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INCREASING THE PRODUCTIVITY OF SOLAR PHOTOVOLTAIC SYSTEMS

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ABSTRACT

State-sponsored incentives have played a significant role in driving the demand for residential and small commercial photovoltaic (PV) systems. All state incentive programs are tied to the power rating of the system, though some states also offer energy production incentives. Unfortunately, there is a disconnect between the power rating of a PV system and the energy that system produces over its lifetime. It is extremely important to consider system productivity, which goes well beyond the efficiency of the components. System productivity is tied directly to the structure of the array, not just the efficiency of the components and the quality of the installation. This paper examines the issues associated with improving solar PV system productivity. The focus is on comparing a series-parallel array configuration to a series-string array configuration and the impact on energy production. Partial shade is used to highlight substantial differences between the operation of the two array configurations.

NOMENCLATURE

T_0	Test temperature at which the parameters are obtained.
V_{OC}	Open circuit voltage (at T_0).
I_{SC}	Short circuit current (at T_0).
k_C	Temperature coefficient for short circuit current.
k_v	Temperature coefficient for open circuit voltage.
G_0	Standard light irradiance value.
I_L	Solar cell photocurrent.
I_D	Solar cell forward diode current.
I	Terminal current provided by the solar cell.
R_S	Series resistance in the solar cell model.
R_{SH}	Shunt resistance in the solar cell model.
v_D	Forward voltage across the diode in the solar cell model.
v_T	Solar cell terminal voltage.

INTRODUCTION

State-sponsored incentives have played a significant role in driving the demand for residential and small commercial photovoltaic (PV) systems. All state incentive programs are tied to the power rating of the system, though some states also offer energy production incentives [1]. Unfortunately, there is a disconnect between the power rating of a PV system and the energy that system produces over its lifetime. This has lead to a migration in system design that de-emphasizes effective energy production. Since it is the energy captured by the system that drives system payback and value to society, increasing the energy capture by a few percentage points can have a substantial positive impact.

Consideration of system productivity is extremely important. A more productive system is able to pay for itself more quickly, bringing greater economic benefit to the homeowner and better value to the agency that provided the installation incentives. System productivity goes well beyond component efficiency. It is tied directly to the structure of the array, not just the efficiency of the components and the quality of the installation.

This paper examines issues associated with improving the productivity of solar PV systems. The following section discusses different approaches to system configuration. Subsequent sections address the issues that require attention to maximize PV

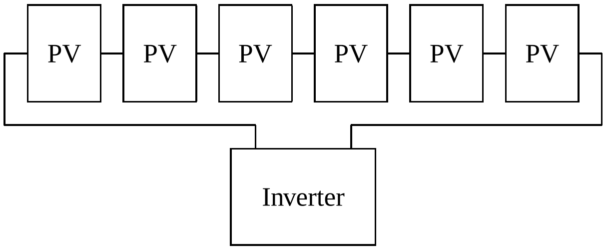

Figure 1. THE SERIES-STRING ARRAY CONFIGURATION THAT LEADS TO A HIGH-VOLTAGE SYSTEM.

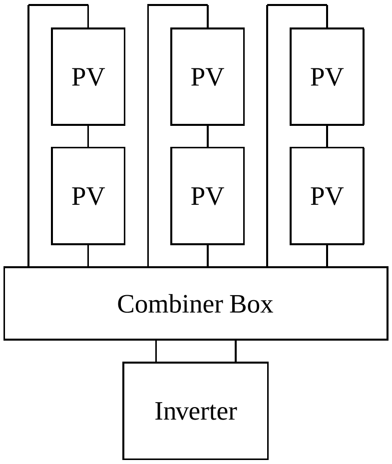

Figure 2. THE SERIES-PARALLEL ARRAY CONFIGURATION THAT LEADS TO A LOW-VOLTAGE SYSTEM.

system output.

