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Comparison of different simplistic prediction models for forecasting PV power output: assessment with experimental measurements

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Abstract:

This paper tested the energy outputs of different types of PV modules and evaluated the accuracies of different simplistic PV module power prediction models. A test rig was developed in Hong Kong to assess the PV power outputs of ten PV modules. The solar radiation, ambient temperature and power generation are recorded. The evaluated models include simple efficiency model, temperature correction model and one-diode model. The results show that the mono-Si PV module is the highest in terms of the annual energy outputs per unit area, and a-Si PV modules is the lowest. The simple efficiency model overestimates the power output of all types of PV modules for more than 10% except for a CdTe PV module. The one-diode model demonstrated the highest accuracy for mono-Si and poly-Si PV modules. The accuracies of the evaluated models are low for thin-film PV technologies. Although the mean bias error of the one-diode model is larger than 10% for the thin-film PV modules (expect for one CdTe PV module), the one-diode model has the highest accuracy among the three models. Further studies should be conducted to investigate the energy performance of thin-film PV modules and then improve their prediction accuracy.

Keywords: PV technologies; PV module model; Simple efficiency model; Temperature correction model; One-diode model

1. Introduction

With the rapid growth of population and economy, the world is facing a significant increase of energy demand. The abuses of fossil fuels could result in global warming and environmental pollution. In this context, photovoltaic (PV) power systems have drawn more and more attention since they can directly transform a free inexhaustible source of solar energy into electricity [1].

The PV technology and PV market grows rapidly in the 21st century. In the last 10 years, the efficiency of average commercial wafer-based silicon modules increased from about 12% to 17%, and the efficiency of CdTe module increased from 9% to 19%. The development of PV technology further promotes the development of PV market. According to statistics, the Compound Annual Growth Rate (CAGR) of cumulative PV installations including off-grid was 35% between year 2010 to 2019 [2]. Besides these development, the PV technologies have been proved to be sustainable and environmental-friendly [3]. It can be seen from the above conditions that there is still great potential for PV development in future.

The deployment of PV systems needs an optimal design to consider its economy under different weather conditions [4]. This necessitates an accurate simulation model to estimate the power generation performance of PV systems [5, 6]. A PV power prediction model is a simulation model which is used to assess the power output of PV systems. Any such a model includes several parts: POA (plane-of-array) irradiance sub-model, PV module power prediction sub-model, DC losses sub-model, inverter sub-model and AC losses sub-model, etc. POA irradiance model estimates the solar irradiance incident on the plane of the PV array based on the horizontal global solar irradiance and environmental conditions [7]. PV module power prediction model calculates the power output of PV modules taking the POA irradiance and temperature into account [8]. The DC losses and AC losses are the electrical losses generated on the DC side and the AC side, respectively. The inverter model is used to calculate the AC output of the PV system according to the DC input with a conversion efficiency [9].

A PV module power prediction model is of vital importance in the whole PV performance model. Different PV module power prediction models with different complexity have been developed by researchers. PV module power prediction models could be classified into two types: one is the empirical models based on predetermined fitting efficiency values; and the other one is the physical models based on the Shockley and Queisser diode equations[10].

Empirical models are empirical descriptions of maximum power values in relation to the corresponding working conditions [10]. The simplest empirical model is the simple efficiency model which estimates the PV power output based on the POA irradiance and the conversion efficiency under standard test conditions (STC). The simple efficiency model is useful for preliminary performance predictions to determine a PV system's installation capacity. Furthermore, the simple efficiency model could be improved with the incorporation of temperature correction considering the power loss with the temperature rising. There are several kinds of temperature correction models with different temperature coefficients adopted, such as Osterwald's method and Constant Fill Factor method [11, 12]. Furthermore, Sandia array performance model is also an empirical model developed for different PV technologies by Sandia National Laboratory [13, 14]. Nevertheless, it needs 39 pre-determined parameters in total, and most of the parameters are not provided by manufacturers, thus it is a relatively complex simulation model.

Physical models are equivalent electric circuit models[10]. They are able to calculate the I-V curve of PV modules, because solar cell is basically a semiconductor diode whose p-n junction is exposed to light [15]. According to the diode number used, equivalent electric circuit models can be clssifieded as one diode model [16, 17], two diode model [18-20], and three diode model [21], etc. Although the two diodel model and three diodel are higher in accuracy, the One diode model is more widely used since it offers a good compromise between simplicity and accuracy [17, 22]. The one diode model can be further divided into four-parameter model [23, 24] and five-parameter model [25, 26]. The five-parameter model is usually utilized to simulate the PV performance, while the four-parameter model which neglects the effects of the shunt resistance was inadequate to fit I-V and P-V figures [27]. However, equivalent electric circuit models are based on assumptions that are only held for idealized p-n junction solar cells, thus they are not suitable for thin-film PV modules, such as a-Si solar cells.

