Energies **2012**, *5*, 770-789; doi:10.3390/en5030770

OPEN ACCESS
energies
ISSN 1996-1073
www.mdpi.com/journal/energies

Article

Analysis and Prediction of Energy Production in Concentrating Photovoltaic (CPV) Installations

Francisco J. Gómez-Gil [1,*], Xiaoting Wang [2] and Allen Barnett [3]

[1] Department of Electromechanical Engineering, University of Burgos, Burgos 09006, Spain
[2] Department of Electrical and Computer Engineering, University of Delaware, Newark, DE 19716, USA; E-Mail: xiaoting@udel.edu
[3] School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney 2052, Australia; E-Mail: allen.barnett@unsw.edu.au

* Author to whom correspondence should be addressed; E-Mail: fjggil@ubu.es; Tel.: +34-947-258918; Fax: +34-947-259088.

Received: 23 January 2012; in revised form: 29 February 2012 / Accepted: 12 March 2012 / Published: 16 March 2012

Abstract: A method for the prediction of Energy Production (EP) in Concentrating Photovoltaic (CPV) installations is examined in this study. It presents a new method that predicts EP by using Global Horizontal Irradiation (GHI) and the Photovoltaic Geographical Information System (PVGIS) database, instead of Direct Normal Irradiation (DNI) data, which are rarely recorded at most locations. EP at four Spanish CPV installations is analyzed: two are based on silicon solar cells and the other two on multi-junction III-V solar cells. The real EP is compared with the predicted EP. Two methods for EP prediction are presented. In the first preliminary method, a monthly Performance Ratio (PR) is used as an arbitrary constant value (75%) and an estimation of the DNI. The DNI estimation is obtained from GHI measurements and the PVGIS database. In the second method, a lineal model is proposed for the first time in this paper to obtain the predicted EP from the estimated DNI. This lineal model is the regression line that correlates the real monthly EP and the estimated DNI in 2009. This new method implies that the monthly PR is variable. Using the new method, the difference between the predicted and the real EP values is less than 2% for the annual EP and is in the range of 5.6%–16.1% for the monthly EP. The method that uses the variable monthly PR allows the prediction of the EP with reasonable accuracy. It is therefore possible to predict the CPV EP for any location, using only widely available GHI data and the PVGIS database.

Keywords: concentrating photovoltaics; CPV; energy production; prediction; analysis

1. Introduction

Concentrating Photovoltaic (CPV) technology concentrates solar radiation onto high efficiency Photovoltaic (PV) cells. In 2008, this technology underwent large-scale deployment with the installation of new plants. Spain houses 15 MW of total global CPV power, which amounted to approximately 20 MW CPV in 2009 [1]. The development of CPV will depend, amongst other points, on it offering the same predictability in Energy Production (EP) as flat plate PV.

Two of the main types of CPV technologies in Spain are Amonix-Guascor Foton and Concentrix installations. The Amonix-Guascor Foton installations house silicon cell-based systems while the Concentrix installations have multi-junction solar-cell-based systems. To our knowledge, published research on EP in CPV installations is very limited. The EP of Amonix CPV installations is analyzed in [2] and a method for predicting the EP in Concentrix CPV installations is presented in [3]. Finally, the real EP of several CPV installations is reported in [4–6].

The Amonix web page presents several pieces of research on real installations. These report the total EP of several installations at different locations and times, but only contain partial data that is insufficient for an EP study [2]. The earliest Amonix publications examine the performance of the high efficiency Amonix back contact Si cells in CPV and in space applications under high concentration conditions [7–10]. Their back contact Si cells are based on the previous works of Lammert, Swanson and Sinton [11–13]. The Amonix CPV system and the improvements and refinements made to its hardware are described in [14]. EP estimates and costs are given in [15], but no real EP data is provided. However, there are articles that can provide information on the real performance. [16,17] report correlation between output power and DNI. This output power was measured at the module output, and does not take into account losses in the wiring and the inverter. The latest works from Amonix focus on multi-junction operation in CPV systems [18–21], although they do not report real EP data, but provide only EP predictions for several locations [18,20].

The Concentrix web page presents several scientific papers. Some [22,23] describe the Concentrix company, its evolution from the Fraunhofer ISE and Ioffe-Institute, and its Flatcon technology. Others explain the use of III-V solar cells in the Concentrix system. Sun tracking and accuracy considerations are covered in [24,25]. Since multi-junction solar cells are very sensitive to the spectrum, a model for EP simulation is presented that takes the spectrum into account [3]. The utilization of secondary optics in a new Concentrix CPV system is explained in the context of the performance of this system [26].

Previous comparative studies by our team have focused on the energy production (EP) of four photovoltaic system configurations: fixed, 1-axis and 2-axis tracking flat plate, and concentrating photovoltaics (CPV) [27–29]. It was found that, in comparison with the fixed flat plate systems, 1-axis and 2-axis tracking flat plate systems have less annual EP gain than theoretically predicted. The EP from CPV systems is quite close to that from fixed flat plate systems. Moreover, the analysis also shows the PR decreases in the order: fixed, 1-axis, 2-axis tracking flat plate, CPV.

Our team has presented preliminary results of this work in [30]. In the present work, we add quantitative information to the figures that were mentioned in previous work. Additionally, more details that were not mentioned before but are important for the readers to repeat all the calculation and fully understand the methodology have been added.

Overall, little research has been published on EP analysis and prediction in CPV installations. Moreover, in order to predict the EP for a CPV installation, Direct Normal Irradiation (DNI) must be measured over a lengthy period of time, nevertheless DNI is not a widely measured parameter. In contrast, Global Horizontal Irradiation (GHI) data and the PVGIS database are widely available.

Therefore, the aim of this study is to analyze the EP of CPV installations and to present a method for its prediction, by using GHI data and the PVGIS database, rather than real DNI data measurements. First, a method of predicting monthly EP at each installation is proposed, assuming a constant PR, and estimating the DNI from PVGIS database and weather stations. Second, a lineal model for each type of installation-Amonix and Concentrix- and a new method that implies a variable monthly PR over the year are presented.

2. Methods

2.1. CPV Installations Analyzed

Four Spanish CPV installations are analyzed (Figure 1). Two are based on silicon solar cells (Amonix-Guascor Foton installations), and the other two based on multi-junction III-V solar cells (Concentrix installations).

Figure 1. Locations of the analyzed installations.

2.1.1. Amonix-Guascor Foton Installations

2.1.1.1. Villafranca CPV Installation

The 7.8 MW CPV power plant located in Villafranca (Navarra, in northern Spain), was grid connected in 2008. It is the world's largest CPV installation, despite its location receiving poor irradiation. The Photovoltaic Geographical Information System (PVGIS) database reports an annual average of 1439 kWh/m^2 DNI. Each unit system is called a tower that has power of 25 kW. The reported EP comes from 23 of the total 313 towers housed by the installation. Irradiation data from six weather stations (Barranco, Yugo, Cadreita, Funes, Traibuenas and Plano) surrounding the CPV installation location are available. These stations are located around the installation within a distance of 8 km [31].

2.1.1.2. Écija CPV Installation

The 1.5 MW CPV power plant at Écija, in the province of Seville, southern Spain, was grid connected in 2008. Situated 600 km from the Villafranca installation, it is the second largest in the World and operates with the Amonix-Guascor Photon CPV system. Écija is known as "la sartén de España" (the Spanish frying pan), because of its hot weather, and the location receives high levels of irradiation. The PVGIS database reports an annual average of 1880 kWh/m^2 DNI. The EP provided by the 60 towers in the 1.5 MW CPV installation is given in kWh/kW. In contrast, the EP estimate of the Écija CPV for an average year from the PVGIS database is 1659 kWh/kW.