SOLAR PV SYSTEM CONFIGURATION

A PV array is configured to match the voltage generated by the panels to the voltage input range of the inverter, taking into consideration multiplication factors for temperature extremes. Virtually all inverters on the market for grid tie systems accept input voltages in the range of 250 V to 600 V, though some input voltages may go lower. In the early grid tie market there were inverters that accepted much lower input voltages, in the range of 50 V to 90 V. The transition from the lower voltage range to the higher voltage range was promoted as a way of simplifying system installation. While this is true for installation only, it discounts the impact array configuration has on energy production.

A low-voltage array is created by installing many short series strings of panels in parallel. A high-voltage array would use much longer series strings of panels. Figures 1 and 2 show the differences in configuration between the high-voltage and low-voltage installations, respectively.

A low-voltage system will raise the installation cost by 1.9% for a 3 kW (dc) system to cover the cost of additional wire, a slightly more expensive disconnect, the combiner box, and the associated labor. However, this additional installation cost is more than offset by improved system productivity, as discussed in the section on productivity considerations.

Installation Issues

Some installers would prefer to install a high-voltage string array rather than a low-voltage series-parallel array. This preference is based on installation preferences that do not take into consideration energy production issues:

1. High-voltage arrays require fewer parallel connections than low-voltage arrays.
2. High-voltage arrays are marginally less expensive to install than low-voltage arrays.
3. High-voltage arrays use less wire.

Looking at these separately, the relative ease of installation is a direct result of the array voltage and required panel wiring. Since power is the product of voltage and current, a low-voltage system will need to supply more current than a comparably power-rated high-voltage array. As a result, more conductors will be needed for the low-voltage system. In addition, instead of simply daisy-chaining the panels in a series configuration, the low-voltage installer is left with a number of sub-arrays that all need to be connected in parallel. This requires the use of a separate junction or combiner box that is not needed in a high-voltage system.

The difference in installation expense between the two systems is an artifact of four clear points:

1. There are more conductors required for the series-parallel array configuration.
2. The combiner box is additional hardware not needed in the high-voltage system.
3. The dc disconnect required by the National Electric Code needs to carry a higher current rating in the low-voltage system, though it does not need to support as high a voltage.
4. The time required to pull more conductors and make more cable terminations translates into slightly higher installation labor costs.

Table 1 summarizes the incremental installation cost increase of $544 for a 3 kW (dc) PV series-parallel array relative to a series-string array. The installed cost of the series-string array is $29,400, so the series-parallel array is

$$\frac{\$29,400+\$544}{\$29,400} = 1.0185 \quad ,$$

giving a 1.85% cost increase.

Table 1. INCREMENTAL INSTALLATION COST ADDITIONS FOR A SERIES-PARALLEL ARRAY.

Combiner Box:	$139
Breakers for Combiner Box:	$60
Increased Conduit Size:	$68
Additional Wire:	$147
Miscellaneous Fittings:	$50
Labor:	$80
Total:	**$544**

Flexibility of Design

High-voltage strings are somewhat limiting to the designer/installer. Greater emphasis must be placed on the voltage of the series-string under all conceivable operating conditions, as open-circuit voltages go up in the colder climates. In addition, since the modules behave effectively as current sources, care must be taken to ensure that each panel in the string sees the same lighting conditions. Partial shading of a single panel will reduce the output of the entire array, a significant issue that is unavoidable for most arrays for various reasons:

1. The sun rises in the east and sets in the west, thus creating a creeping shade effect.
2. Trees tend to grow over time.
3. Birds and other animals are unpredictable.
4. Snow does not immediately or uniformly clear from panels.
5. Subsequent structures tend to be erected without regard to existing arrays.
6. Panels dispersed over multiple roof surfaces exist in a permanent condition of partial shade.

In other words, shade happens!

The inability of a series-string array to accommodate shading also makes installations on multiple roof pitches problematic as all modules do not see the same levels of irradiance, a condition akin to partial shading.

The low-voltage array is much less sensitive to shading, as non-uniform irradiance will result in a smaller percentage of panels being current limited by the offending shade. This provides more energy per rated watt over the lifetime of the system – a benefit that can easily surpass the added cost of a low-voltage system in certain installations. Following this logic, the following circumstances may indicate that a low-voltage system would be a better design choice:

1. Flat-roof installations where roof projections may present even the slightest level of shading during the day.
2. Installations that have wires overhead, particularly if those wires attract birds.
3. Installations where rapidly growing vegetation may occasionally shade panels or shed leaves that limit panel output.
4. Installation in the proximity of future construction that may block panels.
5. Installations that must occur on east- or west-facing roof pitches instead of a south-facing pitch.
6. Installations that are spread over multiple roof surfaces.
7. Installations that experience snow.

