr)} \times \textit{Solar flux at true noon } (w/m^2)$$

  The hours of sunlight, i.e., the hours from sunrise to sunset, are calculated based on the latitude of Crater Lake (43 degrees) and the day of the year. For example, see Equation 4.7, page 71, text by Twidell and Weir (1986). Substitution of the daily solar flux data of Table 1 into the second equation permits the noontime solar flux to be calculated. Then by the first equation, the solar flux incident on a horizontal surface may be determined for any hour of the day.

  The beam and diffuse components of the instantaneous energy flux for a horizontal surface are then determined for any hour of the day selected.

Next, the orientation of the panel is considered, and the solar energy incident on the panel is determined.

- It is assumed the practice of mounting the PV panels above the entrance of the observatory room of Watchman Lookout will be continued. In this position, the PV panels are assumed to "look" 20 degrees east of true solar south. (Note, this angle has not been measured.)

- The tilt of panels from the horizontal is 55 degrees for the period from October 1st to June 30th, and 20 degrees from July 1st to September 30th.

- From the angles assumed, the angle of incidence of the beam component of the solar radiation incident on the PV panel is determined. The equation used is given in texts on solar energy, e.g., see Equation 4.8, page 74, text by Twidell and Weir (1986).

- The beam component of the instantaneous solar radiation incident on the PV panel is determined based on the angles of incidence for the PV panel and the horizontal surface. The diffuse component of instantaneous solar radiation incident on the panel is determined based on the tilt angle, and the component of solar radiation from reflection off of the surface forward of the PV panel is determined based on the tilt angle and the reflectivity of the surface.

- The three components of solar radiation are summed to give the total instantaneous solar energy flux (w/m^2) received by the PV panel. This calculation is performed for each hour of each day selected. The days selected are the mid-month days, e.g., June 15th. Summation of the hourly valves over the day gives the total solar energy received by the panel for the day of interest (watt-hr/m^2/day). Comparison of this energy to that measured for a horizontal surface (Table 1) gives the "orientation gain" of the PV panel. This is listed in Table 2. Gain during wintertime is greatest – because of 55 degrees tilt of the PV panels. Attenuation of the solar energy occurs in June – because the panels have not been adjusted to the summertime angle.

With the solar energy incident on the PV panels determined, the electrical energy generation of the PV panels can be determined for PV panels of known efficiency and area. An additional factor requiring consideration is the temperature of the PV panels. For every 10 degrees C temperature increase, the efficiency of the panels decreases about 4% (relative) – e.g., see page 160, Twidell and Weir (1986). The equation for determining the daily electrical energy generation of the PV panels is:

Daily electrical energy generated (w-hrs/day) =
Daily solar energy flux (w-hr/m^2/day) x Panel area (m^2) x
Standard panel efficiency (based on total area) x Temperature factor

The manufacturer's full-sunlight rating of the PV panels is given by the equation:

Power rating (w) = Panel area (m^2) x Standard panel efficiency x 1000 (w/m^2)

In order to estimate the temperature factor, we have conducted a heat analysis of the PV panel. Heat gain by solar radiation is balanced against heat loss by radiation (i.e., infrared loss from the PV panel) and by convection (i.e., wind). The amount of the solar energy converted to electricity is also considered in the analysis.

Standard temperature is 25 degrees C, at this temperature the PV efficiency is that quoted by the manufacturer, and the temperature factor is 1.0. Maximum panel temperature indicated by the analysis (for a hot, sunny, low-wind summer day) is about 60 degrees C. Nominal summertime temperature of the panels is about 45 degrees C, corresponding to a temperature factor of 0.92 [i.e., 1 – (45 – 25) x 0.004 = 0.92], a loss of 8% (relative) in the PV electrical power output. Minimum panel temperature (for a cold, cloudy, windy winter day) is about minus 15 degrees C. Nominal wintertime temperature is about zero degrees C, corresponding to a temperature factor of 1.10 [i.e., 1 – (0 – 25) x 0.004 = 1.10], a gain of 10% (relative) in the PV electrical power output. The temperature factor assumed for each month is listed in Table 2.

Table 2
Parameters Used in Analysis of Electrical Energy Generation by PV Panels for the Watchman Lookout

Month	Diffuse Fraction	Surface Reflectivity	Tilt Angle (degrees)	Orientation Gain	Temperature Factor
Jan	0.70	0.75	55	1.40	1.100
Feb	0.62	0.75	55	1.38	1.050
Mar	0.56	0.75	55	1.22	1.000
Apr	0.50	0.75	55	1.06	0.985
May	0.44	0.65	55	0.92	0.970
Jun	0.36	0.40	55	0.78	0.970
Jul	0.28	0.20	20	0.98	0.920
Aug	0.32	0.20	20	1.03	0.920
Sep	0.36	0.20	20	1.11	0.970
Oct	0.50	0.40	55	1.26	1.010
Nov	0.70	0.65	55	1.40	1.060
Dec	0.75	0.75	55	1.47	1.100

Results for the monthly-average daily solar energy flux received by the titled PV panel at Crater Lake are plotted in Figure 8. The results have been multiplied by the temperature factor. Also plotted in Figure 8 is the solar energy flux received by the horizontal surface – this is a repeat of the curve of Figure 7.

Figure 8. Monthly-Average Daily Solar Energy Flux Received by Titled PV Panel at Crater Lake.

Multiplication of the results of Figure 8 for the tilted PV panel by the panel area and efficiency, that is by the full-sunlight power rating of the panel divided by 1000 w/m^2, gives the electrical energy output of the PV panel over the day (watt-hr/day). This is plotted in Figure 9 for two panel systems, 120 watts (the power rating of the present panels) and 270 watts. Additionally, the electrical energy available from the battery system is included. The 120 watts panels are assumed to have a battery system of 240 amp-hours wintertime capacity, and the 270 watts panels are assumed attached to a 300 amp-hours battery pack (wintertime rating). For each battery pack, steady discharge of the full capacity is assumed to occur over 30 days. A nominal battery voltage of 12.5 v is assumed. The results of Figure 9 indicate the 270 watts panel system is capable of generating 400 to 500 watt-hours/day of electrical energy under average December-January solar conditions at Crater Lake.

In Figure 10, the electrical energy output of the 270 watts panels is compared to the electrical demands of Watchman Lookout. The new radio-repeater operating under normal duty cycle, as determined earlier in this report, requires 130 watt-hr/day of energy. This demand is easily met by the 270 watts PV system. In the emergency mode postulated earlier, involving 6 hours per day of radio transmission, the energy demand jumps to 420 watt-hr/day. Under average solar conditions, the 270 watts PV system is just capable of providing 420 watt-hr/day of energy in the worst month for sunlight, December. No drain of the battery pack is indicated.

Figure 9. Electrical Energy Generated by 120 and 270 watts PV Systems Operating Under Average Solar Flux at Crater Lake

Figure 10. Comparison of Energy Generated by 270 watts PV System Operating Under Average Solar Flux with Energy Demands at Watchman Lookout

With lighting added to normal battery operation, the demand jumps to 490 watt-hr/day. (The lighting demand of 360 watt-hr/day, which is added to the radio demand of 130 watt-hr/day to give 490 watt-hr/day, is developed in the next section.) The 490 watt-hr/day demand can be met over most of the year. In fact, lighting plus emergency radio demand could be provided by the PV system, without battery draining, over approximately the 1-March to 15-October period. [Note each month on the figures represents mid-month.] Nonetheless, it is recommended the lighting system be activated only over the late June to late September/ early October period, to avoid the possibility of wintertime drain of the batteries by the lighting system.

Poor weather in the wintertime places the greatest stress on the PV system. Thus, the response of the system to worst-case episodes in the wintertime is examined.

Plotted in Figure 11 are two curves. The upper curve gives the average daily solar energy incident on a horizontal surface of one square meter in worst-case winter weather as a function of the duration of the worst-case episode. The upper curve follows directly from the results discussed earlier for lowest solar fluxes for one day, one week, two weeks, and four weeks. As the episode persists, the possibility of a few periods of improved weather increases, thus the average daily solar energy received by the horizontal surface over the episode increases. The lower curve gives the amount of electrical energy produced per day by a PV panel of 270 watts full-sunlight rating when exposed to the solar flux of the upper curve. Assumptions are 100% diffuse solar radiation, leading to a 0.95 orientation gain (i.e., radiation collected by the 55-degree-tilted panel divided by radiation received by a horizontal surface), and 1.10 temperature factor.

The demand of the radio-repeater is 130 watt-hr/day for normal operation. The lower curve of Figure 11 indicates worst-case episodes of less than two weeks will not provide solar radiation sufficient to sustain normal operation of the radio-repeater. Partial discharge of the battery pack will be required. For an emergency, the radio repeater demand is 420 watt-hr/day. This is well below the output of the 270 watts PV panel in worst-case weather of all durations plotted. Significance reliance on the battery pack will be required.

Plotted in Figure 12 is a worst-case scenario. A five-day emergency is assumed to coincide with five days of worst-case weather. Over the five-day period, the average electrical generation per day by the 270 watts panel is 85 watt-hours. The daily demand is 420 watt-hours. The initial condition of the battery pack is 300 amp-hr at 12.5 volts, for an initial stored energy of 3750 watt-hours. The 300 amp-hr capacity is estimated for wintertime service based on the manufacturer's data (C&D Technologies, 1998). After five days, the battery pack has been drained to 55% of capacity. That is, the net drain of the battery pack is 9% (absolute) per day. The 45% drain is greater than the recommended 20%

discharge for shallow-cycle batteries, and can only be tolerated one-to-a-few times per year over the battery lifetime.

The five-day worst-case weather is assumed embedded within a month (30 days) of worst-case weather. Over the month, the average daily electrical energy generation is 160 watt-hours, that is, five days of 85 watt-hours per day followed by 25 days of 176 watt-hours per day. At the end of the month, assuming normal radio demand for the balance of 25 days, the battery pack recovers to 86% of capacity. The daily net recovery is about 1.25% (absolute).

The worst-case scenario depicted in Figure 12 is thought acceptable, so long as the coincidence of worst-case weather and emergency is infrequent, and so long as a second emergency closely following the initial emergency is unlikely.

Figure 11. Solar Energy and Electrical Generation for Worst-Case Weather

Figure 12. Battery Charge in Worst-Case Weather and 5-Day Emergency

Preferences for the Photo-voltaic System at Watchman Lookout

Based on the discussion and analysis in the sections above, the preferences for the new PV system for Watchman Lookout are summarized in this section. A schematic drawing of a preferred system is shown below in Figure 13. The heart of this system is three single-crystalline PV panels, each rated at 90 watts in full sunlight (at standard temperature), for a total rated wattage of 270. The full area of the system is 1.89 $meter^2$, a 35% increase over the existing system. Efficiency based on total area is slightly above 14%, a 70% increase over the efficiency of the existing PV panels.

The monthly-average daily electrical energy that would be produced by the 270 watts PV system at Watchman Lookout has been shown above in Figures 9 and 10 for average solar conditions at Crater Lake, and in Figure 11 for worst-case wintertime episodes. Under average solar conditions, the 270 watts system will produce electrical energy sufficient to handle emergency radio-repeater use, even in December, with essentially no discharge of the battery pack. Only under the coincidence of an emergency and less-than-average December-January solar flux will partial discharge of the battery pack occur. A worst-case scenario has been analyzed in the previous section of this report.

Although the primary function of the system is to provide energy for the radio-repeater, it is desired to add lighting capability. Summertime and early-autumn visitors to Watchman Lookout would use this lighting. The following lighting is assumed:

- Lighting in each of the two washrooms. Fluorescent lighting of about 20 watts maximum should suffice for each washroom.

- Lighting in the storage room. This room contains the radio-repeater. Fluorescent lighting of 40 watts maximum should suffice for this room.

- Lighting in the observatory room. Fluorescent lighting of 40 watts maximum should suffice for this room.

By this scenario, the full lighting requirement is 120 watts. Lighting is not envisioned for the remaining room – the museum room.

The duty cycle for the lighting is somewhat problematic, since no experience exists with electrical lighting at the Watchman Lookout. However, a duty cycle of 4/1/4 for the number of hours per day for the washroom / storage room / observatory room lighting should cover normal maximum usage. This duty cycle is equivalent to 360 watt-hours of electrical lighting per day. If this amount of energy is added to the daily energy draw of the narrow-band radio-repeater operating in nominal duty cycle (130 watt-hours), the total daily energy draw jumps to 490 watt-hours. However, if the radio-repeater is operating in emergency duty cycle (420 watt-hours), the total daily energy draw increases to about 780 watt-hours. By Figure 10 above it is noted this emergency-plus-lighting energy requirement can be met by the new system from about 1-March to 15-October.

