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The Long-term Viability of Concentrated Photovoltaic Systems in the Southwestern US

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ABSTRACT

Total lifetime costs of photovoltaic (PV) systems are important determinants of profitability. Yet such costs are not always accurately measured and compared against fluctuating electricity costs. Concentrated photovoltaic (CPV) systems, for example, may offer the promise of lower cost, significantly higher efficiency and greater energy production over traditional fixed flat-plate PV installations in high-irradiance regions. But confidence in CPV technologies has fallen because of their perceived economic limitations. In this study, we calculate the energy production and corresponding revenue generation for a 28kW concentrated photovoltaic (CPV) unit and for an 821 kW single-axis tracker field, both located within the Las Vegas region of Nevada.

Working with two models, one a simple annual model that uses only the direct normal solar insolation; the other a more complex hourly model that uses direct normal solar insolation, ambient temperature, and wind speed to predict energy yield, we have produced a cost matrix that provides a threshold for profitability. That matrix then provides a threshold against which manufacturing, installation and O&M costs can be compared.

As a result of our calculations, we anticipate that CPV systems will still be viable in high flux areas because they offer promise for cost reductions in decreasing cell costs and/or increases in overall efficiency. Nonetheless, other factors, such as long-term reliability and O&M costs, must be addressed if CPV is to outcompete other simpler technologies such as single-axis PV trackers, which are becoming more attractive to potential customers.

INTRODUCTION

Concentrated photovoltaic (CPV) systems have been in development and commercialization for several decades by many different companies. Their appeal has always been the promise of lower cost, significantly higher efficiency and greater energy production over traditional fixed flat-plate PV installations. However, as the price of flat-plate PV panels has fallen, total lifetime costs have become a critical factor in choosing among different PV technologies. These lifetime costs are complex, taking into account such variables as the costs of manufacturing, shipping and installation; lifetime production estimates; O&M requirements, and the local price of electricity, which fluctuates over time, etc.

For the past three years, we have collected production data from a CPV system installed at the US Department of Energy (DOE) Regional Test Center (RTC) in Henderson, Nevada. This site, which is located at the Southern Nevada Water Authority's River Mountains Water Treatment Facility, is one of five such RTCs across the US. The RTC program, which is managed by Sandia National Laboratories (Sandia) for the DOE, supports technical innovation in the US solar sector by collecting high-fidelity performance data on a diversity of solar technologies and systems installed in different climates for a minimum of three years.

Manufacturers, also known as RTC industry partners, who wish to have their equipment validated at one or more RTCs are selected via a competitive process and work closely with Sandia on an installation and validation plan, which Sandia then executes by installing monitoring equipment and collecting high-accuracy data for performance analysis. Once installed, Sandia provides technical oversight ensuring that systems are regularly inspected, properly maintained, and any faulty or under-performing equipment is replaced.

In 2013, the former CPV manufacturer, Soitec,¡ requested technical assistance from the RTC program to conduct a validation study of an 84kW dual-axis CPV tracker system at the Nevada RTC. Following a technical-merit review, Sandia accepted Soitec into the program and asked the Center for Energy Research at the University of Nevada, Las Vegas (UNLV) to manage the project and provide technical assistance.

With additional support from the US DOE SunPATH program, Soitec began installing three 28kW tracker units at the NV RTC in late 2013. Sandia designed the monitoring system, which UNLV installed, and Sandia declared the system fully operational in April 2014 (*see Figure 1***Error! Reference source not found.**).

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Figure 1. Soitec CPV system at the NV RTC

This paper summarizes one year of high-fidelity performance data from the Soitec system. See *Table 1* for a list of the system's monitoring equipment and types of data collected, which include string-level DC voltage and current, back-of-cell and lens temperatures and AC power output. The data is collected at five-second intervals and then compiled into one-minute intervals.

Table 1. Monitoring Equipment Installed on the CPV Trackers

Equipment/Sensor	Measurement
Omega T-type thermocouples	Temperature
Empro Shunt Type MLA	DC current
Voltage divider	DC voltage divider
Advantech ADAM-3014	Isolated DC I/O module
ICP-DAS M-7019R	DAQ module
Shark 100T	AC power meter
Campbell Scientific CR-1000	Datalogger

We also collected research-quality weather data from the onsite RTC meteorological station against which we compared the CPV system's performance. The station measures direct normal irradiance (DNI), global horizontal irradiance, diffuse horizontal irradiance, spectral values, ambient temperature, relative humidity, pressure, wind speed/direction, and precipitation.

Utilizing the data collected from the RTC weather station and Soitec monitoring system, we successfully generated long-term energy production models, against which we modeled projected revenue from the electricity generated, and then determined maximum allowable system cost for the three-tracker system.

TECHNICAL OBJECTIVES

Widely viewed as cost-competitive in regions that have high DNI, such as the desert southwest, CPV had a rapid growth spurt from two to five years ago, but the technology has slowed since then, at least in the US, for perceived economic reasons. This paper provides a mechanism for evaluating the return-on-investment for CPV and also provides data to show how cost-competitive CPV is in high-DNI regions, such as Nevada.

CPV TECHNOLOGY

Each CPV unit measures 14.63 wide by 8.03 meters tall and has 12 CX-M500 CPV modules with 2400 triple-junction cells per module. Each cell has a silicone point-focusing Fresnel lens on glass with a concentration ratio of 500x. Six modules are connected in parallel for each string, for a total of two strings. The manufacturer's rating of a single unit is 24.2 kW DC ±10% at a DNI of 900 W/m^2, an ambient temperature of 20 degrees Celsius and a wind speed of 2 m/s [1].

The units track the sun in three ways: 1) using astronomical calculations for the sun's position and aligning the tracker with the sun's position, based on the encoder readings; 2) through the use of a sun sensor; and 3) by tracking via the first method but using a peak-power tracking algorithm to perturb the tracker throughout the day to find the peak power point.

