

ENERGY PRODUCTION OF CPV POWER PLANTS AT ISFOC

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ABSTRACT

Concentrator Photovoltaic (CPV) technology is on the brink of large-scale deployment in the solar market following the completion of technology demonstration programs such as the ISFOC in Spain. SolFocus has installed first-generation CPV systems totaling 0.5 MW peak AC capacity at two separate CPV plants. This paper describes the advantages of SolFocus' 500x reflector-based concentrator design and specifications for the panel, system, and plants. These CPV systems have demonstrated advantages over conventional PV on a kWh per kW basis due to its high efficiency design, dual-axis sun tracking, and high temperature performance. At the plant level, the site was optimized for energy production by maximizing array spacing and selection of inverter architecture. Based on the IEC-defined set of concentrator standard test conditions (CSTC), the power ratings was determined by taking on-sun measurements and normalizing the data to CSTC using empirical and theoretical methods. At DC peak power, the systems measured above specifications at CSTC. Predictions of plant production were calculated based on peak installed capacity, solar insolation, and the kWh/kWp ratio. Actual plant production for a clear, high DNI day was measured and resulted in plant output of over 95% of the design specifications. The DC and AC power generation measured at SolFocus' 0.5 MW installation validates the energy capabilities of CPV systems.

ISFOC PROJECT

Project Goals

The installation of concentrating photovoltaic (CPV) plants in Central Spain was initiated by Instituto de Sistemas Fotovoltaicos de Concentración (ISFOC) through an R&D project sponsored by the Ministry of Education and Science in the autonomous government of Castilla La Mancha [1]. With 3MW of CPV plants consisting of 7 different designs, the goal of the ISFOC program is to promote the industrialization of CPV technology through demonstration of reliability, performance, and pilot manufacturing.

SolFocus was awarded two CPV plants totaling 0.5MW of installed peak AC power. SolFocus delivered turn-key CPV systems providing energy to the transformer. The first site, with a CPV plant capacity of 200kW_{ac}, was located at Puertollano and a second site, of 300kW_{ac} capacity, was located at Almoduvara. Each site had distinct field conditions and solar radiation described herein. The ISFOC headquarters was located at Puertollano which was co-located with 3 different CPV technologies which shared a common grid connection point and meteorological data station. The Almoduvara site was dedicated for SolFocus CPV systems.

Site Specifications

The specifications for Site #1 (Puertollano) and Site #2 (Almoduvara) are shown in the Table I. The plant ratings were based on the sum of inverter capacities which defines the maximum AC power delivered to the grid. This is the requirement for the permit to receive feed-in-tariffs under the the Spanish Royal Decree 661/2007 and limits the maximum amount of AC electricity delivered to the grid for feed-in tariff revenues.

	Site #1	Site #2
Location	Puertollano	Almoduvara
Systems	33	54
AC Plant Rating (kW _{ac})	200	297
% Annual Shading	< 4%	< 2%
Inverters	33	27

Table I. Site Specifications for CPV Plants

Both sites were optimized for maximum energy generation through array spacing and inverter selection. Shading analysis was computed using commercial PV system design software [2]. Site #1 had land constraints of 0.9 hectares, therefore east-west spacing was maximized to minimize annual energy losses to <4%, assuming linear shading losses. Site #2 had annual energy losses of <2% based on a larger area of 2.1 hectares.

The inverters for the CPV plants were selected to reduce the effects of partial shading and intermittent cloud cover. In CPV optical designs, only the direct normal incident (DNI) light can be captured and power generation is sensitive to changes in direct sunlight to poorly collected diffused sunlight. Reduced DNI and increased diffuse light from shading and clouds will result in inverter operation outside of their maximum power point tracking (MPPT). In extreme cases, inverters will shut down with sudden voltage drop and require up to 5 minutes to re-start. For conventional solar fields, MW-sized PV plants utilize central inverter schemes where fixed-tilted Silicon and Thin Film systems continue to operate under extreme diffuse line conditions. If applied to a CPV plant design, a centralized inverter scheme may have issues when the operation of a single CPV system could affect the rest of the plant and reduce the energy generated in situations with excessive shading and cloud cover. Therefore, to minimize these inverter losses, Site #1 had one inverter per array while Site #2 had one inverter for every two arrays.

SF-1000 CPV DESIGN

Optical Design

The SF-1000 concentrator design is SolFocus' first generation CPV optical design (see Figure 1). The basic power unit consists of a set of reflective optics that includes a primary mirror, secondary mirror, and tertiary optical rod to channel the direct beam light towards a highly efficient III-V solar cell. All the optics are manufactured from glass which makes the system extremely stable, especially at high temperatures, and compatible with volume manufacturing, similar to automotive headlamp industry.