2.1.2. Concentrix Installations

2.1.2.1. Puertollano CPV Installation

The CPV power plant located at the Institute for Photovoltaic Concentration Systems (ISFOC) in Puertollano (in southern Spain), was grid connected at the end of September 2008. This location is a good irradiation location. The PVGIS database reports an annual average of 1894 kWh/m^2 DNI. The installation has 18 sun trackers, each with a power of 5.75 kW [5].

2.1.2.2. Seville CPV Installation

The CPV installation located in Sanlúcar la Mayor, close to Seville in southern Spain, is also located at a good irradiation location. The PVGIS database records an annual average of 1944 kWh/m^2 DNI. The CX-P6 system began operation at the end of April, 2008.

2.2. Procedure

2.2.1. Data Collection of Real Energy Production for 2009

Monthly EP data were obtained from installation owners and from published works. The real 2009 EP data for the two Amonix installations were directly reported by the owners. Data on the Villafranca installation were published in [32]. Real EP data for the Puertollano CPV installation were taken from ISFOC and Concentrix papers [5,6]. Finally, real EP data from the Seville CPV installation were taken from Concentrix papers [4] that reported the monthly cumulated yield of the power plant.

2.2.2. Calculation of Estimated Direct Normal Irradiance (DNI)

Real-time DNI is needed rather than the DNI of an average year, in order to predict the EP of the CPV installation for a given year. However, as DNI is not a widely measured parameter, this article proposes calculating DNI by using real-time GHI, a parameter that is measured at most weather stations [31].

It is assumed that 2009 monthly DNI increments with respect to an average year will be the same as the 2009 monthly GHI increments. The irradiation data for an average year is taken from the PVGIS database. 2009 real GHI data from weather stations are averaged for each month and compared to the monthly GHI from the PVGIS database. The ratio is then applied to the monthly DNI from the PVGIS database to calculate the 2009 monthly DNI:

$$DNI_{09} = DNI_{PVGIS} \cdot \frac{GHI_{09}}{GHI_{PVGIS}} \quad (1)$$

2.2.3. Calculation of the Estimated Performance Ratio (PR)

Using the estimated 2009 DNI and the real 2009 EP, the PR of an installation can also be estimated. This parameter takes into account the global effect of losses due to temperature, the incomplete utilization of the irradiation and the failures or efficiency losses of the system components. PR, as indicated in IEC 61724 [33], is calculated as:

$$PR = \frac{Y_f}{Y_r} = \frac{E_U \cdot G_{I,ref}}{P_0 \cdot H_I} = \frac{EP \cdot 850}{DNI_{09} \cdot 1000} \quad (2)$$

where:

- Y_f, the final yield, is the daily portion of energy supplied to the grid per 1 kW of the installed PV array. $Y_f = \frac{E_U}{P_0}$ is in hours per day (h/d) and represents the number of hours per day that the system needs to operate at its PV array's rated power, P_0, to generate the same daily energy that was supplied to grid E_U. In this case, rated power, P_0, is alternating current (AC) rated power not peak power.
- Y_r, the reference yield, is the total daily in-plane irradiation normalized to the PV module's in-plane reference irradiance $G_{I,ref}$. $Y_r = \frac{H_I}{G_{I,ref}}$ is in h/d and represents the number of hours per day that the solar radiation would need to be at reference radiation levels, in order to contribute the same incident energy. CPV is usually rated at $G_{I,ref}$ = 0.85 kW/m^2. H_I is the number of hours per day that the installation would have experienced at a constant radiation of 1 kW/m^2.

2.2.4. Energy Production Estimate for Averaged Year with Constant Performance Ratio

The EP is estimated for an average year for each CPV installation using data from PVGIS and the U.S. National Aeronautics and Space Administration (NASA) databases. The estimates assume that the systems are working with a constant Performance Ratio (PR) of 75%. PR is defined in [33] and is presented in Equation 2. Only estimated monthly DNI is considered as the input.

2.2.5. Energy Production Prediction in 2009

Two methods are used to predict the estimated EP for 2009. In the first method, a constant Performance Ratio (PR) is used together with the estimation of Direct Normal Irradiation (DNI). In the second method, a variable PR model is used along with the monthly DNI estimation.

2.2.5.1. First Prediction Method: Constant Performance Ratio

Applying the estimated monthly DNI in 2009 in the previous step, the EP is predicted for that year by assuming a constant monthly PR of 75%. For each month, the PR is multiplied by the estimated monthly DNI, and multiplied by a factor 1000/850 to take in account the 850 W/m^2 rating of the CPV systems:

$$EP = DNI \cdot PR \cdot \frac{1000}{850} \tag{3}$$

2.2.5.2. Second Prediction Method: Variable Performance Ratio

A lineal model is proposed that correlates the monthly EP with the estimated DNI, in order to predict the EP of the CPV installation for any given year. The model is built with the real data from 2009 of the two types of installations—Amonix and Concentrix. First, the monthly DNI is estimated as described in the previous section. Secondly, the regression line of the 2009 monthly EP is extracted and DNI is estimated (Equations 4 and 5). Finally, the regression line equation is applied to the estimated monthly DNI for the desired months.

2.2.6. Energy Production Comparisons

Finally, the real 2009 EP data for the four installations were compared to EP predictions using the two proposed methods. The comparison is made on an annual and monthly basis:

- The annual percentage difference between predicted and real monthly EP, is the annual error in the EP prediction, divided by the real annual EP.
- The monthly percentage difference between predicted and real monthly EP, is the sum, in absolute values, of the monthly EP prediction errors, divided by the real annual EP.

3. Results

The real EP in 2009, the EP predictions using both methods for the four installations, and their respective comparisons are presented below.

3.1. Method 1: Prediction Supposing Constant Performance Ratio

This section presents the first method of estimating the monthly EP, assuming that the monthly PR was constant throughout the year, regardless of irradiance. It also presents an EP estimate of an average year, assuming a constant monthly PR.

3.1.1. Amonix-Guascor Foton Installations

3.1.1.1. Villafranca, 7.8 MW CPV Installation

The monthly EP estimates for an average year using PVGIS and NASA databases, and real EP for the Villafranca CPV installation in 2009 are presented in Figure 2 and Table 1. The annual DNI from the NASA database is 12.7% greater than that from PVGIS. However, the PVGIS database covers 1981 to 1990 and more recent data (1983 to 2005) from the NASA database [34] indicates that the PVGIS might underestimate actual average irradiation.

Figure 2. Real monthly EP in 2009 and EP estimates using PVGIS and NASA databases, for the Villafranca CPV installation.

