Just How Big Is a 2 kW Photovoltaic System?

Analysis of hourly metered data collected from 19 residential grid-tied PV systems in California helps to answer questions about actual system power output.

by Kurt Scheuermann

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In recent years technology advances, environmental considerations, and economic factors have contributed to an increased interest in grid-tied photovoltaic (PV) systems for homes. Well-funded support and promotional programs in Japan, Germany, and California have created active markets in these locations for this renewable distributed-generation technology.

For homeowners, builders, or designers considering installation or specification of PV technology, access to reliable performance information is critical. Performance information for individual components under nominal rating conditions is readily available. System performance under actual operating conditions is another matter altogether—and this performance information is sparse.

To fill in this information gap, in January 1999 the California Energy Commission (CEC) and Regional Economic Research, Incorporated (RER) jointly developed a project to monitor the in-field performance of PV systems that had been funded in part by the CEC's Emerging Renewables Buydown program.

RER, the company I work for, monitored the key performance parameters of 19 PV systems for which incentives had been distributed through the CEC's Buydown program. We collected data on energy production, power output, and net impact on utility system loads from mid-February 2000 through December 2001. Because of monitoring system moves and other factors, varying quantities of data are available for the different sites.

To ensure that we would monitor a diverse range of PV systems, we selected systems based on the following criteria: geographic diversity, system size and configurations, equipment, retail suppliers, and installation vendors. The system sizes ranged from 1 kW to 12 kW (see Table 1). The sites are located all over California, from San Diego County in the south to Willits in the north. Several sites are located in coastal areas, while sites located well inland include Grass Valley and Mariposa in the Sierra Nevada foothills.

What Does That Power Rating Mean?

The power output of PV systems varies depending on irradiance level and module temperature, which makes specification of system AC capacity a complicated endeavor. Manufacturers of PV cells and modules typically rate their products at standard test conditions (STC), comprising 1,000 watts per square meter (W/m^2) irradiance and a cell temperature equal to 25°C. The resulting DC power output ratings are often incorporated into model numbers. Because these ratings constitute the most readily available size information, we used them when listing system sizes in Table 1. However, when these systems are actually operating in the field and receiving irradiance levels of 1,000 W/m^2, cell temperatures often exceed 25°C. The higher cell temperatures can cause observed power outputs to fall short of nominal nameplate ratings.

There are alternative approaches to developing system capacity estimates that are based on weather rather than on cell temperatures, and these estimates can be more representative of actual in-field conditions. One commonly used alternative rating system was developed by the Photovoltaics for Utility Scale Applications (PVUSA) national public-private partnership. The weather that constitutes PVUSA test conditions (PTC) consists of 1,000 W/m^2 plane-of-array irradiance, 20 °C ambient temperature, and wind speed equal to 1 meter

(left) A power center with backup storage batteries is located in a shaded porch area. *(right)* A combiner box combines DC circuits from several PV panels.

per second (see "PV Vocabulary," p. 29). Since cell temperatures influence power output, it is important to calculate what the cell temperatures would be for each system under these weather conditions. Estimations of what cell temperatures would be under PTC conditions, which will vary from system to system depending on a variety of factors, may be made using experimental or theoretical methods.

To estimate actual system AC capacity at PTC conditions, we collected hourly metered data for each system on plane-of-array solar radiation and module temperature. Specifically, the parameters we monitored included solar radiation (on plane of array); PV module temperature; whole-building electricity consumption (AC kWh) measured near point of interconnection with the utility (main breaker panel); inverter energy output (AC kWh); and PV array output (DC kWh). The monitoring system platform consisted of

Table 1. Characteristics of Monitored Sites

Site	PV Mount Type	Battery Storage	Nominal System Size (DC kW)
1. Orinda	Fixed	No	12.00
2. Saugus	Manual	No	5.82
3. Monrovia	Fixed	No	2.88
4. Los Altos Hills	Fixed	No	2.16
5. Hermosa Beach	Fixed	No	2.16
6. San Francisco	Fixed	No	2.06
7. Hollister	Fixed	No	2.06
8. Cupertino	Fixed	No	1.80
9. Orinda	Fixed	No	0.90
10. Willits	Manual	Yes	4.80
11. Ben Lomond	Fixed	Yes	4.32
12. Winters	Tracking (2-axis)	Yes	4.32
13. Paso Robles	Tracking (1-axis)	Yes	4.00
14. Cupertino	Fixed	Yes	3.12
15. San Luis Obispo	Fixed	Yes	2.66
16. Sunnyvale	Fixed	Yes	2.40
17. Ramona	Fixed	Yes	2.05
18. Grass Valley	Manual	Yes	1.92
19. Mariposa	Tracking (1-axis)	Yes	0.96