Another aspect of design flexibility is the ability to build a system incrementally. Even with incentives, a PV system is expensive. A series-parallel array allows the system to be built with a smaller number of panels initially, thereby making PV accessible to more people. It may be possible to add panels incrementally to a series-string array, but only after a large number of panels have been used in the initial installation.

Energy Storage

A series-parallel array is more directly compatible with back-up energy storage than a series-string array. Work by others has shown that integration of energy storage can help to maximize the value of PV systems [2]. Frequently, the consumer is surprised to discover that the utility-interactive PV installation that they purchased does not provide electricity when the utility grid is interrupted.

Because a series-parallel array outputs a lower voltage than a series-string array, a series-parallel array can be configured to support the input of a charge controller that is used to regulate the voltage on a battery bank. The output of a series-string array is generally too high to efficiently convert down to the 48 V of a battery bank. An inverter with an input voltage range comparable to that of a charge controller would support the addition of battery backup in the future.

PRODUCTIVITY CONSIDERATIONS

To appreciate the significance of productivity, it is useful to understand why people choose to buy solar systems. Strictly on the basis of current-day economics, solar PV is still difficult to justify. Payback periods, without government incentives and tax credits, would be on the order of 30 years with today's equipment and electric prices. The modules would need replacing just as the system would finish paying for itself.

Even with incentives, the payback periods are still more than 10 years, a time longer than most people will remain in their current residences. So what motivates people to purchase these systems for their homes? Although a fool and his money soon part, it would take a lot of fools to drive module manufacturers to increase production capacity and support annual growth rates in excess of 30%. There are a number of factors the typical PV consumer considers when deciding to buy:

1. Energy prices: Purchasing a PV system is a hedge against increases in fossil-fuel costs.
2. Cash flow: A $20,000 vacation home or boat will not pay monthly dividends, however, the equivalent investment in a PV system will.
3. Home improvement: An investment in PV will increase the resale value of the home.
4. Green power: "If my electric bill is reduced each month, I am generating some of the electricity that I use. This is all green power and that makes me feel good."

The value of a PV system to the consumer is a direct result of its ability to produce electricity during daylight hours. The more energy it captures, the faster it pays for itself, and the owner's satisfaction is maximized when energy production is maximized. Until now, little effort has been made to ensure that the solar PV industry supplies systems that maximize energy production and, therefore, customer happiness. This should be corrected. The following sections discuss several performance issues that affect lifetime energy production.

Shading Issues

It might seem counterintuitive to suggest that two PV systems of comparable wattage-rating can have significantly different capacities for energy production. The confusion arises from the physical difference between power and energy. We speak of the power company, but we do not buy power, we buy energy. Energy results from power being produced over time. In that regard, it makes more sense to evaluate systems based on their total energy output, since this is the best measure of a system's usefulness.

Under shaded conditions, a PV array is not able to produce its rated power. However, confining the impact of shade to only a small section of the array will minimize the drop in array output. Shading effects are difficult to quantify because shading rarely happens under textbook conditions. Shading effects also are complicated by the maximum power-tracking algorithms used in inverters. Attempts to characterize shade are given in [3, 4].

Figures 3 through 5 show situations that are indicative of shade [5]. Figure 3 shows a PV array that is comprised of panels on multiple roof faces. This will generate an effect that is similar to shade since the panels do not see the sun from the same orientation. Figure 4 shows a similar situation where the PV array is used to form a building entry. Figure 5 shows an array that has many tall trees in close proximity that will provide diffuse shading during some portion of the day. From these three examples, it is clear that shading effects are introduced in any number of ways.