About the evaluation of PV module power prediction models, some researchers tried to validate one PV module model for different PV technologies. Boyd et al. [28] evaluated the accuracy of the five-parameter model for a wide range of PV technologies, including mono-Si, poly-Si, a-Si and copper indium diselenide (CIS). Ishaque et al. [29] proposed an improved modeling approach for the two-diode model and validated its accuracy with the test results of six PV modules (mono-Si, poly-Si and CIS). Massi Pavan et al. [30] proposed an explicit model and validated the model using poly-Si, CdTe, CIGS and HIT modules. Some other researchers compared the prediction performance of different PV module models for a certain type of PV technology. Roberts et al. [31] evaluated the accuracy of the POA irradiance models, PV module models, and inverter models for poly-Si PV systems. Torres-Ramírez et al. [12] verified two simple empirical modeling for thin-film PV modules.

In addition, studies have also been conducted to evaluate different PV module models for different PV technologies. Cameron et al. [32] evaluated the ability of the SAM model to predict the energy production of different PV systems. Lee et al. [33] compared the measured data with the simulated results of four PV modeling software tools. Six different PV systems were studied, including two mono-Si arrays, two poly-Si arrays, an a-Si array and a CdTe thin-film array. Although a lot of models have been developed and there are studies on the evaluation of PV module models for different PV technologies, the studies are far from enough for giving guidelines in the selection of suitable models for PV technologies.

In order to evaluate the accuracy of different models for different PV technologies, a PV test of different solar PV panels should be conducted under the same weather conditions. Makrides et al. [34] estimated the accuracy of four PV module models for twelve different grid-connected PV systems by calculating the annual DC energy prediction errors against outdoor measurements from 2006 to 2010. The models evaluated include the single-point efficiency model, single-point efficiency with temperature correction model, photovoltaic for utility-scale applications (PVUSA) model and the one-diode model. After nearly 10 years, the efficiencies of PV modules have been greatly improved, and a new PV test should be conducted to represent the development of various PV technologies.

According to the literature review, the objective of this study is to test the energy outputs of different types of PV modules and evaluate the ability of various simple PV module models in terms of predicting the power outputs. In the design phase of a solar PV project, there is limited information about PV modules. Usually, only the datasheet values were provided by the manufacturer. Thus, the models evaluated in this project will only use the datasheet values which could guide the design of PV projects in the pre-design stage.

2. PV module test rig

In this study, the performances of five different PV modules are tested, including mono-Si, poly-Si, a-Si, CIGS and CdTe. Mono-Si and poly-Si belong to the first-generation PV technology which is called wafer technology. A-Si, CIGS, and CdTe are the second-generation PV technology which is called thin-film technology. The material demand of thin-film PV technology is less than that of the wafer technology, but its energy conversion efficiency is lower than that of the wafer technology as well [35]. In order to identify the universality of the PV technologies and simulation models, two modules from different manufacturers are chosen for each given technology. As showed in Figure 1, a test rig was built in Hong Kong to measure and study the energy performance of different PV technologies. The characteristics of the measured PV modules are listed in Table 1 (all the manufacturer and brand names are not shown here).

