SIMULATION AND VALIDATION OF CPV PERFORMANCE WITH TRNSYS

Jiunn-Chi Wu[1], Ya-Ling Chen[1]

[1] Graduate Institute of Energy Engineering/National Central University, Jhong-Li, Taiwan

1. Abstract

The concentrating photovoltaic (CPV) technology has greater potential to generate high PV electricity in high insolation area. Assessment of CPV's performance is vital for disseminating this technology. Most current modeling softwares in PV sector are targeted for non-concentrating PV, such as TRNSYS, PVsyst, HOMER, etc. We have modified the PV array component in TRNSYS with parameters adjusted for CPV array. In these modified parameters, temperature coefficients of short-circuit current and open-circuit voltage, and transmittance-absorptance product are either taken from available measurements or algebraic calculation. The CPV system used for field test consists of high accurate two-axis solar tracker with two CPV modules installed. In sunny days, prediction of power output of CPV module agreed well with measured CPV power in Jhong-Li, Taiwan. Our study has extended the applicability of TRNSYS for dynamic modeling of PV system.

2. Introduction

Electricity obtained by PV panels is increasingly used in many countries. To improve the efficiency of the system usually PV panels are mounted on mobile structures that rotate with respect to vertical and horizontal axes for tracking the sun trajectory in the sky. CPV, in particular, is an emerging PV technology (Luque and Andreev, 2007) which has the niche application able to generate high electricity under the high insolation. In 2008, it is estimated that the installation of CPV reaches can over 50 MW 2012 (Prometheus, 2008). Although, the current installation of CPV is much smaller the current PV installation worldwide (12 GW), it has greater potential of cost-equivalent to PV once the CPV system efficiency reaches to 28%. Thus, the potential assessment and validation of field test in CPV system with the help of PV simulation tool is vital to the deployment of CPV technology.

To properly disseminate the installation of PV system and promote simulation tools in PV system for better assessment, the simulation software designed for PV system should including the following features: 1) detaily analyze system characteristics under field operation condition, 2) study effect due to various load profiles, 3) calculate the optimum size of PV module, 4) assess the feasibility of life cycle cost and economic of PV system. As more PV systems are installed, there will be increasing demand for software that can be used for design, analysis and diagonsis. There are a number of PV simulation software available, TRNSYS, PVsyst, HOMER, SAM, Solar Pro, etc. Among them, TRNSYS (2007) has developed more than 30 years and evolved as a flexible tool designed for simulating the transient performance of thermal energy systems which earns its reputation in providing valuable modeling in PV system. Gow et al. (1999) have developed various mathematical model for PV components (inverter, PV panel, etc) for simulate the total PV system. Davis et al. (2003) calibrated paremeters in empirical formula for various types of solar cell to predict the performance of PV. Perez et al. (2004) developed PV simiulation model for simulating PV output performance. Mondol et al. (2009) used TRNSYS to investigate PV array capacity, declination angle, azimuth angle, load curve, buyback electricity price, feed-in tariffs, capacity and cost ratio of PV and inverter to the economics of grid-connected PV system.

Cameron et al. (2010) used Solar Advisor Model (SAM), developed by NREL, in which four conversion models were analyzed, they are the Sandia PV model, CPV model (simulation of power output is corrected with temperature conpensation), simple solar hour model (system power output and rated output is proportional to direct normal insolation) and ASTM E2527-06 code. In their study, the performance of CPV system with multijunction solar cell is simulated, and one month measurement from two types of CPV system was collected, including weather data, insolation and system performance. Klise and Stein (2009) have ducumented and discussed various PV performance softwares (most of available softwares were included) in support of the PV and grid-connected project.

The objective of this study is to evaluate the performance of CPV system in Taiwan for continuous contribution of reliability and improvment of CPV technology from our previous study (Wu, et al., 2010). Both experimental approach (under longtime field test) and numerical simulation (using TRNSYS) are conducted and compared. We also testing other softwares (SAM and PVsyst) now. Their comparison will be reported in elsewhere.

3. Approach

3.1 CPV system

The CPV system (see Fig. 1) consists of a two-axis azimuth-elevation type of solar tracker, which is designed and made in house with two CPV modules (111 W, module efficiency 23.5%, Delta, Taiwan). This system uses the solar position algorithm to attain high accurate sun-tracking and has been measured CPV performance for more than one year in Jhong-Li, Taiwan. We also developed a very accurate tracking offset-angle device using PSD (position sensitive device) for monitoring the tracking performance (Wu, et al., 2010). Accurate tracking lower than 0.5^{o} during the high insolation condition can be achieved, while lower tracking $0.5\text{-}1^{o}$ in cloudy day. Beside the CPV system, system power output (DC/AC power) can be recorded via the inverter connection, and a micro weather station dynamically measured the solar irradiation. Detail of the system setup can be found in Chen (2011).