There is also significant anecdotal information about the influence of shading. Consider:

> "There is a large eucalyptus tree on the neighbor's property that shades any given panel in the array for about an hour each day during the "winter." The first panels start to get shade around solar noon and shade leaves the last panels around 3 pm. The panels continue to produce power even while shaded, but only 1/3 to 1/2 the amount that they do when under direct sunlight. From about two weeks after spring equinox until about two weeks before the fall equinox, the panels were no longer shaded at any time.
> The panels are arranged in a 6 × 6 (physical) array, with nine (series) panels in each of four (parallel) strings. When shading occurs, it first takes out 2/3 of the first string, then the remainder of the first string and 1/3 of the second string, then all of the second string. Shade overtakes the third and fourth strings in similar fashion. At the height of the shading, the entire array is in the shade. Shade clears from the panels in the same manner." [6]

While the array is completely shaded there is nothing that can be done to increase productivity (short of cutting down the neighbor's tree). However, as the array is moving in and out of shade, there is some energy that is being missed because of the long strings.

Less extreme examples are far more common: shade from trees or roof projections that nibble away at the irradiance along the outside edges of the array. This is particularly common as the sun gets lower in the sky during winter months. On our own series-string array shading 0.28% of the array caused the inverter output to drop 7.5%.

A model was used to compare the performance of two arrays under various lighting conditions. Since there are many ways shade can manifest itself, we have developed our model to apply shade to two arrays, a 20×1 series-string array and a 4×5 series-parallel array (5 paralleled strings of 4 panels in series). Each array is formed by four rows of five panels each. As a baseline comparison, Figs. 6 and 7 show the array output voltage, current, and power without shading. As expected, peak array power is the same for both array configurations. The data of Figs. 6 and 7 were generated by self-consistently solving the panel voltage-current terminal characteristics for a voltage imposed on the array. Sweeping the voltage imposed to the array simultaneously generates array currents that correspond to array voltage. Array power is the product of array current and voltage. For the simulations, the Kyocera KC158G panel is used, making the nominal rating of each array 2.5 kW. The details of the panel model are given in Appendix A.

Shading is difficult to predict and quantify. Here we consider a number of scenarios under which some panels are shaded, i.e.,

Figure 3. A SOLAR PV ARRAY CONSTRUCTED ON MULTIPLE ROOF FACES, GIVING AN EFFECT SIMILAR TO THAT OF DIFFUSE SHADING.

Figure 4. A SOLAR PV ARRAY CONSTRUCTED AS A BUILDING ENTRY, GIVING AN EFFECT SIMILAR TO THAT OF DIFFUSE SHADING.

they do not receive full irradiance. These scenarios are not intended to represent the full range of possible shading conditions. Rather, they are intended to illustrate some situations that are easy to envision and to identify the difference in potential output power between a series-string array and a series-parallel array.

The shading is assumed to be diffuse, rather than complete. Diffuse shading effectively reduces the irradiance seen by the panel, whereas complete shading would drop the irradiance to zero. Diffuse shading is by far the most common type of shading seen by PV panels; it is rare to block all of the light to the panel.

Table 2 summarizes a number of shading scenarios along with the power available from the two arrays and the percentage improvement offered by the series-parallel array. The percentage improvement is based on the global maximum of output power for each array configuration. The results show that relatively little shading can have significant impact on power production for the PV array. Figures 8 and 9 show the output of the string and series-parallel arrays for the first shading scenario given in Table 2, respectively, and provide an example of how shading impacts the output characteristics of the array. The array characteristics are shown as the array voltage as a function of array current, along with array output power as a function of array voltage and array current. The outputs for other shading scenarios is similar in nature to those shown in Figs. 8 and 9.

It is worthy of note that partial shade creates multiple peaks in the output power as a function of voltage in the output of the series-string array. These peaks do not have the same value, so shade increases the difficulty in performing maximum power-point tracking since there are now local maxima that can trap the algorithm and prevent it from getting to the global maximum. The series-parallel array output is also impacted by shade, but not nearly to the same degree and in the same way. Figures 8 and

Figure 5. A SOLAR PV ARRAY SURROUNDED BY MANY TALL TREES THAT CREATE SHADE ON THE ARRAY DURING THE DAY.