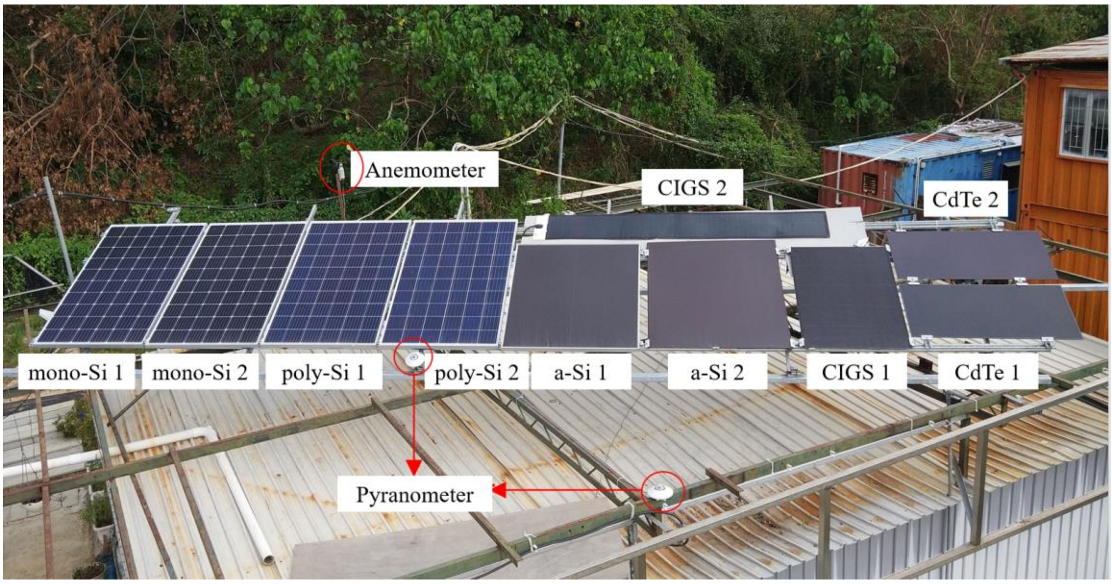


Fig. 1 Test rig of the PV modules in Hong Kong

Table 1 Specifications of the 10 PV modules

Solar Cell-technologies*	Mono-Si 1	Mono-Si 2	Poly-Si 1	Poly-Si 2	A-Si 1	A-Si 2	CIGS 1	CIGS 2	CdTe 1	CdTe 2
Nominal Power (W)	305	300	280	275	140	120	140	115	107.5	80
Short circuit current (A)	9.94	9.77	9.37	9.35	5.28	2.65	1.79	4.52	1.75	0.95
Open circuit voltage (V)	40.2	39.76	38.65	38.72	42.3	71	106.7	37.6	86.6	118.9
Current at maximum power point (A)	9.24	9.26	8.86	8.77	4.34	2.22	1.62	3.87	1.57	0.85
Voltage at maximum power point (V)	33.0	32.41	31.61	31.36	32.2	54	86.5	29.7	68.6	94.1
Temperature coefficient of Pmpp, γ_{Pmp} (%/^{o}C)	-0.39	-0.39	-0.40	-0.40	-0.47	-0.29	-0.32	-0.38	-0.34	-0.214
Temperature coefficient of Isc, α_{Imp}(%/^{o}C)	+0.059	+0.04	+0.058	+0.04	+0.10	+0.07	+0.01	+0.008	+0.04	+0.06
Temperature coefficient of Voc, β_{Vmp} (%/^{o}C)	-0.30	-0.28	-0.33	-0.29	-0.38	-0.32	-0.27	-0.28	-0.29	-0.321
Module Efficiency (%)	18.7	18.0	17.1	16.5	9.6	8.4	14.9	12.0	14.9	11.1
Dimension (mm×mm×mm)	1650*991*40	1670*1000*32	1650*991*35	1670*1000*32	1310*1110*40	1300*1100*6.8	1190*790*7.3	2598*370*17	1200*600*6.8	1200*600*6.8

* The datasheets are derived from the information of the ten PV modules provided by different manufacturers. However, the details of the PV modules are faded away to avoid dispute on the performance of PV modules.

Figure 2 shows the schematic diagram of the PV module test system. The main instruments are listed in Table 2. One pyranometer was used to measure the horizontal global solar radiation and the other one was used to measure the solar radiance on the plane of PV array. The air temperature and the backside temperatures of the PV modules were measured with resistance thermometers. An anemometer was adopted to measure wind speed. The above environmental data was collected by a data logger with a sampling interval of 1 min.

Since the I-V characteristics of the various PV modules are different, each PV module is connected to a power optimizer to adjust the current to ensure the PV modules can be connecting in series. Meanwhile, the power optimizers could track the maximum power point of the connected PV modules for maximum power output from the system. The performance of each module could also be monitored by the monitoring system to realize the module-level operation and maintenance. The inverter converts direct current to alternating current, and uploades power generated by the PV modules to the utility grid.