3.2 TRNSYS simulation

In TRNSYS package, its PV component (type 94) is originally designed for non-concentrating PV (most of them are silicon-based cell). User can change the input parameters of PV module according to the specification of PV array and weather data. However, most of CPV modules adopt III-V solar cell instead of Si-based cell, the former has distinct photo-electrical features compared with silicon-based cell. Therefore, these parameters must be adjusted and validated if one wants to apply TRNSYS for modeling the CPV array.

We identify four parameters should be modified due to outdoors temperature and semiconductor properties which different from the standard test condition and non-silicon based solar cell. Brief descriptions of these parameters are given below.

3.2.1 Temperature coefficients of short-circuit current and open-circuit voltage

As our laboratory did not measure the temperature of CPV module during outdoor operation, hence the parameters of all temperature coefficients of short-circuit current (TC_{Isc}) and open-circuit voltage (TC_{Voc}) of the CPV module cannot be obtained. Instead, we adopt the measured correlation between temperature and CPV module from Kinsey et al. (2009) and Peharz et al. (2011). Kinsey et al. (2009) use multi-junction solar cells manufactured by Spectrolab under the solar simulator, for indoor testing of temperature variations and electric characteristics of solar cells where temperature varies from 25^{o}C to 75^{o}C. Their measurement show that the value of TC_{Voc} varies in the range of -0.13%/^{o}C. Peharz et al. (2011) use solar simulator with adjustment of controlling temperature and investigate effect of temperature change on parameters (I_{sc}, V_{oc} and fill factor) for three FLATCON CPV modules. From measurement, they are able to obtain the value of TC_{Isc} changes between 0.05%/K and 0.13%/K while TC_{Voc} was fixed as -0.18%/K. Based on reviewing above literatures, we conclude that the reasonable value TC_{Isc} varies in the range of 0.05-0.13%/K and TC_{Voc} is ranging between -0.13 %/K and -0.18 %/K.

Next, range of values of TC_{Isc} and TC_{Voc} are evaluated for their effect on the power output. First TC_{Isc} is set as

0.13%/K and varies TC_{Voc} within a reasonable range (between -0.13%/K and -0.18%/K) and compared the simulation results based on these input values with consecutively seven days of field measurement of CPV power output. Prediction shows both output power are essentially equal under the changing range of TC_{Voc}. Next, TC_{Isc} is made varied form 0.05%/K to 0.13%/K and compare this effect on power output. Again, power output of CPV system are simulated for consecutive seven day and agreement between field measurement and simulation is good with maximum difference of power 2.39 W.

The simulation indicates that variation of TC_{Voc} (between -0.13 and -0.18%/K) has minor effect on the prediction of power output, but the change of TC_{Isc} (from 0.05%/K to 0.13%/K）has a larger effect. This is because in the study of Peharz et al. (2011), the Fresnel lenses (concentrating lenses) are affected by the elevated temperature inside the CPV module, which degrades the index of refraction. In addition, thermal expansion induces by the elevated temperature also cause the deformation of lense. These combined effects lower the absorbed solar irradiance of solar cell. Since one of the CPV modules has a secondary optical component, functioning as homogenize the incoming sun light on the cell surface to avoid hot spot, thus the temperature coefficient of I_{sc} (0.13%/K) for module 1 is higher than that of module 2 (0.05%/K), but as discussed already, temperature coefficient of I_{sc} has minor effect on simulation result.

The CPV module used in our test also has secondary optical component for homogenizing the incoming solar light. This additional optics can lower value of the temperature coefficient. Thus, based on all these considerations, parameters in type 94 of TRNSYS are set as I_{sc} of 0.13%/K and V_{oc} of -0.18%/K. These parameters are further converted into the required unit (TC_{Isc} set as 0.13×1.29/100, and TC_{Voc} set as -0.18×115.6/100), and resulted in values for TC_{Isc} and TC_{Voc} are 1.68×10^{-3} A/K and -0.208 V/K, respectively. In Table 1, value of TC_{Isc} and TC_{Voc} for silicon-based solar cell is 1.66×10^{-3} A/K and -0.126 V/K, respectively. After unit conversion to %/K one obtain temperature coefficient of I_{sc} and V_{oc} as 0.03%/K and -0.25%/K, respectively. These shows the III-V solar cell used in CPV module is less sensitive to the degradation of temperature.

