EARLY PERFORMANCE FOR THE ROOF-MOUNTED, 20-kW THIN FILM CdTe PV-ARRAY AT JASPER RIDGE

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ABSTRACT

Here we report early performance for the grid-connected, 20-kW CdTe PV array installed on the roof of the Leslie Shao-ming Sun Field Station at the Jasper Ridge Biological Preserve. The array was installed in May 2002. Data are reported for 20-mos beginning April 2003.

The array originally consisted of 275, BP Solar 80W thin-film CdTe modules arranged in 11-module strings. The monitoring system logged data from 9 sensors on 1-min intervals. Monitoring showed problems with maximum power tracking associated with module degradation, elevated module temperatures, and the finite voltage window of the 208VAC-3p inverter.

The problems were addressed in May 2004 by re-wiring the array and reprogramming the inverter, resulting in a 20% increase in energy production.

Introduction

The *Leslie Shao-ming Sun Field Station* is a 9,800 sf single-story green building that supports the teaching and research activities of the *Jasper Ridge Biological Preserve*. Completed in 2002, it is Stanford University's first modern green building [1]. The *Sun Field Station* is designed to embody the values of the *Preserve* by minimizing its environmental footprint through energy efficiency, reliance on renewable energy, and reduced material waste. A detailed description of the building may be found elsewhere [2].

Among the building's green features is a 20-kW, roof-mounted, cadmium-telluride (CdTe) thin-film photovoltaic (PV) array for generating much of its electric energy. The array is installed on the north part of the "V-style" roof structure as shown in Figure 1. The grid-connected array was installed in May 2002, though its performance went largely unmonitored until a building energy-monitoring system became operational in April 2003 [3]. The monitoring system has yielded nearly 20 months of performance data making this one of the first CdTe arrays in operation for which such detailed data are available.

Fig. 1 Photograph of the roof of the west wing of the Sun Field Station. The roof has an inverted geometry with a single central valley for water collection. PV modules are installed on the north part of the roof.

Array Description

In its initial configuration the array consisted of 275, BP Solar TF-80B, thin-film CdTe modules arranged in 25, 11-module strings. The 61.0 in x 24.0 in modules had an initial power rating of 80 W (at 25°C, AM1.5 illumination) and a 20-year warranteed power rating of 75 W. All modules were mounted with a 14º tilt from horizontal, matching the roof pitch. The 14 strings on the west wing of the building face due south. The 11 strings mounted on the east wing of the building are rotated 12º to the west owing to the orientation of the building (see Figure 2). Strings are wired in parallel to form three sub-arrays (west, middle, and east) whose direct currents are individually monitored before the sub-arrays are connected in parallel at the *Trace/Xantrex* model PV-20208, 20-kW inverter. The 3-p, 208VAC inverter output is connected to the grid via a *Square-D*, 20 kW isolation transformer.

An energy monitoring system was installed in the *Leslie Shao-ming Sun Field Station* in April 2003. Built around a *Campbell Scientific, Inc.* (CSI) model cr23x logger, the system records average readings from 14 sensors on 1-minute intervals to a database for subsequent retrieval and analysis. It also posts real-time and summary performance data on the world-wide-web at http://jr-solar.stanford.edu. Details of the monitoring system may be found elsewhere [3]. This monitoring system has been crucial for identifying and correcting performance problems and has greatly enhanced the educational value of the PV Array.

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Nine of the 14 sensors characterize PV array performance. These include three, *Empro* MLA-20-200 current shunts for monitoring sub-array currents I_1, I_2, and I_3, a 100-to-1 voltage divider for monitoring array voltage V_{dc}, and an *Ohio Semitronics, Inc*. GW5, bi-directional AC power transducer for measuring power in and out of the PV isolation transformer. Incident solar radiation for each of the two module orientations is monitored with a CSI model CM3 thermopile-type pyranometer. We opted for the thermopile sensors over the cheaper Si photodiodes due to concerns about the spectral response of the CdTe modules [4]. Module temperature for each orientation is measured with a CSI Type 107 thermistor sensor attached with conducting epoxy to the back of a PV module.