CPV AC EFFICIENCY

UNLV calculated the following three types of AC efficiency for each unit:

1. *Daily peak power AC efficiency*

$$\eta_{AC_{peak}} = \frac{AC\ Power_{peak}}{A \cdot DNI_{peak}} \quad (1)$$

Typical peak power AC efficiency for the Soitec system falls between 26 and 28% (see *Figure 2.*)

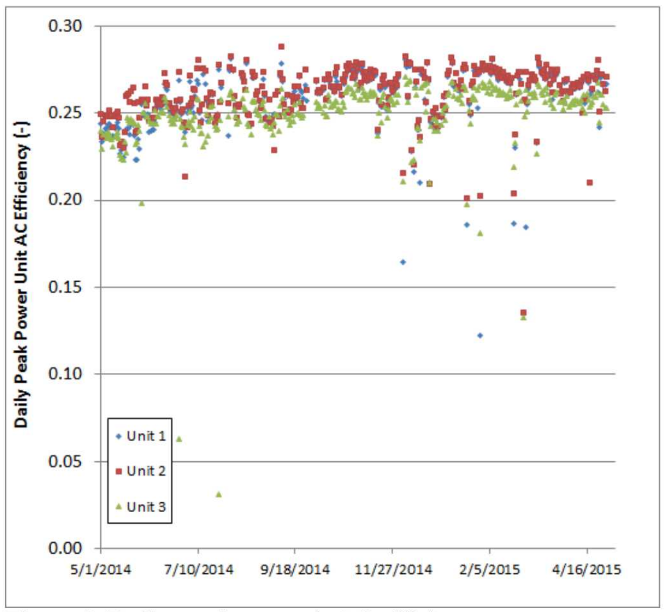

Figure 2. Daily maximum unit AC efficiency

2. *Average daily generation AC efficiency*

This efficiency is calculated only when the unit is generating power, thus it excludes any irradiance data below the tracker elevation limit, and any system downtime, regardless of cause (see *Figure 3.*)

$$\eta_{AveGenAC} = \frac{AC\ Energy_{gen} - AC\ Energy_{par}}{A \cdot I_{gen}} \quad (2)$$

As depicted above, this efficiency typically falls in the 24 to 26% range.

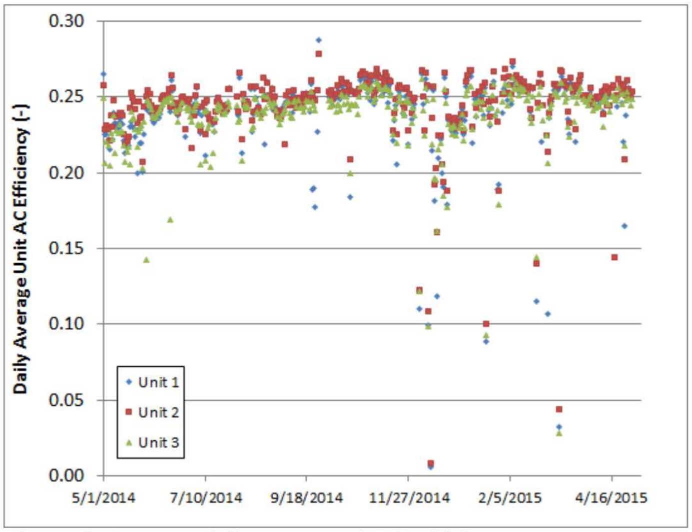

Figure 3. Average daily generated AC efficiency

3. *Total daily average unit AC efficiency*.

This measure of efficiency is the total energy generated per day divided by the total direct normal solar insolation for the day, with lower values occurring on hazy to intermittently cloudy days (see *Figure 4.*) It takes into account shading losses (for this particular configuration), tracking losses (tracking error/minimum elevation angle), inverter start-up time, and downtime.

$$\eta_{AveAC} = \frac{AC\ Energy_{gen} - AC\ Energy_{par}}{A \cdot I_{total}} \quad (3)$$

This efficiency is typically between 21 to 24%. If we are trying to calculate expected annual production from a short term data set, downtime becomes very important when picking which type of efficiency to use in the calculation. If major downtimes occurred during the dataset than the daily average efficiency would be closer to what is achievable assuming any issues causing downtime are resolved. When comparing these efficiencies to other PV technologies, the maximum efficiency of these CPV units exceeds every other category of PV module at least by 6% to 18% and typically by 12% to 20% [2].

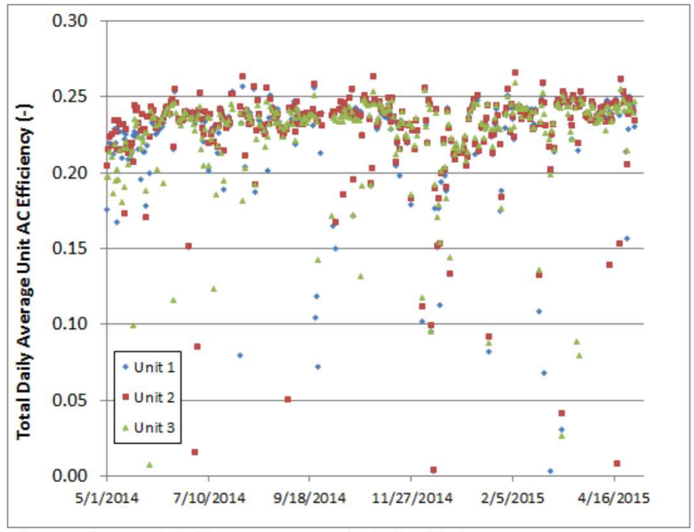

Figure 4. Total daily average unit AC efficiency

We also measured the parasitic load, that is, the amount of electricity consumed by the system that goes to operate the system. Parasitic loads for these CPV trackers are attributed primarily to three components: the automatic dryer unit, which prevents condensation from occurring inside the modules, the drive motors, which operate the tracker's movements, and the controller, which tracks positioning relative to the sun.

