

PERFORMANCE ANALYSIS OF LARGE SCALE, AMORPHOUS SILICON PHOTOVOLTAIC POWER SYSTEMS

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ABSTRACT

With the benefit of two years of data from the largest Uni-Solar Triple-Junction Amorphous Silicon, Photovoltaic Power system currently operating near Bakersfield, CA, this paper provides an in-depth analysis of "real world" performance for this technology. This 500 kW (ac) system has been consistently performing, meeting or exceeding its design goals. The performance data from this large-scale installation affirms and validates similar data that have been gathered over time from smaller systems and proves that this thin film PV technology can be successfully used in power generating plants on this scale, with consistent performance.

Introduction

Solar panels using triple-junction amorphous silicon alloy technology are now being widely used for grid-tied power applications. In December of 2002, Uni-Solar commissioned a 500kWAC, ground-mounted, photovoltaic power system. This large-scale PV power plant was designed to provide a renewable energy power source to help provide electrical power for pumping oil in the ChevronTexaco Midway Sunset Field in Fellows, CA. The system was equipped with data acquisition equipment that allows both ChevronTexaco and Uni-Solar to monitor the performance of the system. The economics of the project are contingent on a certain level of energy being supplied to the facility from the 500kWAC system. Based on observations over the last two years, it has been confirmed that the energy delivered by this system is equal to or greater than the designed requirements. Although originally rated at 490kWAC, the power output has consistently been at least 5% to 10% higher.

The energy (kWhr) delivered has been at or above expectations due primarily to the superior performance of triple-junction products in diffused or lower intensity light level and at high temperature as well as their inherent tolerance to shadows and soiling. The ChevronTexaco PV power system (named "Solarmine") has been delivering upwards of 1,000,000kWhr per year.

This paper describes the photovoltaic properties of this amorphous silicon technology and how it benefits the performance of larger scale systems. The paper includes a description of the installed system, the basis for the system design and system architecture, and an analysis of the performance data.

Performance of the Triple Junction Thin Film Technology

United Solar Ovonic, LLC, over the past 20 years, has developed and refined a thin-film technology that is quite unique in several aspects. Probably the most significant step in this development is the 1997 introduction of the Triple Junction product that provides relatively high levels of efficiency and stability (stabilized aperture area cell efficiency of 8.0-8.5 %). [1] Each cell in the triple junction layer is composed of three semiconductor layers deposited on a 5 mil-thick sheet of stainless steel. The bottom cell absorbs the red light, the middle cell the green/yellow light and the top cell absorbs the blue light. The resulting thin film photovoltaic product has the ability to capture a greater percentage of the incident light energy which is one of the keys to higher efficiencies and higher energy output, especially at lower irradiation levels and under diffused light. [1] The unique roll-to-roll process, developed to produce the Uni-Solar Triple Junction cells, incorporates a patented deposition process that uses less than 1/300th of the amount of silicon material normally used in the production of standard crystalline silicon solar cells. The result is a flexible, light-weight solar cell. Once the solar cell material has been provided with suitable electrodes, the cells are encapsulated in UV-stabilized, weather-defying polymers. This laminating process incorporates EVA and the fluoropolymer TEFZEL[®] (a DuPont film) on the top (sunny) side. The bottom side of the finished product is a Polyester material suitable for adhesives. The inherent flexibility of the Uni-Solar Triple Junction Laminate as well as the durable encapsulate, results in a lightweight, photovoltaic module that has a broad range of applications. The module manufacturing and assembly processes allow bypass diodes to be connected across each cell. The bypass diodes maintain the series circuit, allowing the modules to produce power even when partially shaded or soiled.

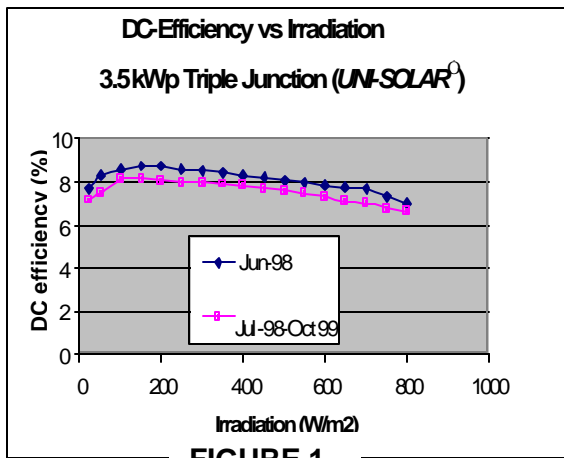


Figure 1 shows the field-test results that demonstrate the increase in cell DC efficiency as the light intensity is decreased. When this characteristic is translated into system performance, the result is greater delivered energy because even at the lower light levels, the Uni-Solar array produces enough power to “turn on” the inverter and feed power to the utility panel.