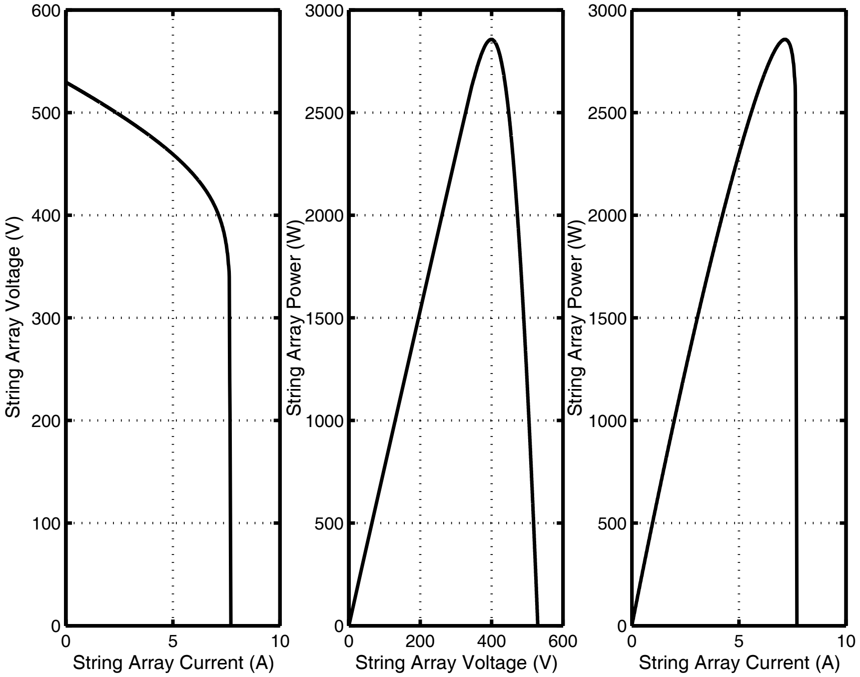

Figure 6. MODELED OUTPUT PERFORMANCE FOR THE SERIES-STRING ARRAY UNDER UNIFORM LIGHT INTENSITY.

9 show robust maximum power-point tracking is easier with the series-parallel array than the series-string array.

Inverter Efficiency

The input voltage of the inverter can have an effect on some metrics of inverter efficiency. This is an artifact of higher input currents at the lower voltage translating into higher conduction losses. But the reality is that two different well designed inverters should not vary more than 1 or 2% in efficiency. Is a 95% efficient inverter better than a 93% inverter? To the unwary consumer, the answer is “yes.” To the savvier purchaser, the more likely answer is “it depends.”

The difficulty in assessing inverter efficiency is that it has multiple dependencies. The most prominent system parameters that affect the inverter efficiency over its operating spectrum are inverter input voltage, inverter temperature, and operating power level. Ideally one would prefer an inverter that provides $> 90\%$

Table 2. A COMPARISON OF POWER OUTPUTS OF SERIES-PARALLEL (4×5) AND STRING (20×1) ARRAYS UNDER VARIOUS SHADING SCENARIOS. EACH MATRIX UNDER “SHADING SCENARIO” PROVIDES THE ASSUMED IRRADIANCE FOR EACH PANEL IN THE ARRAY. THE VALUES GIVEN FOR EACH SHADING SCENARIO REPRESENT THE IRRADIANCE IN $\mathrm{W/m^2}$ THAT IS ASSUMED TO BE HITTING THE PANELS. VALUES OF LESS THAN $1000\,\mathrm{W/m^2}$ ARE PANELS SUBJECTED TO DIFFUSE SHADE.