We combined parasitic load measurements for one of the three 28kW Soitec units and produced a daily plot (see *Figure 5.*)

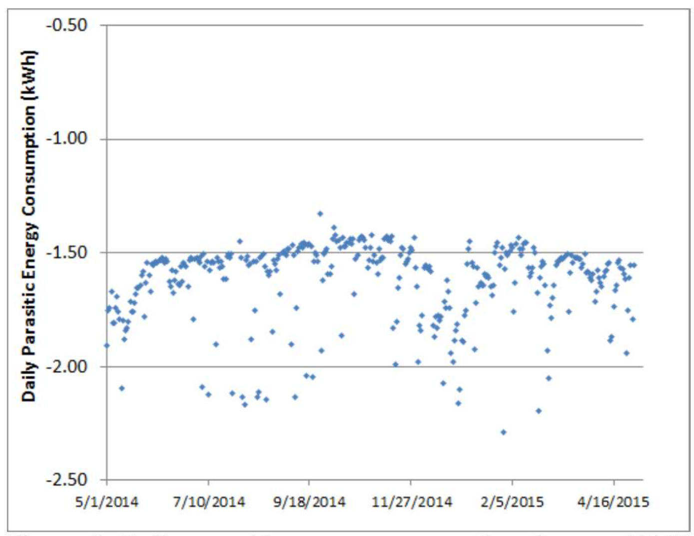

Figure 5. Daily parasitic energy consumption for one 28kW tracker unit

Over the course of a year, the loads from the controller are fairly constant, whereas the loads for the drive motors and automatic dryer unit are not. A small trend can be seen in the summer, when longer days require more tracking and thus more energy than in the winter. Humidity conditions also introduce variability, so the automatic drying unit may run at different times and for different durations.

Overall, the average daily parasitic energy consumption for this one-year period was 1.62 kWh; total annual consumption was 585.45 kWh. In terms of percentage of annual generation per unit, this amounts to about a one-percent loss of electricity that could be sold to the grid.

METHODOLOGY FOR MODELING CPV PERFORMANCE

We have developed a simple and fairly accurate model to forecast what a CPV system will produce for the next 30 years using Typical Meteorological Year (TMY) data [3] [4], local DNI and actual system energy production data. With high-fidelity data from three 28kW CPV units, we plotted each unit's daily generated AC electricity against the total incident DNI energy while generating power and then calculated the slope (see *Figure 6.*)

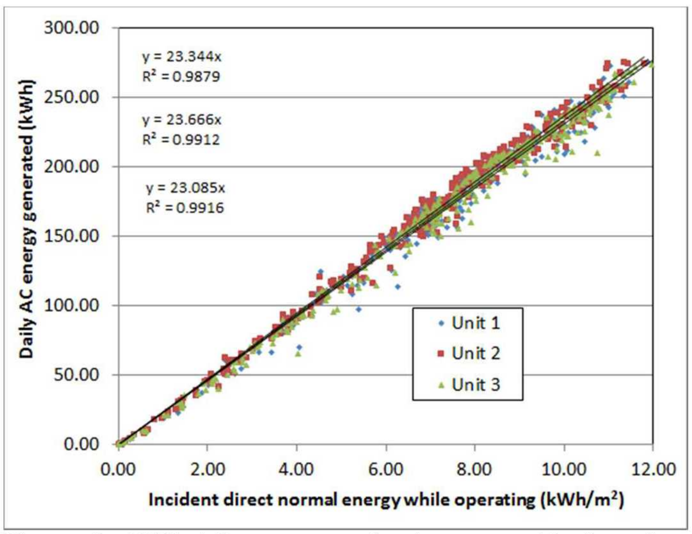

Figure 6. CPV AC energy production rate with downtime removed

We then plotted each unit's daily AC electricity generation against the total daily measured incident DNI energy, which includes the times when irradiance levels were low and the units were not generating electricity (e.g., early morning, early evening, tracking down.) We did, however, remove any events, such as grid power outages or other non-system related failures (see *Figure 7.*)

We then calculated the slopes for each of the units and averaged them for both total daily incident DNI energy and incident DNI energy while operating. These two averages were then used to calculate minimum and maximum generation when multiplied by monthly direct beam solar radiation minimums and maximums for the Las Vegas area [5]. We then used the average of these minimums and maximums as the average expected monthly output. Figure 8 shows a single unit's maximum and minimum possible monthly generated energy, median monthly generated energy, modeled generation based upon a local normal irradiance pyrheliometer (NIP), and actual averaged per unit energy generation. Our modeled calculations of annual generation were within 1.75% of the actual measured annual generation. The discrepancy, moreover, can be explained by identified technical issues: a data logger communication problem that occurred in late July 2014, problems with some of the encoder couplings, and misconfigured electrical wiring to the inverters.

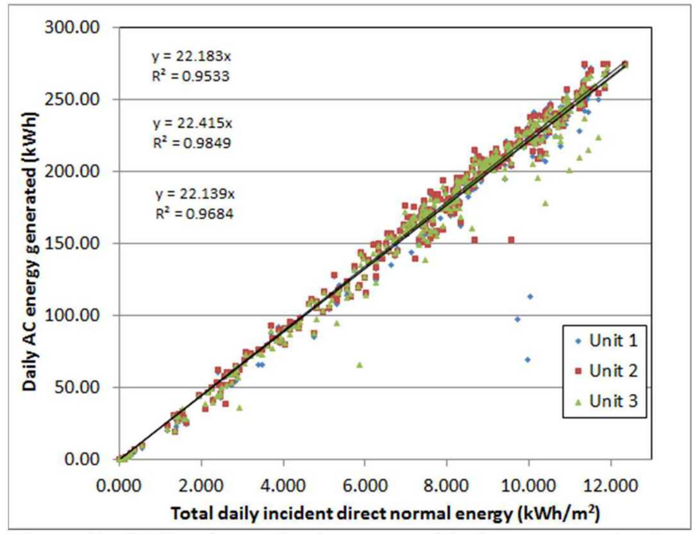

Figure 7. CPV unit production rate with data removed when downtimes were not related to system incidents or failures.