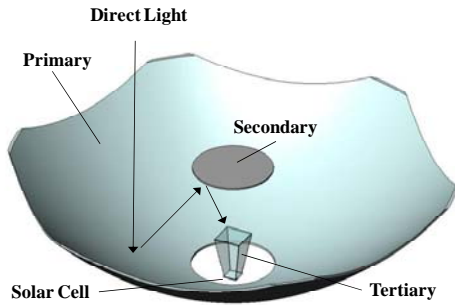


Figure 1. SolFocus SF-1000 optical design

The optical efficiency for the power unit is up to 85% for light rays making the path from the primary mirror to the cell. The concentration ratio of 500 times (500x) is the light intensity on the primary mirror area compared to the cell area, and includes losses in reflectance, absorption, and scattering. The power is generated from the multi-junction solar cell consisting of InGaP/GaAs/Ge with an efficiency of approximately 35% under 500x concentration.

The acceptance angle is defined as the angle of incidence away from normal where the power is 90% of maximum power (see Figure 2). The SF-1000 concentrator has an acceptance angle of +/- 1 degree which is the widest among commercially-available CPV panels. The flat profile of the acceptance angle allows the SF-1000 to maintain the power output over the angular range within with acceptance angle limits.

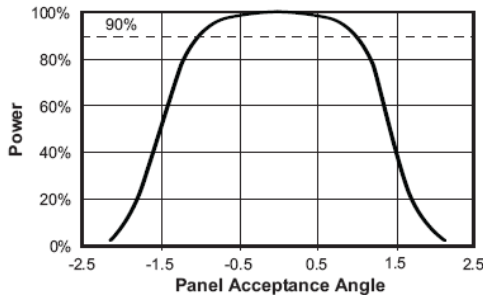


Figure 2. Acceptance angle of the SF-1000 power unit

Panel and System Design

The SF-1000P panel integrates 16 power units and is rated at 210W based at Concentrator Standard Test Conditions (CSTC). Based on the active area of the panel, the SF-1000 conversion efficiency is >23%. A summary of the panel and system specifications are shown in Table II.

Specification	Value
Panel Peak Power (W)	210
System DC Power (W)	6150
# Panels	30
Integration Losses	2%

Table II. SF-1000 panel and system specifications

At the system level, 30 panels are integrated into an array, with 10 panels connected in series and 3 strings connected in parallel. The system power is specified at 6.15kW peak DC based on nominal 210 W panels, less losses from mispointing and mismatching. The aperture is 46m² and is designed for a maximum flexure of 0.3 degrees under wind load. Under normal operation, the tracker control system will track until the wind speed reaches 36km/hr and can withstand a maximum wind condition of 100km/h4. The tracker pointing accuracy achieves 0.1 degrees from the tracker controller algorithms and mechanical drive. In comparisons to flat PV trackers with accuracy between 1-5 degrees off-axis, the CPV tracker is up to 50 times more accurate.

POWER RATING AND NORMALIZATION

Concentrator Standard Test Conditions (CSTC)

Under the International Electro-technical Committee (IEC) 62108 [3], a set of test conditions for ratings called Concentrator Standard Test Conditions (CSTC) is being developed for on-sun outdoor measurements. As shown in Table III, the CSTC is based on direct solar irradiance of 850 W/m², different from flat-plate PV standard test conditions (STC) of 1000 W/m² global solar irradiance. The ratio of the direct to global radiation was chosen at 85% from a NREL study in the Southwest United States [4].

Parameter	Value
DNI (W/m2)	850
Ambient Temperature (°C)	20
Wind Speed (m/s)	< = 4%
ASTM Spectrum	G173

Table III. CSTC Rating Conditions

Indoor measurement test conditions for concentrators have yet to be determined since there are no standards for concentrator simulator requirements of

collimation, uniformity, spectrum, and temperature conditions. Independently CPV manufacturers have developed simulators for their own testing [5] and several are being commercialized.

Normalizing On-Sun Measurements

At Site #1, system DC power measurements were taken on-sun and normalized to CSTC. Both empirical and theoretical methods were employed to compare variability of the power ratings at CSTC.