Shading Scenario					**String Output (kW)**	**Series-Parallel Output (kW)**	**Series-Parallel Performance Advantage**
1000	**1000**	**1000**	**1000**	**1000**	2.439	2.636	8.07%
1000	**1000**	**1000**	**1000**	800			
1000	**1000**	**1000**	**1000**	800			
1000	**1000**	**1000**	800	700			
1000	**1000**	**1000**	**1000**	**1000**	2.148	2.278	6.06%
1000	**1000**	800	**1000**	**1000**			
1000	800	700	800	**1000**			
800	700	600	700	800			
1000	800	**1000**	**1000**	**1000**	2.542	2.578	1.42%
1000	**1000**	800	**1000**	**1000**			
1000	**1000**	**1000**	800	**1000**			
1000	**1000**	**1000**	**1000**	800			
1000	**1000**	**1000**	**1000**	**1000**	2.142	2.142	0.00%
1000	**1000**	**1000**	**1000**	**1000**			
1000	**1000**	**1000**	**1000**	**1000**			
600	600	600	600	600			
1000	**1000**	**1000**	**1000**	600	2.285	2.624	14.83%
1000	**1000**	**1000**	**1000**	600			
1000	**1000**	**1000**	**1000**	600			
1000	**1000**	**1000**	**1000**	600			
1000	900	800	900	**1000**	1.841	1.957	6.33%
900	800	700	800	900			
800	700	600	700	800			
700	600	500	600	700			
1000	**1000**	**1000**	800	700	2.254	2.567	13.90%
1000	**1000**	**1000**	800	700			
1000	**1000**	**1000**	800	700			
1000	**1000**	**1000**	800	700			

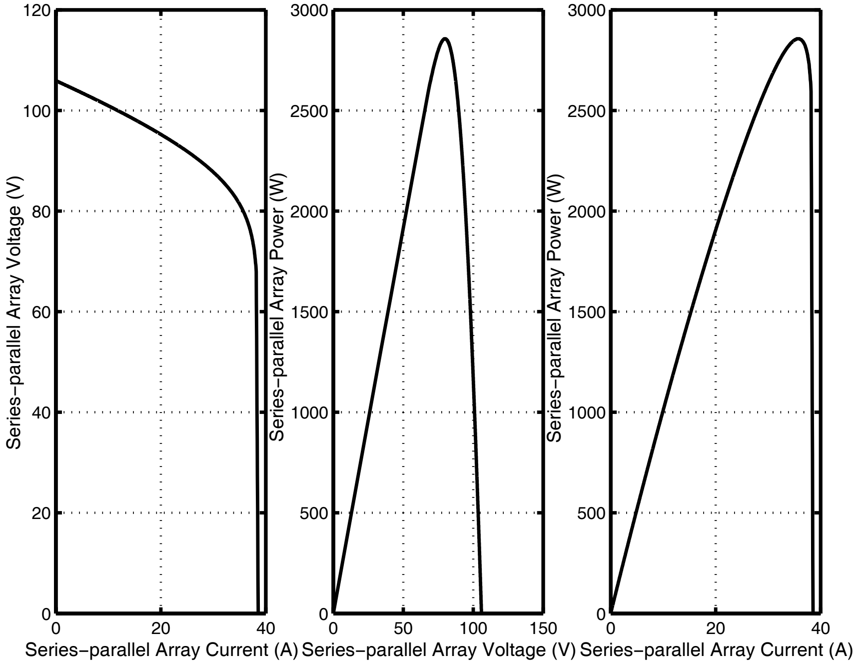

Figure 7. MODELED OUTPUT PERFORMANCE FOR THE SERIES-PARALLEL ARRAY UNDER UNIFORM LIGHT INTENSITY.