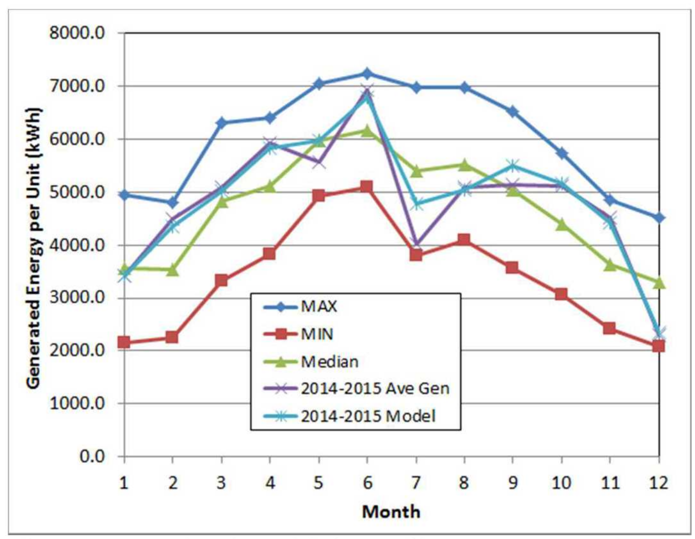

Figure 8. Actual and modeled monthly energy generation per CPV unit

We then used the median annual generated energy calculations to make 30-year projections using Soitec's stated production warranty of 97% production in the first year, with 0.7% loss every subsequent year for 30 years.

Our next objective was to calculate costs. Since most companies are usually not forthcoming with what the actual system and installation costs are, we did a backwards calculation based on the cost threshold required to breakeven or to make a profit. Of course, many calculations are possible, depending on the time period and prevailing interest rates. Consider a particular CPV system with a known production rate of $kWh_{electric}/kWh_{irradiance}/m^2/day$. The total cost will vary depending when it is purchased and installed and with what financing, e.g., a 5% interest rate over a 20-year period. But one can nonetheless calculate what the maximum total cost of a system *should* be, based on the revenue from the sale of its generated energy (see *Figure 9*).

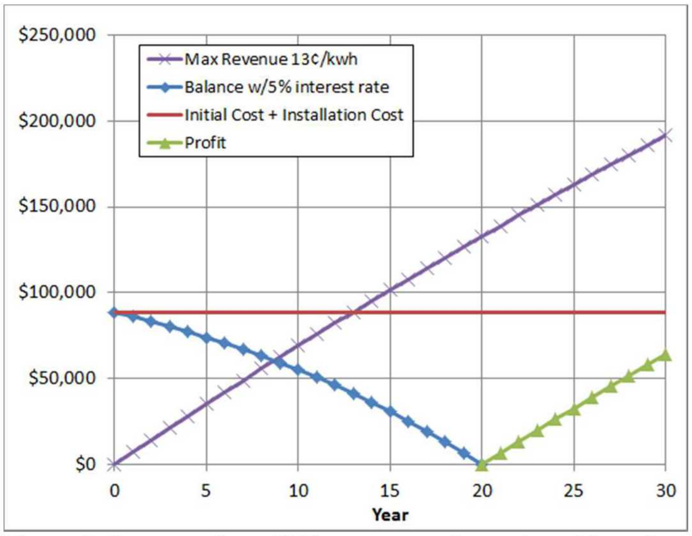

Figure 9. Revenue for a CPV system can be projected based on installed system costs and modeled energy production, with assumptions made about financing.

This method for calculating the maximum total cost of the system can be performed for different electricity prices, interest rates, and terms. One can calculate the payback, for example, for electricity sold during peak demand when the cost per kilowatt is highest or during periods of low demand when the cost is lowest. Consider Las Vegas, with its high per capita consumption of electricity, as an example of a city where the value of energy generated by solar PV systems is generally greatest when used to lower peak energy demand rather than to generate excess and sell it to the utility.

For this study, we looked at different electricity price schemes, such as fixed-price of electricity and time-of-use rates. However, because the time-of-use electric rate scheme requires more complex calculations to determine how much revenue a single unit can produce in a typical year, we looked at time-of-use calculations in two ways. First, we conducted a simplified AC power calculation based on DNI only. This approach, however, didn't account for seasonal temperature and wind variations so we tried a second approach, which took DNI, ambient temperature and wind speed into account. For the first analysis, UNLV plotted each unit's peak AC power vs. the peak DNI at the NV RTC and then performed a 3rd degree polynomial regression, averaged for the three units (see *Figure 10*).

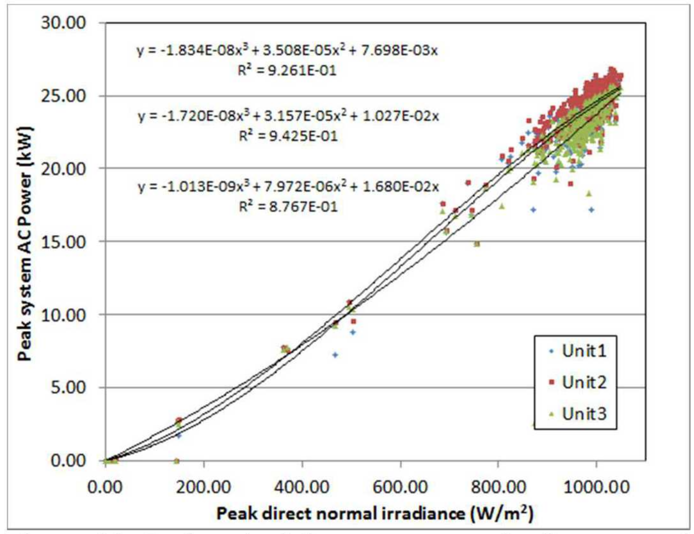

Figure 10. Peak unit AC power vs. peak direct normal irradiance

We then applied our average equation to calculate how much energy is generated hourly based on TMY2 and TMY3 data for Las Vegas, NV. We also applied the following three corrections: an hourly shading model, which was previously developed in MATLAB,® for the middle Soitec unit; an elevation limit for power generation to account for the units' limit of 5 degrees in elevation; and the daily energy consumption for powering the unit controller, motors, and other parasitic loads that we subtracted from the total. Validation of the shading code was performed by comparing the calculated elevation and azimuth angles with NREL's Solar Position Algorithm and by comparing the positions of the CPV unit's shadows on other CPV units, as depicted in digital images. As an example, images of shading were taken on August 15th, 2014 (*See Figure 11* and *Figure 12*).