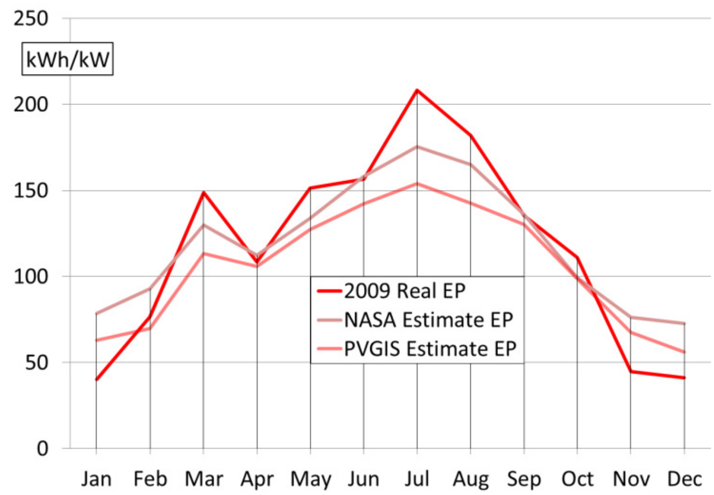


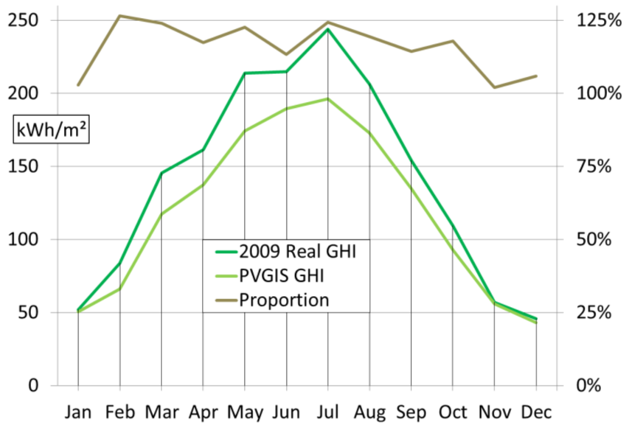
Table 1. Annual EP estimates using PVGIS and NASA for an average year, real EP in 2009, and predicted EP in 2009 using constant PR, at the Villafranca CPV installation.

	Energy Production kWh/kW	Ratio
PVGIS estimate for averaged year	1269	90.4%
NASA estimate for averaged year	1430	101.9%
2009 real	1403	100.0%
2009 prediction constant PR	1489	106.1%

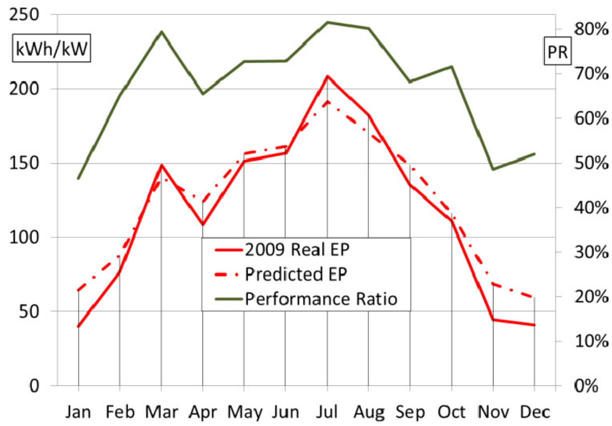
The difference between the PVGIS estimate and the real EP in 2009 is 9.6% for the annual EP, and 18.1% for the monthly EP. This difference is because data on one year may not be compared with the average data given by PVGIS or NASA databases.

Figure 3 presents the 2009 monthly GHI from PVGIS, and from weather stations near the Villafranca CPV installation. The ratio of the latter to the former is also presented. Annual GHI, calculated by integrating the area under the curves, is 17.9% greater for the real weather station data than for the average data from the PVGIS database.

Figure 3. (**a**) Real GHI, PVGIS GHI, and real/PVGIS GHI in 2009; (**b**) Real EP, EP prediction based on constant PR, and estimated PR values for Villafranca CPV installation in 2009.



(**a**)



(**b**)

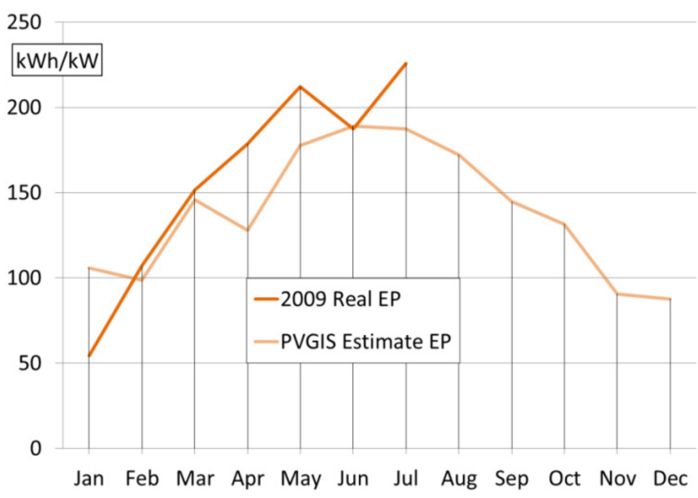
With the estimated monthly DNI for 2009, the monthly EP can be calculated by assuming a constant PR of 75% as described in the Section 2 (Methods). Figure 3b and Table 1 present the predicted EP, and compare it to the real EP. The difference between the prediction and the real data is 6.1% for the annual EP and 11.3% for the monthly EP.

The 2009 monthly estimated PR for the Villafranca CPV installation is presented in Figure 3b. It is assumed that the system capacity rating for each tower is 25 kW, as specified by the system developer. The annual estimated PR is therefore 70.3%.

3.1.1.2. Écija, Seville, 1.5 MW CPV Installation

Figure 4 presents the real monthly EP of the Écija installation from January to July 2009, and the estimate EP for the Écija CPV for an average year.

Figure 4. Real EP in 2009 and monthly EP estimate from PVGIS for the Écija CPV installation.



2009 EP data for this installation was only available from January to July. Although this data does not cover the whole year, these months cover the range from minimum to maximum irradiation. The estimated EP for the Écija CPV for an average year from the PVGIS database is 1659 kWh/kW.

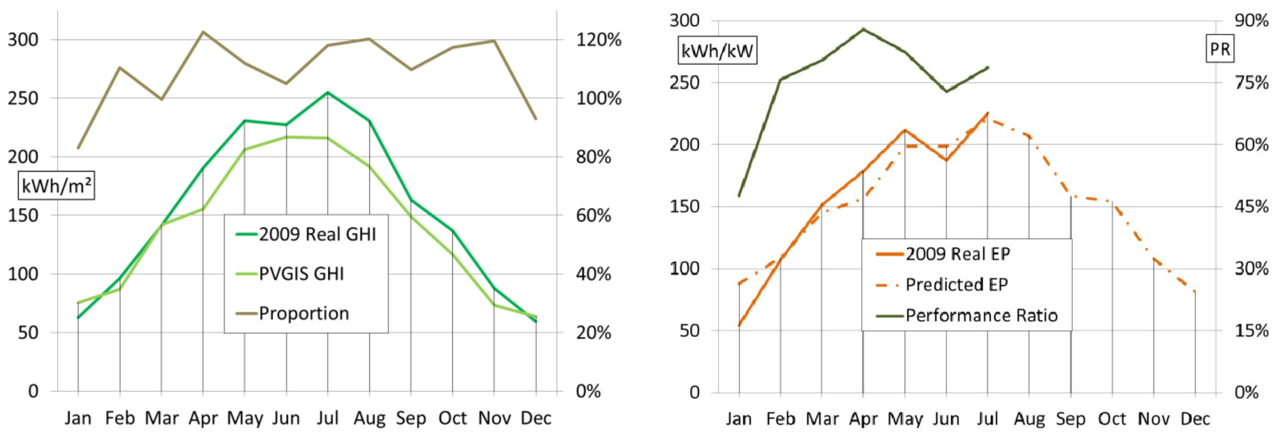
For the 7 months under study, the difference between the total estimated EP based on PVGIS averaged data and the total real EP is 7.6%. The average difference between the PVGIS estimate and real monthly EP values is 17.1%.