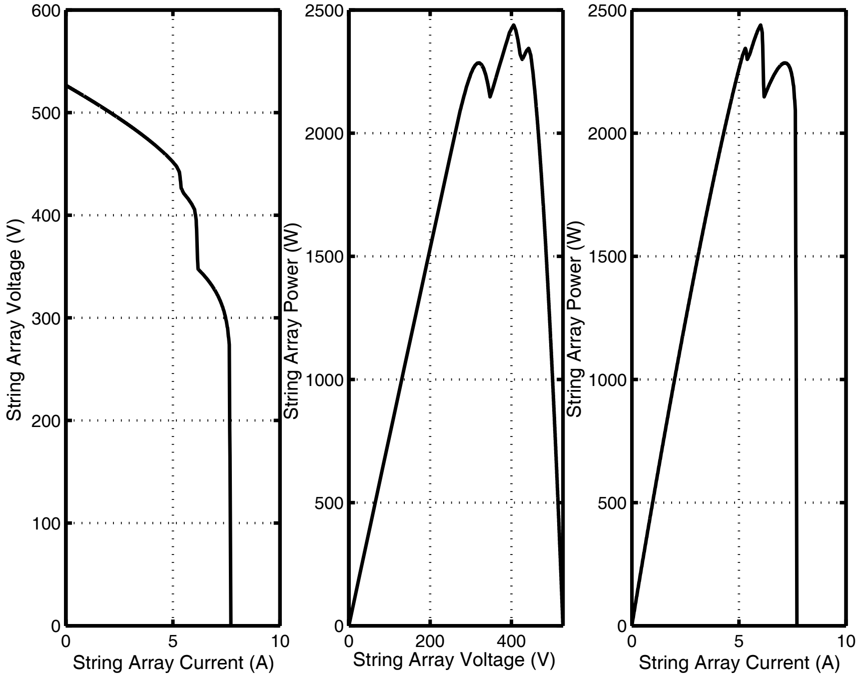

Figure 8. THE AVAILABLE OUTPUT FROM THE SERIES-STRING ARRAY FOR THE FIRST SHADING SCENARIO OF TABLE 2.

efficiency over all operating powers and operating temperatures. Unfortunately, most inverter manufacturers specify efficiency as the highest value they can measure. While the California Energy Commission requires a weighted average of inverter efficiency, there is no guarantee that the consumer will see that efficiency. A 95% efficient inverter might only provide 88% of the available power from the array over most of its typical operating spectrum of input voltage and power. Therefore, more emphasis must

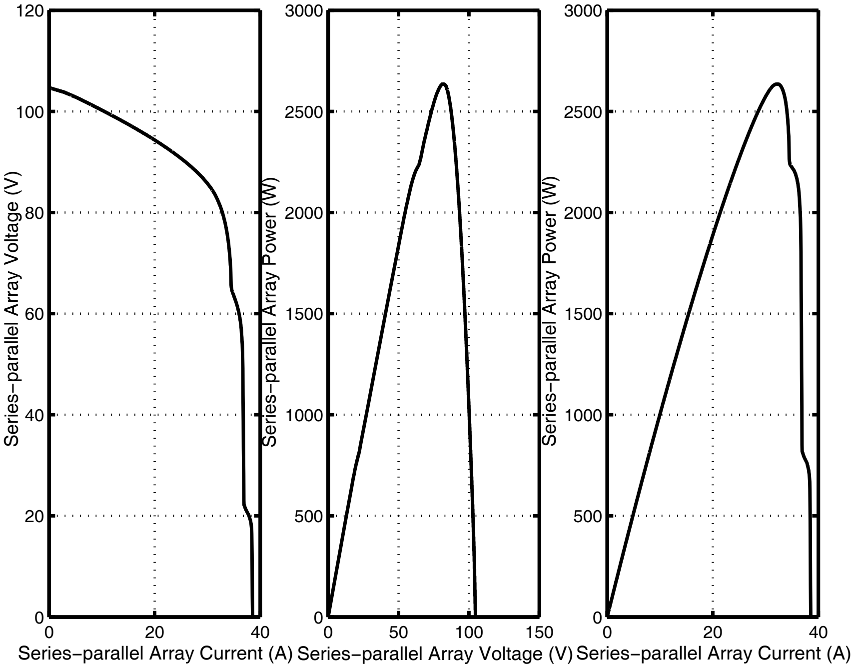

Figure 9. THE AVAILABLE OUTPUT FROM THE SERIES-PARALLEL ARRAY FOR THE FIRST SHADING SCENARIO OF TABLE 2.

be placed on the efficiency spectrum associated with variations in input voltage and power rather than the manufacturer's rated peak efficiency. To put it in perspective, a 96% efficient 2500 W inverter generates 100 W of heat losses. This value is comparable to an incandescent light bulb. So if losses are limited to 100 W over the entire operating range, why did the manufacturer put such a large finned heat sink on the enclosure?