Figure 11. Shading of Unit 2 from Unit 1 on August 15th, 2014 at 6:05 AM PST.

The first image was taken at 6:05 AM PST when the code calculated the solar azimuth and elevation position to be 98.99 degrees east of south and 12.52 degrees above the horizon. NREL's SPA calculator gave 98.43 degrees east of south and 12.37 degrees above the horizon. The shading code uses a simpler calculation for solar position [6] over NREL's more accurate Solar Position algorithm. Whereas the image shows a shaded area of 34.72%, the shading code calculated a shaded area of 33.56% which is within 1.16% of the image. For the second image, which was taken the same day at 6:29 AM PST, the code calculated a solar azimuth angle of 95.62 degrees and a solar elevation angle of 17.33 degrees, while the SPA calculated angles of 95.04 degrees and 17.17 degrees. The shading code calculated a shading area of 12.6% while the image gave a shaded area of 11.1%, which was within 1.5% of the image.

Figure 12. Shading of Unit 2 from Unit 1 on August 15th, 2014 at 6:29 AM PST.

Our simplified approach took only the DNI into account; whereas our more complex approach considered ambient temperature, and wind speed, in addition to DNI. We filtered the raw minute-data for each unit to include only the data collected between 10 AM and 2:30 PM, when DNI was greater than zero, and when the units were all generating power. We then performed a 3rd degree polynomial multivariable regression on that filtered data set to calculate unit power as a function of DNI, ambient temperature, and wind speed (See equation 4).

$$P_{Unit} = C_0 + C_1 \cdot T_{amb} + C_2 \cdot T_{amb}^2 + C_3 \cdot T_{amb}^3 + C_4 \cdot DNI + C_5 \cdot DNI^2 + C_6 \cdot DNI^3 + C_7 \cdot WS + C_8 \cdot WS^2 + C_9 \cdot WS^3 \quad (4)$$

$P_{Unit} = 0$ if any of the following conditions arise:

$$\text{DNI} < 10 \left(\frac{\text{W}}{\text{m}^2}\right)$$

$$\text{Wind Speed} > 15.6 \left(\frac{\text{m}}{\text{s}}\right)$$

$$\text{elevation angle} < 5°$$

We compared the percentage error of calculated power of a single unit to the average measured power using minute data from the three units. The percentage error is dependent upon the power level and data interval. For example, with minute data, an average absolute error of 5.35% was found for power levels above 1kW while the same error drops to 2.38% for power levels above 17kW. If hourly averages are taken, the error drops further: to 3.99% for power levels above 1kW and to 2.15% for power levels above 17kW. The percentage error decreases with power level partly because the power output for a 28kW unit is usually in the 20kW range midday. If the output drops significantly below 20kW, then haze or intermittent cloud cover has likely occurred, introducing much more variability.

We then used the new equation to calculate hourly generated-energy using the same TMY2 and TMY3 dataset, with the same corrections for shading, elevation angle, and parasitic energy consumption. We found that the total annual generated energy hourly calculations for each method were in good agreement: i.e. within 0.27% of each other (see *Figure 13*), while the total hourly calculations vs. the total average monthly production were within 1.8%.

As seen in Figure 13, our hourly calculations resulted in higher annual production numbers than our monthly calculations. One possible explanation is that our hourly calculations have no downtime; in contrast, our monthly calculations have some downtime built into the production rate. Another possibility is that nearby transmission lines, which shade the units in the early morning, affect the monthly production rate but not the hourly production calculations. When comparing the two hourly production approaches, the effect of ambient temperature can be seen with lower monthly production for the second approach relative to the first during warmer months and vice versa during moderate months.

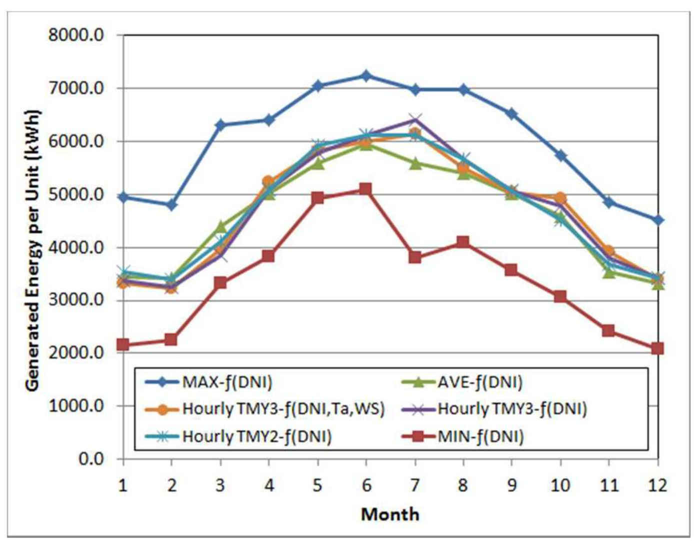

Figure 13. Modeled monthly energy production per CPV unit

A multivariable regression equation allowed us to look at the relations among different variables. For example, if the DNI is fixed at 1000 W/m² and wind speed is fixed at 2 m/s, then the relationship between unit power loss and ambient temperature can be plotted (*see Figure 14**Error! Reference source not***

found.). These particular systems have an odd relationship with ambient temperature. Instead of linearly losing efficiency with increasing temperature, they reach peak efficiency at 21 degrees Celsius, with decreasing efficiency at higher or lower temperatures. Most of that efficiency is determined by cell temperature, but other variables may be involved, including heat expansion/contraction/bending of the module/tracker structure and also expansion and contraction of the Fresnel lens facets.