However, the availability of lighting should probably be restricted to the late June to late September/ early October period to avoid the possibly of a wintertime draw-down of the battery pack by the lighting system. Further, timer-out switches should be placed on the lights to prevent overuse and possible draw-down of the battery pack in summertime. Early-summer activation of the lighting system should probably coincide with the changeover of the panels to level-with-roof mode. Deactivation of the lighting system should probably occur no later than the first week of October, coinciding with the re-positioning of the PV panels to the 55 degree tilt.

A schematic of the PV system with the lighting included is shown in Figure 14. If AC lighting is preferred, a DC to AC inverter will be required as part of the circuit. However, DC lighting is an option.

A close alternative to the system depicted in Figures 13 and 14 would be a 240 watts system consisting of two 120 watts panels of poly-crystalline silicon manufactured by Kyocera. The two-panel area is 1.86 meter^2, and the efficiency based on total panel area is almost 13%. The Kyocera panel is shown in Figure 15, with comparison to the single-crystalline silicon BP Solar panel. The Kyocera panel, although made of poly-crystalline silicon, has a pleasing appearance compared to the traditional poly-crystalline silicon PV panels. In fact, the Kyocera panels may have a more pleasing appearance than the BP Solar panels. The 240 watts system would provide almost 90% the electrical energy generation of the 270 watts system. Only in the darkest period of the winter could the difference be of significance. The 240 watts system would not quite maintain full battery charge under an emergency in a December of average solar flux – battery discharge would be about 1.5% (absolute) for each day of the emergency. For an emergency in worst-case weather, as depicted above by Figure 12, the battery charge would be 54% of full after the five-day emergency and 72% of full after the 30 days of worst-case weather. On the other hand, the two panels of the 240 watts system would be easier and less expensive to mount than the three panels of the 270 watts system, though the two-panel system would provide less fall-back capability than the three-panel system should one of the panels fail.

Figure 13. Layout of 270W System with BP590 Solar Panels (no lights).

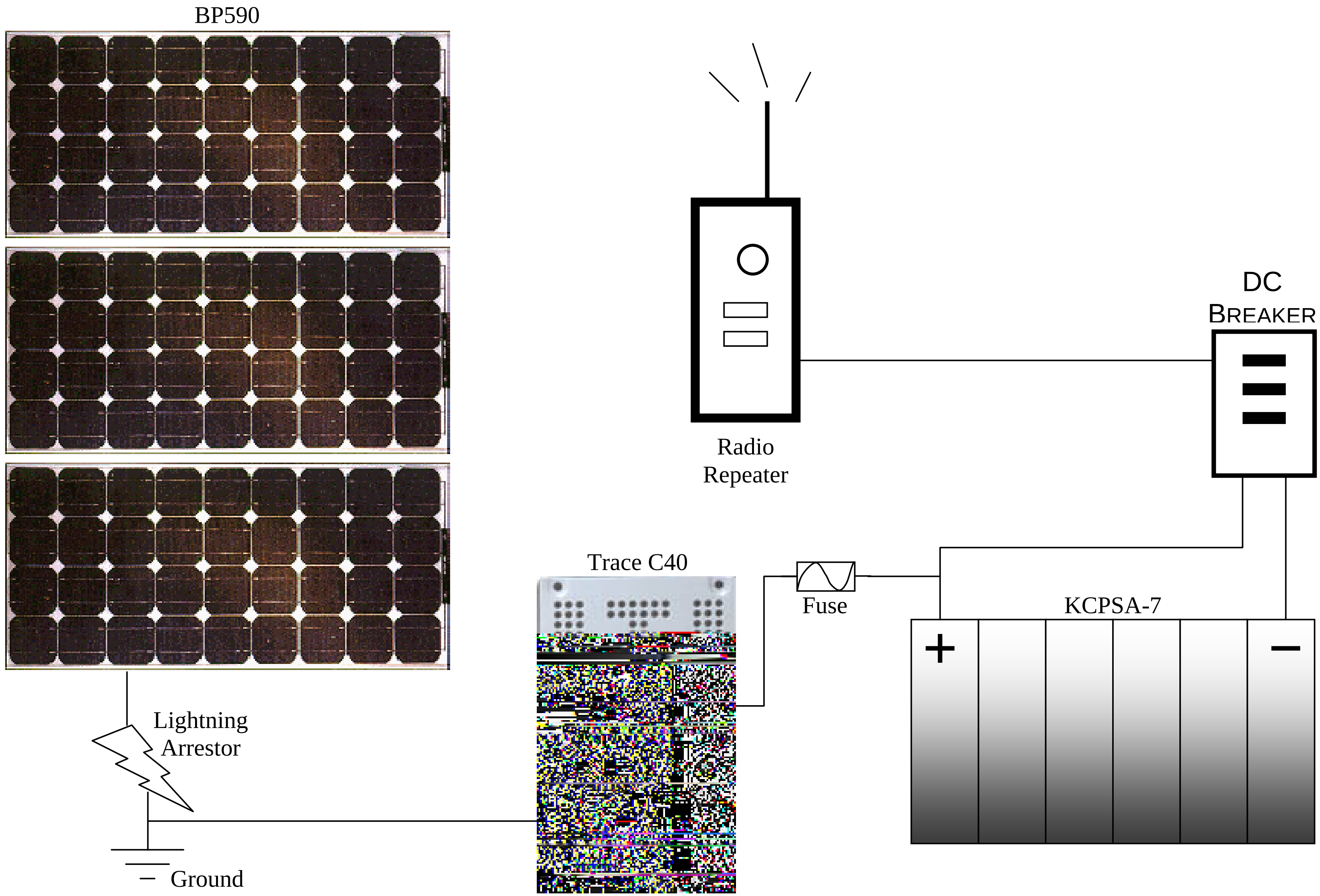


Figure 14. Layout of 270W System with BP590 Solar Panels and Lighting

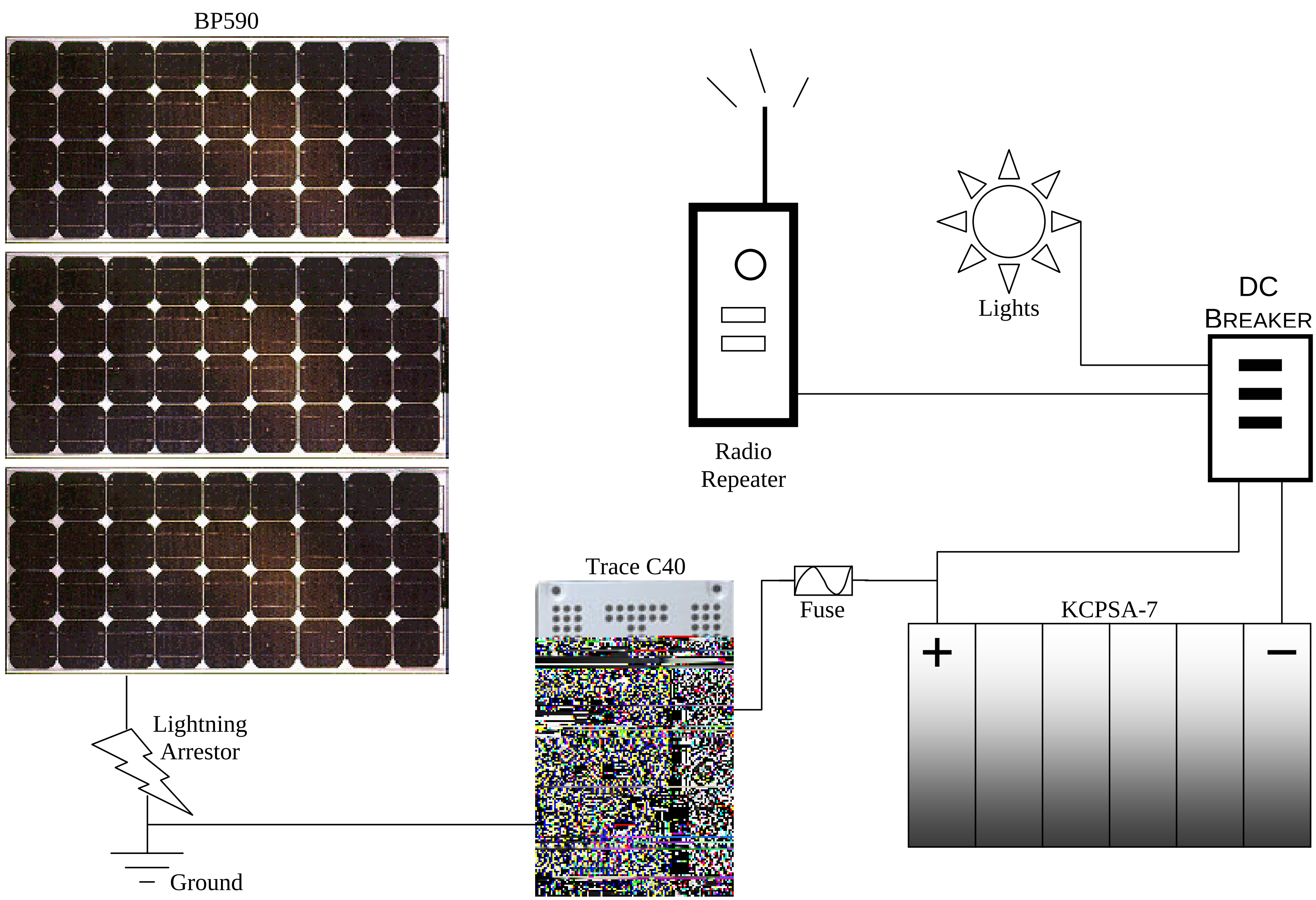
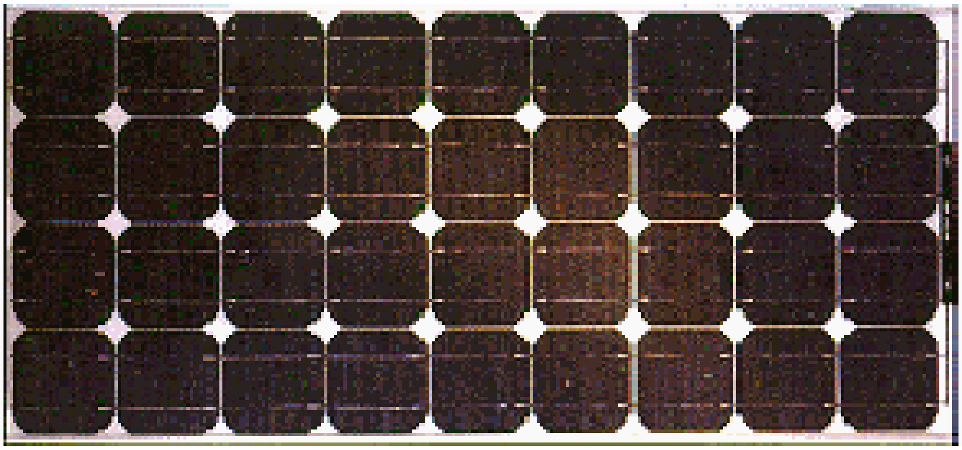
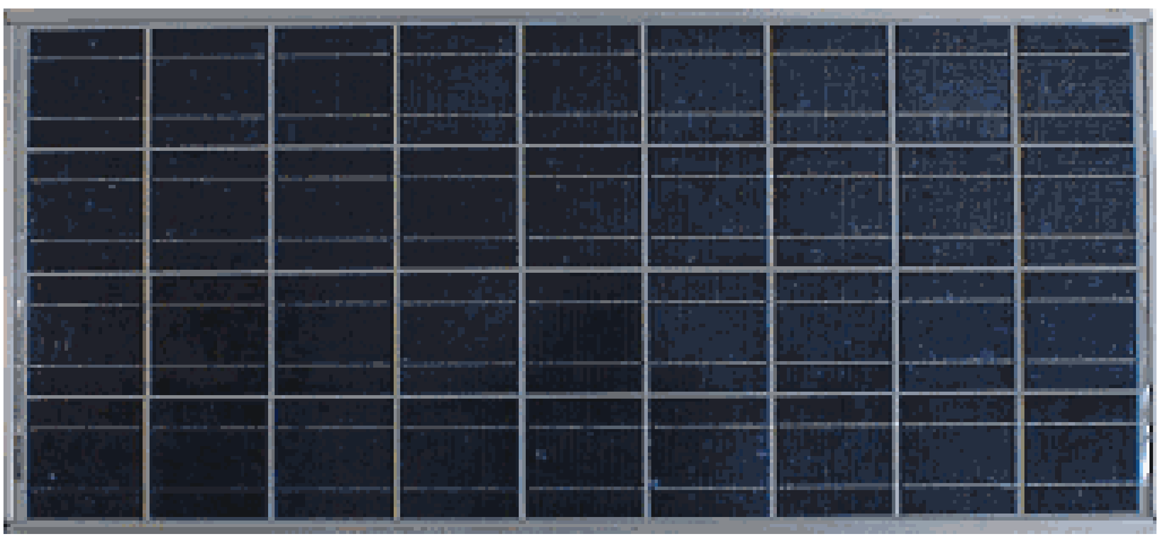


Figure 15: Comparison of Single and Poly-crystalline Solar Panels.
(the panels are shown to scale so that size comparisons can also be made).