Table 2. Actual AC Capacities

	Estimated PTC		Max. Observed	
Site ID	(kW)	(% of Nom)	(kW)	(% of Nom)
1.	7.92	66%	9.04	75%
2.	3.76	65%	4.48	77%
3.	1.86	65%	2.00	69%
4.	1.48	68%	1.73	80%
5.	1.52	70%	1.61	74%
6.	1.26	61%	1.41	69%
7.	1.28	62%	1.45	70%
8.	0.96	53%	1.13	63%
9.	0.52	57%	0.70	78%
10.	2.53	53%	3.23	67%
11.	2.53	59%	2.82	65%
12.	2.74	63%	3.18	74%
13.	2.48	62%	2.91	73%
14.	1.99	64%	2.27	73%
15.	1.59	60%	1.84	69%
16.	1.36	57%	1.58	66%
17.	1.34	66%	1.51	74%
18.	1.18	61%	1.30	68%
19.	0.55	57%	0.64	67%
Mean	2.04	62%	2.36	71%
Median	1.52	62%	1.73	70%

two data loggers, each with an internal modem. One logger was used to measure solar radiation and module temperature, and the other was used to measure AC and DC power quantities.

Power output at PTC conditions cannot be estimated directly with these data alone, because PTC conditions refer to specific ambient weather conditions. Instead, separate regression models were estimated for PV output versus module temperature and module temperature versus weather conditions.

Many Ways to Size

We used these regression analyses to calculate estimates of system AC power capacities for PTC conditions of 1,000 W/m^2 and estimated module temperatures (see Table 2). We found on average that measured AC system capacity at PTC conditions was 38% less than nominal DC system size at STC conditions. The smallest discrepancy was 30%. This difference is attributable to factors such as wiring, module mismatch, and DC-to-AC conversion losses, as well as reduced output at PTC weather conditions compared to STC testing conditions. For each kW of nominal DC module capacity, typical AC system power output for 1,000 W/m^2 plane-of-array irradiance (1-sun conditions) and 68°F ambient temperature was 620 watts. For 1-sun conditions and 100°F ambient temperature, the estimate of typical AC system output falls to 575 watts.

There are many ways to rate system output, and it is important that customers and system integrators understand the basis for the sizing information supplied by manufacturers. Clearly, simply referring to a "1 kW PV system" is insufficient; at a minimum, the plane-of-array solar radiation and ambient or module temperature associated with such a value should be presented alongside the size value.

Energy Production Varies

In addition to power capacities, we looked at several other important measures of energy production for the monitored PV systems (see Table 3). Daily average electricity production and plane-of-array irradiance are calculated directly from the hourly metered data.

Table 3. PV System Energy Production

Site ID	(A) Observed Daily Average Energy (kWh/day)	(B) Observed Daily Average Irradiance (kWh/m^2/day)	(C) Normalized Observed Energy (Wh/W)/ (kWh/m^2)	(D) Assumed Daily Average Irradiance (kWh/m^2/day)	(E) Annualized Energy Production (kWh/yr/kW)
1.	45.4	5.7	0.67	5.3	1,293
2.	26.1	6.8	0.66	5.8	1,388
3.	9.3	5.6	0.58	5.5	1,158
4.	6.8	5.0	0.63	5.4	1,242
5.	7.4	5.2	0.65	5.5	1,306
6.	5.7	5.2	0.54	5.3	1,047
7.	6.0	5.6	0.52	5.3	1,004
8.	5.8	6.2	0.52	5.3	1,008
9.	2.8	5.5	0.56	5.4	1,099
10.	12.7	5.0	0.53	4.6	889
11.	13.1	5.4	0.56	5.3	1,091
12.	18.2	7.5	0.56	7.6	1,555
13.	18.4	7.3	0.63	7.6	1,740
14.	11.0	6.0	0.59	5.3	1,132
15.	7.8	5.6	0.52	5.8	1,110
16.	6.2	5.6	0.46	5.3	892
17.	5.8	5.4	0.52	5.6	1,065
18.	6.7	6.0	0.58	5.8	1,228
19.	1.2	5.5	0.23	7.4	622
Mean	11.4	5.8	0.55	5.7	1,151
Median	7.4	5.6	0.56	5.4	1,110

Average electricity production ranged from 1.2 to 45.4 kWh per day.