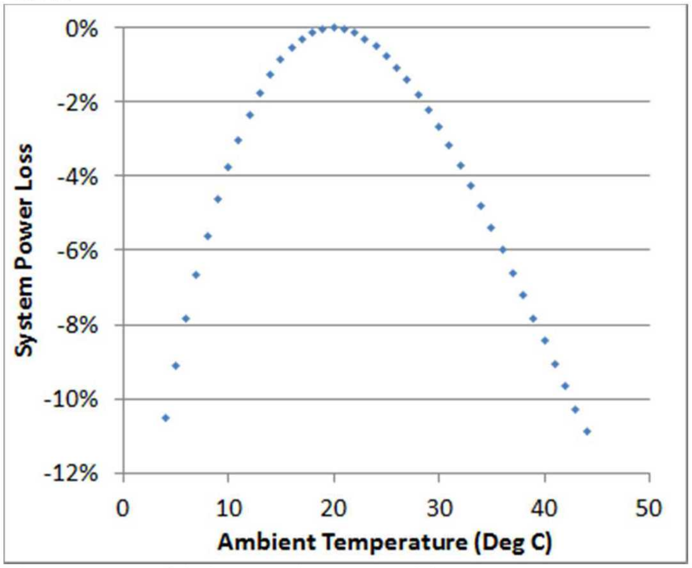

Figure 14. Modeled power loss vs. ambient temperature

CALCULATING THE VALUE OF ELECTRICITY

We calculated the value of the electricity for time-of-use rates using both our simplified and more complex approaches under two different NV Energy time of use schemes. NV Energy, the electric utility that services the greater Las Vegas area, offers its commercial customers different time-of-use rates. The company has the Optional Large General Service-1 Time of Use (OLGS-1-TOU), and the Large General Service-2 (LGS-2) secondary service [7]. We modeled each rate and found that, although the annual energy calculations were within 0.27% of each other, the total annual value of the electricity calculation varied by 2.14% and 0.66% for the OLGS-1-TOU and LGS-2, respectively. We then applied the more complex multi-variable regression equation to calculate the cumulative value of the electricity generated for a single unit, projected out for a timespan of from 10 to 30 years.

The results are included in Table 2, which gives the total value of the electricity produced from a single CPV unit for different time periods using 2016 rates provided by NV Energy, as well as fixed rates of 3 cents and 13 cents per kWh. These values can be used to determine what the total unit cost must be below in order to be cost effective. While the actual total cost numbers are unknown, the 3¢/kWh price results in values that are probably unrealistic, whereas longer terms of from 20 to 30 years produce feasible results for many of the other schemes. When financing is ignored, the time-of-use rates result in an annual average cost of electricity of 7.223 ¢/kWh and 5.885 ¢/kWh for the OLGS-1-TOU and LGS-2 options, respectively.

Table 2. Cumulative value of electricity produced per CPV unit.

	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
10 year	0%	$15,917	$ 68,975	$ 38,326	$ 31,225
	2%	$14,298	$ 61,957	$ 34,426	$ 28,048
	4%	$12,910	$ 55,945	$ 31,086	$ 25,326
	6%	$11,715	$ 50,766	$ 28,208	$ 22,982
	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
20 year	0%	$30,647	$132,805	$ 73,793	$ 60,121
	2%	$25,056	$108,577	$ 60,331	$ 49,153
	4%	$20,825	$ 90,243	$ 50,143	$ 40,853
	6%	$17,576	$ 76,163	$ 42,320	$ 34,479
	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
30 year	0%	$44,190	$191,490	$ 106,401	$ 86,688
	2%	$32,990	$142,957	$ 79,434	$ 64,716
	4%	$25,471	$110,375	$ 61,330	$ 49,967
	6%	$20,276	$ 87,861	$ 48,820	$ 39,775

Our data also show what happens to the value of produced electricity when cell efficiency increases—as is likely—by, say, 5% (see Table 3.) We have already measured maximum measured AC efficiencies above 27% during this study. With a If the maximum AC efficiency increased by 5% to 32%, one can expect an 18.5% increase in energy production and an increase in system profitability.

Table 3. Value of electricity produced by a future CPV unit, assuming an increase in cell efficiency of **5%**

	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
10 year	0%	$18,895	$ 81,880	$ 45,472	$ 37,056
	2%	$16,973	$ 73,549	$ 40,846	$ 33,286
	4%	$15,326	$ 66,412	$ 36,882	$ 30,056
	6%	$13,907	$ 60,264	$ 33,468	$ 27,274
	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
20 year	0%	$36,381	$157,653	$ 87,552	$ 71,349
	2%	$29,744	$128,892	$ 71,580	$ 58,333
	4%	$24,722	$107,128	$ 59,493	$ 48,483
	6%	$20,865	$ 90,413	$ 50,211	$ 40,918
	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
30 year	0%	$52,458	$227,318	$ 126,241	$ 102,877
	2%	$39,162	$169,704	$ 94,245	$ 76,803
	4%	$30,237	$131,027	$ 72,766	$ 59,298
	6%	$24,069	$104,300	$ 57,923	$ 47,203

Our projections of a 5% increase in cell efficiency are not unrealistic; Soitec already holds the current world record for a 46% efficient cell [8].

FIELD COMPARISON BETWEEN SINGLE-AXIS PV TRACKERS AND DUAL- AXIS CPV TRACKERS

In March 2006, the Las Vegas Valley Water District installed an 821kW single-axis tracker PV plant at their Ronzone Reservoir site in the city of Las Vegas. We compared nine years of energy production data from these single-axis trackers with a modeled superimposed field of 32 CPV trackers using the previously generated 3rd degree polynomial regression equation for the CPV units, weather data from the UNLV's weather station [9], and a shading model from May 2006 thru December 2015 (see *Figure 15*). Our objectives were two-fold: to validate the accuracy of our model; and to demonstrate that dual-axis CPV can economically outcompete single-axis PV trackers in geographic regions that have high DNI.

Historical irradiance data for the Ronzone Reservoir site was unavailable so we looked instead at historical weather and irradiance data from the UNLV weather station. The UNLV weather station data from May 2006 to December 2015 was meticulously checked and corrected for problems including missing data, shading of the pyrheliometer and pyranometer, and pyrheliometer tracker issues.