BP590 Solar Panel (90 watt single-crystalline)



Kyocera 120 Solar Panel (120 watt poly-crystalline)



A final alternative for the system design would be to split off the lighting system, by using a separate battery pack for lighting. This would have the advantage of "saving" the shallow-cycle batteries for the radio-repeater. A system could be designed in which the battery six-pack depicted in Figures 13 and 14 (which is of shallow-cycle type) is dedicated to the radio-repeater, and a separate deep-cycle battery pack is devoted to the lighting. Deep-cycle batteries are normally recommended for PV-lighting systems. The deep-cycle batteries could be of relatively modest charge capacity, say about 50 amp-hours, given the feasibility of 80% discharge on a daily basis, and the high probably of daily recharge by the PV system during the summertime. The deep-cycle batteries, however, could significantly deteriorate over the wintertime, given their relatively high rate of self-discharge (compared to shallow-cycle batteries) and the priority given to recharging of the batteries for the radio repeater. Because of this potential difficulty, and because the system has significant over-capacity for the summertime, serious consideration of dual battery system has not been undertaken in this study.

Table 3 outlines the requirements and characteristics of the PV-system preferred for the Watchman Lookout. This includes PV panels of either 270 or 240 watts, rotatable mount, six-pack of shallow-cycle batteries, controller, and monitor.

Table 3
Photo-voltaic System Preferred for Watchman Lookout

PV PANELS	HIGH-EFFICIENCY CRYSTALLINE-SILICON PV PANELS. Panel rating should be 270 watts in full sunlight. Three panels of single-crystalline silicon of 90 watts each are available from BP Solar. These are BP590 modules. At 90 watts, the current output is 4.85 amps, voltage is 18.6 v. Area per panel is 0.63 meter^2. Efficiency based on total area is 14.3%. Panel rating of 240 watts will also suffice. Two panels of 120 watts each are available from Kyocera. These are Kyocera 120 poly-crystalline modules. At 120 watts current output is 7.1 amps and voltage is 16.9 v. Area per panel is 0.93 meter^2. Efficiency based on total area is 12.9%. These panels should be able to maintain full or nearly full battery charge in wintertime, even under an emergency, assuming average solar flux. Further, the panels should permit lighting for the summertime and early autumn.
PANEL MOUNT	ROOF-MOUNTED-ROTATABLE. Location of the panels should be about the same as that of the present panels, close to the edge of the roof to effect slide-off of snow and ice, and facing southeast. Location above the porch of the Watchman Lookout facilitates work on the panels. Panels should be located out of the shadow of the antenna. During summertime, the angle of the panels should be that of the roof (about 20 degrees), essentially eliminating visual pollution by the panels. For wintertime, the panels should be rotated to an angle of 55 degrees. Motorized mounts are available. The energy requirement for repositioning is about 15 watt-hours, i.e., 36 amps @ 12 v for 2 minutes. A remote switch operates the positioning. Manually operated mounts are preferred, however. A simple approach would be to insert structural members to hold the panels at wintertime angle. These would be removed for summertime. Other manual possibilities exist. Any system must withstand inactivity over most of year, and function well and conveniently twice a year over many years.

BATTERIES	SHALLOW-CYCLE BATTERIES FOR PV-BASED COMMUNICATION. The six-pack of KCPSA battery cells provided by C&D Technologies, Inc. has worked well at Watchman Lookout. Because of age, these batteries should be replaced. A six-pack of KCPSA-7 battery cells is recommended. The capacity of these batteries, assuming wintertime temperature and discharge over 20 days, is about 300 amp-hours (versus about 240 amp-hours for the batteries in place). Weight of a KCPSA-7 cell is 58 pounds. An alternative would be a six-pack of KCPSA-9 batteries. These would provide greater capacity – about 400 amp-hours in wintertime – though at 79 pounds per cell, they may be difficult to haul to the Watchman Lookout. In order to reduce the potential for wintertime failure, the batteries should be placed in a well-insulated box.
CONTROLLER	The present system uses a simple, reliable controller between the PV panels and batteries to prevent battery overcharging. The manufacturer is ASC, Inc. For the new system, a Trace-C40 controller for PV systems has been specified, though other controllers are also feasible. The Trace-C40 is rated at 40 amps max, is UL approved, and has an optional LCD that provides volts, amps, amp-hour, and cumulative amp-hour readings. A battery temperature sensor can provide temperature compensation.
MONITOR	It would be helpful to monitor the status of the PV system. For example, it would be helpful to easily check the status of the system from time to time, especially at spring and autumn change-over. An E-meter can be used for this purpose – for example, a Hart Interface E-Meter (Link-10). An RS232 port permits downloading of information from the E-meter to a portable computer. However, E-meters have little data storage capability. Data storage should also be sought, since the information gained could be very beneficial to other sites.
OTHER	The lightning protection and grounding at Watchman Lookout appear adequate (Kossen, 1998).

Shown below are drawings of the Watchman Lookout with the new panels positioned for both summertime (Figure 16) and autumn/ winter/ spring (Figure 17). In order to facilitate slide-off of snow, and provide for ease of maintenance and tilt-change, the panels are positioned along the roof edge-line. This will require repositioning of the antenna, which should not be a problem (Kossen, 1998).

In the remaining sections of the report, background technical information is provided on the PV panels, batteries, and rotatable mount.

Figure 16: Schematic of Watchman with Panels LyingFlat on Roof (summer setup).

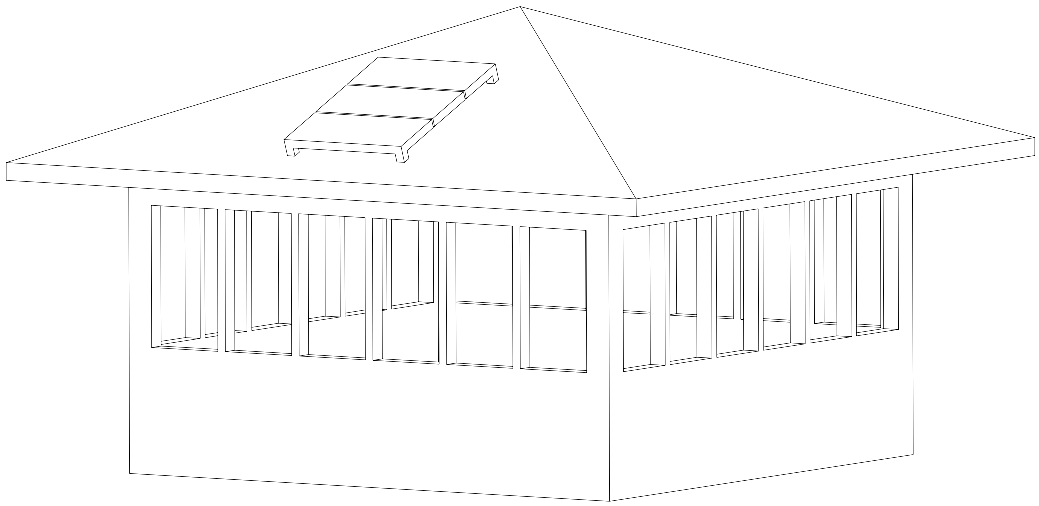
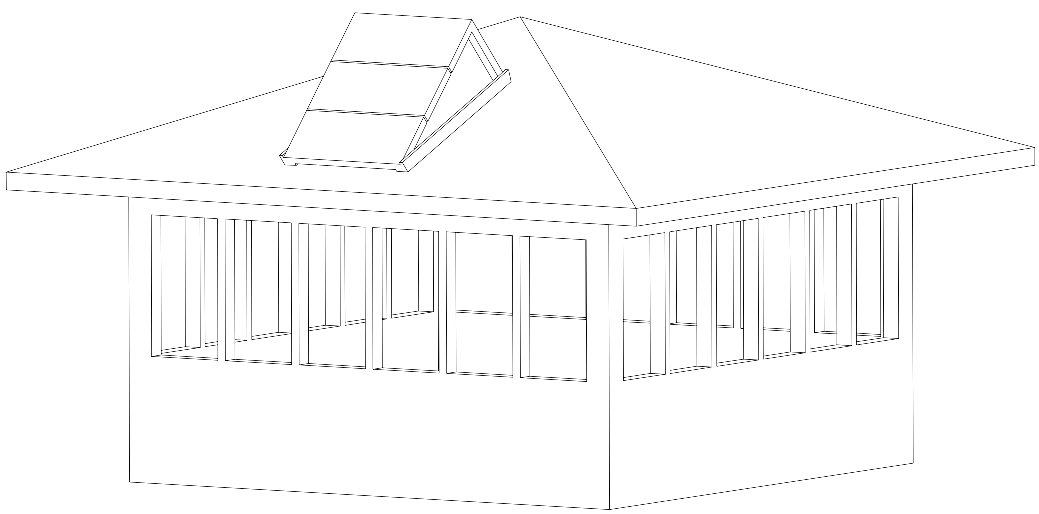


Figure 13: Schematic of Watchman with Panels Raised to 55 Degrees from Horizontal (autumn/winter/spring setup).

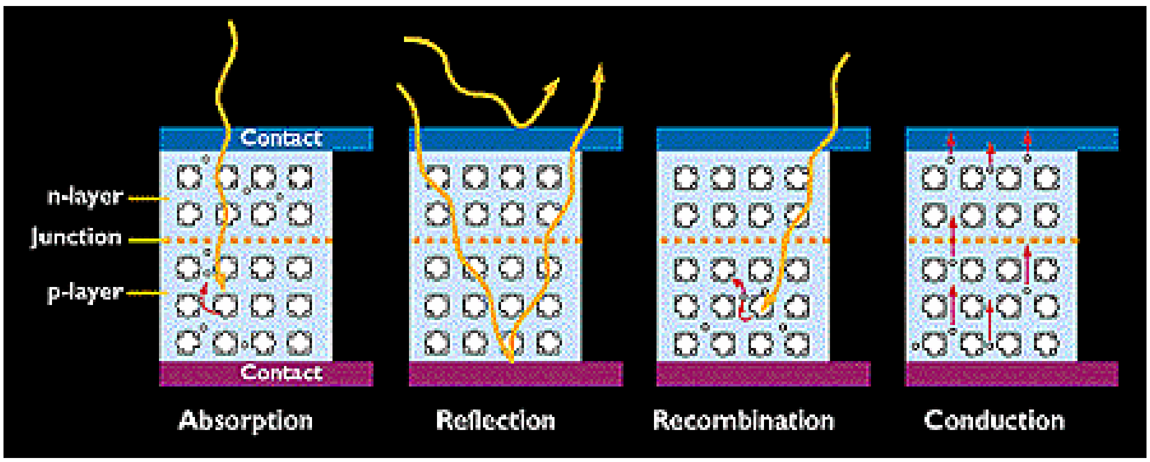


Solar Photo-voltaic Technology

Introduction

Solar energy is becoming more viable with increased efficiency and improved manufacturing processes which lower the cost. When the energy grid is out of reach for villages or individual users the power must be produced on site. The basic concept of the solar cell is shown below with the different ways light interacts with a cell (see Figure 18).

Figure 18. Four modes of light behavior in a solar cell. (www.nrel.gov)



The basic solar cell is a semi-conductor p-n junction, as used in a diode. The sequence of the four modes above shows the following:

1. Absorption of photons by the solar cell. Only photons sufficiently energetic to create an electron-hole pair are effective. The energy of other photons absorbed is dissipated as heat. Also, any photon energy above the threshold required for an electron-hole pair creation is dissipated as heat. For a single-material cell, the maximum percentage of total solar radiation converted to electron-hole pairs is about 25%. Not all of this energy ends up as electrical output, however. The typical maximum overall percentage of sunlight converted to electricity is about 15%.

2. Reflection of photons by the solar cell. These photons are lost to the solar cell. Solar cell manufacturers use anti-reflective coatings as well as other methods to minimize reflection to about 3-10%.

3. Recombination involves loss of electron-hole pairs created by the photon absorption. Thus, the photon involved has no impact on creating electricity.