3.2.2 Transmittance-absorptance product

The power output of solar cell and PV module is proportional to absorbed solar radiation. It is well known that effective absorbed solar radiation for a PV system consists of beam, diffuse, and grounded-reflected components and these relation has been derived by Duffie and Beckmann (2006) in a functional form of the transmittance (τ) and absorptance (α). They further transform the relation in term of the transmittance-absorptance product ($\tau\alpha$), which should be thought of as a property of a cover-absorber combination rather than the product of two individual properties. The value of ($\tau\alpha$) in PV module has been thoughly studied and measured, with its typical values around 0.9.

However, this effect in CPV module has not been studied systemically as III-V multi-junction solar cell has different characteristics of Si-based solar cell. Thus we need to derive the relation of ($\tau\alpha$) for CPV module and it is obtained based on the approach suggested by Duffie and Beckman (2006) with outdoor measurement of cell temperature T_C. They indicate that T_C can be calculated from the energy balance equation, that is part of absorption of solar radiation is converted into electricity and the rest dissipated as waste heat. Which result in the following energy balance equation per unit module area

$$(\tau\alpha)G_T = \eta G_T + U_L\left(T_c - T_a\right) \qquad (1)$$

where η_c is the efficiency of module, G_T is the total radiation of module surface, T_c and T_a is the cell and atmospheric temperature, respectively, U_L is the heat loss coefficient, which combine the heat convection from the top/bottom module surface, heat radiation and heat conduction through solar tracker.

As the atmospheric temperature is different from the indoor standard temperature, the PV sector define he nominal operating cell temperature (NOCT), which is cell or module temperature under under the insolation 800 Wm^{-2}, wind speed 1 m/s, atmospheric temperature 293 K, and no electric load (η_c=0). Substituting NOCT's temperature, atmospheric temperature and insolation into equation (1) as

$$\frac{(\tau\alpha)}{U_L} = \frac{\left(T_{C,NOCT} - T_{A,NOCT}\right)}{G_{T,NOCT}} \quad (2)$$

For traditional PV module, $T_{C,\,NOCT}$ is in the range of 313-323 K, however the cell temperature used in CPV module increases as concentration ratio. We have roughly measured the cell substrate temperature of CPV module with a thermal couple attached on the back substrate of solar cell and much higher temperature (343-363 K) is recorded. Thus G_T is chosen as 800 Wm^{-2} and $T_{C,NOCT}$ uses the average measured temperature 353 K and uses the measured direct normal insolation (DNI) on the CPV module surface for substituting G_T. By simultaneous solving equations (1) and (2) one can obtain the values of (τα) and U_L at different insolation and cell and atmospheric temperature. The average value of $(\tau\alpha)$ is 0.564 based on measured cell temperature at outdoor test.

The parametric setting in Type 94 for a negative value of $(\tau\alpha)$ means the component will perform the calculation of incident angle modifier (IAM) in order to correct the reflective loss of incident sun light. The IAM is defined as the ratio of received insolation on the PV array to the amount under DNI

$$IAM \equiv \frac{(\tau\alpha)}{(\tau\alpha)_{norm}} \quad (3)$$

where $(\tau\alpha)_{norm}$ is $(\tau\alpha)$ value under DNI. Thus, the total effective insolation $G_{T,eff}$ on the CPV array is

$$G_{T,eff} = (\tau\alpha)_{norm}\left(G_{T,beam}IAM_{beam} + G_{T,diff}IAM_{diff} + G_{T,gnd}IAM_{gnd}\right) \quad (4)$$

where IAM_{beam}, IAM_{diff} 和 IAM_{gnd} are correction factor of incident angle for DNI, diffuse and reflective radiation, receptively, and $G_{T,beam}$, $G_{T,diff}$, $G_{T,gnd}$ is the DNI (beam radiation), diffuse radiation and radiation from ground reflection, respectively.

In the study of Mondol et al. (2009), they use TRNSYS to simulate PV electric performance, and set 0.91 for $(\tau\alpha)$ which is similar as used in typical PV module (TRNSYS, 2007). On the other hand, the calculated $(\tau\alpha)$ in present study is much lower. This is consistent with the characteristics of our CPV module, which has additional concentrating optical lenses (Fresnel lenses). Optical lenses has optical loss due to lenses itself and reflection of sun light, and long time exposure of solar radiation. Thus, we use a lower value of $(\tau\alpha)$ that of PV module, which should give better representation of our CPV module.