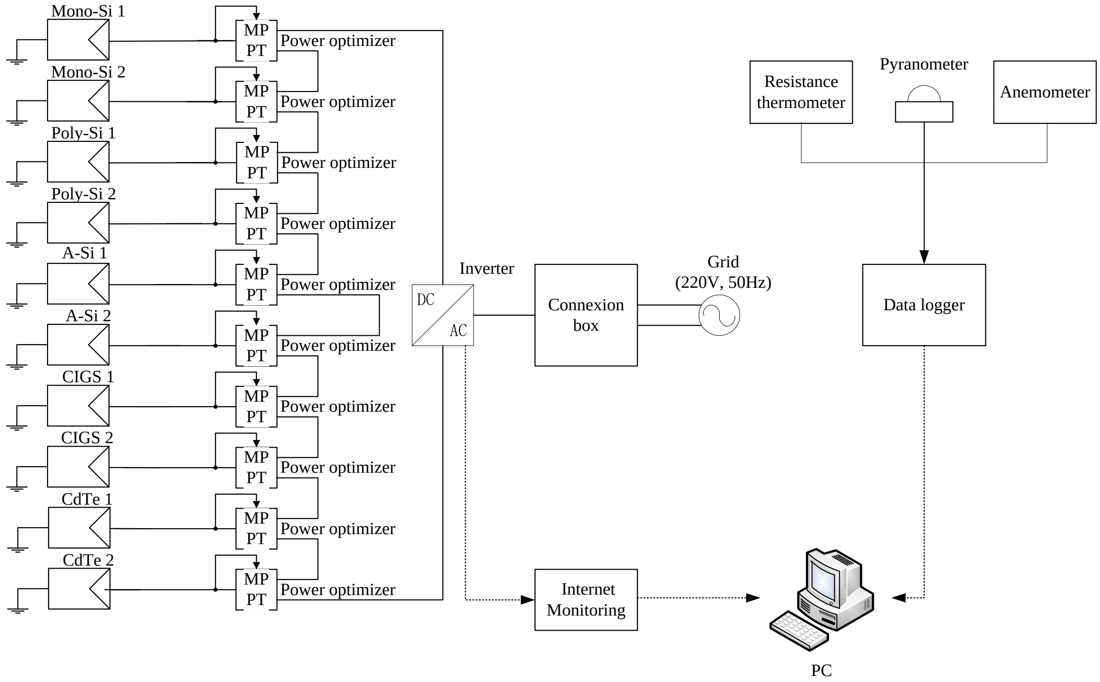


Fig. 2 Schematic diagram of the PV module test rig

Table 2 The key instruments in this study and their specifications

	Function	Manufacturer (Model)	Accuracy/Sensitivity
Pyranometer	Solar irradiation measurement	EKO instruments (MS-802)	Sensitivity: about 7 μV/(W/m^2); Non-linearity<0.2 % (at 1000W/m^2); Accuracy: 2%;
Resistance thermometer	Temperature measurement	RS Components (PT 100 sensor)	Temperature range: -20 ~ 100°C; Accuracy: ±0.15°C;
Anemometer	Wind speed measurement	Zhonghuan TIG (EL15-1C)	Accuracy: ±0.3m/s (≤10m/s); ±0.03*v (>10 m/s);
Power optimizer	Per-module maximum	SolarEdge (P405)	99.5% peak efficiency; 98.8% weighted efficiency; Accuracy of 2.5%

	power point tracking		in voltage and current;
Inverter	Convert DC power to AC power, Record Power generation	SolarEdge (SE2200H)	99% weighted efficiency; Accuracy of 2.5% in voltage and current;
Data logger	Data collection	Graphtec (GL840 Midi Data Logger)	The minimum resolutions are 1 μV and 0.1 °C; Accuracy: 0.01% of measuring range;

3. PV module models

In this study, complex models which need professional knowledge are not included since this study aims to identify a simple and accurate model for engineering use. Besides, the PV module power prediction models which need additional tests or actual measured data are not considered in this study. Though they are usually more accurate, they cannot be used in situations where testing equipment or historical data is not available. The PV module models evaluated in this study are the simple efficiency model, the simple efficiency with temperature correction model, and the one-diode model.

3.1 Simple efficiency model

The simple efficiency model is a simple PV module model considering the conversion efficiency only. As shown in the following equation, the power output of the PV system is estimated based on the energy conversion efficiency at STC, the area of the PV array and the POA solar irradiance [34].

$$P_M = \eta_{STC} A G_{POA} \tag{1}$$

where, P_M is the DC power output, W; η_{STC} is the conversion efficiency of the PV module at STC; A is the area of the PV array, m^2; G_{POA} is the total irradiance incident on the plane of the PV array, W/m^2.

3.2 Simple efficiency with temperature correction model

The simple efficiency with temperature correction model (hereinafter referred to the temperature correction model) is an evolution of the simple efficiency model. It takes the effect that the power output of the PV module decreases with the cell temperature increasing into consideration. The power loss is accounted for the power temperature coefficient and the temperature difference between the operational condition and STC [31].

$$P_M = \eta_T \eta_{STC} A G_{POA} \tag{2}$$

$$\eta_T = 1 + \gamma(T_{module} - T_{STC}) \tag{3}$$

$$T_{module} = T_a + G_{POA}\left(\frac{T_{NOCT} - 20}{800}\right) \tag{4}$$

where, η_T is the power loss caused by temperature rising thermal loss; γ is the power temperature coefficient of the PV module provided by manufacturers, 1/°C; T_{module} is the PV module operational temperature, °C; T_{STC} is the PV module temperature at STC, °C; T_a is the ambient dry-bulb temperature, °C; T_{NOCT} is the PV module temperature at Nominal Operating Cell Temperature (NOCT), °C.

