

A “Real World” Examination of PV System Design and Performance

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ABSTRACT

There is no substitute for experience when it comes to designing a PV power system. Almost all system requirements are unique in some way and the ability to anticipate the on-site challenges and design the system accordingly can help ensure an optimum system performance. It's the system performance that is measured and noted by the system user, not the solar panel performance. Although the solar panel usually gets blamed when performance is less than expected, it is usually a system problem such as a poor choice of components, inefficient system architecture, poor installation techniques, or possibly, the wrong PV technology for the application. Especially for the larger PV systems, the key challenge is to design a system that matches the requirements, the environment, location and application, resulting in a high level of performance.

Introduction

This paper looks at several PV systems, including some in Europe and the US, and examines the completed projects including performance data. Certain sites, such as one installed at a business park in Santa Cruz, CA, have detailed performance data for both thin film and crystalline PV technology, collected over a full year.

A couple of energy-predicting models with associated key parameters are examined, along with the variables that can significantly affect the energy output predictions. This presentation compares some predicted performance data with actual system performance data followed by some observations as to the reasons for any differences.

Key System Design Parameters

Tilt angle. The best tilt angle for any PV array is the one that produces the highest annual energy output for that particular location. The primary reference point is the latitude but other factors are involved as well. The arc of the sun varies with time of year so, typically, the shallow tilt angles produce more energy in the summer months while the steeper angles produce more energy in the winter months. The best, fixed angle is the compromise between the extremes that allows for the greatest delivered energy on an annualized basis. Tilt angle is especially important with crystalline PV technology, which is much more sensitive to the angle of the incident light as well as dust and dirt accumulations than Amorphous silicon PV. The system performance data shown later in this paper demonstrates that fact.

Azimuth. Azimuth, or deviation from True South, has a similar impact on energy production as with tilt angle. Optimum performance is typically obtained with the tilted array aligned with True South. Deviations from True South skew the peak output curves in the direction of the deviation (East or West of True South). Generally, the steeper the tilt angle, the greater the effect that the deviation from true South has on the annual energy output. Again, this is especially true for crystalline PV which is much more sensitive to the direction of the incident light. [3]

For sloped roof-mounted PV systems, both tilt angle and azimuth are dictated by the slope of the roof and the orientation of the building. The greater the difference between the optimum tilt angle and the slope of the roof, the greater the effect on the system performance. This is also true for azimuth, but the impact is usually less, in that it typically moves the peak energy output curve in time, more than it reduces it.

Cell temperature. The power rating criteria for all PV panels are the same; the standard test conditions (STC) of 1,000 watts per square meter, an air density of 1.5, and a cell temperature of 25°C. Under actual conditions, these three values almost never occur simultaneously. Therefore, systems need to be designed based on expected conditions at the site. Thermal coefficients for the various PV technologies vary considerably. The thermal coefficient for mono-crystalline PV cells is about -0.5% per degree C, while the thermal coefficient for Uni-Solar's Triple-Junction Amorphous Silicon is about -0.21% over the expected operating temperatures (it is a non-linear function). [3,4,5]

At the expected 50°C to 60°C cell temperatures during normal operation, the thermal de-rating would be as stated mathematically below:

$$\begin{aligned}60^{\circ}\text{C} - 25^{\circ}\text{C} &= 35^{\circ}\text{C} \\(35^{\circ}\text{C} \times -.5\%/^{\circ}\text{C}) &= -17.5\% \text{ for crystalline} \\(35^{\circ}\text{C} \times -.21\%/^{\circ}\text{C}) &= -7.35\% \text{ for Amorphous}\end{aligned}$$

Therefore, in relatively warm climates, where 60°C cell temperatures are expected, the PV panel power output must be de-rated accordingly. A 100kW (STC) Triple-Junction, amorphous silicon PV array would be rated at 92.65kW and a 100kW (STC) crystalline silicon PV array would be rated at 82.5kW, under the actual site conditions.