3.2.3 Bandgap of semi-conductor materials

The default parameters of type 94 component used in simulation of PV array is for silicon-based solar cell, so the value of semiconductor bandgap is also referred to silicon (1.12 eV). Yet, three-junction III-V solar cell is used in our CPV module, and these two types of solar cell have different semiconductor properties. One is pure silicon-based while ours is three-junction structure (GaInP/GaInAs/Ge). Thus, we refer the technical specification of solar cell released by Spectrolab (the cell manufacture) for calculating the bandgap. The corresponding bandgaps (1.75/1.2/0.66 eV) are averaged and resulting in a value of 1.2 eV. It should be noted this is an approximation yet reasonable approach. Table 1 lists the parameters used in the PV array components (type 94) in TRNSYS and the modified parameters (marked in red) for CPV module. The error (ε_p) between measured and predicted result is given by

$$\varepsilon_p = \frac{P_P - P_M}{P_M} \times 100\% \quad (5)$$

where P_P and P_M are the predicted and measured daily average DC power.

4. Results

The outdoor test of CPV system is affected by the insolation and in particular the percentage of DNI among the global insolation. Cloudy day with highly variation of DNI is definitely resulted in poor power output. Simulation in this cloudy day is also troublesome since it cannot realistically mimic the instantaneous variation of solar irradiance. This is exactly the case shown in Fig. 2, in which comparison of predicted and measured DC power on a cloudy day (average DNI is 240 Wm^{-2} on 8/29, 2010) is made. Large error is observed as high as 47.1%. It should be noted that measurement of DC power output is recorded from 8:20 am to 4 pm. This is because DNI value before 8:20 am and after 4 pm is not high enough to boost the lowest activation voltage of CPV module. However, simulation did not take this into consideration and therefore, discrepancy cannot be avoided. The prediction match well with measured power on a sunny day (average DNI is 866 Wm^{-2} on 9/28, 2010) as shown in Fig. 3. Smooth distribution of solar irradiance is recorded and this ensures good power performance of CPV. The measured power was recorded from 8 am to 4:30 pm. Prediction of TRNSYS depicts the variation of DNI (around 11 am and 1 pm) better than the real measurement. Overall difference is within 0.18%. Thus satisfactory agreement can be expected for higher DNI during sunny summer session.

As PV field test needs long time monitor and monthly power generation is a better record to assess its performance. Fig. 4 shows the measured and predicted cumulated electricity production vs. measured cumulated DNI on August and September, 2010. Error between measured and predicted electricity accumulation were 5.28% and 9.53%, respectively. These two months have higher solar irradiance amounts than yearly average values. Thus agreement between simulation and experimental data are good.

From solar irradiation field monitoring we observe higher amount of DNI always ensure adequate to sufficient power output since it's the nature of CPV. The relation of daily average DNI and error between measured and simulation is given in Fig. 5. As the level of DNI raises to 550 W/m^{-2} the error drop to 10% and at even higher DNI level 850 W/m^{-2} (the reference value suggested by CPV industry) the error further lower to 3%. We also compare for different month. Fig. 6 shows the monthly averaged measured and predicted DC power and corresponding error. Overall, better agreement is obtained in August and September. Both positive and negative values of error are shown, with negative value represents under-predict simulation results and this occur in December which may due to the low atmospheric temperature which may lower the module power generation.

There are other parameters that relate to the characteristics of CPV not being simulated in present study, for example, tracking accuracy and description of the irradiance distribution. The former problem is being studied in Chen (2011). Generally speaking, high accurate can be obtained under sunny weather and with good design of sun-tracking algorithm as demonstrated in Wu et al. (2010) and Chen (2011). Yet, the simulation cannot mimic the realistic tracking deviation. For high concentrating performances require a good knowledge of the beam component. Then accurate models for achieving this evaluation would involve parameter like turbidity, water and aerosol contents of the atmosphere, which are not defined in TRNSYS database.

5. Conclusion

CPV technology has its niche application and unique high performance in efficiency and power generation. Yet, it remains to increase its reliability and its market share. Simulation and field test of CPV are equally important. We have successfully modified the PV array component in TRNSYS software for simulating the CPV module which extends the applicability of TRNSYS. These modified parameters are either taken from available measurements (e.g. bandgap, TC_{Isc} and TC_{Voc}) or calculated based on energy balance equation (transmittance-absorptance product). The prediction of TRNSYS is greatly affected by insolation. In cloudy day, high fluctuation value of solar radiation affect the performance of CPV module. Overall agreement with the outdoor tests and the simulation is reasonable. Our study has extended the applicability of TRNSYS in the area of CPV sector.