3.3 One-diode model

The one-diode model has been widely adopted in PV performance modeling. Usually, the parameters needed by the one-diode model are not provided by manufacturers. Thus, in this study, a software package named System Advisor Model (SAM) was utilized to calculate the power output of the PV modules. SAM is a detailed performance and financial model with the aim of facilitating decision making in renewable energy industry [36]. In the SAM, the CEC (California Energy Commission) performance model with user-entered specifications was selected. This model is a six-parameters model based on the one-diode equivalent circuit[37]. Figure 3 shows the equivalent circuit of the one-diode model which is used to model the performance of solar PV panels.

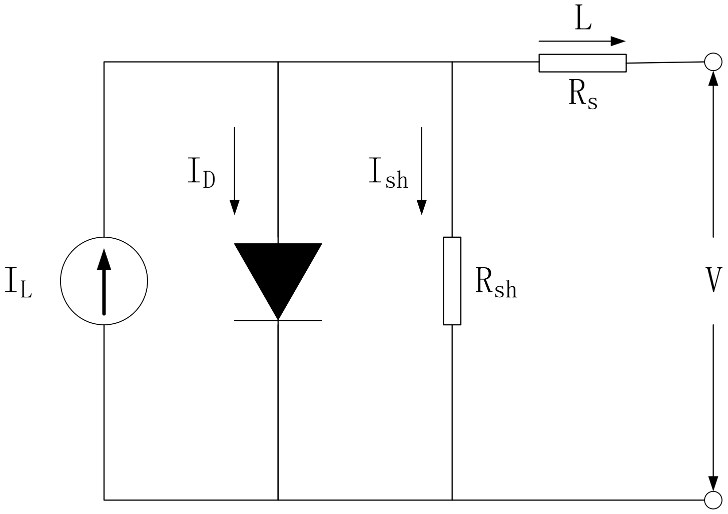


Fig. 3 An equivalent circuit of the one-diode model

3.4 Uncertainty analysis of PV performance models

In this work, the uncertainties of DC energy yield prediction of PV performance models were investigated. However, the one-diode model was not evaluated because the input six-parameters were not acquired from the manufacturer but extracted from the software SAM. One assumption made in this investigation is that the area of each PV module, used as an input variable into the PV performance model, was not associated with any significant uncertainty.

The combined uncertainty of the simple efficiency model was calculated by the following equation with uncertainty propagation techniques [38]. It considered the input parameters such as the STC efficiency of the PV module and the total irradiance in the POA [34]:

$$u_c = \sqrt{\left[\left(\frac{\partial P}{\partial \eta_{STC}} u_{\eta_{STC}}\right)^2 + \left(\frac{\partial P}{\partial G_{POA}} u_{G_{POA}}\right)^2\right]} \tag{5}$$

Similarly, the combined uncertainty of the temperature correction model was also investigated. As shown in Equation (6), the uncertainty of each input parameter propagates through the sensitivity coefficients, which are the partial derivatives of each uncertainty parameter [38]. Thus, the sensitivity coefficients with respect to the parametric uncertainties of

η_{STC}, G_{POA}, γ, T_{NOCT}, and T_a were evaluated and used to obtain the combined uncertainty, u_c. The combined uncertainty of predicting DC power output based on the absolute uncertainties and sensitivity coefficients for the temperature correction model was obtained by combining the individual standard uncertainties using the law of propagation uncertainties and the root-sum-of-squares of all uncertainty components [34]:

$$P_{DC} = \eta_{STC} A G_{POA} + \gamma T_a \eta_{STC} A G_{POA} + \gamma G_{POA}\left(\frac{T_{NOCT}-20}{800}\right)\eta_{STC} A G_{POA} - \gamma T_{STC}\eta_{STC} A G_{POA} \tag{6}$$

$$u_c = \sqrt{\left[\left(\frac{\partial P}{\partial \eta_{STC}} u_{\eta_{STC}}\right)^2 + \left(\frac{\partial P}{\partial \gamma} u_{\gamma}\right)^2 + \left(\frac{\partial P}{\partial T_a} u_{T_a}\right)^2 + \left(\frac{\partial P}{\partial T_{NOCT}} u_{T_{NOCT}}\right)^2 + \left(\frac{\partial P}{\partial G_{POA}} u_{G_{POA}}\right)^2\right]} \tag{7}$$

The uncertainty associated with the annual DC energy yield was evaluated by integrating all calculated uncertainties of power output over a year for each PV technology.