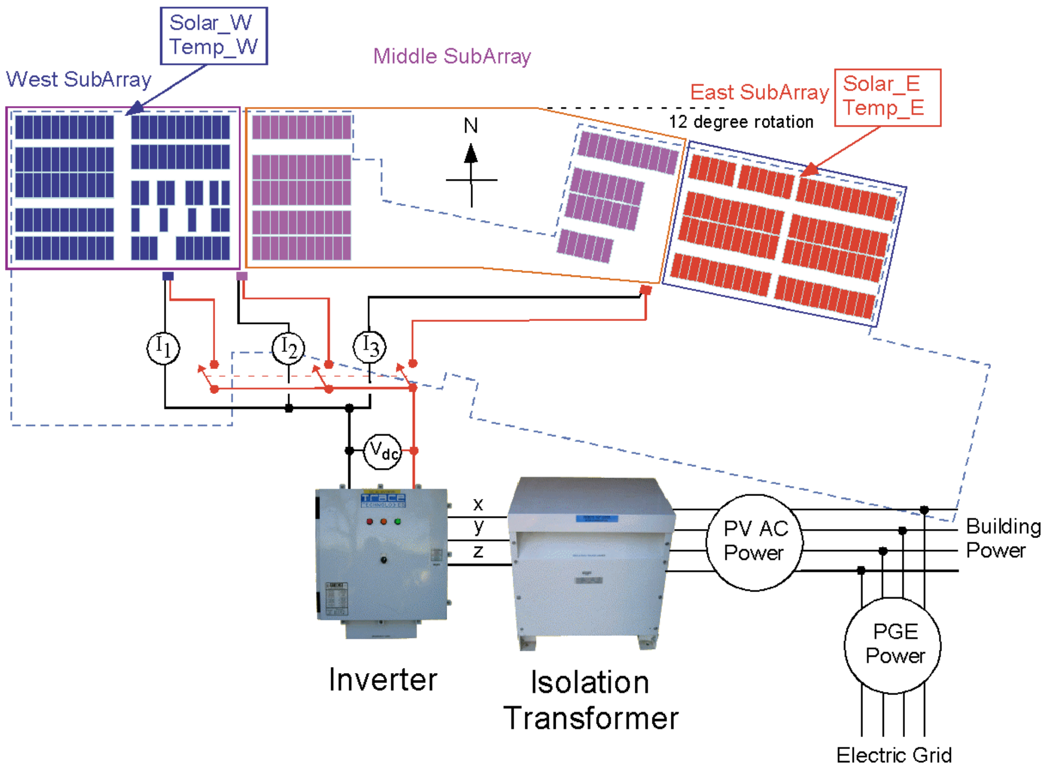

Fig 2. Initial configuration of the 275 modules, wired in three sub-arrays.

Performance Data

The first year monitored energy production for the PV Array is shown in Figure 3. The solid bars show the measured production while the hatched bars show the "projected" production using the web-based *PVWatts* [5] calculator for a 20kW planar south-facing array in San Francisco with a 14° tilt. The array actually produced 23,500 kWh of energy for the 12 months shown – just 2/3 of the 35,000 kWh projected by PVWatts. This corresponds to a 1.067 kWh/W_p ratio of the annual energy produced to the installed peak power.

The disappointing performance turned out to be due to a system problem in that the inverter was not able to track the maximum power point for the array. As shipped, the inverter had a voltage operating-window from 330V to 600V. When installed (Spring 2002) the maximum power point for the array presumably fell in the lower portion of this voltage window. But the modules apparently suffered some voltage degradation during the first year of operation. Since the monitoring began in April 2003 the maximum power point for the array apparently fell below the inverter's 330 V minimum. Hence, rather than operating the array at its maximum power point (something like 280 V) the inverter mostly held the array at its minimum allowed voltage of 330 V.

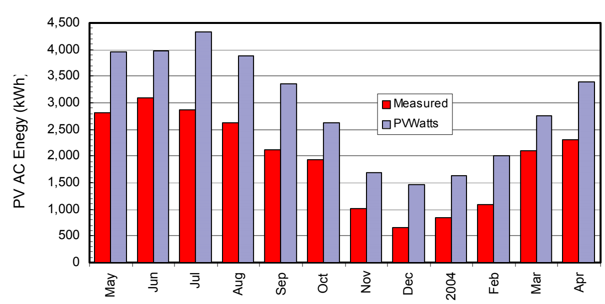

Fig 3. Monthly measured (solid) and projected (hatched) energy production for the 20-kW PV array for the first year of monitoring.

The problem is illustrated in a graph of performance data for June 16, 2003 (Figure 4). The incident solar radiation (insolation) represented by the average of the two pyranometer readings, shows the expected "bell-shaped" curve, peaking at solar noon just below 1000 W/m^2. The

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AC power produced by the system (PVAC), expected to track the insolation, instead shows a flattening near solar noon, saturating at about 12 kW, significantly below the peak rating of the array. The horizontal line represents the array voltage, V_{dc}, that is simply held constant at 330V during most of the day.