Acknowledge

This research is funded by the National Science Council of Republic of China (Taiwan) through grant (NSC 100-2622-E-008-004-CC2) and Lih Kang Industrial Company. The authors wish to thank for their financial support.

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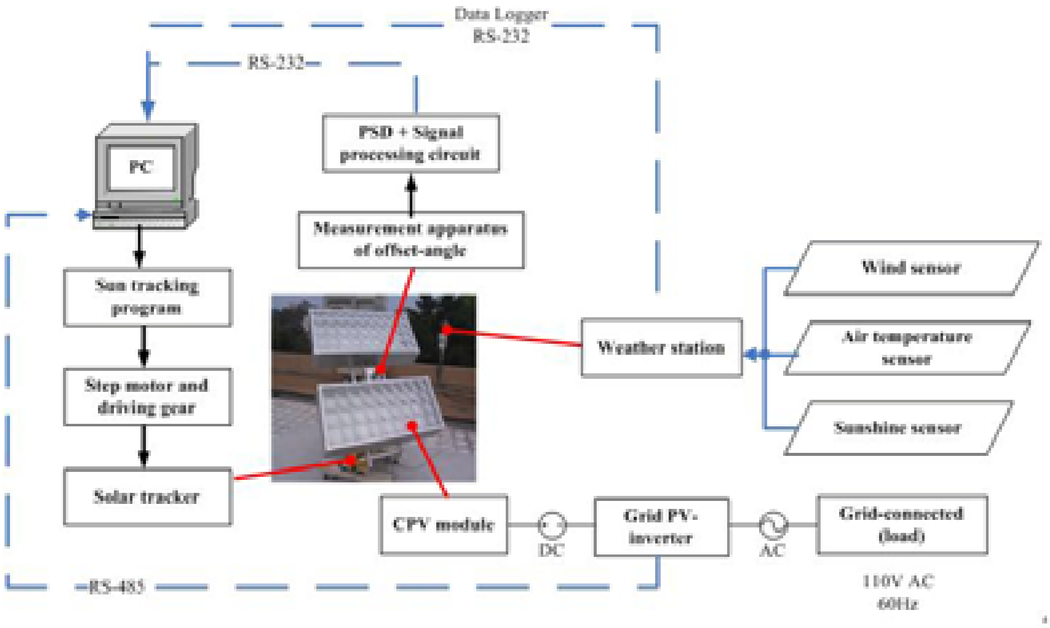

Fig. 1 Schematic diagram of CPV system at National Central University in Jhong-Li, Taiwan.