The considerable variability observed in these results is largely attributable to effects of system sizes, which vary by a factor of more than ten. However, tracking, orientation, slope, shading, module mismatch, module soiling, battery size, inverter settings, and the effectiveness of an inverter's maximum power point tracking capability all contribute to the 40-fold range in electricity production that we observed. Mechanical damage and different levels of accuracy in nominal module sizes also affect electricity production. Tolerances of 5%–10% for actual module size at the time of purchase are common in the industry, and long-term performance guarantees exhibit considerable variability. And even for a specific product, the guaranteed module size can change over time. For example, actual size may be guaranteed to be 90% or more of the nominal size rating for the first 10 years, and 80% or more of the nominal size rating for 20 years.

To net out the effects of system size, tracking, orientation, and shading—and get a clearer measure of how well the systems convert solar energy coming in into electric energy going out—we normalized the energy production results for incident irradiance and system size. Our ability to net out shading is somewhat limited because it is possible for the irradiance sensor to be shaded while some of the modules are not shaded, or vice versa. Not surprisingly, the two systems exposed to the most solar radiation include automatic tracking systems. The orientation of the system exposed to the next most solar radiation is adjusted manually to improve system performance.

We found normalized energy production values that ranged from 0.23 (Wh/W)/(kWh/m^2) to 0.67 (Wh/W)/(kWh/m^2) (see "PV

Table 4. Summary of Net Energy Metering Effects

Site ID	Daily Average Household Electric Use (kWh/day)	Hours Sending Power to Grid (%)	Portion of Production Sent to Grid (%)
1.	39	56%	60%
2.	35	58%	50%
3.	15	61%	54%
4.	16	49%	53%
5.	25	48%	36%
6.	14	53%	49%
7.	23	17%	10%
8.	12	61%	43%
9.	15	29%	10%
10.	14	72%	68%
11.	9	71%	74%
12.	49	33%	46%
13.	28	53%	43%
14.	23	60%	48%
15.	11	66%	62%
16.	15	52%	36%
17.	43	16%	7%
18.	33	36%	21%
19.	38	1%	0%
Mean	24	47%	41%
Median	23	53%	46%

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(top) This rooftop mounted PV system has arrays facing south and west. *(bottom)* These storage batteries provide uninterrupted operation of critical electrical loads even when power from the grid is unavailable.

Vocabulary," p. 29). Along with other factors, these normalized results reflect the effects of battery storage on PV system performance. Chemical reactions in storage batteries produce internal losses that occur continuously even if power from the grid is available and the batteries are not discharged to satisfy household electric loads. A portion of PV system output is used to make up for these standby losses, maintaining batteries in a fully charged state. The energy requirement for this type of battery charging is a function of battery type and storage system size, not PV array size. All else being equal, battery charging will have a larger negative influence on overall system performance for systems that include smaller PV arrays.

This effect appears to be strongly influencing the normalized AC energy production results for the Mariposa site. This system consists of a small PV array and a battery storage system that backs up all house loads. While the sizes of the battery storage systems are unknown because the CEC did not collect these data, systems configured in this manner likely would include larger battery storage systems than those designed to power only a few critical loads when grid power is unavailable. System DC output at this site is seen to compare favorably with performance observed for other systems. System AC net output, however, is significantly less than average, due to battery-charging requirements. When considering only those hours when the PV system is generating AC power, the average DC/AC conversion efficiency for the Mariposa system is 81%. This result is similar to the results calculated for other systems, and it exceeds the overall average efficiency for this site by a factor of approximately two.

A Year of Sun Power

A performance measure of particular interest to owners of residential systems is total electricity production per year. For most of the systems, less than one year of data was available. Therefore, to estimate annual energy production, we combined the normalized AC electricity production results (column C) with National Renewable Energy Laboratory (NREL) estimates (column D) of annual average plane-of-array irradiance for solar collectors. For each site, information concerning actual system orientation was used to select the annual average plane-of-array irradiance value most representative of actual site conditions.

The annual energy production ranged from 622 to 1,740 kWh per year per kW of nominal DC system size. The two systems whose annualized output exceeds 1,500 kWh/yr/kW are both tracking systems. The average for nontracking systems is 1,122 kWh/yr/kW.