The empirical method utilized a temperature coefficient interpolated from array voltage measured with panel temperature. The measured power was then normalized for temperature and DNI to CSTC using the following equation:

$$P_{emp} = (1 + (T_{meas} - T_{CSTC}) * dP/dT * P_{meas} * (B_{CSTC}/B_{meas})) \quad (1)$$

where T_{meas} is the panel temperature at test, T_{CSTC} is panel temp at 20°C ambient condition (CSTC), dP/dT is the experimentally derived panel power temperature coefficient, and B is the irradiance of CSTC or at test.

For the theoretical method, the measured voltage and current pairs (V_i, I_i) of a panel i-v curve are transformed to CSTC, according to the theoretical temperature variation of the open circuit voltage ($V_i + \Delta V_i, I_i \times B_{CSTC}/B_{meas}$). The open circuit voltage variation is described by the equation [6] below, with inputs as shown in Table IV.

$$\Delta V_i = N \frac{0.0257 \times (T_{CSTC} - T_{meas})}{297} \left[\ln \left(\frac{I_{SC,meas} - I_{SC,CSTC}}{I_{SC,meas}} \right) \right] \quad (2)$$

$$+ \left[N(E_{g1} + E_{g2} + E_{g3}) - V_{oc,meas} \right] \left(1 - \frac{T_{CSTC}}{T_{meas}} \right)$$

Item	Meaning	Value
N	Number of cells in system	480
T_{CSTC}	Cell temperature at CSTC	60°C
T_{meas}	Cell temperature, actual	Measured
$I_{SC,meas}$	Short circuit current at operation	Measured
$I_{SC,CSTC}$	Short circuit current at CSTC	15.9 A
$E_{g1} + E_{g2} + E_{g3}$	Cell band gap	3.93 V
$V_{oc,meas}$	Open circuit voltage at operation	Measured

Table IV. Inputs for theoretical calculation of CSTC-normalized voltage from measured values.

The results of the two normalization methods are shown in Figures 3 and Figure 4 for DNI and Temperature. Comparing empirical and theoretical methods, the difference between normalization methods is 1.3%.

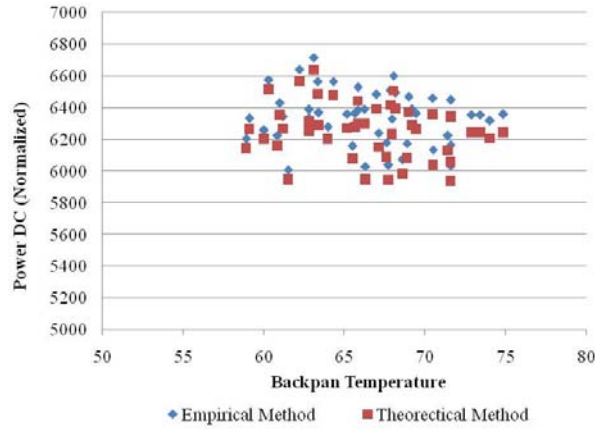


Figure 3. Normalized array power as a function of panel temperature

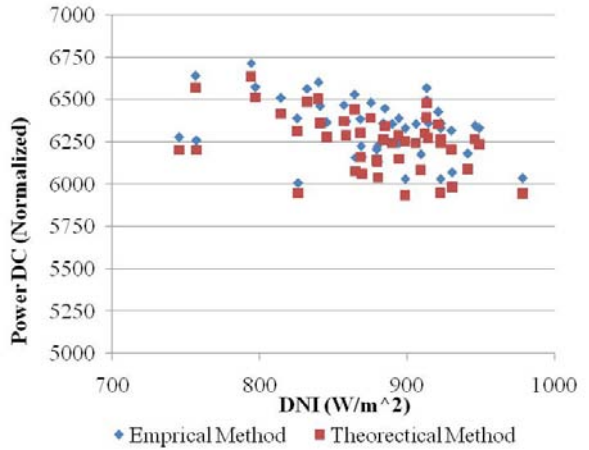


Figure 4. Normalized array power as a function of DNI

Power Rating Compared to Design Specifications

At Site #1, the DC power peak power for 33 systems were individually measured and normalized to CSTC and averaged 6.2kWdc (see Figure 5). These systems performed above the design specification of 6.15kWdc (annotated by the dashed line). The standard deviation for DC power rating over the population was 2%, illustrating a tight manufacturing of panels at the factory and assembly of systems in the field.