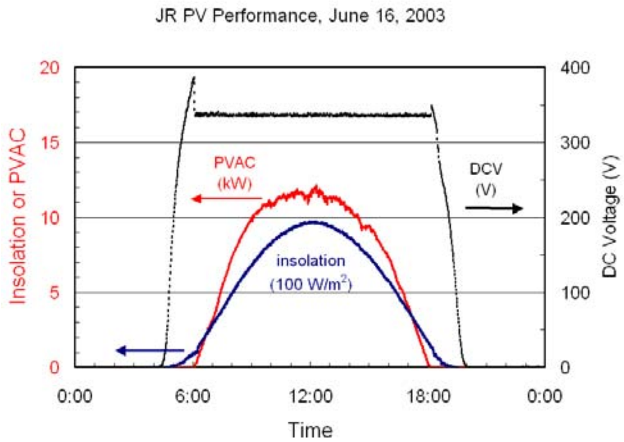

Fig 4. Graphs for June 16, 2003 of the (a) incident solar radiation (insolation), (b) AC Power produced by the PV system, and (c) PV array DC voltage.

This problem was addressed in May 2004 by making two changes: 1) adding 25 modules to the array to increasing string size from 11 to 12 modules, and 2) reprogramming the inverter to lower the minimum voltage to 300 V. These two changes have resulted in roughly a 30% increase in array power – about a third of the improvement due to the increased number of modules and two-thirds due to improved power tracking.

The resulting array performance for June 15, 2004 is shown in Figure 5. Here we see the power (PVAC) peaking at 17 kW without the flattening near solar noon experienced earlier. Also notice that the array voltage varies during the day as the inverter tracks the maximum power point.

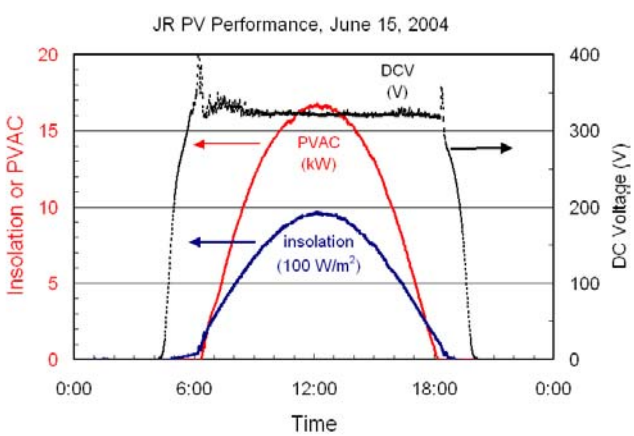

Fig 5. Graphs for June 15, 2004 of the (a) incident solar radiation (insolation), (b) AC Power produced by the PV system, and (c) PV array DC voltage.

A useful way to think about system performance is to examine the ratio of the measured AC power generated to the projected DC power from the array, calculated from the module specifications combined with measured incident solar radiation and module temperature [6]. The "before" and "after" system efficiency curves are graphed in Figure 6. The graph clearly shows the improvement in system performance associated with improved power tracking. After changes the system efficiency is close to 85% for most of the day.

A variety of factors cause this system efficiency to be reduced from the ideal 100%; these include dirt accumulated on the modules, inverter and transformer losses, wiring losses, and module performance degradation. As yet we have not investigated the relative importance of these factors and, instead, have focused on the maximum power tracking problem.

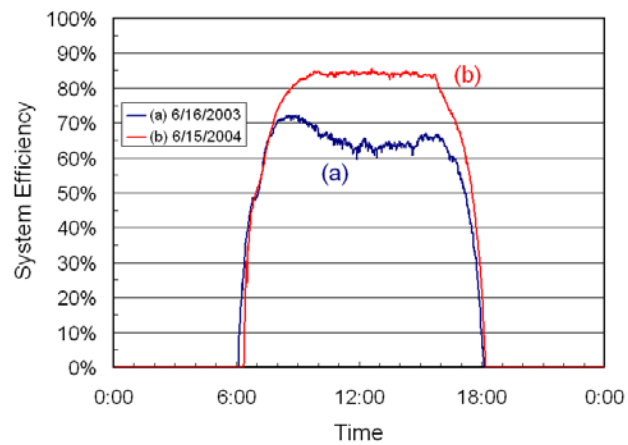

Fig 6. Graphs of system efficiency (see definition in text) for (a) for the initial array configuration (June 16, 2003), and (b) following the changes (June 15, 2004). At solar noon the re-configured array has 85% system efficiency as compared with 63% for the initial array configuration.