The annual energy output estimates that we arrived at are based on an important assumption related to the treatment of shading effects of trees and other obstructions. These estimates are based on interval-metered plane-of-array irradiance measurements. In some cases these values include shading effects of trees and other obstructions in addition to shading effects of clouds. Annual average plane-of-array irradiance estimates presented in column D of Table 3 include shading effects of clouds only, not shading effects of trees or fixed obstructions. When normalized AC energy output results are combined with these unobstructed annual average irradiance data, resulting annual energy output estimates represent the output for a system free of shading obstructions. While this basis is ideal for developing information for consumer education purposes, in cases where obstruction shading is influential, actual output may be less than is indicated in Table 3.

The Value of Net Metering

Net metering arrangements allow participants to send surplus electricity to the grid during hours when renewable energy system output exceeds the rate of household electricity consumption. When this happens, participants become net generators of electricity rather than net consumers and effectively use the grid as a battery. For each site, the extent to which this happens is a function not only of system size but also of lifestyle, appliance types and fuels, number of people in the household, and the weather.

From the perspective of participants, a meaningful measure of net energy production performance may be the net extent to which electricity produced by renewable means displaces power generated by other means that would otherwise have been purchased to satisfy household electric loads. During the monitoring period, energy use varied substantially from participant to participant, averaging 24 kWh per day. Consumption values for particular sites ranged from 9 to 49 kWh per day (see Table 4). PV output as a percentage of total household electric energy use ranged from 3% to 139%.

On average, these PV systems deliver electricity to the grid during 47% of the hours when they are producing electricity. For the average monitored system, 41% of the electricity that is produced is sent to the grid. For these monitored systems, ability to net meter and use the grid as a battery is very important. (For PV's potential usefulness during peak demand hours, see "Matching the Peak," below.)

Matching the Peak

Having generated hourly production profiles for PV systems, we used these profiles to answer the question, What are the net grid effects attributable to grid-tied PV systems on days when electric system demand approaches its maximum values? This measure of PV system capacity benefit is just one of many possible measures, the more rigorous of which would include consideration of the fact that system capacity benefit is a function not only of demand magnitude, but also of the coincidence of available supply and demand. California electric system demand is likely to approach maximum values anywhere between May and October, while renewable system output is by nature variable and seasonal. Interval-metered data for this period are available for the PV systems that were being monitored in the summers of 2000 and 2001.

First, California Irrigation Management Information System (CIMIS) weather data were used to identify particularly hot summer days in 2000 and 2001. Next, actual California Independent System Operator (Cal-ISO) system hourly loads for these days were examined and the hour of system peak was identified. The Cal-ISO is a not-for-profit corporation that is responsible for operating the high-voltage electric backbone transmission system in California.

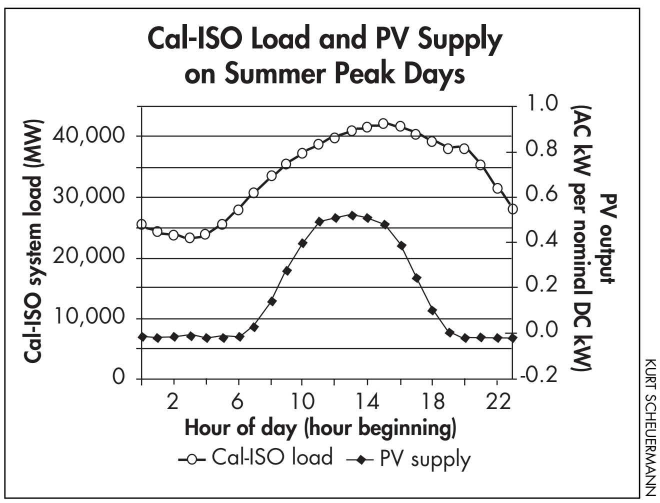

Figure A. Grid-tied PV systems output matched well with Cal-ISO loads on the hottest summer days.

For six days—three in each summer—the system peak occurred during the hour from 3 pm to 4 pm. The average load during this hour was approximately 42,000 megawatts (MW), which compares to a total Cal-ISO system capacity in the neighborhood of 45,000 MW. Metered data were analyzed to determine the contribution of PV systems to meeting these peak Cal-ISO loads. PV output matches fairly well with Cal-ISO system loads (see Figure A).