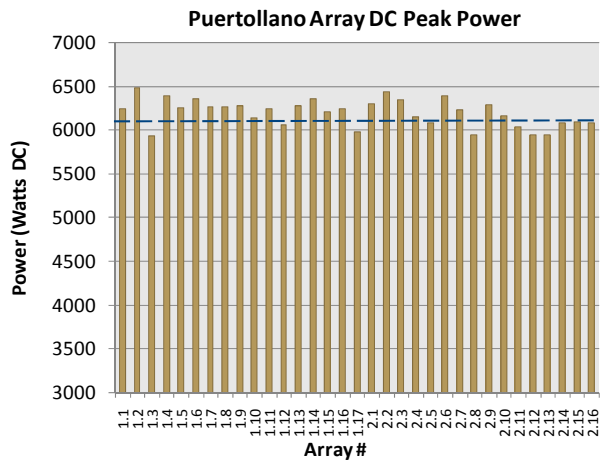


Figure 5. DC peak power for 33 Systems at Puertollano

KEY PERFORMANCE ASPECTS OF INSTALLED CPV SYSTEMS

Temperature Performance

The reduced temperature degradation of SolFocus' systems is a key performance aspect. Based on glass optics and III-V solar cell which are extremely stable with temperature, the array voltage was plotted as a function of panel temperature (see Figure 6). Through data interpolation, the voltage coefficient (dV/dT) was determined to be $-1.26V/^{\circ}C$ which translated to a power coefficient (dP/dT) of $-0.17\%/^{\circ}C$.

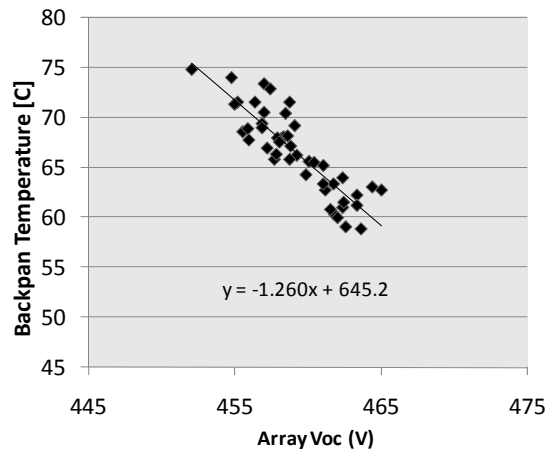


Figure 6. Interpolation of power temperature coefficient for the SF-1000 CPV system

Comparing to conventional PV, the power temperature coefficient is $-0.48\%/^{\circ}C$ for multi-crystalline Silicon panels, not systems, is three times that of SolFocus' CPV systems. At the system level for PV panels, the temperature degradation would be even higher due to the larger number of panels, each with some variation in performance. Therefore, the power output for

CPV systems is shown to be more stable with temperature and has the best performance of PV systems at high temperatures.

DC-AC Losses

While the panels were rated 210W, the systems are are rated at DC peak power at 6.15kW due to DC integration losses. The AC peak power specification is 5.78kW after inverter, dirt, and down-time loss factors shown below.

30 Panels Max Output	6.3kW
Mismatch	-2%
Misalignment	-1%
DC Losses	-3%
DC Peak Power	6.15kW
Inverter	-3%
Dirt	-2%
Downtime	-1%
AC Losses	-6%
AC Peak Power Spec	5.78kW

Table III. SF-1000 CPV system Peak Power Specs

The DC and AC loss factors were estimated at 3% and 6%, respectively. The systems were assumed to be operating at CSTC with no temperature degradation loss therefore even higher energy could be generated in areas where average annual temperatures are below $20^{\circ}C$ ambient on average.

Energy Calculations and kWh/kWp

The energy production was calculated for each site based on the simple equation below:

$$Energy\ Prod = AC\ Peak\ Capacity \times DNI \times (1/0.85) \quad (3)$$

Energy production was calculated for each site (see Table IV) based on equation (3). The 1/0.85 factor accounts for the translation of CPV systems rated at $850W/m^2$ to output $1000W/m^2$ DNI. Therefore for each kWh DNI, the systems will be producing their (AC or DC) peak capacity for 1 hr. For DC power, systems rated at 6.15kWdc at $850W/m^2$ will produce 7.24kWdc at $1000W/m^2$ for each kWh DNI. Likewise for AC power, systems rated 5.78kWac at $850W/m^2$ will produce 6.80kWac at $1000W/m^2$.

The Almuquera site is expected to have almost twice the electricity production than Puertollano site because of the larger installed AC peak capacity, higher DNI, and less shading. This is represented by the annual energy production per peak DC power installed (kWh/kWp) (Table V). Compared with conventional PV, typical fixed flat-plate systems using 13% panels offer 1200-1500kWh/kWp at the same Global irradiation conditions.