4. Energy output

Figure 4 shows the monthly energy outputs of different types of PV modules from Oct 10th 2018 to Oct 9th 2019. The annual energy outputs of the mono-Si 1, mono-Si 2, Poly-Si 1, Poly-Si 2, A-Si 1, A-Si 2, CIGS 1, CIGS 2, CdTe 1 and CdTe 2 are 337.5kWh, 313.2kWh, 299kWh, 292.5kWh, 131.4kWh, 122.4kWh, 132.3kWh, 121.4kWh, 134.7kWh and 76.7kWh, respectively. The annual energy outputs per square meter of the five different solar PV panels rank from the highest to the lowest: mono-Si > CdTe > poly-Si > CIGS > a-Si. The hourly power generations of PV modules are utilized to evaluate the accuracy of power generation models in the next section.

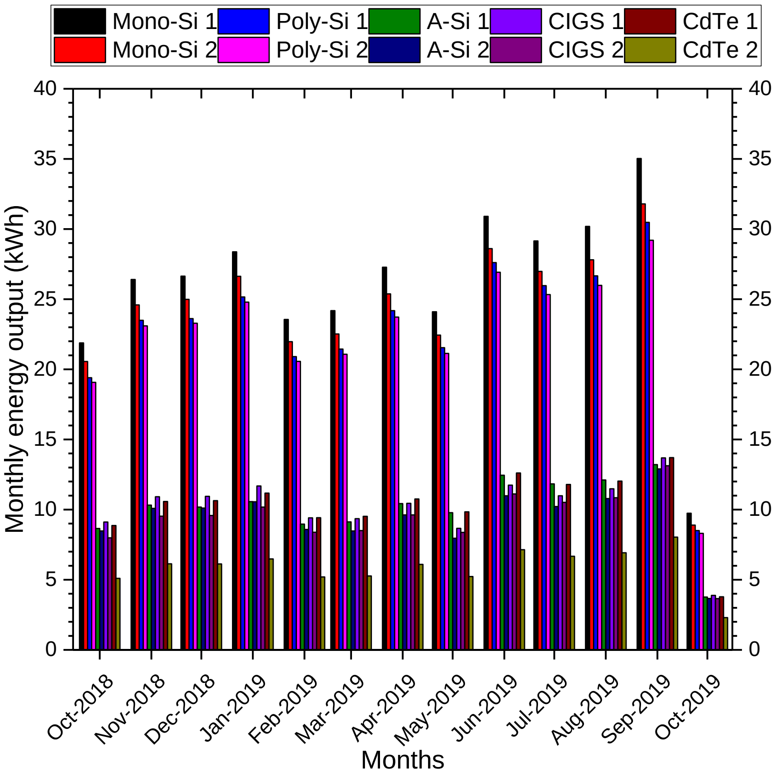


Fig. 4 Monthly energy outputs of different types of PV modules from Oct 10th 2018 to Oct 9th 2019

5. Model accuracy evaluation

In this paper, the solar irradiance on the plane of PV array was measured and imported into the PV module model. The inverter efficiency was assumed to be 98%. The DC and AC losses were assumed to be 4.5% and 1% which are equal to the default values in the SAM, respectively.

5.1 Evaluation indicators

The accuracies of the PV module models were assessed with three statistical indices including the coefficient of determination (R^2), mean bias error (MBE) and root mean square error (RMSE). These indicators are commonly utilized in the accuracy estimation of PV performance models [26, 28, 34]. The R^2 shows how close the simulated data are to the measured data or the fitted regression line. The value of R^2 equals to 1 means the simulation model or fitted regression line perfectly fits the measured data. In general, the higher the R^2, the better the model fits the measured data. The MBE demonstrates the long-term performance of a simulation model. A negative MBE means the model underestimates the calculated value, while a positive MBE means the model overestimates the calculated value. The drawback of MBE is that the overestimation of a simulated value may be offset by an underestimation of another simulated value. RMSE indicates the short-term performance of a simulation model through a term-by-term comparison of the actual deviation. RMSE is always non-negative, and a value of 0 means the model perfectly fitting the measured data. Overall, a smaller RMSE is preferable than a higher one. RMSE could be used to compare forecasting errors of different models for a particular dataset. However, RMSE is scale-dependent and not suitable for comparisons of datasets. ASHRAE Guideline 14-2014 stipulates that the simulation model is regarded to be acceptable in terms of accuracy if the rMBE and rRMSE are lower than 10% and 30%, respectively [39]. The values of MBE, RMSE and their relative values are obtained with the following equations:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(m_i - s_i)^2}{\sum_{i=1}^{N}(m_i - \overline{m})^2} \tag{8}$$