Array soiling or shading. When selecting the roof area for the photovoltaic array, efforts should always be

made to avoid shading or areas known for accumulation of substances that will result in cell shading (soiling). Any material or object that reduces the amount of solar energy that falls on the PV panel will cause a reduction in energy output of that panel. However, due to the design of the individual solar panels, a small amount of soiling or shading can cause a huge decrease in array capacity. This is true primarily for crystalline PV panels in that the output of the normal 36 cell series strings that make up the panel will be reduced to near zero if two cells are "hard shaded" (this would usually be one cell in each series string). The Uni-Solar Triple-Junction PV panels are made with fewer cells (since the amorphous silicon cells are over eight times the area of crystalline cells) and each cell is protected by a bypass diode. The hard shading of any two cells will only reduce a 22-cell Uni-Solar panel output by 9%.

Potential damage to PV panels. Any system installation has to deal with potential damage to the photovoltaic panels during the installation process. Even a small crack in the glass cover will eventually destroy a crystalline PV panel. This can restrict access to the roof area, especially of the crystalline panels are mounted horizontally. Due to the flexible, damage-tolerant nature of the Uni-Solar thin-film PV Laminates, there are far fewer chances for the kind of damage that would require replacement. Once applied to the roofing material, the PV Laminate can be walked on so there is almost no access restriction to the roof areas.

Balance of System Components and System Architecture. The photovoltaic array is only one component of the PV system. The PV panel performance can be either positively or negatively impacted by the balance of system (BOS) design and component selection. All the factors listed below will have a profound effect on the performance of any PV system, regardless of technology.

Selection of System DC voltage. The factors that impact the selection of the system voltage are primarily the input DC voltage range for the inverter, and the desire to minimize wiring losses by keeping the system voltages as high as is practical (within NEC and UL limits). Most of the grid-tied PV systems designed today use nominal DC voltages of 300 to 500VDC.

Array or PV Panel Voltage Mismatch. When PV panels are connected in series to achieve the desired system operating voltage, and the series strings are paralleled to achieve higher system currents, the resulting system voltage is usually an "average" of the individual Vmp ratings of the individual panels. The difference between the new system voltage that is created when the panels and sub-arrays are connected and the Vmp of the individual panels is the "mismatch". As the operating point is moved away from the Vmp, the power output of each affected panel is reduced by some amount.

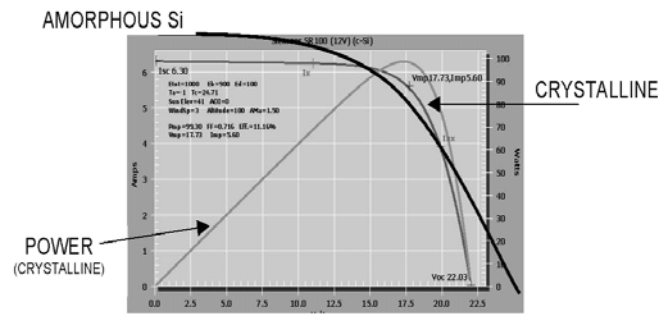


Figure 1 Example PV Panel I-V Curves

The "sharper" the "knee" of the I-V curve of the panel, the greater the effect of moving the Vmp. For example, if the operating voltage is lower than the Vmp, and the current does not change proportionately, the actual power output of the panel will be lower than its rated power. If the I-V curve has a "soft" knee, where the current is increased more significantly as the operating voltage is decreased, there will be less impact on the PV panel power output. The "soft" knee I-V curve is a characteristic of Amorphous Silicon PV panels while the crystalline panels have a "sharp" knee in the I-V curve. Consequently, the percentage allowed for array mismatch losses will be less with Amorphous Silicon arrays than with crystalline.

Wire sizing. The wiring of a PV power system should be specified based on minimizing I^2R losses rather than on ampacity. The "round-trip" wire length needs to be factored against the expected currents to choose a wire size that limits the voltage drop to less than 3%. Systems are sometimes designed correctly but with wire sized for ampacity instead of for minimal line losses. This is acceptable for identifying the smallest diameter wire that can be safely used but it is not acceptable for creating an efficient system. The result is a system with an end-to-end system efficiency that can be as low as 65%.