	Site#1: Puertollano	Site#2: Almoguera
DNI (kWh/m ²)	5.1	5.4
Yearly kWh/kWp	2059	2180
# Systems	33	54
Peak DC Capacity (kWdc)	203	332
Peak AC Capacity (kWac)	191	312
Annual Energy (MWh)	416	728

Table V. Energy Calculations for CPV plants

The AC peak capacity of the Almoguera plants is greater than the maximum permitted inverter capacity, therefore the inverters maximize the inverter capacity and annual kWhs produced. For both sites, the total annual energy production is expected to be over 1GWh. The monthly average and cumulative MWhs are shown in Figure 7.

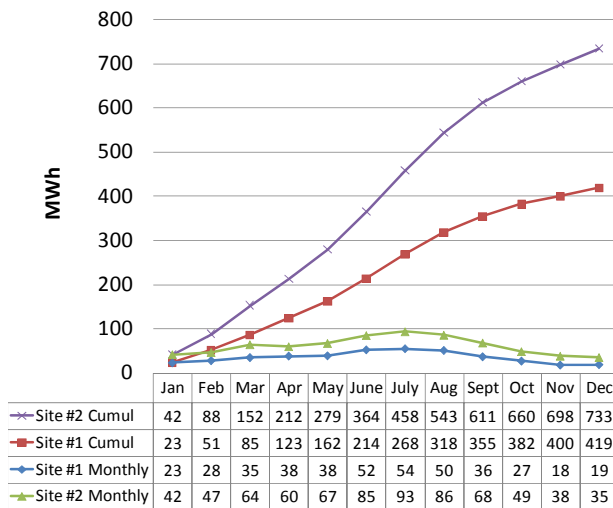


Figure 7. Monthly and cumulative energy production for CPV Plants

ENERGY PRODUCTION AT PLANTS

Site #1 was tied to the grid in October 2009. AC measurements are in progress to validate the Energy Production model. Initial results show an average of 5.5 kWac per system, normalized to 850 W/m², compared to an expectation of 5.78 kWac.

In Figure 8, a daily energy production was selected for a good day with high DNI where the peak solar insolation was above 900W/m² from the pyroheliometer measurements. The power output reached above the 192kWac rating since the solar insolation exceeded the AC rating at 850W/m². When normalized to CTSC conditions, the systems output reached an average >95% of the AC plant specification.

As shown in the middle of the day, normalization was conducted only when the DNI was above 700W/m² where the DNI measurements and correlation were reliable. Further study into the effects of low DNI condition

and spectral effects (at the beginning and ending of the day) is being investigated and will be reported in the future.

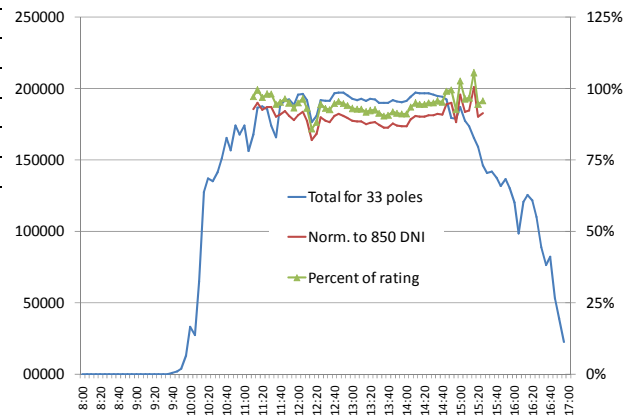


Figure 8: A Daily Energy Production at Puertollano

CONCLUSIONS

Over 0.5MW of SolFocus' CPV systems have been deployed in Castilla La Mancha, Spain at two plants capable of generating over 1GWh/yr. The systems were characterized with on-sun measurements and resulted in performance above DC peak power specifications. Two methods for normalizing temperature and DNI back to CSTC conditions, defined by IEC for rating systems, proved to be within 2% difference of each other. Using the empirical method, the system and plant ratings were calculated for DC and AC peak power and used to predict energy production.

It been demonstrated that the advantages of CPV are the following:

- High Temperature Performance
- High Efficiency Potential
- Tracking for Increased Energy Production
- kWh/kWp in high DNI conditions

From the initial grid connection data, the plant at Site #1 has performed >95% of specifications on a good good DNI day. This performance illustrates that SolFocus' CPV systems can offer high kWh/kWp in high DNI conditions beyond that of conventional and leading edge PV systems.

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