Figure 5 presents the GHI given by PVGIS, the real GHI measured in weather stations, and their respective ratios. The weather station is located in the same town as the installation. For Écija, the annual GHI is 11.1% higher than the estimate from PVGIS, and 9.0% higher from January to July (Table 2).

Table 2. January to July PVGIS GHI, real GHI and their ratio for the CPV installation location in 2009.

	January–July GHI kWh/m^2	Ratio
PVGIS	1105	100.0%
Real	1204	109.0%

Figure 5. (**a**) Real GHI, PVGIS GHI, and real/PVGIS GHI in 2009; (**b**) Real EP, EP prediction based on constant PR, and estimated PR values for the Écija CPV installation in 2009.



(**a**) (**b**)

The predicted 2009 monthly EP from January to July from GHI is presented in Table 3 and Figure 5b. The predicted EP from January to July 2009 is 1111 kWh/kW while the real EP over the same time period is 1117 kWh/kW. The difference between the predicted and real January-to-July values is only 0.5% and the average difference between the predicted and real monthly EP values is 8.5%.

Table 3. January to July PVGIS EP estimate for an average year, real EP in 2009, and predicted EP for 2009 using constant PR, for the Écija CPV in 2009.

	Energy Production kWh/kW	Ratio
PVGIS estimate for averaged year	1032.5	92.4%
2009 real EP	1117.2	100.0%
2009 prediction constant PR	1111.4	99.5%

Figure 5b also shows the monthly estimated PR from January to July 2009 for the Écija CPV installation. This parameter is calculated using Equation 2 with a calculated 2009 DNI and a real 2009 EP. The average estimated PR for January to July is 77.1%.

3.1.2. Concentrix Installations

3.1.2.1. Puertollano CPV Installation

Figure 6 and Table 4 present real monthly EP in 2009 for the Puertollano CPV installation and the monthly EP estimate calculated from the PVGIS for an average year, assuming that the system is working with a constant PR of 75%.

Figure 6. Real EP and monthly EP estimate from PVGIS for Puertollano CPV installation in 2009.

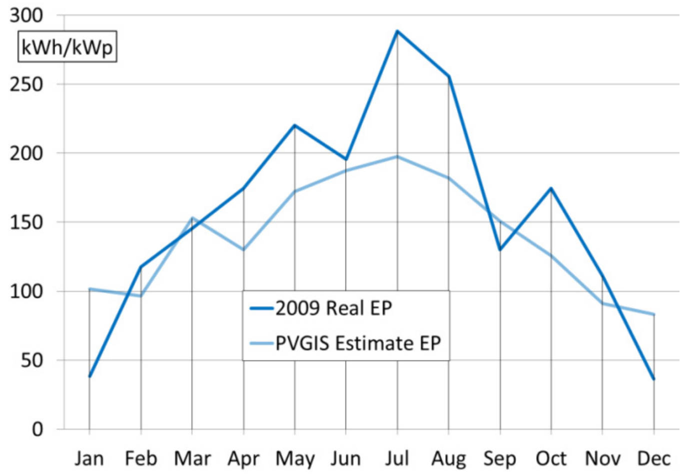


Table 4. PVGIS estimate for an average year, real EP in 2009, and predicted EP in 2009 using constant PR, for the Puertollano CPV installation in 2009.

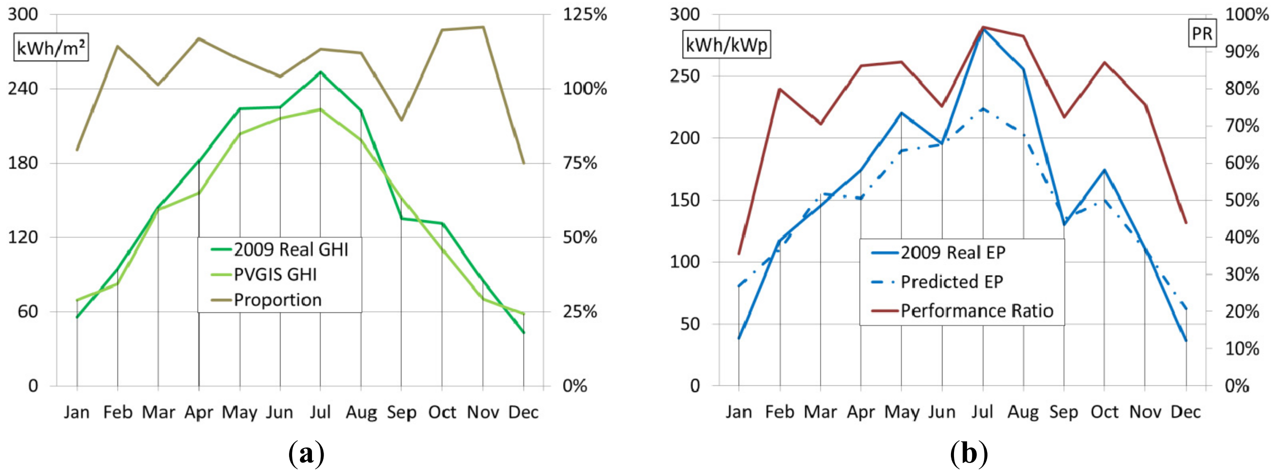
	Energy Production	**Ratio**
PVGIS estimate	1671 kWh/kW	88.5%
2009 real	1888 kWh/kW	100.0%
2009 prediction constant PR	1768 kWh/kW	93.6%

The estimated annual EP for an average year is 1671 kWh/kW and the real annual EP in 2009 was 1888 kWh/kW. Thus the difference between the PVGIS estimate and the 2009 real data is 11.5% for annual EP, and 26.1% for monthly EP. Table 5 and Figure 7 present the GHI estimate given by PVGIS for the installation, the real GHI measured by the weather station, and their respective ratios. The nearest weather station is located in Ciudad Real. For this location, real GHI in 2009 was 6.8% higher than the GHI estimated by PVGIS.

Table 5. PVGIS GHI, real GHI and their ratios at that Ciudad Real weather station in 2009.

	GHI	**Ratio**
PVGIS	1682 kWh/m^2	100.0%
2009 WS	1796 kWh/m^2	106.8%

Figure 7. (**a**) PVGIS GHI, real GHI, and their proportion in 2009; (**b**) Real EP, EP prediction based on constant PR, and estimated PR values for Puertollano CPV installation in 2009.



The annual and monthly EP predictions for 2009 are shown in Table 4 and Figure 7b, respectively. The predicted EP was calculated by estimating the DNI from weather station data, and by assuming a constant PR of 75%, as indicated in Section 2 (Methods). The annual DNI measured by ISFOC for 2009 was 1974 kWh/m^2, as indicated in [6], while the annual DNI estimated in this work was slightly higher, at 2003 kWh/m^2. Thus the difference between the estimate and the real measured value is only 1.48%.

The difference between the predicted and real annual EP is 6.4% and the average difference between the predicted and real monthly EP is 15.1%. Figure 7b also presents the monthly estimated PR for this installation, calculated by Equation 2. The estimated average PR for 2009 was 80.1%.

3.1.2.2. Seville CPV Installation

Figure 8 and Table 6 present the real monthly EP and the EP estimate for the Sanlúcar la Mayor installation from May 2008 to April 2009. Using the PVGIS for an average year and assuming the system is working with a PR of 75%, from May 2008 to April 2009, the estimated annual EP is 1715 kWh/kW and the real annual EP is 1981 kWh/kW. The difference between the PVGIS estimate for an average year, and the real EP from May 2008 to June 2009 is 13.4% and the average difference between the predicted and real monthly EP is 30.6%.