Inverter selection. The system efficiency is significantly impacted by the inverter efficiency. The inverter losses usually account for at least 6% to 10% of the system losses. In three-phase systems, the isolation transformer that accompanies the inverter adds a loss of 2.5% to 3% over the inverter losses. This can be reduced to 1.5% to 2% by using a high efficiency transformer (more windings) but they are more expensive than the standard type. Inverters that incorporate contactors in the secondary winding circuit further reduce losses by disconnecting from the AC line when the inverter shuts down. This effectively removes the nighttime load otherwise created by the secondary winding of the isolation transformer. Often times, this "parasitic" load will drain a measurable portion of the power that the PV system delivered during the day.

System Performance Measurements

Key system performance parameters:

- Insolation level (W/m^2) or (Whr/m^2)
- Cell Temperature
- Array DC current and voltage
- Inverter AC output current and voltage
- Power delivered to AC line
- Energy delivered to AC line

From these measurements, the following quantities can be derived:

- Energy conversion efficiency
- System efficiency
- Inverter efficiency
- PV Array performance under specific site conditions

Predicting PV System Performance

There appears to be no “standard” way of predicting system performance. Assumptions are made regarding the previously listed factors and some algorithms are developed to calculate the expected energy production referenced to regional weather trends. The accuracy of the generally used methods is dependent on the specification of several variables. These include the following:

- Weather data (solar insolation levels)
- Factors for expected soiling
- Factors for expected shading (trees, adjacent structures, installation hardware)
- Performance characteristics of photovoltaic technology used
- Tilt angle and azimuth
- Seasonal snow cover
- Ground reflectance (primarily for rack-mounted systems)
- Array mismatch
- Inverter efficiency
- Distribution losses

The key to the proper use of any modeling tool is a good understanding of the PV technology, how it performs under a range of conditions, and how each of the factors affects the particular system in the particular location. There is no “plug and play” model where you can enter a couple of values and get an accurate prediction. It is better to use the “rule of thumb” to get a rough estimate before getting into a detailed performance analysis. The “rule of thumb” in this case, is just multiplying the installed AC capacity in watts by the “peak-sun-hour” factor for that region and then multiplying that number by 365 days to arrive at an annual electrical energy production estimate.

Example: A 30kWAC system in Sacramento, California has a 34kWDC PV array mounted at a 30° slope, facing south. The peak-sun-hour factor is 5.5. The simple math is $30kWAC \times 5.5hrs/day \times 365days/year = 60,225kWhr/year$. A computerized modeling tool for this 30kW system predicts 52,778kWhr/yr. The Clean Power Estimator™ [2] for that same system gives 53,827kWhr/yr. A proprietary modeling tool comes up with 58,189kWhr/yr. All of these predictions deal with

the variables differently and consequently, produce different results. The intent here isn't to identify the “best” means of estimating energy output, but to show that there are several methods used. The variables, mainly the weather, are predicable in their unpredictability, so the predictions can only be estimates or “best guesses” based on historical data and data from similar systems.

If we look at some systems that are described later in this paper, a comparison can be made using the actual measured performance data against some prediction estimates. One of the things that is illustrated by actual test data compared to predicted performance based on measured incident light energy is that the PV panels perform differently than light energy meters. The following is a list of typical input parameters used in various modeling tools:

Location: Santa Cruz, CA
Tilt Angle: 0° and 30°
Array DC Capacity: 2.5kW
Inverter efficiency: 94%
Shading factor: 0
Soiling factor: 3%
Distribution losses: 1%
Array mismatch: 2%
Wiring Losses: 3%
Thermal Coefficient: $-.21\%/^{\circ}C$ (Amorphous Silicon) & $-.5\%/^{\circ}C$ (Crystalline)
Seasonal snow cover: 0%

Rule-of-thumb, peak sun-hour method = $2.2kWAC \times 5.2hrs/day \times 365days/year = 4,175kWhr/yr$

The list below compares the “rough estimate” to some modeling results:

- Rule-of-Thumb = 4,175kWhr/yr (at a 30° Tilt Angle)
- Modeling tool with NREL data = 4,118kWhr/yr (at a 30° Tilt Angle)
- Clean Power Estimator™ [2] = 4,082kWhr/yr (at a 30° Tilt Angle)
- Proprietary Modeling tool = 4,205kWhr/yr (at a 30° Tilt Angle)
- Proprietary Modeling tool = 3,570kWhr/yr (at a 0° Tilt Angle)