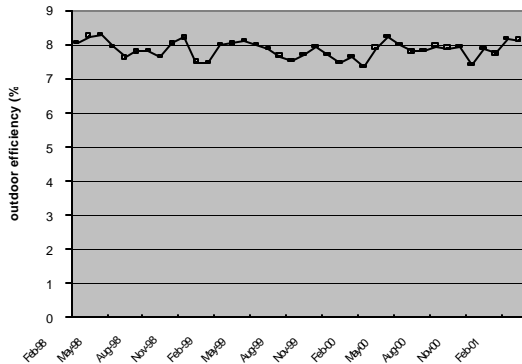


FIGURE 2 – Outdoor cell efficiency of a UNI-SOLAR[®] module measured by Forschungszentrum Jülich from February 1998 to February 2001. Data by courtesy of FZ Jülich

In Figure 2, which shows the three-year results of an outdoor cell efficiency test, small seasonal variations in conversion efficiency can be seen. This periodic variation is the result of two competing processes: a deterioration of the cell quality created by the Staebler-Wronski effect and the thermal annealing of those light-induced defects at higher temperatures. The impact of the Staebler-Wronski effect is greater during the colder winter months and the thermal annealing process is prevalent during the summer months. [3,4]

This brings up the measured performance characteristics of the Triple-Junction thin-film technology at “real-world” operating temperatures. All photovoltaic cells and modules are rated at STC (Standard Test Conditions). The STC in this case includes a cell temperature of 25°C (77°F), a light energy of 1,000W/m², and an air mass of 1.5. Each of these is a significant factor in the resulting performance of any photovoltaic module, regardless of technology. However, the cell operating temperature provides a technology-differentiating factor that helps explain the 10 to 20% higher energy output of the Triple-Junction thin-film over conventional crystalline PV products, when compared on a watt-to-watt basis.

The thermal coefficient for crystalline photovoltaic cells is a negative constant of approximately (neg.) 0.5% per °C while the thermal coefficient for Triple-Junction photovoltaic cells is on the order of (neg.) 0.21% per °C. [2] This means that at a normal cell temperature of 60°C, the relative power output of a crystalline module would be reduced by about 17% from the STC rating while the Triple Junction module output would be reduced by about 4 - 6%. The obvious effect of this characteristic is a higher level of energy output at normal to high cell temperatures. The February, 2003 NREL test report that updated the USSC PVUSA Power Rating Performance, documented the degradation, over time, of the Uni-Solar amorphous silicon PV arrays. One of the early concerns with amorphous silicon PV was the magnitude of the expected performance degradation. The results of the testing, shown below, verify less than 1% degradation. This is approximately the same as for crystalline silicon PV panels. [5] This is one of several well-documented tests that verify the long-term stability of this amorphous silicon photovoltaic technology.

USSC 1.8 kWp Array
PVUSA Power Rating vs Time (Irr >800 W/m² and P > 1500W)
 Plant installation March 1994, long term stability analysis started after 5 years of operation