4. Conduction shows the preferred situation: electron-hole pairs created which result in an electric current.

Semiconductor technology is very well developed in the computer age we live in. Many of the ideas and processes used for semiconductors are used in solar module production. The increase in sales of solar modules has caused many companies and governments to invest in research for better ways of producing solar modules. Increased interest in photo-voltaic applications is causing several new technologies to emerge. Many different styles of solar modules are in use today including; single-crystal, poly-crystalline, thin-film amorphous, concentrator cells, and others that we will not discuss.

Below is a discussion of the manufacturing process, pros, cons, efficiency, cost, and availability for several types of solar module constructions.

Manufacturing Processes

Techniques used to manufacture the different types of cells are discussed in this section.

Single crystal:

Nearly all of the single crystal silicon is produced using the Czochralski process. Single-crystal silicon of six inches in diameter and six feet long are now being grown for use in solar modules. The process involves dipping a “seed” crystal into a crucible of molten silicon. The seed is then slowly pulled from the molten silicon. The silicon attaches to the bottom of the seed and begins to solidify forming a cylindrical ingot of pure silicon. The diameter and length of the ingot depend on the capacity of the crucible and size of the pulling machine. A dopant is usually added in small amounts during the crystal forming process to produce the desired electrical properties. The dopant, usually boron, is incorporated during crystal growth to produce p-type material.

The ingot is now ready to be cut into cells. The thickness of the cut-wafers is approximately 300 microns. One of the cutting methods commonly used involves a washer-shaped saw blade. The cells are cut individually and the blade is a thin metal coated with diamond. The cutting edge is located on the inside diameter of the washer-shaped saw. The outside diameter of the blade is well supported to give a straight and smooth cut.

Adding phosphorous atoms to the top few microns of the cut-wafer creates the p-n junction. Since boron atoms are already present in the material from the growth process, more phosphorous atoms are added than boron atoms to the top layer. The n-layer is often added by heating the wafers to a temperature below the melting point and exposing the surface to phosphorous-containing gas. The temperature and time of exposure determine the depth and quantity of phosphorous atoms diffused into the wafer. Two wafers are often sealed together to prevent both sides of the wafer from creating an n-layer.

Another option for creating the p-n junction is ion implantation. Ions are shot at the surface of the wafers. The ion penetration depth is determined by its speed. The thickness and density of the n-layer can be carefully laid out using this method. Ion implantation lends itself to high quality cells, but is an expensive process.

At this point the cell is now operational but to extract the electricity one must apply metal contacts to the front and back of the wafer. Light penetrates the cell on the front side so the goal of the front contact is to transmit current while covering as little of the cell surface as possible. The front contact consists of a grid of small fingers covering the entire cell. Palladium-silver works well for the fingers of the front contact. The method of application of the palladium-silver front contact material varies between manufacturers. Some companies vacuum-evaporate the palladium-silver through a photo-resist to make the initial layer, then use electroplating to increase the thickness.

The back contact is a solid sheet of material since one does not want light to pass through. Since some of the light passes through the cell without being absorbed the back contact material is reflective so the light is redirected through the cell material for a second chance of absorption.

Silicon reflects about 35% of light it comes in contact with, so an antireflective coating is a must for all modules. The anti-reflective coating used for a module is the same that is used on high quality cameras and binoculars, so the process is readily available from methods developed over the past few decades. The coating material is often silicon monoxide or titanium dioxide and the thickness is about 0.1 micron. For the sake of comparison, the thickness of a wafer is approximately 300 microns, so the antireflective coating represents a very small percentage of the total cell thickness. The coating is often applied to the silicon using a vacuum evaporation process. The material is heated in a vacuum environment until it begins to boil off and travel in straight lines until it contacts the cool silicon surface.

After the electrical contacts and antireflective coating are applied the cells are ready for assembly into modules. In order to reduce manufacturing cost, many companies are automating the soldering and spot-welding processes which connect the cells together. An example setup of a module is shown below in Figure 19.

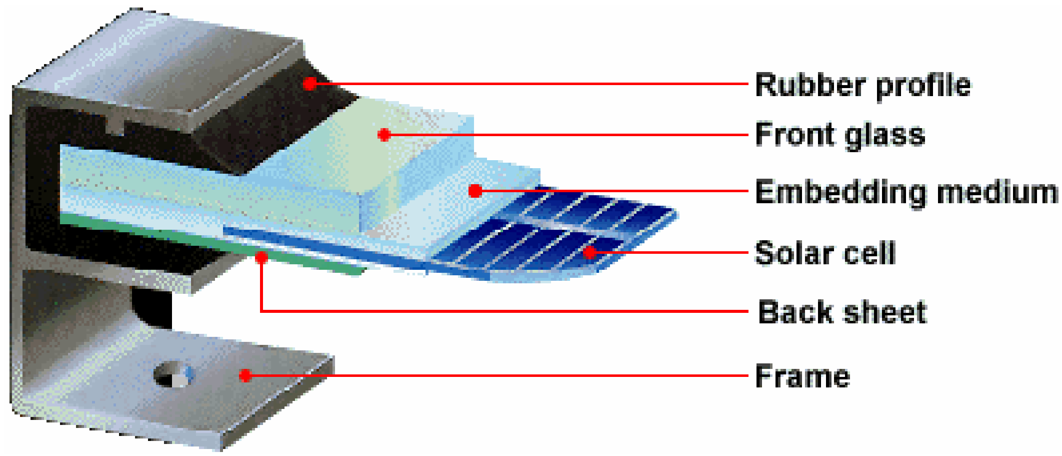


Figure 19. Schematic of module for single-crystal cell. (www.solarpv.com)

Poly-crystalline:

Poly-crystalline cell manufacturers use a different method for refining the silicon used in the solar cells. Casting is the method of formation used for forming the poly-crystalline solar cells. To cast the silicon the manufacturers start by purchasing silicon with acceptable purity levels. The silicon is melted and then cast into blocks of preferred size. The resulting wafers that are cut from the silicon block are rectangular allowing for the best use of module surface area. The grain structure that results from the casting process is an array of various grain sizes, shapes and orientations. The grain size of the crystals is very important, bigger grains are better since they result in fewer defects. The grain boundaries cause resistance in the wafer so if the effect of the boundaries could be minimized then the grain size would not be a big factor in cell efficiency. Kyocera claims to have minimized the effects of grain boundaries on cell performance so their grain sizes do not greatly influence cell efficiency. The claim made by Kyocera appears reasonable, since the efficiencies of poly-crystalline cells are becoming very competitive with most single-crystalline cells. The orientations of the grain boundaries are also important, since if they are perpendicular to the cell surface the grains act like several small cells in parallel, and effectively, the cell performance is closer to that of the single-crystal cell. Grain boundaries that are parallel to the cell surface create problems in the formation of the p-n junction.

Once the poly-crystalline material is made, the remaining manufacturing processes include formation of the p-n junction, adding the front and back electrical contacts, and assembling the cells into modules. These final steps use similar processes as the single-crystal cells discussed above.

Since many of the manufacturing processes are shared with single-crystal and poly-crystalline solar cells, the difference in cost is largely determined by the cost of silicon production. The process for producing poly-crystalline silicon is simpler and cheaper than the process for producing single-crystal silicon, so the cost of poly-crystalline solar cells is generally lower. The lower-cost poly-crystalline solar cells have lower cell efficiency, although not much lower, than the single-crystal solar cells.

Thin-film Amorphous:

Glass is an example of an amorphous material; the lack of long crystal structure is a defining characteristic. The usual method for manufacturing thin-film amorphous solar cells is to start with a substrate and use a technique called sputtering to deposit the material. Sputtering involves placing the substrate between two electrodes in the presence of gas containing silicon, like silane (SiH_4), and using a high voltage DC to create a layer on the substrate. This process is repeated until the desired layers have been deposited.

For the amorphous solar cells, the diffusion length of the charge carriers (i.e. electrons and holes) is so small that only a small part of charge carriers can be collected. The solution is to introduce an intrinsic layer between the p-layer and n-layer. The intrinsic layer allows nearly all of the charge carriers to reach the p-n junction. Another improvement for amorphous cells is multiple layering. A single-layer thin-film amorphous solar cell has an efficiency of less than 5%, so to improve efficiency multiple layers are used. Each layer is a stand-alone p-n junction separated by an intrinsic layer, which allows for sunlight-to-electricity efficiencies in field-use of around 8% or more.

Companies are using the method of multiple layers of amorphous material, each absorbing in different parts of the light spectrum, to compensate for the low efficiency of amorphous cells. Each layer absorbs a progressively higher energy photon so the first layer absorbs the low energy photons and the higher-energy photons pass through and are absorbed by the following layers. An example of a multi-layer thin-film amorphous cell is shown below in Figure 20.

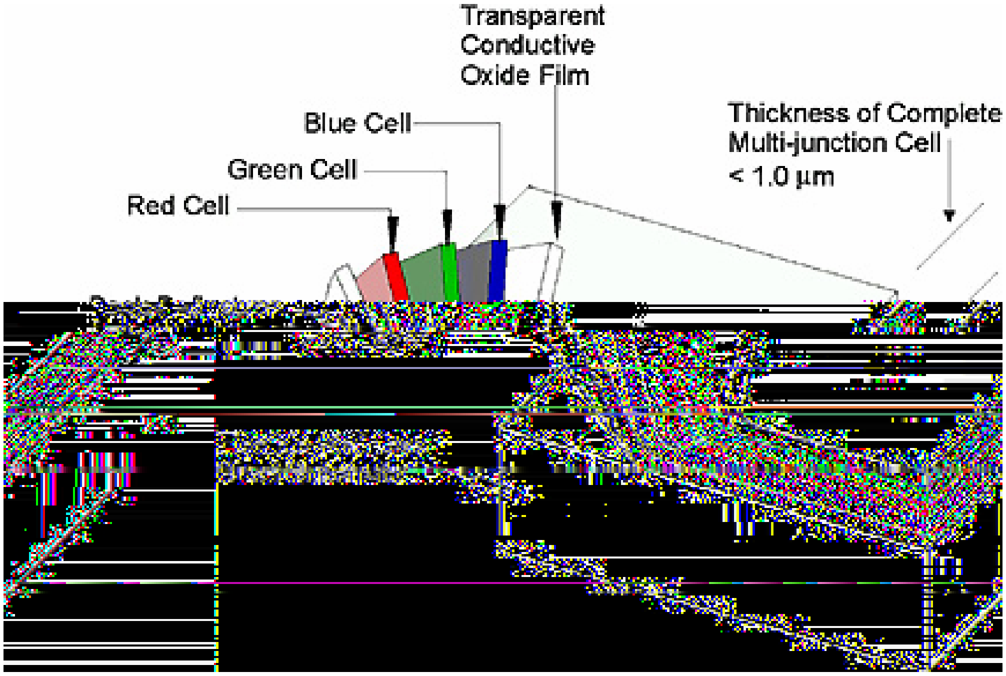


Figure 20. Multi-layer amorphous cell. Each cell color absorbs a different spectrum of light. (ovonic.com/unisolar.html)

Concentrator systems:

Silicon cells used in concentrator systems are much the same as those used in flat plate PV construction. The cell is placed a given distance from a lens which concentrates the sun much the same way a magnifying glass will do when placed the correct distance from a surface. The ratio of areas for the lens and cell make up the concentration factor, often called the number of suns.

Concentration factors of three to four will not overheat normally-produced cells, but concentration factors of two to three hundred are possible so extra precautions are required for the high levels of concentration. The higher concentration levels create high heat so these concentrators require special precautions. Cooling fins or forced air maintain the cell at acceptable temperature. The basic setup for the concentration system is shown below in Figure 21.