Table 6. PVGIS EP estimate for an average year, real EP in 2009, and predicted EP in 2009 using constant PR at the Sanlúcar la Mayor CPV installation.

	Energy Production	Ratio
PVGIS estimate	1715 kWh/kW	86.6%
2008-2009 real	1981 kWh/kW	100.0%
2008–2009 prediction constant PR	1783 kWh/kW	90.0%

Figure 8. Real EP and the monthly PVGIS estimate of EP at the Sanlúcar la Mayor CPV installation for 2008–2009.

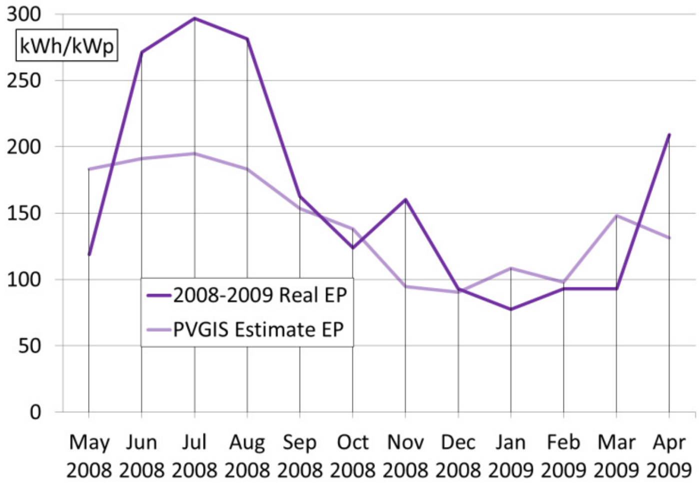
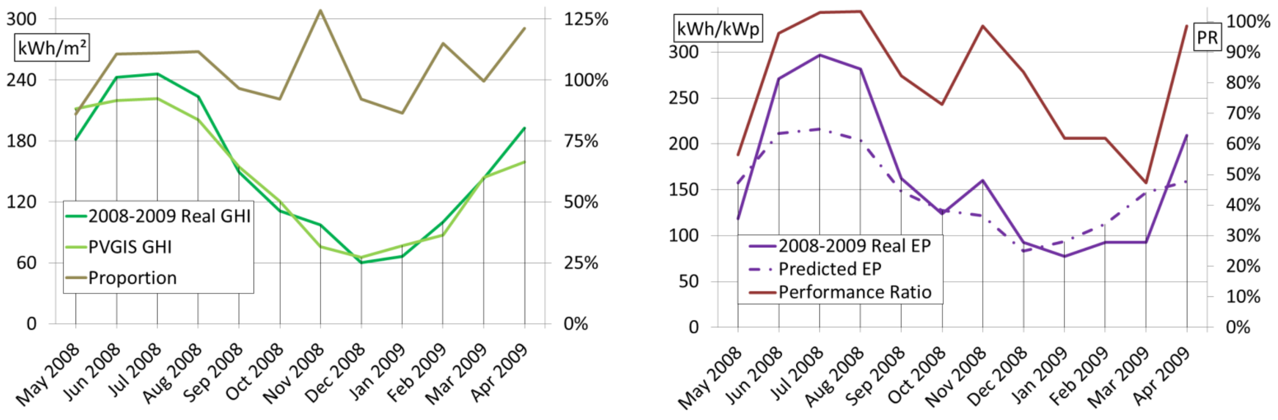


Table 7 and Figure 9 present the GHI estimate given by PVGIS, the 2008–2009 real GHI measured at weather stations, and their respective ratios. The weather station is located in the same town at the installation: Sanlúcar la Mayor. From May 2008 to April 2009, the aggregated real GHI was 4.5% higher than the PVGIS estimate.

Table 7. PVGIS GHI, real GHI from weather stations, and their ratios from May 2008 to April 2009, at the Sanlúcar location.

	GHI	Ratio
PVGIS	1736 kWh/m^2	100.0%
2008–2009 WS	1814 kWh/m^2	104.5%

Figure 9. (**a**) PVGIS GHI, real weather station GHI, and ratio between them; (**b**) Real EP, EP prediction based on constant PR, and estimated PR values at the Sanlúcar la Mayor CPV installation for 2008–2009.



(**a**) (**b**)

Monthly predicted EP from GHI is presented in Table 6 and Figure 9b. These predicted values were calculated by estimating DNI from the weather stations with a PR of 75%. The difference between predicted and real annual production is 10.0% and the average difference between predicted and real monthly EP is 23.4%. Figure 9b presents the 2008–2009 estimated monthly PR for the Sanlúcar la Mayor CPV installation, calculated by Equation 2. The estimated average PR for the months under study is 83.3%.

3.2. Method 2: Predictions Models with Variable Performance Ratio

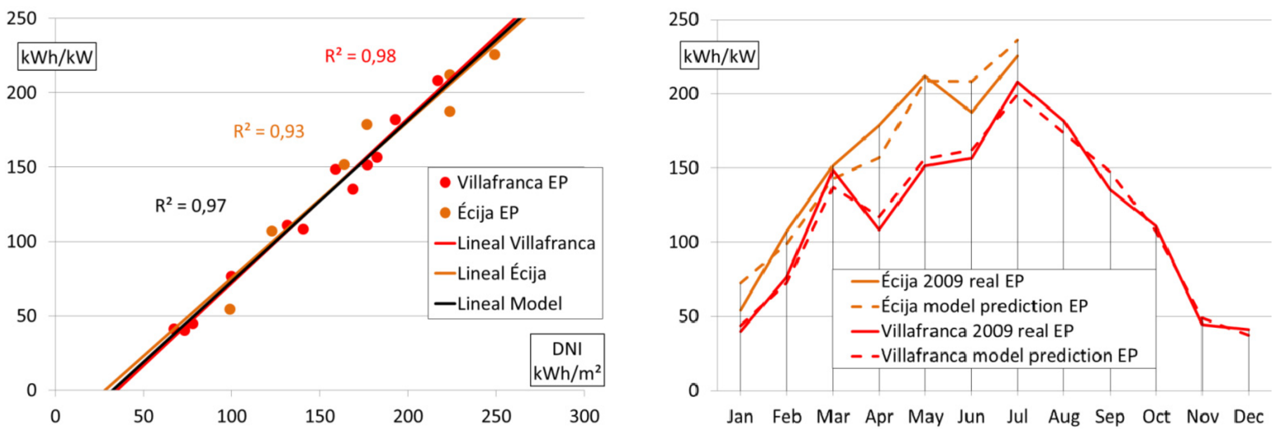
3.2.1. Amonix Prediction Model

Figure 3b and Figure 5b show that the predictions considering a constant PR tend to overestimate the EP in low radiation months, and to underestimate them in high radiation months.

Figure 10a plots the correlation between the real monthly EP and the calculated monthly DNI. It also gives three linear trend lines, two for each installation and the third for both. The correlation coefficient values for all three are very close to one, indicating near perfect linearity. Thus, the performance of the CPV installation can be modeled linearly. As the trend lines do not start from the origin, it shows that the CPV installations rarely generate energy at very low levels of irradiation. Moreover, this indicates that the PR is dependent on the DNI, because its EP/DNI ratio is not constant.

Both installations, which are of the same type, have a very linear performance. Moreover, their lineal regressions match even though they are located in places with very different irradiation characteristics. This indicates that CPV performance can be modeled linearly with the same model for both locations.

Figure 10. (**a**) Correlation of real monthly EP with calculated monthly DNI at the Villafranca and the Écija CPV installations in 2009 (individual installations and the combined model); (**b**) Real monthly EP and EP predicted by the model with variable monthly PR at the Villafranca and the Écija CPV installations in 2009.