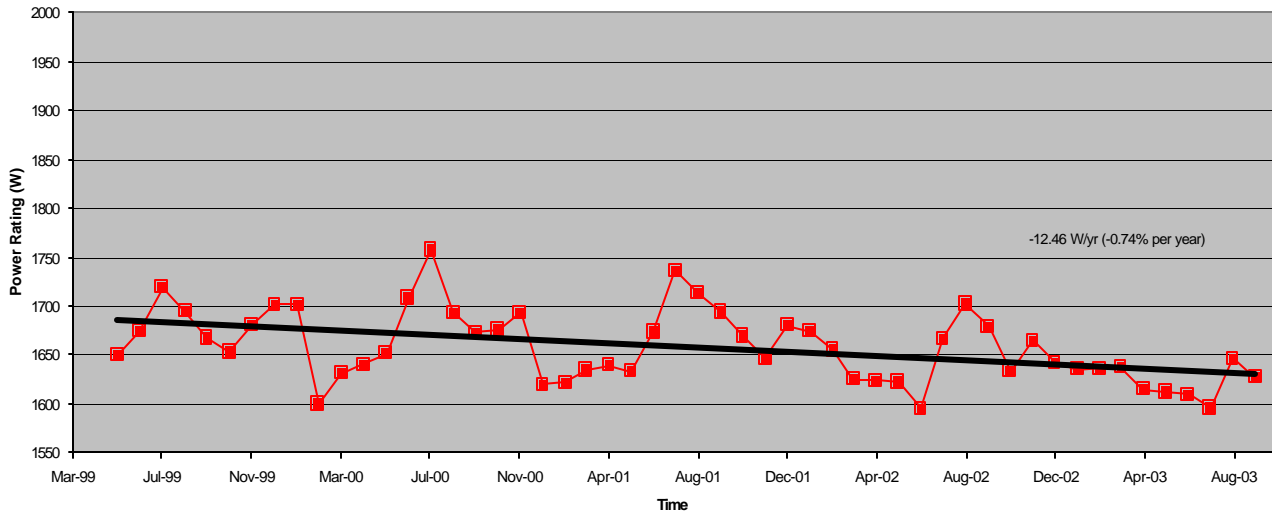


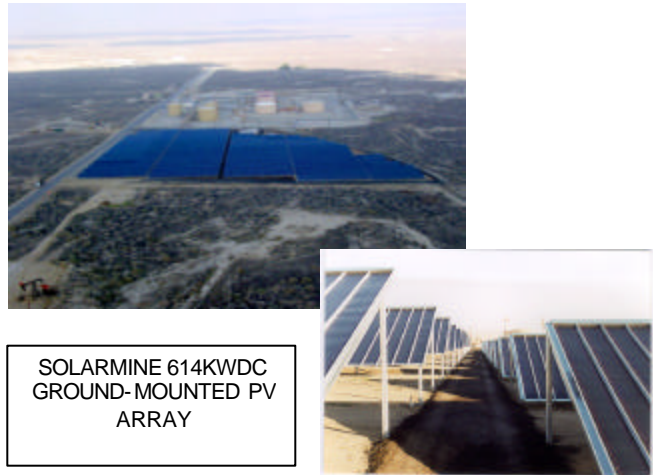
Figure 3: UNI-SOLAR 'Triple Junction'- Technology demonstrates a stabilized Efficiency with annual cyclic variation and an average degradation not higher than 0.74% (NREL Report) [5]

The measured performance of Uni-Solar Triple-Junction, amorphous silicon photovoltaic panels related to both cell temperature and low/diffused light has been noted by the California Energy Commission in their "CEC Rating" chart (www.energy.ca.gov). Comparing the STC rating of each type of PV panel, it can be seen that it actually takes a greater installed capacity of crystalline panels than Uni-Solar panels to generate the same amount of energy.

For example, a 140-watt (STC) BP crystalline PV panel has a CEC rating of 122.1, which is 13% lower than its nameplate rating. The Uni-Solar PVL-136 PV Laminate has an STC rating of 136W and a CEC rating of 130watts. This is only 4% lower than its STC rating. Expanding this quantification to a large PV array, and using the CEC rating as an energy production value, it would take a 10% larger crystalline array to equal the expected performance of a triple-junction amorphous silicon array.

Solarmine PV Array. The 614kW, ground-mounted PV array at "Solarmine" is constructed with Uni-Solar's Triple-Junction PV Laminate product (PVL-128) adhered to standing seam metal roofing pans secured to racks that hold the sub-arrays at a 20 degree slope. Each rack holds as many as seven strings of twelve PV Laminates, but some smaller racks were designed to hold as few as two twelve-panel strings. There are anywhere from 25 to 42 strings in eleven sub-arrays, wired to each of eleven combiner boxes. Electrically, there are twelve, 128W (STC) PV Laminates in each of 400 series strings for a total of 4,800 laminates and 614.4kW. The power from the combiner boxes feed two DC to AC, grid-tied inverters. The inverters have capacities of 225kW and 300kW

respectively and are connected to the utility grid through three-phase isolation transformers.