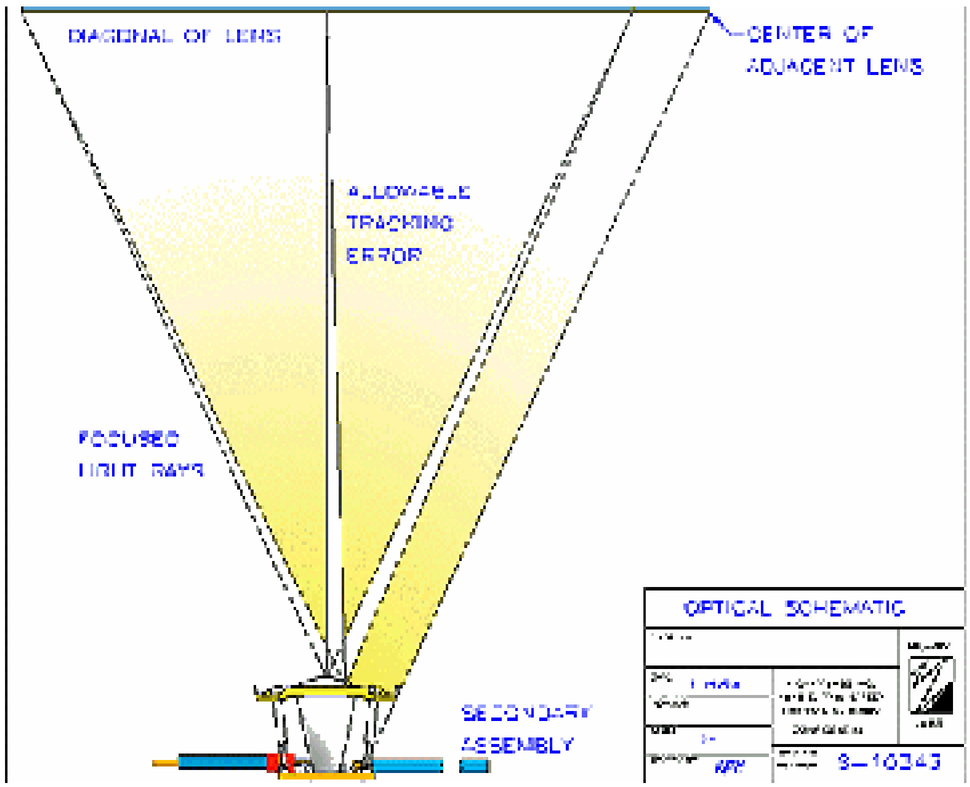


Figure 21. Concentrator system. (www.megsinet.net/~midway)

Since concentrator PV systems require direct sunlight, a tracking device, and a cooling system, they are not used nearly as often as the simple non-concentrator systems. Currently, concentrator systems are not practical in areas where it is often cloudy, they work best in highly sunny climates.

Efficiency

The table below shows the highest sunlight-to-electricity efficiencies of various solar modules in both field use and laboratory testing. (The cell temperature is assumed to be 25 degrees C.)

Table 4. Solar Cell Efficiencies

Cell Type	Highest Efficiencies as Quoted by Manufacturer (Field-Lab)
Single crystalline	14.5-18.8%
Poly-crystalline	14.3-17.2%
Amorphous multi-layer	8-13%

The difference in efficiency between amorphous cells and single and poly-crystalline cells requires interpretation. For consistency of measurements the efficiencies of all cells are measured at standard operating conditions. The standard conditions are 25 degrees C cell temperature and 1000 watts/meter^2 normal solar flux. The standard temperature condition favors single-crystalline and poly-crystalline cells because of the thermal expansion coefficient. Amorphous material has a thermal expansion coefficient of 0.01-0.02% per ^{0}C, while the coefficient for crystalline cells is around 0.04% per ^{0}C. The normal operating temperature for solar cells is around 50^{0}C. Amorphous solar cells perform better than crystalline solar cells at normal operating temperature due to the difference in thermal expansion coefficients. Crystalline solar cell sunlight-to-electricity efficiency drops as temperature rises. Amorphous cell efficiency drops but not nearly as much as that of the crystalline cells. So as the temperature increases (above 25 degrees C) the performance gap between the crystalline and amorphous cells decreases.

Efficiency Improvements

Single Crystal:

Single crystal silicon reflects large amounts of light, which translates into lost efficiency. Anti-reflective coatings are added to the surface to reduce losses, but this process is costly and time consuming. One solution for reflection losses is to create grooves in the surface so the light is reflected to an opposing surface (as shown in Figure 22). Surface texturing reduces the surface reflection from the level of 35% to about 10%.

Surface blockage by the front contact electrodes also affects the efficiency by reducing the surface area available for light absorption. One way to reduce surface coverage for the front contacts is to bury the contacts in the cell material.

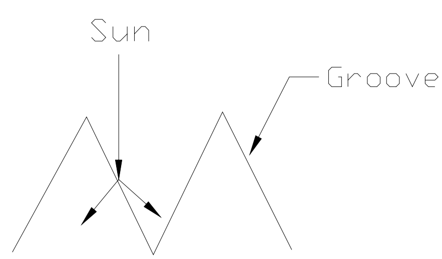


Figure 22: Schematic of surface texturing for single-crystal solar cells.

Laser grooved front contacts improve cell efficiency by about 1%, but the cost of the process is usually too high to justify the added efficiency.

Poly-crystalline:

Surface texturing is also an option for polycrystalline cells. However, the grain boundaries and orientations make texturing less effective than for single crystal cells.

Amorphous:

Cell degradation over time is called the Staebler-Wronski effect. However, even today this effect is not fully understood. A possible explanation for the cell degradation is the breaking of weak silicon-hydrogen bonds, which increases defect density, and lowers cell efficiency. The hydrogen in the amorphous material comes from the silane (SiH_4) gas, which is used during the deposition of the layers onto the substrate. Further understanding of the Staebler-Wronski effect will allow for better compensation of cell degradation and higher efficiency.

<u>Cell-type Advantages</u>

The advantages of the types of solar cells discussed above are summarized below.

Single crystalline:

- Highest efficiency.
- Technology is well developed from research of silicon use in computer applications.
- Appearance of cells much cleaner than conventional poly-crystalline due to no grain boundaries.
- Wide selection of manufacturers and products.

Poly-crystalline:

- Efficiencies are somewhat lower than single-crystalline solar cells, but competitive.
- Less expensive due to production simplicity.

Thin-film, Multiple-layer Amorphous:

- Efficiencies on the rise, as technology improves.
- Confidence in long term aspects evident from companies turning plants to sole production of amorphous cells.
- Some crystalline module manufacturers are introducing amorphous research into their facilities with thoughts of future trends.
- Modules are less reflective and are more easily hidden in the architecture.

- Resiliency of material is high due to flexible nature.
- No glass outer layer necessary for protection from elements, so modules can survive impact without having glass shatter (though proprietary protective film is applied).
- Many cells in the field for over a year are still performing higher than rated output levels due to manufacturer overestimation of cell degradation.

Concentrator systems:

- Reduced use of expensive silicon.
- High potential for improvement.

Cell-type Disadvantages

The disadvantages of the various solar cells are listed as follows:

Single crystalline:

- Processing silicon to extreme purity is very costly.
- Cutting wafers causes loss of large amounts of expensive silicon, around 35%.
- Cost reduction in future is not promising.

Poly-crystalline:

- Material is electronically poor due to impurities, grain boundaries, and dislocations.
- Modules are not aesthetically pleasing due to non-continuous colors in cells from grain boundaries. However, the new poly-crystalline cells overcome this disadvantage. See Kyocera PV panel pictured in Figure 15.

Thin-film, Multiple-layer Amorphous:

- Degradation of output over time (reasons not fully understood).
- Although manufacturers have warranties of ten years or more on modules, the reliability has not been tested in the field for any great periods of time.
- Not many companies from which to choose when looking for modules.

Concentrator systems:

- High heat from sun concentration necessitates active cooling system and special consideration for production of cells.
- Expensive tracking system a must.
- System works well only in sunny climate.

Cost

The cost of solar modules is determined by many factors including material, technology, module components (other than solar cells), framework, and installations of array. An approximate breakdown of the above costs is shown in Figure 23 below.

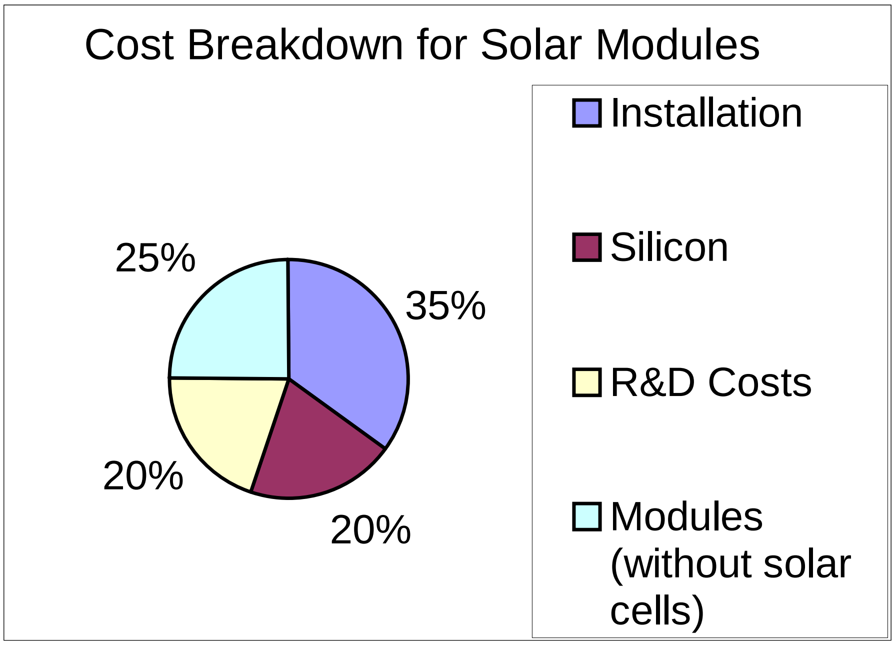


Figure 23. Cost breakdown for solar module.

The benchmark for cost comparison of solar energy is dollars per watt. To be cost competitive renewable energy must deliver more energy for the consumer's dollar. Every solar company is trying to lower the cost with better and more efficient cells. Many factors determine the cost including system size, quality, durability, and the list goes on. The current nominal cost is US$4 per watt for the cell. System cost, including battery storage, is about US$10 per watt.

As an example of the cost of a small (64-watts) system, below is the cost breakdown of a recently specified system for the University of Washington. The table below shows the components of this small system, but larger systems use much the same hardware. The one item commonly used in larger systems that is not in the table below is a standby generator.

Table 5. Components and Cost of 64 watts PV System

Qty	Item	Description	Price	Supplier
1	Solar Panel	Uni-Solar US64 Module 64W rated output, 29x54x2 inches	$ 329.00	Sunelco
1	Controller	Trace C-12 pulse width modulated charge controller 12Amp max, UL approved, 2pounds	$ 98.00	Sunelco
1	Option	Battery Temp sensor option for temperature compensation	$ 19.00	Sunelco
1	Surge Prot.	SOV Silicon Oxide Varistor Shunts excess voltage to ground	$ 39.00	Sunelco
1	Inverter	Statpower Prowatt 250 250W constant, 500W 5min surge	$ 69.00	West Marine
2	Batteries	Trojan T-105 Deep Cycle 6V "Golf Cart Batteries" 225AH @ 8hour discharge	$ 170.00	West Marine
1	Cable	Battery Cable Interconnects multiple batteries	$ 5.00	West Marine
	Misc.	Fuse block, Fuses, wire, disconnect, shipping	$ 75.00	West Marine
		Tax	$ 68.34	
		Total	**$ 872.34**	

Suppliers and Manufacturers

Some of the contacts used in this study are listed in the table below:

Table 6. PV System Suppliers in Pacific Northwest

Company	Description	Location	Contact	Phone	Web
Cruising Systems	Specializing in system monitors (e-meter/link-10)	Seattle Washington	Michael	1-206 784-8100	
NW Energy	Full system providers, specializing in larger systems.	Colburn Idaho	Rob	1-800 718-8816	www. nwes.com
Sunelco	Full system providers, covering large system size range.	Hamilton Montana	Chris	1-800 338-6844	www. sunelco.com
West Marine	Marine supply company	Seattle Washington		1-206 292-8663	

Just as with automobiles, a few companies dominate the majority of the solar module market. The four major manufacturers of solar modules include Siemens, Kyocera, Solarex, and BP. The power capacity of all solar modules sold worldwide last year is about 100MW. The solar cells sold by Siemens, Kyocera, Solarex, and BP have total power ratings of 22MW, 15MW, 11MW, and

10MW, respectively. The pie chart below shows the market share for the four main solar module companies (Figure 24).