(**a**) (**b**)

Figure 10 also plots a third linear trend line for both installations where the correlation coefficient R^2 is close to one. Thus EP can be modeled linearly. Notably, the linear trend lines for both installations match each other, even though they represent different irradiation conditions. The linearity between monthly EP and monthly DNI is quantified in Equation (4):

$$EP = 1.084 \cdot DNI - 35.550 \quad (4)$$

Thus, this model allows the prediction of the EP of any CPV installation using data from nearby weather stations and from the PVGIS database.

Figure 10b presents the results of applying the prediction model to the installations at Villafranca and at Écija. It shows the real EP and the EP predicted by the model. For the Villafranca installation, the real 2009 EP is 1403.4 kWh/kW while the EP predicted by the model is 1403.5 kWh/kW. For the Écija installation, the real EP from January to July 2009 is 1117.2 kWh/kW while the predicted EP is 1124.5 kWh/kW. Thus, the difference between the predicted and real annual EP is 0.01% and 0.65% for the Villafranca and Écija installations, respectively; and the average difference between predicted and real monthly EP is 5.6% and 8.3%, respectively.

Table 8 and Table 9 summarize the differences between the real EP values and those predicted by the two methods: supposing constant monthly PR, and utilizing the proposed model with a variable PR.

Table 8. Percentage differences between real and predicted monthly EP with the two prediction methods.

Monthly	Constant PR	Model variable PR
Villafranca	11.3%	5.6%
Écija	8.5%	8.3%

Table 9. Percentage differences between real and predicted annual EP with the two prediction methods.

Annual	Constant PR	Model variable PR
Villafranca	6.1%	0.01%
Écija	0.5%	0.65%

3.2.2. Concentrix Prediction Model

This model is established in the same manner as the model for the Amonix installations, and it predicts the EP using DNI calculated from the GHI data of nearby weather stations and the PVGIS database, assuming a variable PR. Figure 7b and Figure 9b show that the predictions, considering a constant PR, tend to overestimate the EP in low-radiation months and to underestimate them in high-radiation months.

Figure 11 plots the correlation between the monthly EP of the Puertollano and Sanlúcar la Mayor CPV installations and their monthly calculated DNI. It also gives three linear trend lines, two for each installation and one for both. The two installations are of the same type and their performance is similar. This indicates that although the installations are at different locations, their performance is, on average, the same. As the trend lines do not start from the origin, it means that the CPV installations rarely generate energy at very low levels of irradiation. Moreover, this indicates that the PR is dependent on the DNI, because its EP/DNI ratio is not constant.

Figure 11. Correlation between monthly EP and monthly estimated DNI at the Puertollano and the Sanlúcar CPV installations (individual installations and the combined model).

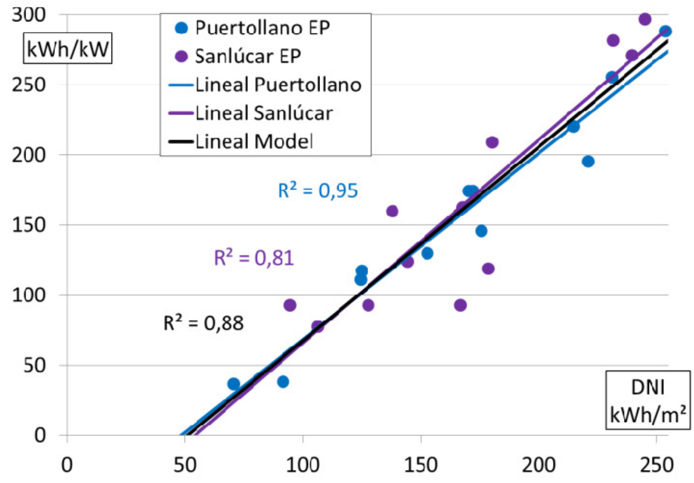


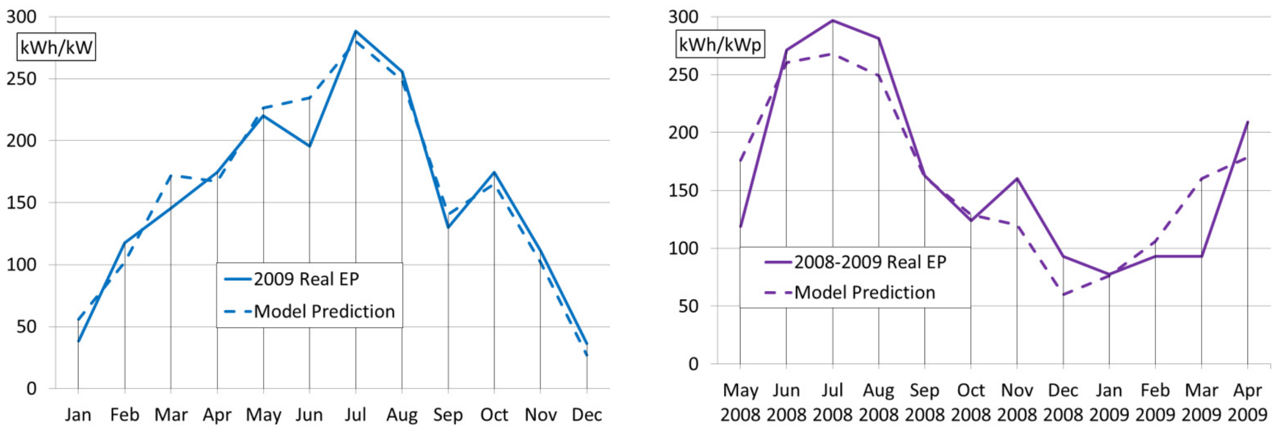
Figure 11 also presents a third regression line, which is the relationship between real monthly EP and calculated monthly DNI for both CPV installations using a unique regression model. Thus, a performance model is proposed and expressed by:

$$EP = 1.3819 \cdot DNI - 70.525 \quad (5)$$

For the Puertollano CPV installation, real EP and predicted EP are shown in Figure 12a. The annual real EP is 1968.8 kWh/kW and the EP predicted by the model is 1961.9 kWh/kW. Thus, for this installation, the difference between the predicted and real values for annual EP is 1.7%, and that difference for monthly EP is 8.8%.

For the Sanlúcar CPV installation, the real EP and the EP predicted by applying the model are shown in Figure 12b. The real EP from May 2008 to April 2009 is 1980.9 kWh/kW and the EP estimated by the model is 1987.7 kWh/kW. Thus, for this installation, the difference between the predicted and real values for annual EP is 1.7%, and the difference for monthly EP is 16.1%.

Figure 12. (**a**) Real monthly EP and predicted monthly EP with the variable PR model at the Puertollano CPV installation for 2009; (**b**) Real monthly EP and predicted monthly EP with variable PR model at the Sanlúcar CPV installation for 2008–2009.



(**a**) (**b**)

Table 10 and Table 11 summarize, for the Concentrix installations, the differences between the real EP values and those predicted by the various methods: using only PVGIS, using PVGIS and weather stations, and utilizing the proposed model with a variable PR.

Table 10. Monthly percentage differences between real and predicted monthly EP for the two prediction methods.

Monthly	Constant PR	Model
Puertollano	15.1%	8.8%
Seville	23.4%	16.1%

Table 11. Annual percentage differences between real and predicted annual EP for the two prediction methods.