This system was conservatively designed using estimated losses normally seen with ground-mounted crystalline arrays. It was assumed that the end-to-end system losses would be on the order of 20% of the STC capacity. Therefore, the system integrator expected about 490kW AC from a 614kW DC array. However, the pair of inverters allows a total of at least a 525kW continuous output. The point of measurement for the delivered AC power is at the output side of the inverters. Power measurements taken at this point are affected by the inherent system losses including the following:

- Interconnection (wiring) losses (I^2R)
- PV string mismatch losses (PV panel strings have

slightly different Vmp voltages that when paralleled, incur some small power losses. These losses are very low with Amorphous Silicon in that the “knee” of the IV curve is very “soft”, allowing the operating voltage to vary without

affecting the net power output.)

- Inverter (conversion) losses
- Soiling losses (accumulation of dust on PV array)
- Thermal losses

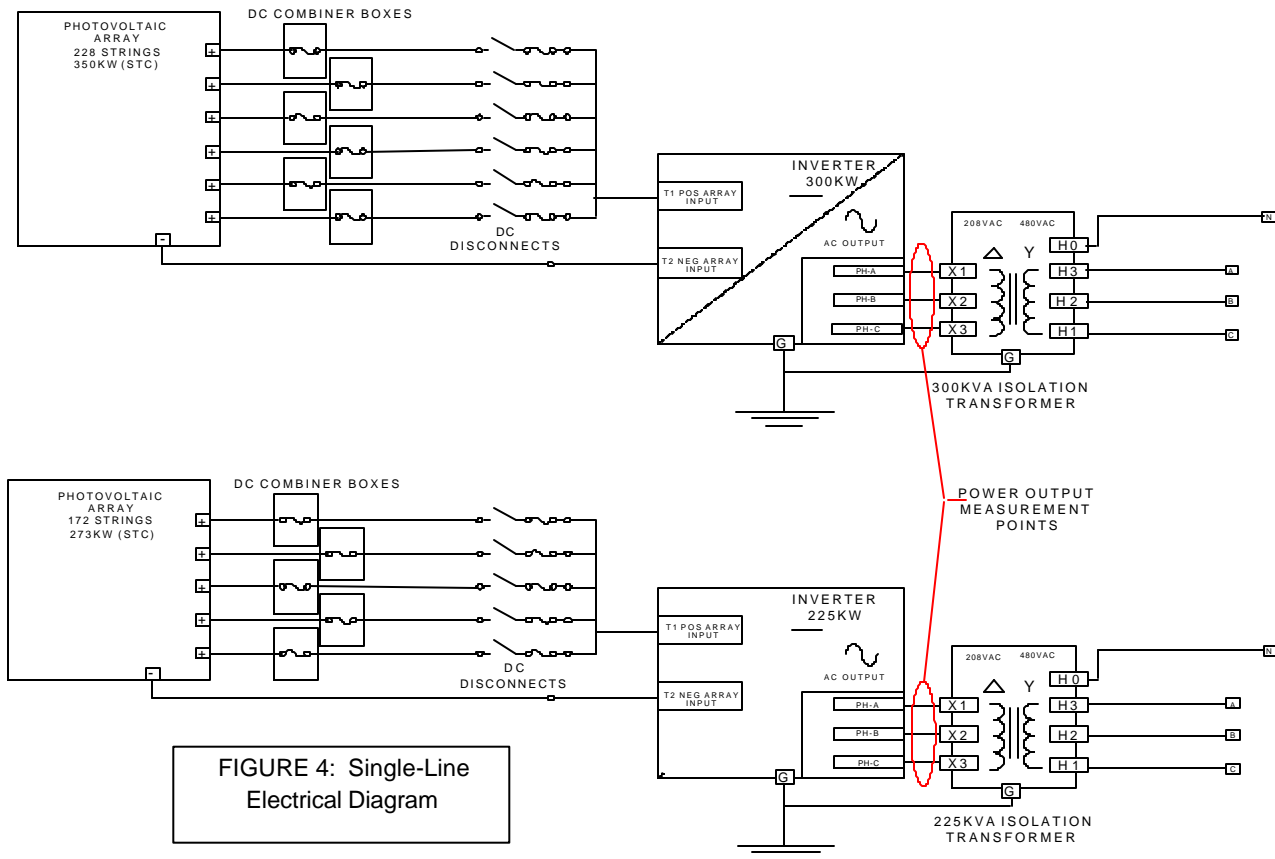


FIGURE 4: Single-Line Electrical Diagram

By taking the measurements at the output of the inverter, the resistive and magnetic losses from the downstream isolation transformer are not included. The expected power losses through a typical three-phase transformer are 2.5% to 3%. Total system losses in this case were initially estimated at 20%, so the expected delivered AC power was 491kW. However, as the actual performance charts show, the output has consistently been greater than 500kWAC.

Data has been collected from the Solarmine system since July of 2003 (ChevronTexaco DAS). There were some initial start-up adjustments and some periods of time when the inverters were down for servicing, but these interruptions were brief. The data displayed below shows the energy output for the total system on a monthly basis to illustrate the long-term trends. The electrical energy output is referenced against the available light energy for that same period. There were significant inverter problems during the months of April and May of 2004. This is evidenced by the much larger difference between the available light energy and the actual delivered electrical energy.