To create a virtual CPV plant on the site, we opted for a grid spacing of 25 meters east/west and 27 meters north/south and chose the number of units that would most appropriately match the existing single-axis field. With 32 CPV units, our modeled field has a DC rating of 896 kW.

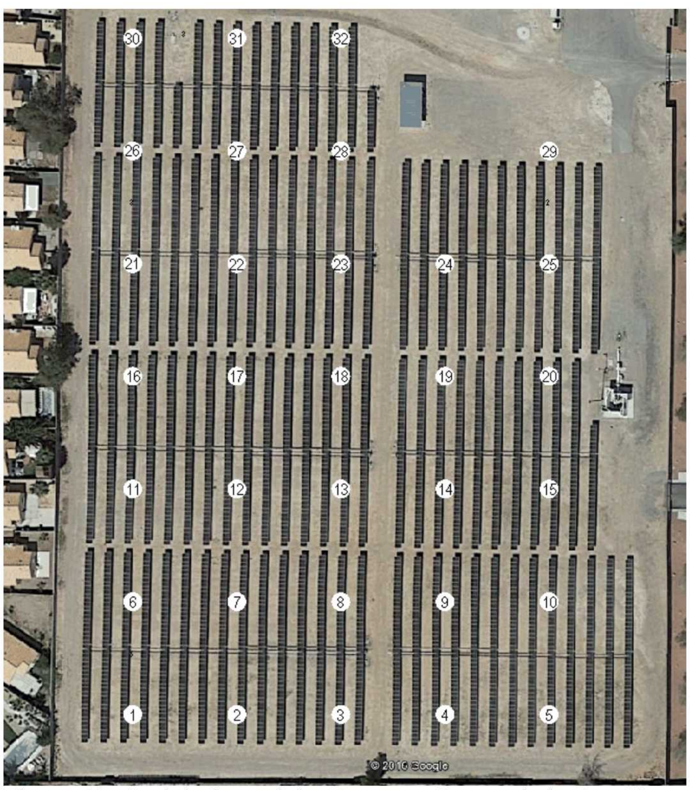

Figure 15. Aerial view of the Ronzone Reservoir in Las Vegas showing single-axis trackers in vertical rows. Numbers indicate locations of modeled CPV units

To compensate for CPV losses attributable to row shading, we developed a shading model in MATLAB® to calculate the shadows each CPV tracker cast on every other tracker in the field. We calculated shading for the field for several cases using both area-weighted and DNI-weighted methods and did not double-count overlapping shadows. Table 4 below gives the field average, unit maximum and unit minimum shading loss in annual percentage loss for the field of 32 CPV units.

Table 4. Field-shading results for different cases in percentage loss

	Field alone	Field alone	w/walls-trees	w/walls-trees	w/walls-trees
	area weighted	TMY3 weighted	area weighted	TMY3 weighted	9 year model weighted
Ave	3.28	1.55	4.39	2.36	1.91
Max	4.55	2.14	10.01	6.45	5.27
Min	0.69	0.43	0.69	0.43	0.16

Our model uses minute-interval data from the UNLV weather station, with shading calculated only for elevations above 5 degrees. Although the PV plant was installed in May 2006, we excluded that half-year from the shading analysis, leaving a complete nine years of data, from 2007 to 2015. Since the TMY3 data was hourly, shading was limited to above 4 degrees to try to minimize error due to the larger time intervals. The average results for the field shading loss when using the TMY3 data and UNLV's weather station data were very close with the TMY3 average being slightly higher. The nine-year modeled shading losses from year to year changed very little, with a maximum unit shading loss standard deviation of 0.25%.

To compare the field model results with the previously calculated value of electricity using the TMY3 data, we replaced the first year 2006 with the average of the following nine years (*See Table 5)*.

Table 5. Comparison of 10-year value of electricity per CPV unit

	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
Field Model	0%	$ 16,316	$ 70,703	$ 36,679	$ 30,893
	2%	$ 14,656	$ 63,509	$ 32,947	$ 27,750
	4%	$ 13,234	$ 57,346	$ 29,750	$ 25,057
	6%	$ 12,009	$ 52,038	$ 26,996	$ 22,737
TMY3	Interest Rate	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 - 2nd
	0%	$ 15,917	$ 68,975	$ 38,326	$ 31,225
	2%	$ 14,298	$ 61,957	$ 34,426	$ 28,048
	4%	$ 12,910	$ 55,945	$ 31,086	$ 25,326
	6%	$ 11,715	$ 50,766	$ 28,208	$ 22,982

Our predicted values of electricity output per CPV unit were fairly close to each other when comparing use of the UNLV weather station data or the TMY3 data. The OLGS-1-TOU rates, however, do not apply to this large a field of CPV units, the output of which can exceed 299 kW. To qualify for OLGS-1-TOU pricing, the CPV plant would have to be about 1/3 the size, with only 11 CPV units. This leaves the LGS-2 as the only remaining time-of-use scheme available for an installation that outputs less than 1000 kW annually.

We also looked at accumulated energy production and accumulated value of the electricity for both the modeled 32 CPV units, using UNLV weather station data (see Table 6) and for the single-axis tracker field (see *Table* **7**.) Note that the numbers in Table 6 have a built-in reduction of 3% the first year and an additional 0.7% reduction in subsequent years. This would amount to approximately one system not functioning for the first year and gradually increasing system losses in subsequent years.