Since the array was reconfigured we have six months of performance data that may be directly compared with performance before the changes. Figure 7 shows

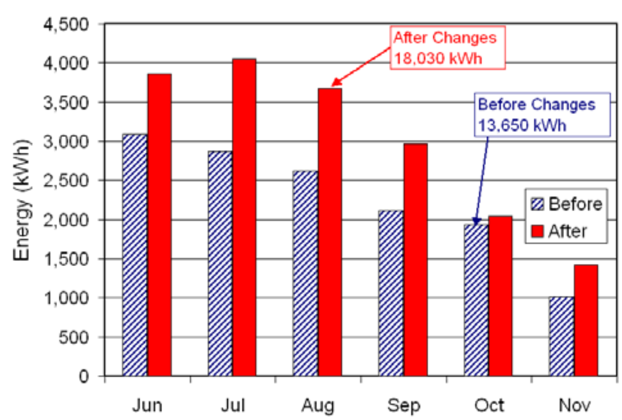

Fig 7. Energy generated by the PV Array for six month period before (solid) and after system reconfiguration.

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monthly energy generated by the PV system for six months (June through November) before (2003) and after (2004) system changes. As the graph clearly shows, the addition of 25 new modules (9%) resulted in a 32% improvement. (hatched). Increasing string size from 11 to 12 modules (adding 25 modules) resulted in 32% increased output.

Discussion

On the surface it would appear that the array was poorly designed – that the string size should have been 12 or even 13 modules. In fact the problem is more complex and related to the National Electric Code (NEC), the temperature coefficient for V_{oc} for these modules, voltage loss during early module operation, and the current state of inverter technology. These issues need to be addressed for wide-spread commercialization of thin-film CdTe and CIS thin film PV arrays.

Initial specifications for these CdTe modules have the open circuit voltage (V_{OC}) as 45.2V (at 20ºC), the voltage temperature coefficient as -150 mV/ºC, and a voltage (V_{MP}) at maximum power as 32.3 V (AM1.5, 20ºC). Responding to NEC requirements manufacturers list 600V as the maximum voltage for all system components. Initial V_{OC} for a 12-module string will exceed 600 V for temperatures below -12 ºC (10 ºF). A conservative array designer then chooses 11-module strings so as to avoid the 600V threshold.

But on hot days under intense illumination measured module temperatures have exceeded 65ºC! V_{MP} for an 11-module string at 65ºC is predicted to be 281V, well below the 330V minimum operating voltage for the standard Trace/Xantrex 208VAC-3p inverter. Inverters can certainly be designed otherwise, but the standard inverter, optimized for crystalline Si, does not have the necessary voltage range for modules with such a large voltage temperature coefficient. The problem is exacerbated by the fact that these modules have experienced some voltage loss during their first months of operation – a common problem with thin-film PV technologies.

This effect is the origin of the 2003 depression in system efficiency near solar noon shown in Figure 6. As modules heat up, V_{MP} drops further below the 330V inverter minimum. Late in the afternoon the modules cool and the power tracking problem is reduced as V_{MP} rises again, closer to the 330V minimum.

We do not know how widespread this problem is – relatively little has been written regarding field performance of CIS or CdTe, grid-connected, thin-film PV arrays. We do note, however, that the voltage temperature coefficient for CIS modules has been measured to be even higher than for these CdTe modules [6].

Our experience highlights the value of a performance monitoring system. Prior to the installation of the monitoring system, the only feedback for PV Array performance was the reduced monthly electric bill and the pleasure of witnessing the (mechanical) building electric meter run backwards on sunny days. But these measures are insufficient to determine array performance. Within weeks of installing the energy monitoring system it was obvious that array performance was not optimal, though it took more time to diagnose the cause.

Unfortunately performance monitoring frequently receives low priority and is not included in initial project funding. This practice is spurred by the fact that government tax credits for PV systems do not cover the performance monitoring system. Ironically, the added value of the performance monitoring system far exceeds the marginal benefit of spending the same money on additional PV modules! It is our recommendation that performance monitoring be included up front as a critical component for any PV power system.

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References

[1] Today's green buildings are not so much recent inventions as much as a rediscovery of the past. Buildings in Stanford's main quad, built in 1891, contained extensive thermal mass, natural ventilation (including arcades) operable windows, contained no VOCs, and made extensive use of local materials. Unfortunately many were badly damaged in the 1906 earthquake.

[2] Alex Wilson, "Green building: a natural for this biological preserve," *Solar Today*, Sep/Oct 2003, pp.60-63. Also see http://jasper1.stanford.edu/home/fieldstation.html.

[3] John H. Scofield, Philippe S. Cohen, Cary Tronson, and Scott Gould, "Real-time, web based energy monitoring system for a solar academic building ," *Solar 2004 Conference Proceedings*, Portland, OR., July 11-14, 2004 (in press).

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[5] http://rredc.nrel.gov/solar/codes_algs/PVWATTS/.

[6] K. Emery, et al., "Temperature dependence of photovoltaic cells, modules, and systems," *25th IEEE PVSC*, 1996, 1275-1278.

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