$$MBE = \frac{\sum_{i=1}^{N}(m_i - s_i)}{N} \tag{9}$$

$$rMBE = \frac{\sum_{i=1}^{N}(m_i - s_i)}{\sum_{i=1}^{N}(m_i)} \tag{10}$$

$$RMSE = \sqrt{\left(\sum_{i=1}^{N}(m_i - s_i)^2 / N\right)} \tag{11}$$

$$rRMSE = \frac{\sqrt{\left(\sum_{i=1}^{N}(m_i - s_i)^2 / N\right)}}{\overline{m}} \tag{12}$$

where, m_i is the measured value for the instance "i"; s_i is the simulated value for the instance "i"; N is the number of data in the dataset; $\overline{m}$ is the average value of all measured data.

All of the above three indices have their merits and limitations, but they could give a comprehensive evaluation of the PV module model together.

5.2 Results of the mono-Si PV modules

Fig. 5 compares the measured data and the simulated results calculated by three different models for the two Mono-Si PV modules. If the simulated AC power equals to the measured one, the spot would fall over the solid line (y=x). The dashed line is the best linear fit of the scatter data, whose slope and R^2 values are also present in the figure. Table 3 summarizes the evaluation indicator values of the three PV module models for the Mono-Si PV modules.

The simple efficiency model overestimates the power generation of the Mono-Si 1 and Mono-Si 2 PV modules by 11.1% and 17.5%, respectively. The higher the POA irradiance, the larger the regular residual. It is because the temperature of the PV module increases with the increase of POA irradiance, which leads to a large fall-off of the PV energy output.

Since the rMBE and rRMSE are lower than 10% and 30%, both the temperature correction model and the one-diode model are acceptable for the mono-Si PV modules' power output prediction. Among the three models, the one-diode model has the highest accuracy for predicting the energy output of the mono-Si technology. It underestimated the power generation of the Mono-Si 1 PV module by 3.1% and overestimated the power generation of the Mono-Si 2 PV module by 3.4%.