The consumer can make better choices if inverter manufacturers provided efficiency curves that characterize performance across a spectrum of usage. Just as automobiles rarely live up to their EPA mileage rating, every inverter should carry the caveat "Your efficiency may vary." Further, an inverter with a higher peak-efficiency rating than another inverter may not necessarily always provide higher efficiency under similar conditions. In other words, just because the efficiency is higher at one set of operating conditions does not imply that the efficiency is always higher.

Beyond the issue of inverter efficiency are all of the other factors of system design and implementation that affect energy capture. There are a number of places beyond the inverter where power can be lost. A list of these factors is given at [8], where the default derating factors for conversion from dc into ac give a 16.3% reduction in power *before* the inverter efficiency is even considered. Clearly there is a lot of room for improvement in system performance beyond that of the inverter.

SUMMARY

Our industry has gravitated toward solar PV systems based on high-voltage series-string arrays, due in large part to limitations in technology available in the past. Over the past several years, a number of competitors have entered the market with similar products, likely motivated by a rapidly expanding market. This paper shows that there are inherent limitations to high-voltage series-string arrays that make them less-than-ideal in a variety of installation scenarios. The effects of random shading and inverter efficiency on lifetime energy production have been shown, suggesting that the current emphasis on inverter efficiency, while valid, is perhaps a much less important issue than shading and lifetime energy production. If the goal of the solar PV industry is to maximize the return on investment for solar energy, it is critical to look more closely at the effects of shading and non-ideal system siting. Low-voltage PV systems based on series-parallel arrays offer greater productivity in diffuse partial shade, as well as providing other positive attributes, such as compatibility with battery back-up and a smaller initial number of panels for systems built incrementally.

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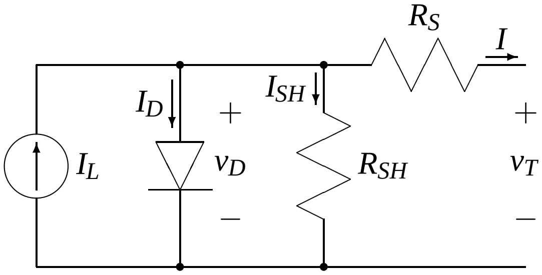

Figure 10. A STANDARD ELECTRICAL CIRCUIT MODEL OF A SOLAR CELL. THE STRUCTURE OF THE PANEL MODEL IS THE SAME.

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Appendix A: A Solar Panel Model

A circuit model for a solar cell is shown in Fig. 10, where I_L represents the current generated by exciting the cell with light. The other circuit components model the losses and nonlinearities of the cell. More information about modeling solar cells and panels is given in [7].

A panel is comprised of an array of solar cells. Aggregating the behavior of cells is rather complex, particularly when bypass diodes are taken into consideration. We can expect through aggregation that the model will retain a similar structure, with a few changes. For example, the effective diode $v-i$ characteristic will change substantially because there are now a large number of diodes connected in series and parallel. The current sources also will add to create a larger current, and the series resistances will add in series and parallel as the panel model is formed.

Table 3. PARAMETERS OF THE KYOCERA KC158G SOLAR PANEL.

V_{OC}	28.9 V
I_{SC}	7.58 A
k_C	6.08 mA/C
k_v	$-0.11\,\mathrm{V/C}$
G_0	$1000\,\mathrm{W/m^2}$
T_0	47 C

Table 4. CALCULATED MODEL PARAMETERS FOR THE KC158G PANEL.

R_S	424 mΩ
I_S	15.843 nA
I_L	7.7137 A

For the simulations, the Kyocera KC158G panel is used. The panel parameters, taken from the KC158G data sheet, are given in Table 3.

Due to the nonlinear nature of the panel model, the panel parameters are solved numerically. Table 4 summarizes the results.

The data of Table 2 was generated by using the panel model for each of the 20 panels in the array. Each panel had its own irradiance as given in the table. The outputs of each panel were aggregated according to the array structure to determine the peak available output power. In the model, we assume each panel is uniformly illuminated even when shaded. This approach is justified since very little shading is required to affect panel output. The data given in Table 2 assume that each panel is at a temperature of 25 C.