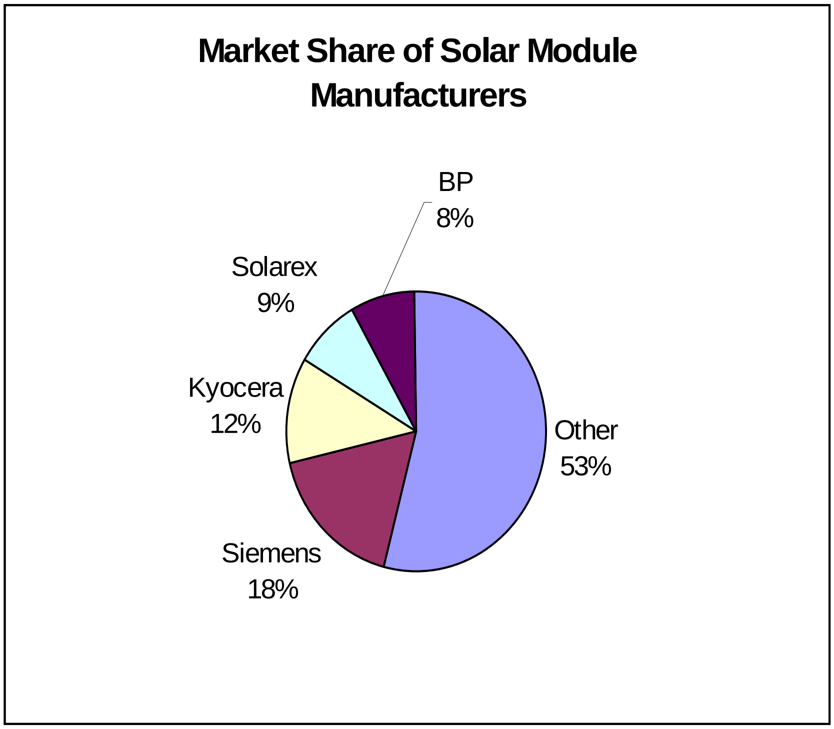


Figure 24. The percentages of market share of each company based on rated power output of solar modules sold in 1997.

Below is a summary of key points gained from discussions with the PV suppliers and manufacturers.

Single crystalline:

The single-crystalline PV module manufactured by BP Solar, the BP590, has been shown above in Figures 13, 14, and 15.

The largest manufacturer of single-crystalline solar modules is Siemens. Many vendors carry Siemens products and recommend them based on reliability and track record. Siemens single-crystalline solar cells have efficiencies of about 14.5%. Although Siemens is very successful with their crystalline solar modules their main area of research is with thin-film technology.

Thin-film Modules:

The new Siemens solar cells are copper-indium-deselinide (CID) thin-film. Based on tests conducted by the National Renewable Energy Laboratory, NREL, the new CID cells are producing efficiencies of 11.8%. Although the efficiencies of the CID cells are lower than the single-crystalline cell efficiencies, Siemens is confident in the possibilities. Thin-film solar cells do not require gaps between cells as crystalline modules do, so when looking purely at surface area of the module the thin-film performs better. When looking at total surface area, conventional single-crystalline solar modules have efficiencies of about 9-14%, so the new CID cells show potential. The CID modules are available this year in 5 and 10-watts capacities. The figure below shows a Siemens single-crystalline solar module with a 55 watts rated power output.

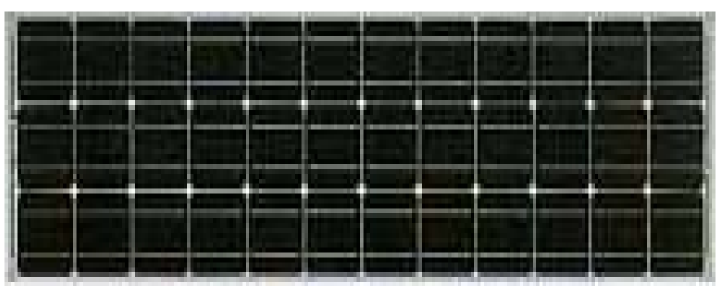


Figure 25. Siemens SM55 Module

Poly-crystalline:

A major manufacturer of poly-crystalline solar modules is Kyocera. The company is based in Japan, but sells worldwide. The main challenge with poly-crystalline solar cells is minimizing the effects of grain boundaries on cell performance. Kyocera claims to have solved the problem, so the resistance caused by grain boundaries is minimized. The efficiency of commercially available solar modules from Kyocera is 14.3%, and they claim to have cells in laboratory conditions with 17.2% efficiency.

Kyocera has researched amorphous solar technology for ten years but they stopped three years ago because they felt the market for poly-crystalline cells would remain strong for at least ten more years. The figure below shows a Kyocera poly-crystalline solar module with a 60 watts maximum power output. The Kyocera 60 module has about the same surface area as the Siemens SM55 module shown above. The texture and color of the module is very good compared to conventional poly-crystalline PV panels.

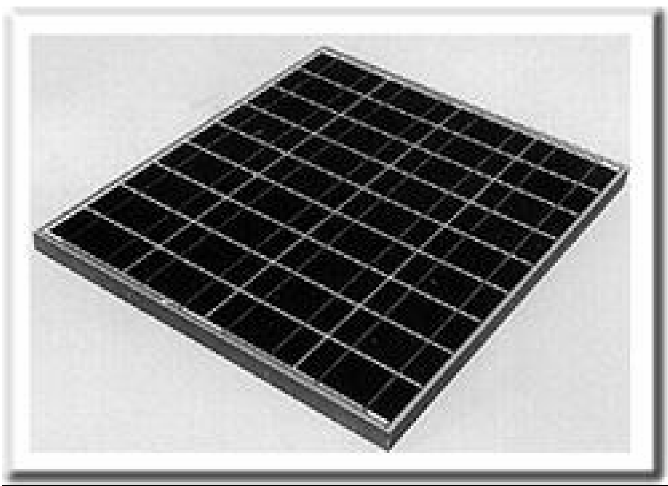


Figure 26. Kyocera 60 Module

Thin-film Amorphous:

United Solar appears to be the forerunner in the race to create amorphous solar cells that can compete with the crystalline modules. Challenges for amorphous silicon solar manufacturers include increasing efficiency of the cell and to better understand the cell degradation that takes place during the first two months of exposure to the sun. The current method for dealing with the cell degradation of amorphous modules is to rate the cell below the expected power output. Modules from United Solar are still producing higher than rated energies after a year of service.

United Solar expects to gain larger percentages of the renewable energy market in the near future as the module durability becomes established. The figure below shows an amorphous triple-junction solar module from United Solar with a 64 watts rated power output.

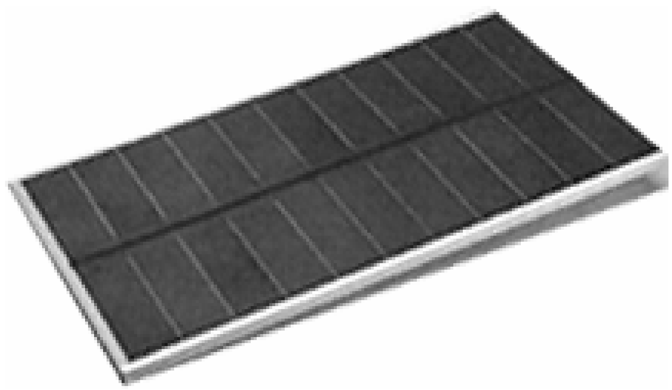


Figure 27. United Solar US64 Module

United Solar also manufactures thin-film amorphous cells in the form of roofing shingles. The shingles are designed to look like conventional asphalt shingles. They are weather resistant and are installed similar to conventional shingles. The shingles come in two different sizes and produce 15 or 17 watts each. The shingle type solar panels are shown below in Figure 28.

Figure 28. United Solar Roofing Shingle PV Collectors

United Solar also designs roofing panels for solar energy production (shown below in Figure 29). These roofing panels come in two sizes producing up to 120 watts each. The panels function as traditional metal channel roofing.

Figure 29. United Solar Roofing Channel PV Collectors

United Solar has really taken the lead in producing solar modules that are both functional and aesthetically pleasing. With improved efficiencies these panels will be hard to beat when trying to combine form and function.

Storage Battery Technology

Introduction

Since solar energy is available only during daylight hours, and since it is significantly reduced during cloudy and stormy weather, a storage device must be utilized so energy can be used when needed. The storage method of choice for photo-voltaic systems is the battery.

The automotive industry has developed lead-acid battery technology over the past several decades. The main purpose of the SLI battery for automobiles is to give high torque for short periods of time. The energy requirement for starting an automobile does not drain the battery much below full capacity. When a battery is rarely discharged below about 80% of maximum capacity (i.e., when the battery is discharged about 20% at most), the battery method is called shallow-cycling. The automotive battery is a shallow-cycle battery. When batteries are discharged to 50% capacity or lower on a regular basis they are called deep-cycle batteries. Shallow-cycle batteries that are deeply discharged on a frequent basis will eventually fail.

Many factors must be considered when choosing a battery, but essentially the choice comes down to deep-cycle versus shallow-cycle. Before discussing different types of batteries, we discuss the basic battery features.

Battery Operation and Construction

Lead-acid batteries consist of plates, spacers, electrolyte, and a case. The plates are made mostly of lead. There are two types of plates; one is positive (made of lead oxide) and one is negative (made of lead). Each rectangular plate is about a quarter inch thick and has square holes in it that form a grid separated by webbing about 1/16 inch thick. The holes making up the grid are about a half-inch square. The holes in the positive plates are designed to house a lead oxide paste. The reason paste is used in the grid is to create large surface areas for the chemical reaction. The surface area available determines the rate of chemical reaction, and solid material has a low surface-to-volume ratio, so paste is a good choice. The paste is pressed into the holes and cured. Then the plate is ready to be inserted into the battery.

Each positive plate has a counterpart negative plate. The plates are sandwiched together as tight as possible to save space but plates can not touch each other, so between each plate is a separator. If any two plates contact, a short circuit occurs, so the spacer is essential. Once the plates and spacers are in place, electrolyte is added. The electrolyte carries the charge between plates; the most common electrolyte is sulfuric acid. The acid is added to the plates and soaks into the “paste”.

The plates are connected together to create a cell. Each automotive battery cell has about 17 plates, 8 positive and 9 negative. The cell has a voltage of 2.1

volts (2 volts nominal). The numbers of plates per cell, the size of the plates, and the number of cells in a battery make up the battery size. For a 6-volt battery, there are three 2-volt cells connected in series. A 12-volt battery has six 2-volt cells connected in series. A cell is an individual container with its own electrolyte and plates. If electrolyte is allowed to flow between the cells, the voltage is not additive -- the result would be a very large capacity 2-volt battery.

Capacity is the total electrical charge stored in the battery, specified as amp-hours (AH). A 100 amp-hour battery will produce 1 amp for 100 hours, 12.5 amps for 8 hours, or 100 amps for 1 hour. However, the capacity rating is somewhat reduced for rapid discharging (such as the case of 100 amps for 1 hour), since the chemical reactions occurring at the positive and negative plates (i.e., at the cathode and anode, respectively) cannot keep up with the high rate of discharge. Since batteries cannot be discharged to zero capacity without damage, the actual capacity of the battery is some percentage of the total capacity. If a 100 AH battery is not to be discharged below 50% capacity then it will only supply 50 AH before requiring recharge. The life of the batteries is greatly influenced by the cycle depth. If the batteries are cycled to 90% capacity, 10% discharged, they will last many times longer than batteries cycled regularly to 50% capacity.

Batteries must be handled with care. Most batteries used in solar energy applications are flooded batteries. Flooded batteries require adding distilled water periodically to replenish the electrolyte. When flooded batteries are fully charged they product gas, which diminishes the supply of electrolyte. The gas produced by the flooded battery is poisonous and explosive so the batteries must be kept ventilated.

Sealed batteries are designed to overcome the gassing problem. A sealed battery is essentially the same as a flooded battery except the electrolyte is a different material. The problem with sealed batteries is that one cannot add electrolyte. If batteries are discharged to zero the only way to rejuvenate them is to overcharge them. Flooded batteries can often be saved after being discharged to zero. Just as in flooded batteries, when sealed batteries are overcharged they will produce gas, and since electrolyte cannot be added to sealed batteries they are ruined when discharged to zero. Also, sealed batteries cause hazards when charged beyond capacity because of pressure buildup that can cause an explosion. Since sealed batteries are sensitive to mistreatment they are rarely used in renewable energy systems.

<u>Deep-Cycle versus Shallow-Cycle Batteries</u>
One problem with batteries being used in solar energy systems is self-discharge. All batteries will self-discharge if left unattended sufficiently long. Some batteries will “die” in a few weeks, while other batteries will take months to fully discharge with no load. The factors that influence self-discharge rate are closely linked to deep-cycle and shallow-cycle batteries, which are discussed below.

The difference of construction between deep-cycle and shallow-cycle batteries is small, but significant. When batteries are deeply cycled the "paste", or active material, in the plates thermally contracts and expands quite a bit. In order to minimize battery deterioration by the expansion and contraction of the active material, antimony is added to the lead for construction of the plates. The antimony improves the capability of the battery to handle deep cycling. The amount of antimony added to the plate material is between three and six percent. Although the antimony promotes an improved tolerance to deep cycling, it tends to increase the self-discharge rate of the battery.

Shallow-cycle batteries are designed to have low self-discharge rates. One type of shallow-cycle battery is lead-calcium. The electrolyte of a lead-calcium battery is still sulfuric acid, but the antimony in the plates is replaced with calcium. The calcium in the plates causes the self-discharge rate to drop dramatically. The calcium in the plates, being relatively brittle, does not hold the paste in the grid as well as the antimony. Thus, the lead-calcium battery cannot be often deep-cycled, i.e., strongly thermally cycled. Usually, lead-calcium batteries are kept between 80% and 100% of full charge.