PV System Examples

To illustrate the “real world” PV system performance characteristics, this paper looks at various systems that have been operating for an extended period of time. Examined first is the data collected from some European systems. Each of these functioning systems incorporate a different manufacturer's PV panels connected in 2kWp to 10kWp arrays. Table 1 below compares the performance of several roof-mounted systems based on kWh/kWp.

| Roof# | Module Type | # Module | kWp | AC-Energy Yield (kWh/kWp) | Technology |
|----------|-------------------|-----------|--------------|---------------------------|---------------------------|
| 1 | Total TE1206 | 24 | 2.88 | 706.5 | mono |
| 2 | Photowatt PW1000 | 24 | 2.4 | 694 | poly |
| 3 | Total TE1206 | 24 | 2.88 | 649.6 | mono |
| 4 | BP Solarex MST-43 | 55 | 2.75 | 795.6 | Tandem-Junction-Thin-Film |
| 5 | US-64 | 44 | 2.816 | 845.5 | Triple-Junction-Thin-film |
| 6 | Total TE1206 | 24 | 2.88 | 729.9 | mono |
| 7 | Total TE1206 | 24 | 2.88 | 688.2 | mono |
| 8 | Photowatt PW1000 | 24 | 2.4 | 652.1 | poli |
| 9 | Photowatt PW1000 | 24 | 2.4 | 685 | poli |
| 10 | Total TE1206 | 24 | 2.88 | 698.5 | mono |
| 11 | Photowatt PW1000 | 24 | 2.88 | 678.3 | poli |
| 12 | Total TE1206 | 24 | 2.88 | 692.9 | mono |
| 13 | Photowatt PW1000 | 24 | 2.4 | 643.6 | poli |

Table 1 These 13 Systems, located in Germany, were commissioned in December, 2002 time frame with measurements taken at least one year after installation.

| Location | Module Type | Inverter | kWp | Inclination | Azimuth | AC-Energy Yield (kWh/kWp) |
|---------------|-----------------------|----------------------|------|-------------|---------|---------------------------|
| Burg | UNI-SOLAR® US-64 | Fronius Sunrise Midi | 2.05 | 20° | 0° | 923 |
| Heiligenhafen | Photowatt (polik. Si) | SMA2500 | 3 | 45° | 0° | 830 |
| Nendorf | Isofoton (monok. Si) | SMA 2000+1500 | 4 | 45° | 0° | 861 |
| Heiligenhafen | GPV (polik. Si) | n.b. | 2.4 | 15° | 0° | 870 |
| Heiligenhafen | Siemens (monok. Si) | n.b. | 1.98 | 35° | 8° | 779 |
| Meischendorf | Photowatt (polik. Si) | SMA 2000+2500 | 5 | 30° | 10° | 812 |
| Sabnensdorf | Photowatt (polik. Si) | 4X SMA2500 | 10.2 | 15° | 0° | 788 |

Table 2 Performance measurements for systems in various locations around Germany.

Again, here in *Table 2* the performance is quantified as energy production using kWh/kWp.

Santa Cruz Site

The next comparison is actually a set of systems co-located on the same roof in the city of Santa Cruz, CA. This is a demonstration site as well as a test site to, at least in part, quantify the performance differences between crystalline and Uni-Solar Triple-Junction PV systems, as well as the effect of tilt angle on annual energy production.

Three simple systems were designed and installed on the same, low-slope, spray-in-place polyurethane

foam (SPF) roof. Two were conventionally mounted, framed solar panels, arranged in 2.5kW arrays, side-by-side, at the same tilt angle. Each of these two arrays is connected to an SMA, 2.5kW inverter, mounted on the roof as well. Monitoring was done at both the DC and AC levels to quantify the system performance.

The third system uses a 2.5kW PV array made up of 128W Uni-Solar PV Laminates mounted to the horizontal roof surface at effectively, a zero slope. This array is also connected to a 2.5kW SMA inverter.