Table 6. Accumulated value of electricity and energy production for modeled CPV field

Year	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 -2nd	MWh
2006	$ 37,924	$ 164,337	$ 97,342	$ 74,486	1,264
2007	$ 93,858	$ 406,718	$ 221,624	$ 180,137	3,129
2008	$149,549	$ 648,044	$ 346,142	$ 285,436	4,985
2009	$202,454	$ 877,300	$ 461,119	$ 384,792	6,748
2010	$256,390	$1,111,021	$ 588,163	$ 488,117	8,546
2011	$311,268	$1,348,827	$ 712,042	$ 592,086	10,376
2012	$366,101	$1,586,439	$ 832,979	$ 695,361	12,203
2013	$419,298	$1,816,957	$ 946,685	$ 794,834	13,977
2014	$470,853	$2,040,362	$ 1,061,212	$ 892,154	15,695
2015	$522,112	$2,262,485	$ 1,173,723	$ 988,569	17,404

Table 7. Actual accumulated value of electricity and energy production for single-axis tracker field

Year	3¢/kWh	13¢/kWh	OLGS-1-TOU	LGS-2 -2nd	MWh
2006	$ 34,572	$ 149,811	$ 109,258	$ 74,147	1,152
2007	$ 84,360	$ 365,559	$ 240,674	$ 174,509	2,812
2008	$132,341	$ 573,479	$ 361,723	$ 269,875	4,411
2009	$181,382	$ 785,989	$ 488,207	$ 368,118	6,046
2010	$231,197	$1,001,853	$ 622,753	$ 469,225	7,707
2011	$278,076	$1,204,998	$ 745,735	$ 563,535	9,269
2012	$326,635	$1,415,420	$ 870,283	$ 660,586	10,888
2013	$374,240	$1,621,705	$ 992,688	$ 755,810	12,475
2014	$419,609	$1,818,307	$ 1,110,246	$ 846,753	13,987
2015	$463,033	$2,006,475	$ 1,222,569	$ 933,764	15,434

After nearly 10 years, the modeled CPV dual-axis trackers produced 1,970 MWh more electricity than the PV single-axis trackers, however the value of that electricity fluctuated, depending on the electricity-pricing scheme. The accumulated value of the electricity for the single-axis tracker field using NV Energy's OLGS-1 time-of-use rate was actually worth $48,846 *more* than the modeled CPV field, but worth $54,805 *less* under the LGS-2 rate. The differences can be explained by higher rates in winter for the LGS-2 versus the OLGS-1 rate and the summer peak rates not worth as much.

In addition, CPV production is more consistent throughout the year whereas the single-axis trackers are more efficient at the higher elevation angles during the summer. However, the OLGS-1-TOU rates would only be applicable if both fields were reduced to 1/3 the size. The value of the electricity over the 10 years for the 1-axis plant was 7.921 ¢/kWh and 6.05¢/kWh for the OLGS-1 and LGS-2 rates respectively while the value of electricity for the CPV field was 6.744¢/kWh and 5.68¢/kWh. At flat rates, the CPV field generates 12.8% more revenue and energy than the single-axis system and 5.9% more revenue with the LGS-2 rates.

O&M CONSIDERATIONS

The O&M costs associated with both CPV and PV systems are important determinants of profitability. If a CPV tracker has a part failure it will almost always stop power generation on that unit, whereas a single-axis tracker may still generate power, although at a reduced rate. Even low-cost parts, such as encoder couplings, can shut down a CPV unit. As a result, CPV manufacturers should guarantee output on their systems for at least 10 to 20 years and also ensure that all nuisance issues are mitigated at the beginning of system installations, so O&M costs will not significantly impact revenue over the long term. We recommend, in fact, that the design phase include a careful evaluation of component costs vs. projected O&M costs, with preference given to higher cost components if they significantly increase reliability.

A rough estimate of O&M costs for the 84kW tracker system at the NV RTC underscores the impact of O&M on lifetime operating costs. In the first evaluation year of operation described here, one tracker has been down 154.6 generation hours; the total of all three is 381.24 generation hours. Technical difficulties have ranged from encoder breakage to inverter wiring problems to module condensation. And while Soitec has been very responsive and helpful, our rough estimate of parts and labors for this period is $755.

In addition, the three units need to be cleaned regularly to maintain their efficiency, especially in the arid dusty environment typical of Nevada and other parts of the US Southwest. With a cleaning schedule of once every six weeks, our cleaning costs for a single unit on a per cleaning basis for the first year, which included purchase of a deionized filtration tank, resin, fiberglass cleaning pole, and a labor rate of $20/hour was $70.60/cleaning/unit. Costs dropped in subsequent years, when only resin refill kits had to be purchased, which brought the cleaning cost down to $39.66/cleaning/unit.

Overall, we believe that investing in reliability and therefore trimming O&M costs will result in significant soft-cost reductions and could increase not only a system's profitability but its attractiveness to potential customers.

CONCLUSIONS

1. Our model can accurately predict the power and energy output of a single Soitec CPV unit based on incident direct normal irradiance, ambient temperature and wind speed. The data can then inform revenue projections and help prospective

developers determine the maximum reasonable cost for the installed system.

2. The TMY3 dataset for Las Vegas provided close estimates of CPV performance and revenue generation over a 10-year period when compared to estimates using a much shorter-interval dataset with one-minute data.

3. Future increases in cell efficiency will greatly increase revenue generation of future CPV systems.

4. Comparing the performance of a similarly sized dual-axis CPV field with a single-axis tracker PV field, shows the CPV field will produce about 12.8% more energy and revenue under fixed electric-pricing schemes and 5.9% more revenue under NV Energy's Large General Service 2 rates.

5. O&M costs will ultimately determine whether CPV systems maintain a revenue advantage and must be reduced as much as possible to be economically viable.

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NOMENCLATURE

A	CPV unit aperture area (m^2)
AC	Alternating current
$AC\ Energy_{gen}$	daily AC energy generation (kWh)
$AC\ Energy_{par}$	daily parasitic AC energy consumption (kWh)
CPV	Concentrated photovoltaics
DNI	direct normal irradiance (W/m^2)
I_{gen}	solar insolation during generation (kWh/m^2)
I_{total}	total daily solar insolation (kWh/m^2)
W	power (Watts)
kWh	energy (kilowatt hours)
LGS	Large General Service
m/s	meters per second
NIP	Normal irradiance pyrheliometer
OLGS	Optional Large General Service
PV	Photovoltaics
T_{amb}	Ambient temperature (°C)
TOU	Time of Use
TMY	Typical meteorological year
WS	Wind speed (m/s)
¢	cents in US currency
η	Efficiency
$	dollars in US currency

[i] In 2015, Soitec announced the closing of its solar division and is no longer manufacturing CPV tracker systems but has donated the 84kW NV RTC tracker system to UNLV for research purposes.

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