For the system peak hour of 3 pm to 4 pm, average PV system output is 0.47 kW per kW of nominal DC system size, which is 91% of maximum PV output. The potential for PV to help meet Cal-ISO system peaks is sensitive to the time of the peak, because the slope of the PV supply line is steep in the region where Cal-ISO system peaks occur. The coincidence of PV output and Cal-ISO loads could be optimized by orienting PV modules toward the southwest, or by the use of tracking systems.

PV Vocabulary

Air mass (AM) is used to describe the relative length of the path that the sun's rays traverse through the atmosphere before reaching the ground. An AM = 1 condition occurs when the sun is directly overhead at a sea level site; AM values of 10 or greater occur near sunrise and sunset. The relative performance of PV modules changes as the solar spectrum changes, and the solar spectrum changes throughout a clear day as AM changes.

Plane-of-array irradiance is the intensity of solar radiation incident upon the PV modules, typically expressed in units of watts per square meter. Generally speaking, PV system power output is roughly proportional to the amount of solar radiation striking the surface of the PV modules. A 1-sun condition is equivalent to a plane-of-array irradiance of 1,000 W/m^2.

Maximum power point tracking (MPPT) refers to the practice of controlling DC voltages such that PV modules produce the maximum quantity of power possible. Most systems that have batteries do not have MPPT capability, and the non-battery systems have had varying levels of success tracking maximum power points. The Sunny Boy inverter from Germany seems to MPPT quite well, but no German inverters were included in the study.

Normalized energy consumption, or (Wh/W)/(kWh/m^2). The denominator—(kWh/m^2)—references the amount of solar radiation incident during a given period, where one kWh/m^2 corresponds to an intensity of 1,000 W/m^2 (i.e., 1-sun) for a period of one hour. The numerator—(Wh/W)—references the amount of electric energy produced by the PV system during a given period, per unit of system size. For example, a PV system comprising one 100-Watt PV module producing 56 Watt-hours per hour would be producing 0.56 Wh/W. If during that same hour the intensity of solar radiation was 1,000 W/m^2 then the normalized energy production would be 0.56 (Wh/W)/(kWh/m^2).

Not 100% Reliable

Like most energy conversion equipment, small PV systems are generally not 100% reliable. Hardware and software problems may jeopardize system performance, and the performance of several monitored systems changed through time. The tracking system at the Winters site included three separate, independently operating tracking systems. While details of tracking problems are unavailable, the data suggest that at least two of the trackers experienced equipment problems that reduced system performance substantially. The system installer was notified of the problem, and system performance improved a short time later. The manually adjusted system at the Willits site included unframed PV modules, several of which experienced glass breakage due to unknown causes. At some point during the monitoring period, the owner of the system replaced one of the affected modules with a smaller module from a different manufacturer. Finally, the 1.8 kW, two-inverter system in Cupertino experienced at least two inverter failures that required inverter replacement.

If distributed generation is to play an increasingly large role in the future, its overall reliability must be closely monitored. Detailed data collected for this project contributed to problem troubleshooting. It is likely that some fraction of systems not included in this monitoring project will experience similar problems at some time during their long life. To ensure satisfactory performance throughout the life of a system, some level of ongoing monitoring is necessary. Because system output is a function of weather conditions, both electric generation and weather should be accounted for in any ongoing monitoring plan. Data requirements of such a plan could vary from very minimal to very detailed. For this project, the average cost of the monitoring system hardware was approximately $2,700 per site. The design of a more widely targeted ongoing performance monitoring plan would have to carefully weigh the tradeoffs between the cost of collecting performance data and the value of those data.

Finally, it is worth emphasizing that the PV systems in this monitoring study included small systems that used the technology that was commercially available several years ago. The performance of larger systems could be substantially different, as could that of newer technologies that are now available from domestic and international suppliers. Newer systems may offer improved performance for homeowners who choose to produce their own power.

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For more information:

The NREL assumed daily average irradiance values shown in Table 3 come from NREL's "Red Book." See Solar Radiation Data Manual for Flat-Plate and Concentrating Collectors. Golden, Colorado. USDOE National Renewable Energy Laboratory, 1994.

The Red Book is free! It can be ordered on-line from NREL's Web site at www.nrel.gov.

The data are listed by state and city at http://rredc.nrel.gov/solar/old_data/nsrdb/redbook/sum2/state.html.

Information on the performance of a wide variety of PV systems is available from the following Web sites:

- Solar Electric Power Association (SEPA) www.solarelectricpower.org
- International Energy Agency's Photovoltaic Power Systems Programme (IEA-PVPS) www.oja-services.nl/iea-pvps/home.htm