Factors to Consider in Battery Choice

Factors to consider when choosing a battery for a solar energy application are the following:

1. Weather
   a. Percentages of days with cloud cover.
   b. Length of periods between sun during winter.
2. Location
   a. Accessibility of the batteries.
   b. Should a problem occur, are the batteries easy to service?
3. Importance of Operation
   a. What happens if the batteries fail?
   b. Can one afford to replace batteries because of lack of maintenance?
4. Cost
   a. Initial cost.
   b. Maintenance cost.
   c. Replacement cost.

These are some of the considerations when choosing a battery. The most popular battery for solar energy systems is the deep-cycle, flooded, lead-acid battery. Deep-cycle batteries are generally recommended for photo-voltaic electrification systems. Most solar (and wind) energy companies sell flooded deep-cycle batteries to first-time buyers, because these batteries can take the significant abuse, which is often dealt by the first-time operator.

On the other-hand, shallow-cycle batteries are recommended for communication systems, navigational equipment, and applications such as railroad-crossing gates [C&D Technologies, 1998].

Battery Choice for Watchman Lookout

The battery choice for the Watchman Lookout is as follows:

- Shallow-cycle, low self-discharge, battery-pack for communication system applications.

- Large capacity battery pack, because of long periods of low sunlight and critical need of radio-repeater at the site.

- “Mountaintop” specification, that is an electrolyte of high specific gravity. Upon discharge, the specific gravity of the battery electrolyte decreases, and becomes subject to freezing. In order to guard against this, 1.3 specific gravity sulfuric acid has been used in the batteries at Watchman Lookout. This practice should be continued.

The battery-pack of six KCPSA-7 cells (provided by C&D Technologies, Inc.), or equivalent, has been indicated above for the new photo-voltaic system at Watchman Lookout. As indicated above, the nominal voltage of the battery-pack is 13 volts, and capacity (as given by C&D Technologies, Inc.) would be:

- 77°F, 8 hour discharge: 337 AH.
- 77°F, 100 hour discharge: 358 AH.
- 77°F, 500 hour discharge: 400 AH.
- 32°F, 500 hour discharge: 336 AH.
- 0°F, 500 hour discharge: 293 AH.

As indicated above, although the KCPSA-7 batteries are preferred, in order to provide a greater “factor-of-safety” for wintertime emergencies, KCPSA-9 batteries are an alternative choice. Their capacities are listed below.

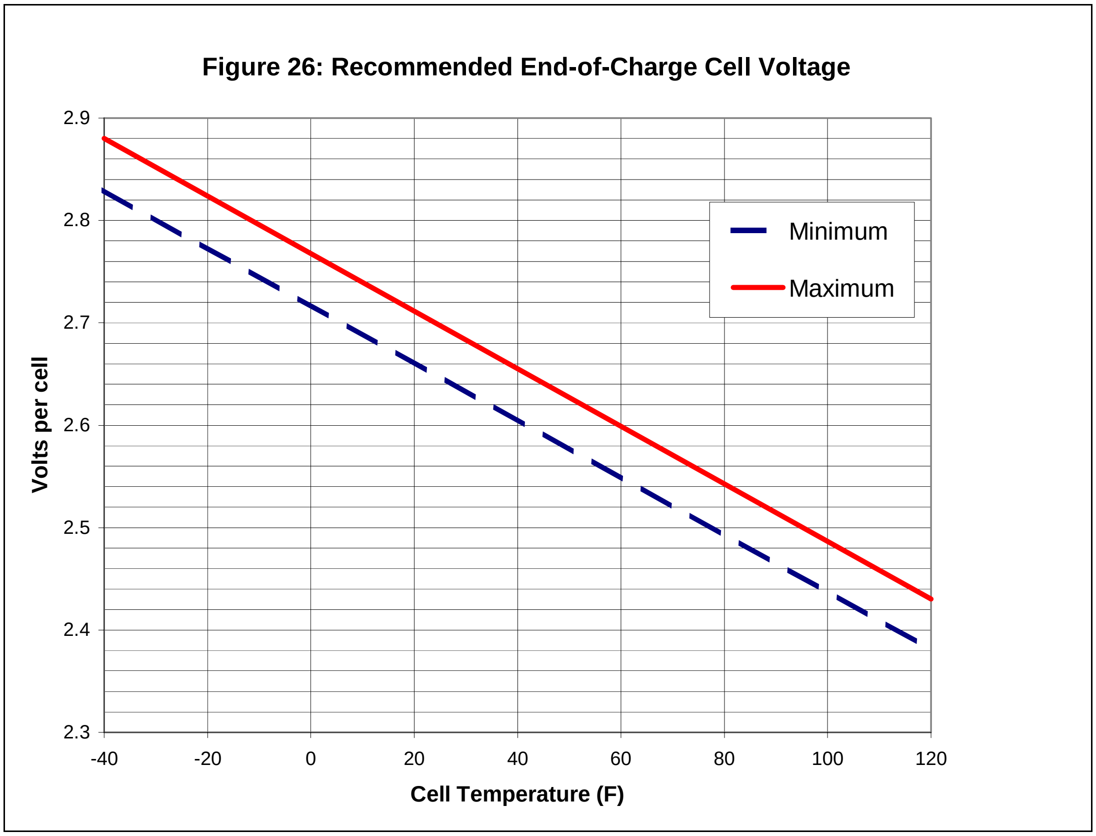
- 77°F, 8 hour discharge: 450 AH.
- 77°F, 100 hour discharge: 509 AH.
- 77°F, 500 hour discharge: 525 AH.
- 32°F, 500 hour discharge: 471 AH.
- 0°F, 500 hour discharge: 384 AH.

Other considerations, most of which have pointed out in the text above, are as follows:

- Aging of the batteries will diminish the capacity by about 20%.
- At 77°F, the recommended full-charge voltage per cell is 2.5 v.

- In cold weather, over-charging to 2.9 v per cell is suggested. The sulfuric gas created will act to overcome stratification of the liquid electrolyte.
- The cell voltage will drop to about 1.9 v as the recommended charge capacity of the battery is used up. Should this occur in cold weather, there is a danger of battery freezing (as noted above).
- Infrequent deep-cycling of the batteries is permitted, though not if freezing is a possibility.

The four figures below provide additional information on the batteries. Most performance conditions of the KCPSA batteries can be determining using the graphs below.



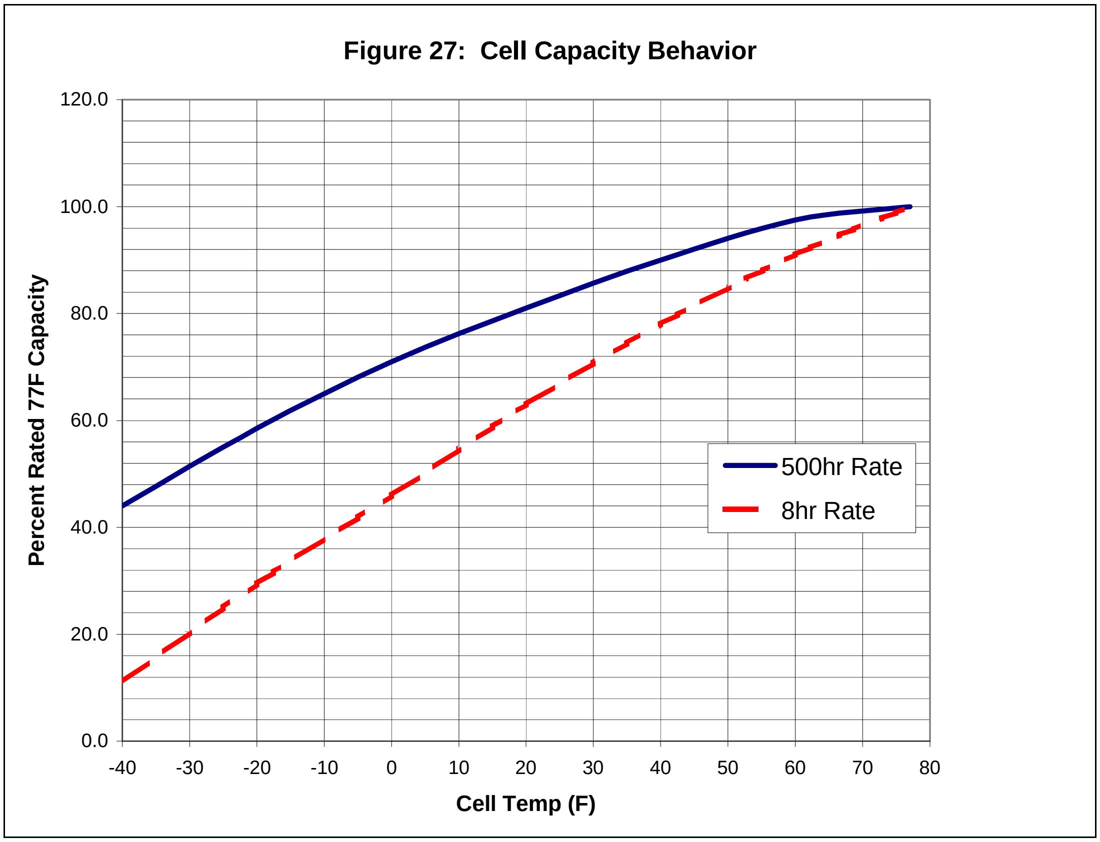


Figure 27: Cell Capacity Behavior
120.0
100.0
80.0
60.0
40.0
20.0
0.0
Percent Rated 77F Capacity
-40
-30
-20
-10
0
10
20
30
40
50
60
70
80
Cell Temp (F)
500hr Rate
8hr Rate

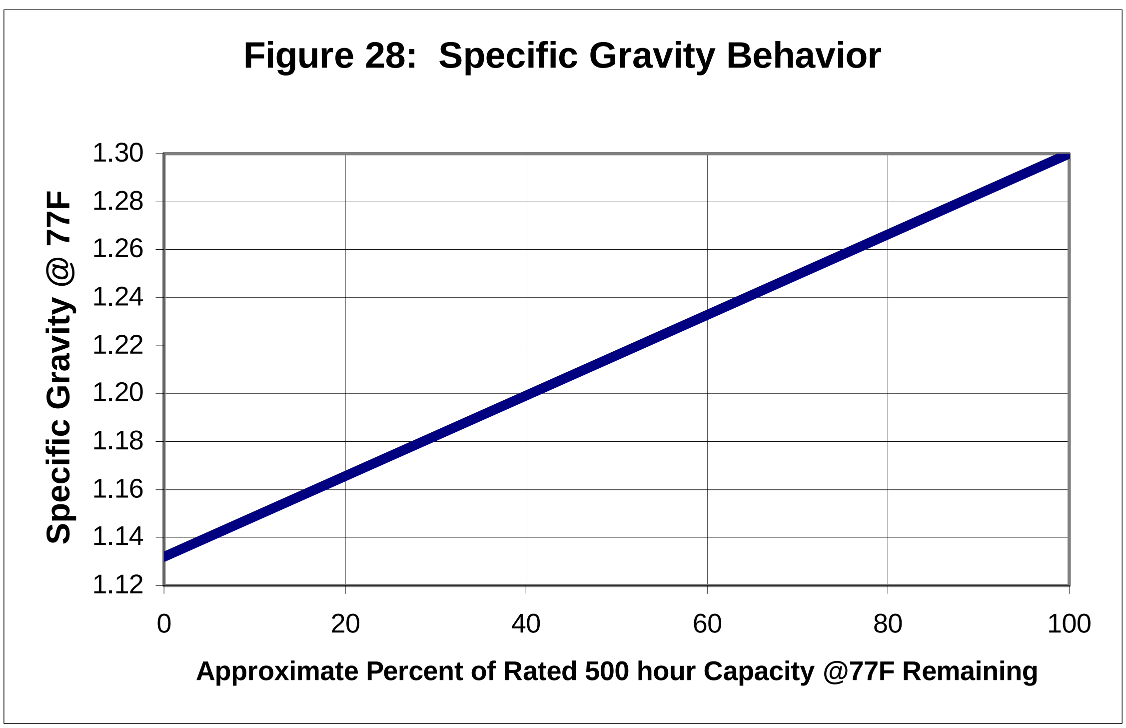
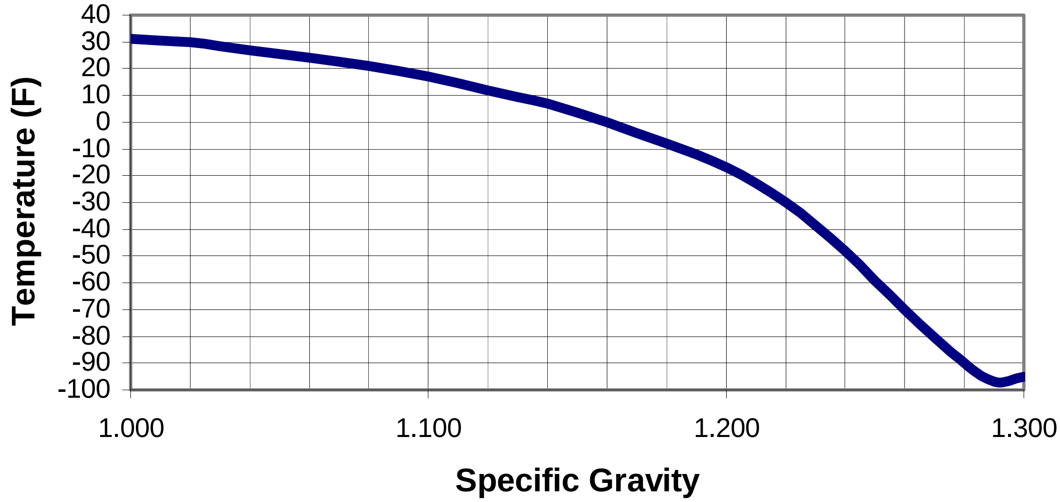