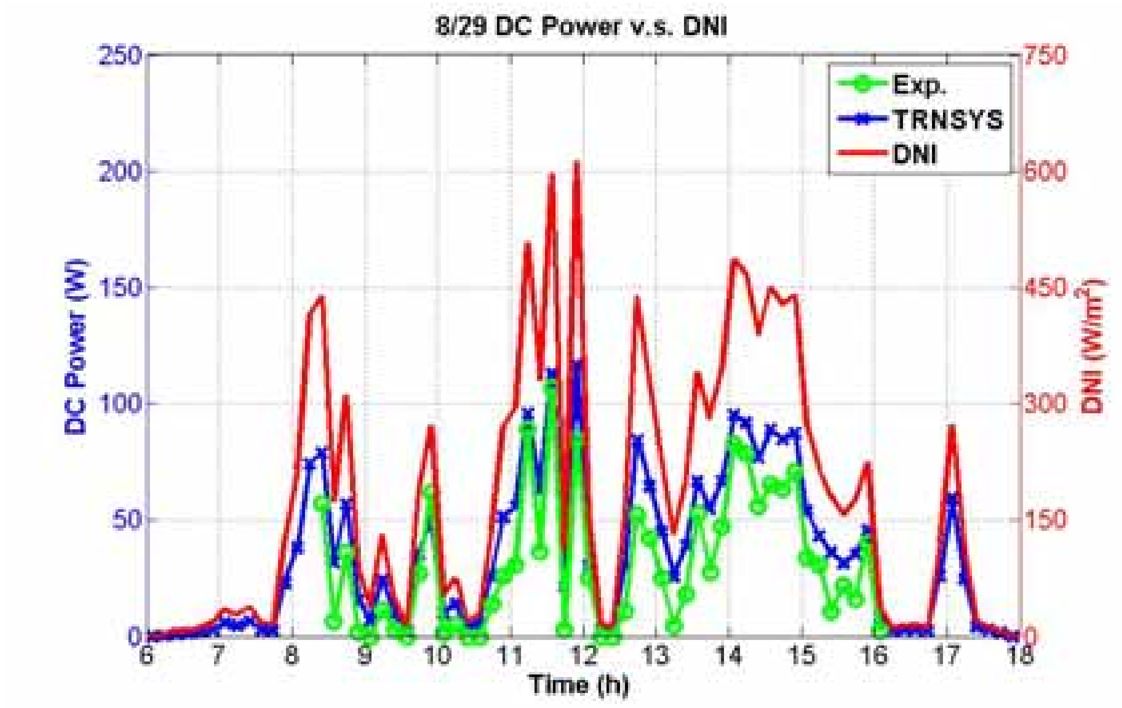

Fig. 2 Comparison of predicted and measured DC power on a cloudy day with average value 240 Wm^{-2}. Error between predicted and measured average DC power was 47.1%.

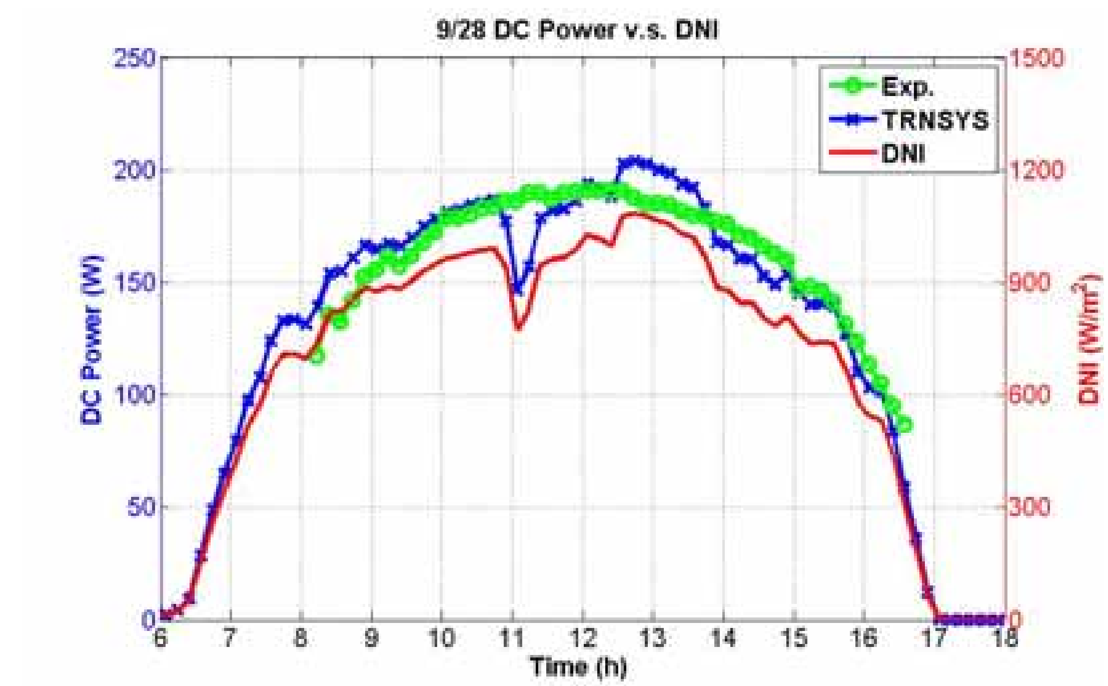

Fig. 3 Comparison of predicted and measured DC power on a sunny day with average value 866 Wm^{-2}. Error between predicted and measured average DC power was 0.18%.