Annual	Constant PR	Model
Puertollano	6.4%	1.65%
Seville	10.0%	1.73%

4. Discussion

In the first method, we predicted EP in 2009 with the assumption of a constant monthly PR. This method tends to overestimate EP in low irradiation months, and underestimate it in high irradiation months. This discrepancy between real and predicted EP comes mainly from the assumption of a constant PR. Using the second new method, we predicted the EP for the CPV installations while considering PR as a variable rather than a constant. This model allows the prediction of the CPV EP using GHI data from nearby weather stations and the PVGIS database.

Three main results have been obtained from the analysis presented in this work. The most interesting finding is that the Correlation Coefficients (R^2) between the real monthly EP and the estimated DNI for the four CPV installations, in 2009, are 0.98, 0.93, 0.95 and 0.81. To the best of our knowledge, no other article has previously identified this feature.

The second interesting result from this study is that the two CPV installations with silicon cells both share virtually same lineal model with a Correlation Coefficient (R^2) of 0.97, even in locations with different irradiation conditions. The two CPV installations with multijunction solar cells share another lineal model with a Correlation Coefficient (R^2) of 0.88. It might be logical to think that under different climatic conditions the CPV installations should present different EP performance patterns. Nevertheless, they have the same lineal model which correlates the monthly EP with the estimated DNI. To the best of our knowledge, no other work has previously identified this characteristic, and this is the first article to study CPV installations based on silicon and multijunction solar cells.

The third main result is the EP lineal method for CPV installations based on GHI from weather stations and data obtained from PVGIS. This allows the prediction of the EP with annual deviations from real values of 0.01%, 0.65%, 1.65% and 1.73%, and average monthly deviations of 5.6%, 8.3%, 8.8% and 16.1%. The proposed simple lineal model significantly improves prediction accuracy, when compared with EP predictions that assume a constant monthly PR. There is little published about CPV

EP [4,35,36], but this is the first proposal for a prediction method without the direct measurement of the DNI.

Some limitations of the current study are worth noting. First, these PR calculations are based on the alternating current (AC) power rating specified by the system manufacturers, not the DC power rating widely adopted by flat plate PV systems. Since the system rating is set by the manufacturers and no clear standards apply, direct comparison of PR across different types of CPV systems does not necessarily indicate the quality of the installation. Rather than the absolute value, the key point with regard to PR is the dynamic variation in different months of a given year. In Figure 9b and Figure 7b, high values of the estimated PR are observed in some months; some values are even greater than 100%. There are two possible reasons. First, the estimated PR is calculated, as indicated in equation 2, from estimated DNI. Therefore, the real value of the PR could be below the estimated if the calculated DNI is underestimated. Second, the rating of system capacity in terms of kW is not based on the peak performance of the system, but incorporates losses in non-standard operating conditions. Therefore, the PR calculated based on this capacity rating can be very high in operating conditions that are close to the standard.

The second limitation is that the EP data of the Seville installations is taken from a Concentrix paper [4] that reports the monthly cumulative yield of the power plant. The precision of the monthly measurements from the graph can give an average error of up to 15%. However, this error is less than 1% over the whole year. This could be the reason why one of the installations presents significantly lower linearity than the others. Finally, rather than taking a direct measurement of DNI, it is estimated from available GHI and PVGIS data. Nevertheless, these estimates are advantageous, insofar as it avoids long-term dependence on expensive DNI measurements for EP prediction at any given location. Future works could evaluate the error introduced into the model, due to DNI estimation, and whether the proposed model will function with equal accuracy both today and in future years. Thus, more R&D efforts should be put into investigation about the long-term operation of CPV systems. The long-term energy production directly affects the energy cost in terms of ¢/k Wh, which is a straightforward metric to assess a PV technology.

A novel and major strength of this study is its proposed EP prediction model without real time DNI measurements that generates quick EP estimations at any given location. The fact that it is an independent study, unconnected to companies or institutions involved in CPV, is a further strong point. Moreover, it is based on real world installations, instead of installations for research purposes.

5. Conclusions

The real Energy Production of the CPV installations studied in this work shows good linearity with respect to the estimated DNI. This characteristic holds true regardless of whether the location experiences low or high irradiation. Moreover, the linearity is observed in both silicon and multi-junction solar cell systems.

This generally applicable linearity allows the establishment of a model with a variable monthly Performance Ratio that predicts energy production at any location using the estimated DNI. This DNI can be derived by using the real-time GHI data measured at nearby weather stations and average-annual GHI and DNI stored on the PVGIS database. Thus, it avoids the need to measure DNI over long periods at the CPV installation location.

Across all the installations, the difference between the predicted and the real annual EP in 2009 is less than 2% with the second method; and the average difference between predicted and real monthly EP lies in the range of 5.6%–16.1%.

In summary, PR variations at different DNI levels should be taken into consideration when predicting energy production. Moreover, the loss mechanisms of CPV systems at low levels of DNI should be further investigated for the purposes of R&D.

References

1. Rubio, F.; Martínez, M.; Hipólito, A.; Martín, A.; Banda, P. Status of CPV Technology. In *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC)*, Valencia, Spain, 6–10 September 2010; pp. 1008–1011.
2. Stone, K.W.; Garboushian, V.; Boehm, R.; Hurt, R.; Gray, A.; Hayden, H. Analysis of five years of field performance of the Amonix High Concentration PV system. In *Proceedings of the Power-Gen Renewable Conference*, Las Vegas, NV, USA, 10–12 April 2006; pp. 1–12.
3. Tobias Gerstmaier, S.V.R., Andreas Gombert, André Mermoud, T.L. Eric duminil software modeling of FLATCON®CPV systems. In *Proceedings of the 6th International Conference on Concentrating Photovoltaic Systems (CPV-6)*, Freiburg, Germany, 7–9 April 2010; pp. 183–186.
4. Gombert, A.; Hakenjos, A.; Heile, I.; Wüllner, J.; Gerstmaier, T.; Riesen, S.V. FLATCON® CPV systems-field data and new developments. In *Proceedings of the 24th European Photovoltaic Solar Energy Conference (PVSEC)*, Hamburg, Germany, 21–24 September 2009; pp. 156–158.
5. Gombert, A.; Gerstmaier, T.; Heile, I.; Riesen, S.V.; Röttger, M.; Wüllner, J. Analysis of long term operation data of FLATCON® CPV systems. In *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC)*, *5th World Conference on Photovoltaic Energy Conversion (WCPEC)*, Valencia, Spain, 6–10 September 2010; pp. 128–132.
6. Rubio, F.; Martínez, M.; Sánchez, D.; Aranda, R.; Banda, P. Two years operating CPV plants: Analysis and results at ISFOC. In *Proceedings of the 7th International Conference on Concentrating Photovoltaic Systems (CPV-7)*, Las Vegas, NV, USA, 4–6 April 2011; pp. 327–330.
7. Garboushian, V.; Yoon, S.; Turner, J. Radiation hardened high efficiency silicon space solar cell. In *Proceedings of the 23th IEEE Photovoltaic Specialists Conference (PVSC)*, Louisville, KY, USA, 10–14 May 1993; pp. 1358–1362.
8. Garboushian, V.; Turner, G.; Yoon, S.; Vendura, G.J. Development of back junction point contact photovoltaic cells and arrays for space. In *Proceedings of the 25th IEEE Photovoltaic Specialists Conference (PVSC)*, Washington, DC, USA, 13–17 May 1996; pp. 227–230.
9. Yoon, S.; Turner, G.; Garboushian, V. Thin, lightweight, 18% efficient space silicon solar cell and array. In *Proceedings of the 25th IEEE Photovoltaic Specialists Conference (PVSC)*, Washington, DC, USA, 13–17 May 1996; pp. 259–262.