These systems, located very near the ocean, are exposed to alternating sun and cloud cover that varies with season and time of day. The performance of the systems then, will be measured under conditions that are

similar to weather environments across the country. Monitoring was done using an rMeter™ [1] data acquisition system (DAS) that compares the outputs of the set of systems under identical operating conditions and then displays the data on the World Wide Web to enable ready access for project participants and observers.

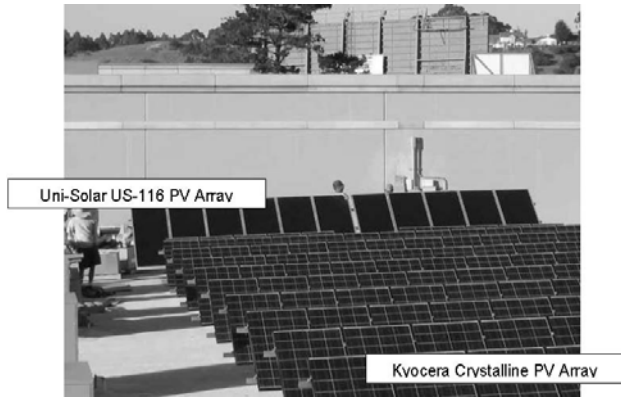


Figure 2 Santa Cruz Site: Framed Solar Panels

The intent of this demonstration/test project was to quantify the performance characteristics of similar systems located on the same roof. The variables were to be PV panel technology and mounting angle. In that way, the other performance variables, sunlight and ambient temperature would be identical for all systems under test. The impact of tilt angle could then be referenced to any installed cost factors that would favor the elimination of the array mounting structure.



Figure 3 Santa Cruz Site: Uni-Solar's Framed Modules



Figure 4 Santa Cruz Site: Laminates mounted horizontally

The photo above is the horizontally mounted PV Laminate array. This is actually two 2,560 W PV arrays, each connected to its own 2.5kW SMA inverter. The roof material is spray-in-place polyurethane foam coated with an acrylic protective layer.

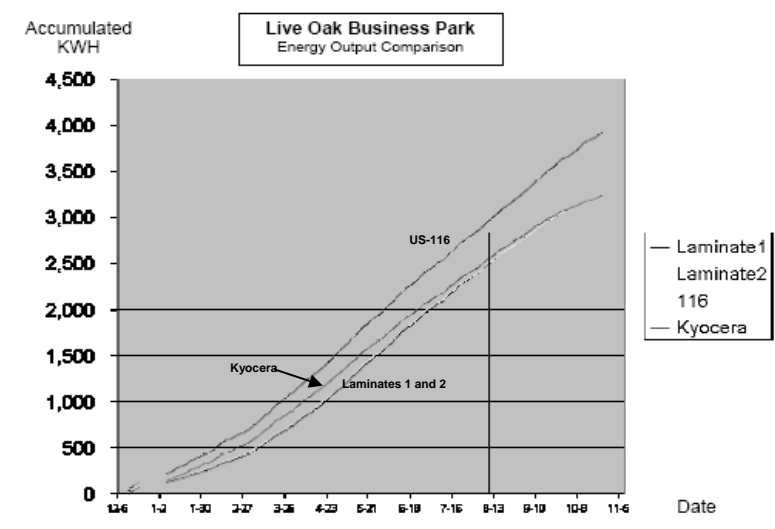


Chart 1 Energy Output Comparison

The chart above shows the accumulated kWh of energy produced by each of four systems. The Laminate 1 and Laminate 2 systems are the horizontally mounted Uni-Solar PV Laminates. The Kyocera system is the same capacity as the other three but this crystalline panel array is mounted at a 30-degree angle, facing south. The Uni-Solar US-116 framed panel array is mounted at the same angle as the Kyocera and is sized at the same STC capacity. It is clear that the tilted Uni-Solar US-116 array produced the greatest amount of energy (about 20% more than the horizontal array and 14% more than the tilted crystalline array). The tilt angle of the crystalline array was changed to a zero slope on August 10, 2004. In the 8 months leading up to that time, production by the horizontally mounted PV Laminate array nearly reached the output of the tilted crystalline PV array. After the change, the horizontally mounted PV Laminates

outperformed the crystalline array.