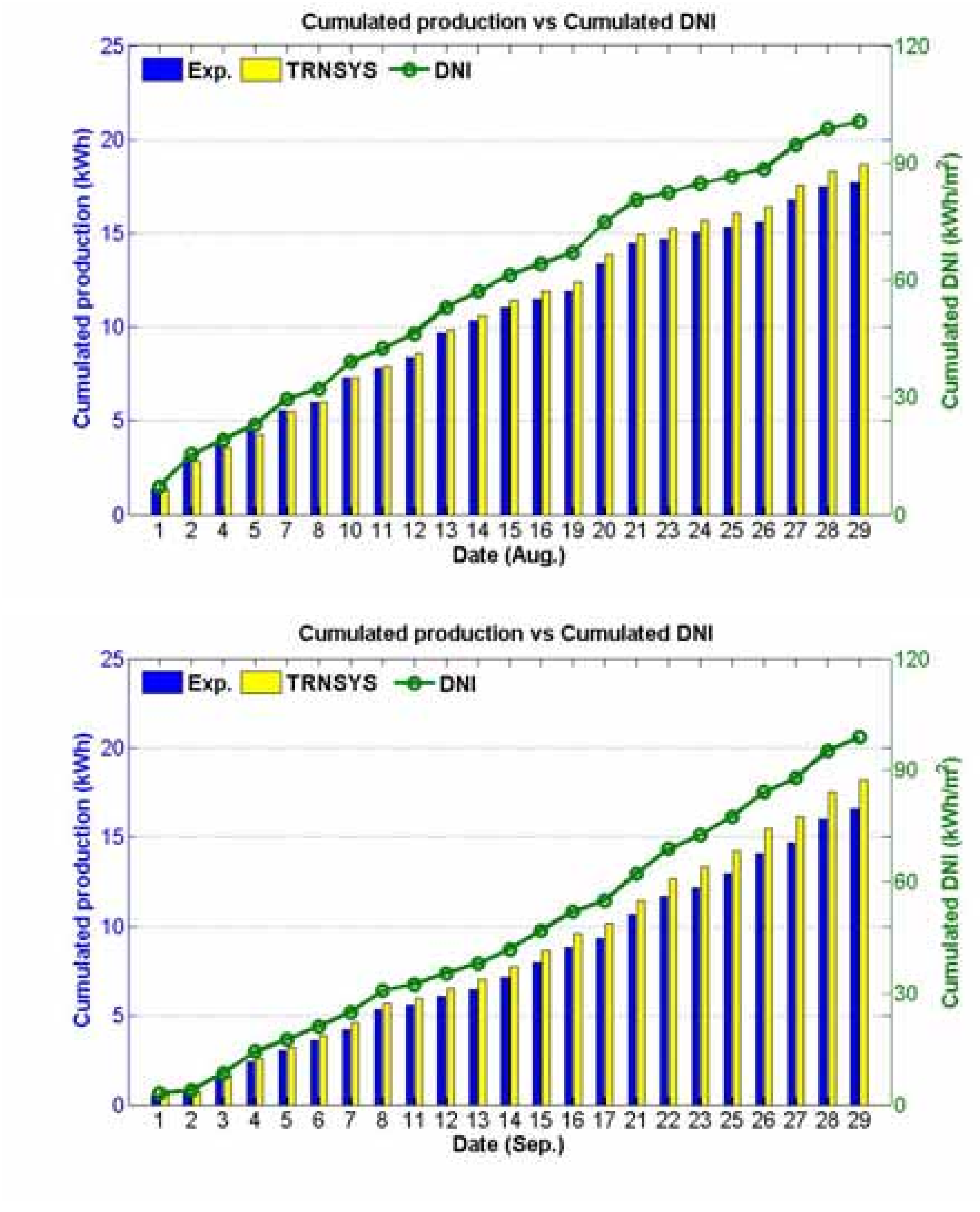

Fig. 4 Measured and predicted cumulated production versus measured cumulated DNI on August and September, 2010. Error between measured and predicted cumulated production were 5.28% and 9.53%, respectively.

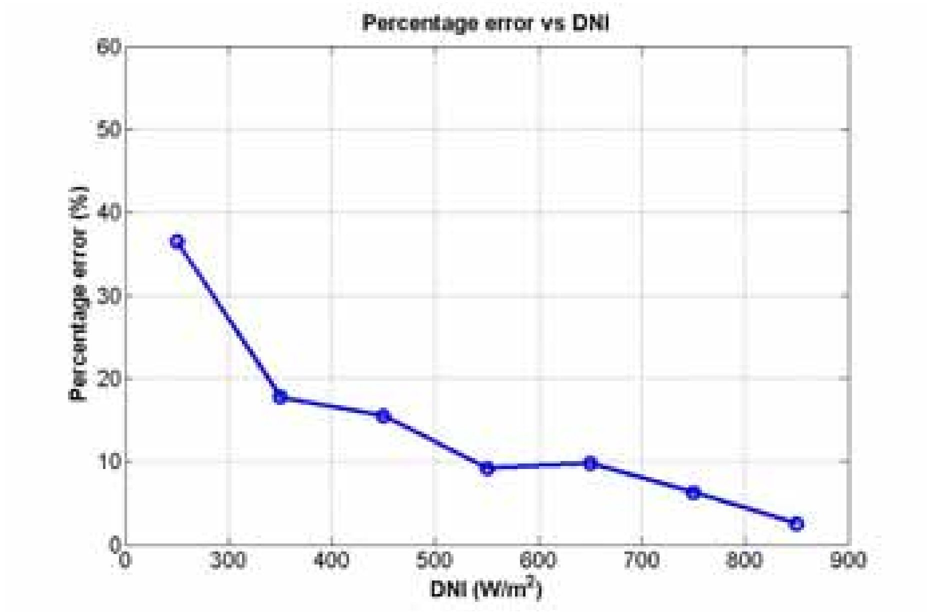

Fig. 5 Error between measured and predicted daily average power as a function of measured daily average DNI.