10. Sewang, Y.; Garboushian, V. Reduced temperature dependence of high-concentration photovoltaic solar cell open-circuit voltage (Voc) at high concentration levels. In *Proceedings of the IEEE First World Conference on Photovoltaic Energy Conversion (WCPEC)*, Waikoloa, HI, USA, 5–9 December 1994; pp. 1500–1504.
11. Lammert, M.D.; Schwartz, R.J. The interdigitated back contact solar cell: A silicon solar cell for use in concentrated sunlight. *IEEE Trans. Electron Devices* **1977**, *24*, 337–342.
12. Swanson, R.M.; Beckwith, S.K.; Crane, R.A.; Eades, W.D.; Young Hoon, K.; Sinton, R.A.; Swirhun, S.E. Point-contact silicon solar cells. *IEEE Trans. Electron Devices* **1984**, *31*, 661–664.
13. Sinton, R.A.; Young, K.; Gan, J.Y.; Swanson, R.M. 27.5-percent silicon concentrator solar cells. *IEEE Electron Device Lett.* **1986**, *7*, 567–569.
14. Garboushian, V.; Roubideaux, D.; Turner, G.; Gunn, J.A. Long-term reliability concerns resolved by third generation integrated high-concentration PV systems. In *Proceedings of the 26th IEEE Photovoltaic Specialists Conference (PVSC)*, Anaheim, CA, USA, 29 September–3 October 1997; pp. 1373–1375.
15. Garboushian, V.; Roubideaux, D.; Yoon, S. Integrated high-concentration PV near-term alternative for low-cost large-scale solar electric power. *Sol. Energy Mater. Sol. Cells* **1997**, *47*, 315–323.
16. Garboushian, V.; Sewang, Y.; Turner, G.; Gunn, A.; Fair, D. A novel high-concentration PV technology for cost competitive utility bulk power generation. In *Proceedings of the IEEE First World Conference on Photovoltaic Energy Conversion (WCPEC)*, Waikoloa, HI, USA, 5–9 December 1994; pp. 1060–1063.
17. Garboushian, V.; Roubideaux, D.; Yoon, S.; Gunn, J.A. An evaluation of integrated high-concentration photovoltaics for large-scale grid connected applications. In *Proceedings of the 25th IEEE Photovoltaic Specialists Conference (PVSC)*, Washington, DC, USA, 13–17 May 1996; pp. 1373–1376.
18. Gordon, R.; Slade, A.; Garboushian, V. A 30% efficient (>250 Watt) module using multijunction solar cells and their one-year on-sun field performance. In *Proceedings of the High and Low Concentration for Solar Electric Applications II*, San Diego, CA, USA, 26–28 August 2007; p. 664902.
19. Kinsey, G.S.; Hebert, P.; Barbour, K.E.; Krut, D.D.; Cotal, H.L.; Sherif, R.A. Concentrator multijunction solar cell characteristics under variable intensity and temperature. *Prog. Photovoltaics* **2008**, *16*, 503–508.
20. Kinsey, G.S.; Edmondson, K.M. Spectral response and energy output of concentrator multijunction solar cells. *Prog. Photovoltaics* **2009**, *17*, 279–288.
21. Kinsey, G.S.; Pien, P.; Hebert, P.; Sherif, R.A. Operating characteristics of multijunction solar cells. *Sol. Energy Mater. Sol. Cells* **2009**, *93*, 950–951.
22. Lerchenmüller, H.; Bett, A.W.; Jaus, J.; Willeke, G. Cost and market perspectives for FLATCON®-systems. In *Proceedings of the 3rd International Conference on Solar Concentrators (SC3) for the Generation of Electricity or Hydrogen*, Scottsdale, AZ, USA, 1–5 May 2005; p. 7.
23. Bett, A.W.; Burger, B.; Dimroth, F.; Siefer, G.; Lerchenmüller, H. High-concentration PV using III-V solar cells. In *Proceedings of the IEEE 4th World Conference on Photovoltaic Energy Conversion (WCPEC)*, Waikoloa, HI, USA, 7–12 May 2006; pp. 615–621.

24. Hakenjos, A.; Wüllner, J.W.; Lerchenmüller, H. Field performance of FLATCON® high concentration photovoltaic systems. In *Proceedings of the 22nd European Photovoltaic Solar Energy Conference (PVSEC)*, Milan, Italy, 3–7 September 2007; pp. 156–159.
25. Lerchenmüller, H.; Hakenjos, A.; Heile, I.; Burger, B.; Stalter, O. From FLATCON® pilot systems to the first power plant. In *Proceedings of the 4th International Conference on Solar Concentrators for the Generation of Electricity or Hydrogen (ICSC-4)*, San Lorenzo de El Escorial: Madrid, Spain, 12–16 March 2007; pp. 1–4.
26. Jaus, J.; Peharz, G.; Gombert, A.; Rodriguez, J.; Dimroth, F.; Eltermann, F.; Wolf, O.; Passig, M.; Siefer, G.; Hakenjos, A.; Riesen, S.V.; Bett, A.W. Development of FLATCON® modules using secondary optics. In *Proceedings of the 34th IEEE Photovoltaic Specialists Conference (PVSC)*, Philadelphia, PA, USA, 7–12 June 2009; pp. 1931–1936.
27. Gómez-Gil, F.J.; Wang, X.; Barnett, A. Energy production of photovoltaic systems: Fixed, tracking, and concentrating. *Renew. Sust. Energy Rev.* **2012**, *16*, 306–313.
28. Gómez-Gil, F.J.; Wang, X.; Barnett, A. *Photovoltaic System Energy Production in Spain: Predictions and Results for 2009*, In *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition (PVSEC)*, *5th World Conference on Photovoltaic Energy Conversion (WCPEC)*, Valencia, Spain, 6–10 September 2010; pp. 4883–4889.
29. Gil, F.J.G.; Martin, M.D.S.; Vara, J.P.; Calvo, J.R. A review of solar tracker patents in Spain. In *Proceedings of the Energy Problems and Environmental Engineering*, La Laguna, Tenerife, Canary Islands, Spain, 1–3 July 2009; pp. 292–297.
30. Gomez-Gil, F.J.; Wang, X.; Barnett, A. CPV energy production analysis. In *Proceedings of the AIP Conference Proceedings*, Las Vegas, NV, USA, 2011; pp. 358–361.
31. Meteorología y Climatología de Navarra Website. Available online: http://meteo.navarra.es/estaciones/mapadeestaciones.cfm (accesed on 18 January 2012).
32. Lecturas Website. Available online: https://spreadsheets.google.com/ccc?key=0AkI8oQ6T9O9zdERBQnNfZmZTd3JvWVNPc2w4NWJrM2c&hl=en#gid=0 (accesed on 18 January 2012).
33. Bureau of Indian Standards (BIS). *Photovoltaic System Performance Monitoring-Guidelines for Measurement*, *Data Exchange and Analysis*; IEC 61724; Government of India: Newlhi, India, 1998.
34. Surface Metereology and Solar Energy Website. Available online: http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?#s01 (accesed on 18 January 2012).
35. Kinsey, G.S.; Stone, K.; Brown, J.; Garboushian, V. Energy prediction of Amonix CPV solar power plants. *Prog. Photovoltaics* **2011**, *19*, 794–796.
36. Kinsey, G.S.; Nayak, A.; Liu, M.; Garboushian, V. Increasing Power and Energy in Amonix CPV Solar Power Plants. *IEEE J. Photovoltaics* **2011**, *1*, 213–218.