It is interesting to note that the tilted Uni-Solar array kWh line, if extrapolated to cover a full calendar year, would closely agree with the model predictions shown in the 'Predicting PV System Performance' section of this paper.

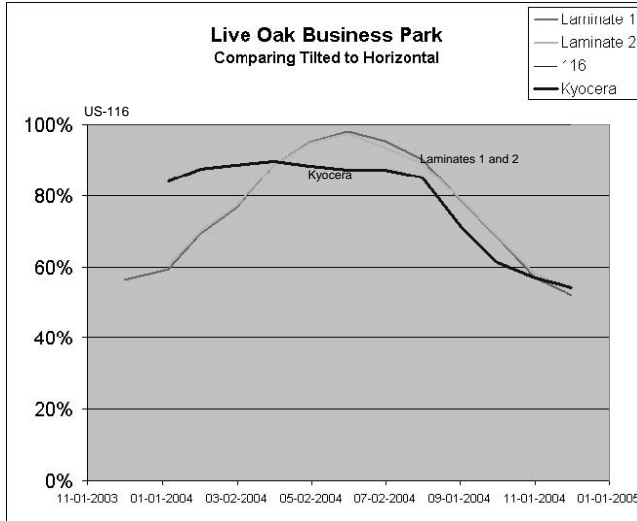


Chart 2 Live Oak Business Park: Energy Production

The chart above quantifies the energy production differences between the tilted Uni-Solar array (100% control line) and the other, co-located arrays. It illustrates that the difference is least during the mid-summer when the sun is tracking more directly overhead. The line representing the Kyocera crystalline array drops drastically, even lower than the Laminate arrays, when the tilt angle for that array was reduced to zero on August 10.

Modeling predicted an averaged 15% difference in energy production between the tilted array and the horizontal array. The actual testing showed the difference to be closer to 20% due to the factors that are only approximated as fixed values in computerized models.

CONCLUSION

To obtain the best performance from any photovoltaic power system, the system design must address all pertinent factors. These include:

- Weather data (solar insolation levels)
- Factors for expected soiling
- Factors for expected shading (trees, adjacent structures, installation hardware)

- Performance characteristics of photovoltaic technology used
- Tilt angle and azimuth
- Seasonal snow cover
- Ground reflectance (primarily for rack-mounted systems)
- Array mismatch
- Distribution losses
- Inverter efficiency

The parameters that can be controlled by the designer must be defined to accommodate the range of variables associated with the factors that can't be controlled such as the weather, soiling, and snow cover. As seen from the data presented in this paper, the selection of the photovoltaic technology plays a major role in determining the performance of the system. Even when all other factors are consistent, the triple-junction, amorphous silicon technology delivers the highest energy. It is more tolerant of less than optimum tilt angles, high temperatures, soiling and shading.

REFERENCES

[1]. rMeter™, The Energy Awareness Engine, combines instrumentation, software and internet connectivity to view and analyze real-time energy and environmental data on the desktop. This tool set is used for education, accounting, systems maintenance and building public awareness.

[2]. Clean Power Estimator™ is an economic evaluation software program the California Energy Commission is licensing for use from Clean Power Research. The program provides California residential electric customers a personalized estimate of the costs and benefits of investing in a photovoltaic (PV) solar or small wind electric generation system.

[3]. M. van Cleef, P. Lippens, J.Call, *Superior Energy Yields of UNI-SOLAR® Triple Junction Thin Film Silicon Solar Cells compared to Crystalline Silicon Solar Cells under Real Outdoor Conditions in Western Europe*,

[4]. E. Bura, N. Cereghetti, D. Chianese, A. Realini and S. Rezzonico, *PV Module Behavior in Real Conditions: Emphasis on Thin Film Modules*, LEEE-TISO, CH-Testing Centre for PV-Modules, University of Applied Sciences of Southern Switzerland (SUPSI)

[5]. David L. King, Jay A. Kratochvil, and William E. Boyson, *Stabilization and Performance Characteristics of Commercial Amorphous Silicon PV Modules*, Sandia National Laboratories, Albuquerque, NM 87185