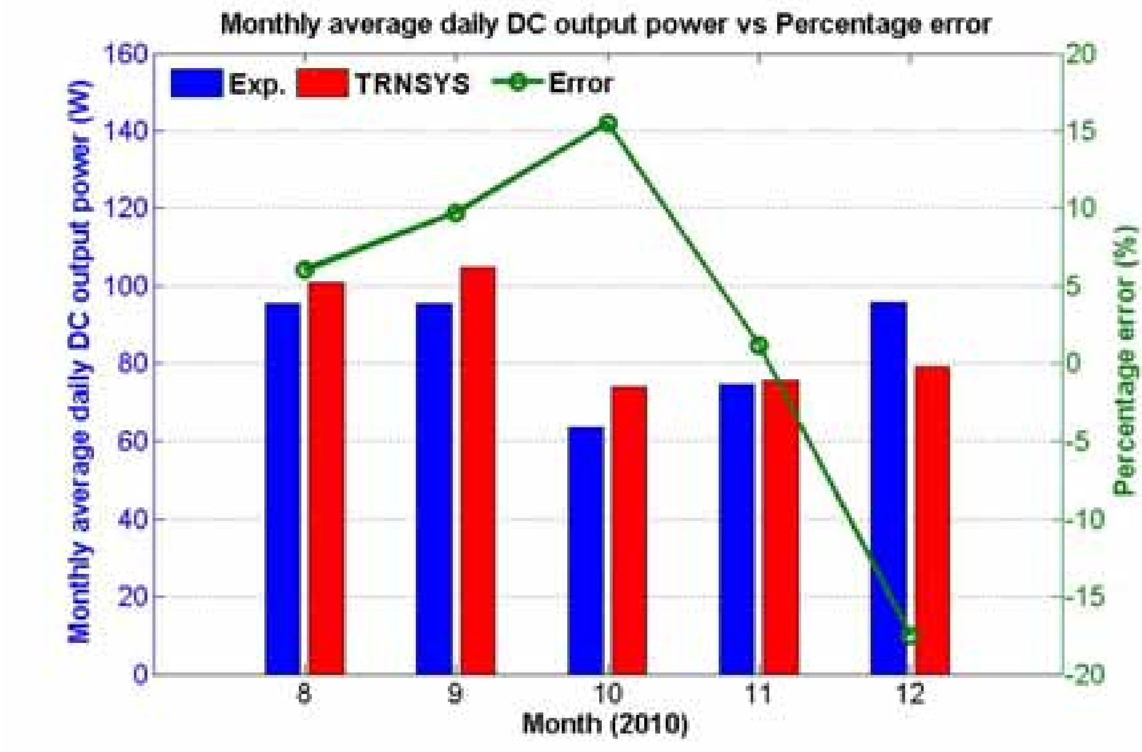

Fig. 6 Monthly averaged daily measured and predicted DC power and corresponding error.

Table 1 PV module characteristic parameter used in PV/CPV array component in TRNSYS.

Parameter	PV	CPV
Module short circuit current at reference conditions (I_{sc})	5.54 A	1.29 A
Module open circuit voltage at reference conditions (V_{oc})	50.3 V	115.6 V
Temperature at reference conditions	298 K	298 K
Irradiance at reference conditions	1000 Wm^{-2}	825 Wm^{-2}
Maximum power point voltage at reference conditions	40.7 V	92.87 V
Maximum power point current at reference conditions	5.05 A	1.2 A
Temperature coefficient of short circuit current (TC_{Isc})	1.66×10^{-3} AK^{-}	**1.68×10^{-3} AK^{-1}**
Temperature coefficient of open circuit voltage (TC_{Voc})	-0.126 VK^{-1}	**-0.208 VK^{-1}**
Module temperature at NOCT conditions	313 K	353 K
Ambient temperature at NOCT conditions	293 K	293 K
Insolation at NOCT conditions	800 Wm^{-2}	800 Wm^{-2}
Transmittance-absorptance product at normal incidence ($\tau\alpha$)	-0.91	**-0.564**
Semiconductor bandgap	1.12 eV	**1.2 eV**
Number of cells in the module connected in series	72	40
Number of modules in series in each sub-array	6	2
Number of sub-arrays in parallel	1	1
Individual module area	1.275 m^2	0.575 m^2