Solarmine Monthly Output KWH vs Solar Insolation

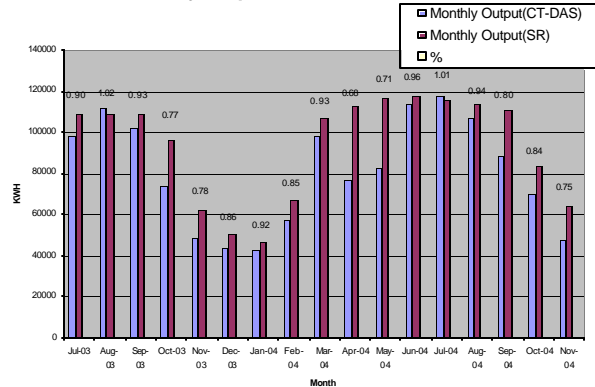
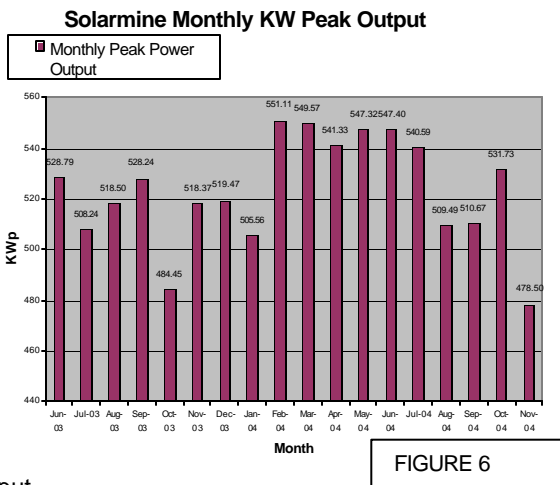


Figure 5 above shows the monthly energy production along side the average solar insolation (SR for solar radiation on the chart). It can be seen from Figure 5 that during the Summer months when the average monthly insolation is high, the array produces more kWh. A precise, mathematical correlation between the insolation

levels and the electrical energy produced could not be made, partly because there were occasions when some of the array strings were not operational. For example, since August of 2004, there have been from two to five strings (7.7kW) that are not contributing due to wiring malfunctions. Also, due to the dusty environment, there are periods where accumulated dust and dirt reduce the amount of light energy that can be absorbed by the PV Laminates. Rainfall and periodic cleanings restore the



output.

Although the Solarmine system was designed for a maximum AC output of 500kW and an estimated nominal AC output of 490kW (based on an estimate of 20% total, end-to-end system losses), Figure 6 shows that for all but two months, the peak power levels measured were greater than 500kWAC. For the months of February through July of 2004, the peak power was measured at over 540kWAC!

CONCLUSIONS

Under actual environmental conditions, the superior performance characteristics of the Uni-Solar Triple-Junction, Amorphous Silicon PV technology as been shown to have very consistent performance over time. Even in large-scale, ground-mounted PV array systems, the performance has been shown to be better than expected. The technology has the long-term stability and rugged durability to be a consistent, practical, energy-generating product.

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