Figure 28: Specific Gravity Behavior
1.30
1.28
1.26
1.24
1.22
1.20
1.18
1.16
1.14
1.12
Specific Gravity @ 77F
0
20
40
60
80
100
Approximate Percent of Rated 500 hour Capacity @77F Remaining

Figure 29: Freezing Point of Sulfuric Acid Electrolyte



<u>Nickel-Cadmium Batteries</u>
Because of the good record of service of the lead/calcium batteries at Watchman Lookout, it is difficult to envision a switch to a different type of battery.

One battery type is currently available that rivals the lead-calcium in many ways. The nickel-cadmium battery has many positive attributes such as:

- Nickel-cadmium batteries are capable of routinely being fully discharged without a fatal effect to the battery. (Although the discharge has some effect on the life of the battery, since the batteries will not be discharged fully on a regular basis, the loss of battery life should be small.)
- The batteries can be discharged and stored over long periods of time without damage.
- Since the batteries are “deep-cycle” one does not have to oversize the battery capacity for emergency situations.
- Ni-Cd batteries perform very well in low temperatures (see Figure 34).
- The self-discharge rate is low, about 2.5% for the first eight weeks, then it drops to less than 1% per week (see Figure 35).
- Nickel-cadmium batteries do not form a “memory”.
- The batteries weigh about half as much per cell as lead-calcium batteries. (Ni-Cd batteries produce lower voltage per cell, 1.2 volts nominal versus 2.0 volts nominal per cell for lead-acid batteries, so the weight advantage is not as significant as it appears, but the cells are certainly more manageable.)
- If well maintained, the nickel-cadmium batteries can last up to 25 years.

Nickel-cadmium batteries have many positive qualities, but there are also some negative attributes, which include:

- Cost is the main detriment of the Ni-Cd battery, cost is about twice as much as the lead/calcium batteries. (But considering the Ni-Cd battery life expectancy is more than 20 years, the life-cycle cost is not that high.)
- Disposal options for the batteries are limited. There is currently one recycling facility for Ni-Cd batteries in the US, which is located in Pennsylvania. (The lack of recycling sites is due to the demand not being high enough to make it economic for expansion of recycling facilities.)
- The batteries contain cadmium, which is a highly toxic metal. (Although disposal options are limited, the recycling process reuses most of the materials in the battery, including the cadmium and the nickel, so the contribution to environmental degradation is minimal.)

The above discussion referenced two figures, which are shown below:

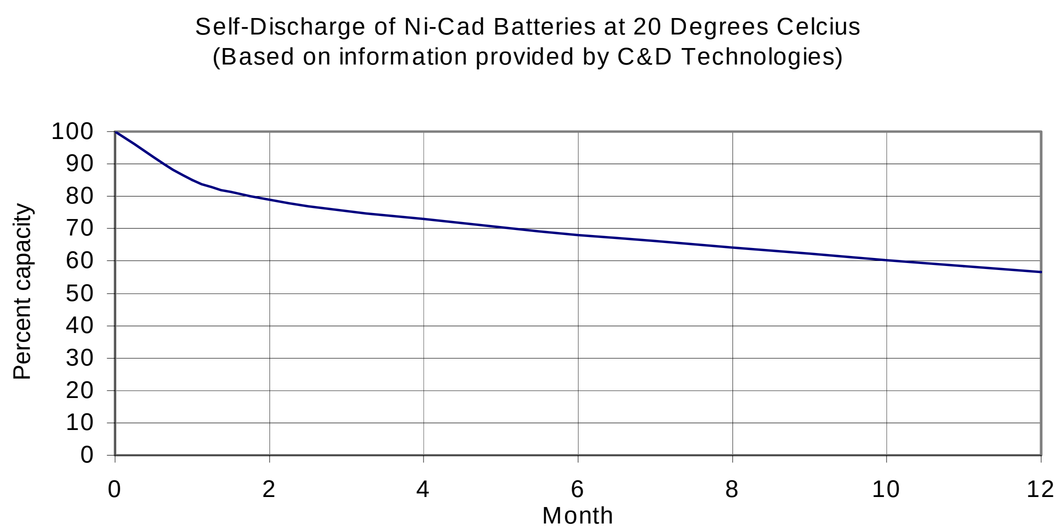


Figure XX

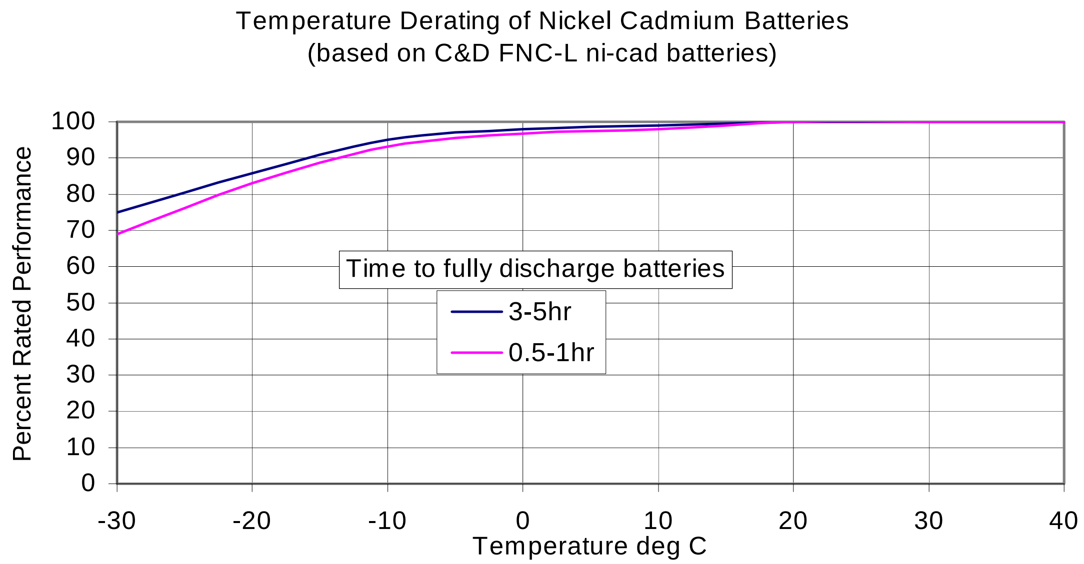


Figure XX

Nickel-cadmium batteries are rated at 1.2 volts per cell (nominal), thus a 12 volt system requires ten cells, as opposed to six cell for the lead/calcium system. The electrolyte solution of the Hoppecke nickel-cadmium battery sold by C&D Technologies includes 20% potassium hydroxide (KOH), lithium hydroxide (LiOH) additive, with the balance of the solution being distilled water. Since the electrolyte is not acidic, the effect of a spill is not as detrimental to the environment as spilling the lead/calcium battery electrolyte.

The battery used at Watchman is the KCPSA from C&D Technologies, with a six-pack cost of round $1800. The most promising Ni-Cd battery found to date is the FNC-409L, which has a ten-pack cost of $3450. The cost of recycling for the Ni-Cd batteries is $0.70 per pound, so the price for recycling a ten-pack of FNC-409L would be about $175 plus shipping.

The nickel-cadmium cells are light, are cost effective when considering longevity, are probably as safe as batteries can be expected, and are not easily damaged from high discharge. The Ni-Cd batteries could offer a very reliable and long-lasting solution to the energy storage requirements for Watchman Lookout. The main concerns for this application are two-fold: 1) the lack of experience, and 2) the uncertainty regarding the need to replenish the batteries with distilled water (which could be a major drawback for a hard-to-access-in-wintertime site such as the Watchman Lookout).

Mounting Structures for Solar Arrays

Many options exist for mounting solar panels to a roof or pole. Suppliers offer mounts that are stationary and ones that track the sun as it moves across the sky. Generally, the added energy from tracking and the added expense for the mount are not justified unless the system is sufficiently large. Tracking mounts are only cost effective if there are four or more modules in the array.

Mounting a solar array is relatively straightforward. If the module is to be mounted at the angle of pitch for the roof, then the mount is simply a frame used to secure the modules and create an appropriate airflow for cooling. If the module is to be tilted at some angle other than the roof pitch, the mount becomes somewhat more complicated. Most tilting roof mounts allow for 10-degree increments of adjustment. If the optimum angle is not available from the preset options, a simple hole drilled in the frame will allow for any angle to be acquired.

Most photo-voltaic systems with passive tracking use two set points so they only have to adjust the array two times per year. One set point is the ideal angle for summer sun acquisition. The other set point is for optimal setting of winter sun angle. Many times a few bolts can be used to adjust from one set point to another, but if the array is in a difficult place to access an automatic adjustment is handy. NorthWest Energy Storage in Colburn, Idaho claims to be the only company that offers a motorized roof mount. The cost for the roof mount with three panels would be approximately US$465, which includes the remote switch for operation. Energy required for rising and lowering panels would be about 30amps for 2 minutes. On the other hand, the cost of materials for a manual mount would probably US$100-200.

As discussed earlier in the text, any mounting system would need to be able to withstand the winter weather conditions of Crater Lake National Park, and function well twice a year for many years. The manual mounting system would require work on the roof twice a year, especially if the raising and lowering are accomplished by inserted and removing structural members at the back of the a panel. Such a simple manual system should be weatherproof, if appropriate materials of construction are used.

Through discussions with the National Park Service, manual mounting has been selected as the preferred approach. A follow-on study is planned for the design of the rotatable manual mount.

COST OF NEW PHOTO-VOLTAIC SYSTEM FOR THE WATCHMAN LOOKOUT

The estimated cost of the new photo-voltaic system for the Watchman Lookout is given in the table below:

Table 6. Estimated Cost for New Photo-voltaic System

	Type	Qty.	Cost (each)	Cost (total)
PV Panels	BP590	3	$520	$1560
Battery Cells	KCPSA-7	6	$250	$1500
Battery Rack	3 ft. Tier	1	$275	$275
Shipping	N/A	N/A	$400	$400
Controller	Trace C-40	1	$175	$175
Meter (optional)	Trace DVM	1	$90	$90
Mount (manual)	Custom	1	TBD	TBD
Miscellaneous	N/A	N/A	$250	$250
			TOTAL (w/o mount)	$4250

The system cost shown above is an estimate based on quotes from manufacturers at the time of writing of this report. The total is subject to change based on the metering option and the mounting structure designed. The current price for the meter assumes the simplest situation.

Listing of manufacturers and discussion of products are used for purposes of reviewing the technology available, developed the general system components, and estimating the cost of the system. Product endorsement is not intended in this report.

References

C&D Technologies, Personal communication, 1998.

Crawford, Greg, Personal communication, Oregon State University, 1998.

Dunstan, Joe, Personal communication, Columbia Cascades Office, Seattle, National Park Center, 1998.

Kossen, Mel, Personal communication, Olympic National Park, National Park Service, 1998.

Kreith and Kreider, *Principles of Solar Engineering*, Hemisphere Publishing Corporation, New York, 1978.

Todd, Ray, Personal communication, Denver Center, National Park Service, 1998 (including reference to text by McClelland, Linda, *Building the National Parks: Historic Landscape Design and Construction*, 1998*).*

Web sites referenced:

rredc.nrel.gov

www.neqsinet.net/~midway

www.ovonic.com/unisolar.html

www.nrel.gov

www.solar.pv.com