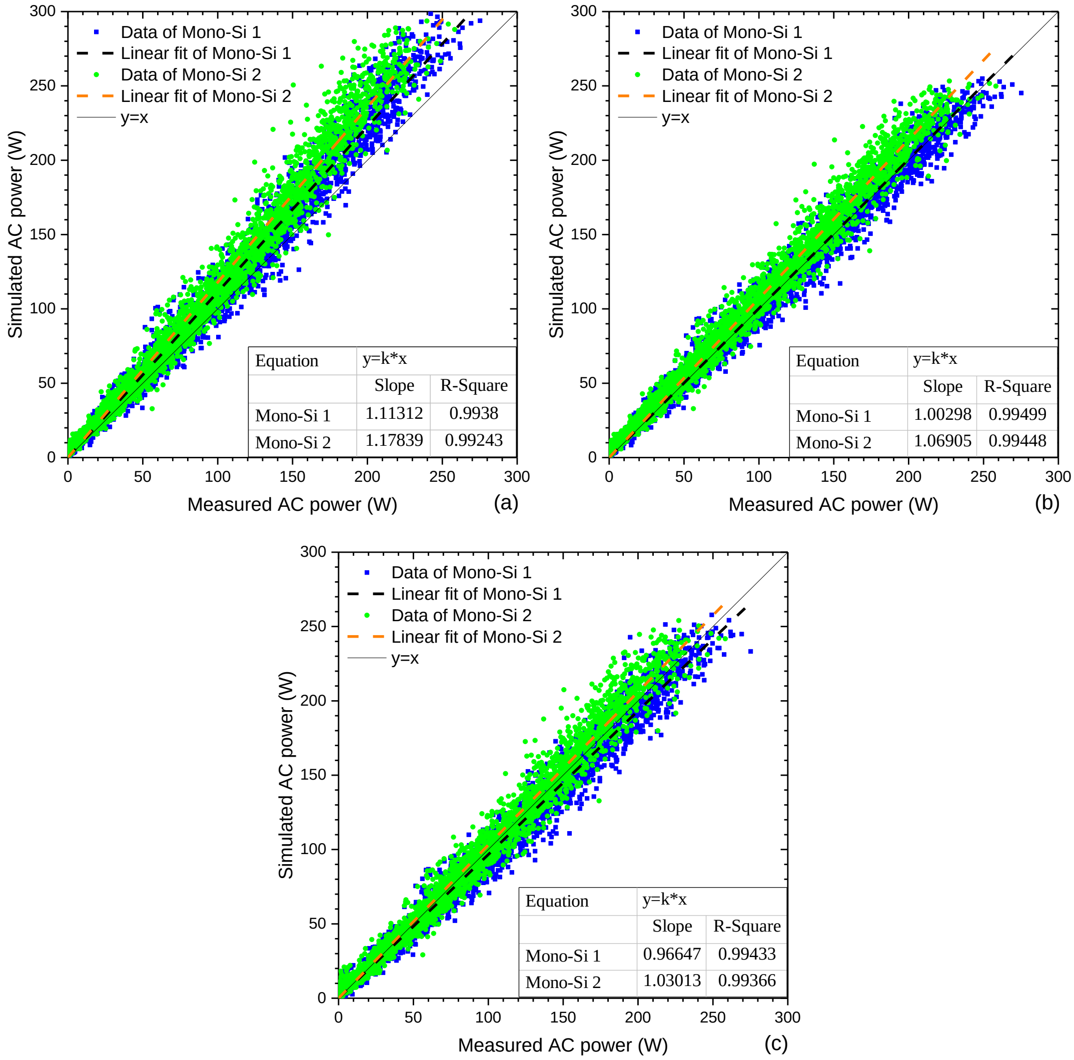


Fig. 5 Comparison between simulated results and measured data for the Mono-Si PV modules

(a) Simple efficiency model (b) Temperature correction model (c) one-diode model

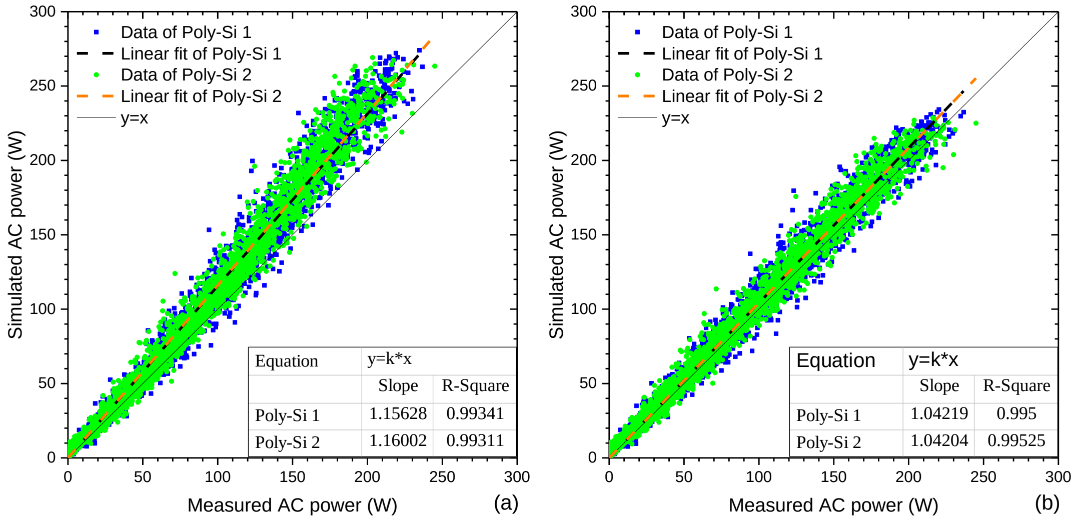
Table 3 Summary of the PV module models for mono-Si PV modules

PV module	PV module model	Indicators		
		R^2	rMBE (%)	rRMSE (%)
Mono-Si 1	Simple efficiency model	0.972	11.1	27.6
	Temperature correction model	0.993	2.1	13.7
	One-diode model	0.991	-3.1	15.4
Mono-Si 2	Simple efficiency model	0.942	17.5	39.6
	Temperature correction model	0.985	8.5	20.2
	One-diode model	0.989	3.4	16.8

5.3 Results of the poly-Si PV modules

Figure 6 compares the measured data and the simulated results calculated by the three different models for the two poly-Si PV modules. Table 4 summarizes the evaluation indicator values of the PV module models for poly-Si PV modules. The simple efficiency model overestimated the power generation of the poly-Si 1 and Poly-Si 2 PV modules by 15.0% and 15.2%, respectively.

Similar to the results of the mono-Si PV modules, the temperature correction model and one-diode model could also predict the performance of the Poly-Si PV modules at an acceptable accuracy level. Overall, the one-diode model has the highest accuracy for both poly-Si PV modules. The one-diode model overestimated the power generation of the poly-Si 1 PV module and Poly-Si 2 PV modules by 2.4% and 1.3%, respectively.



Equation	y=k*x	
	Slope	R-Square
Poly-Si 1	1.15628	0.99341
Poly-Si 2	1.16002	0.99311

Equation	y=k*x	
	Slope	R-Square
Poly-Si 1	1.04219	0.995
Poly-Si 2	1.04204	0.99525

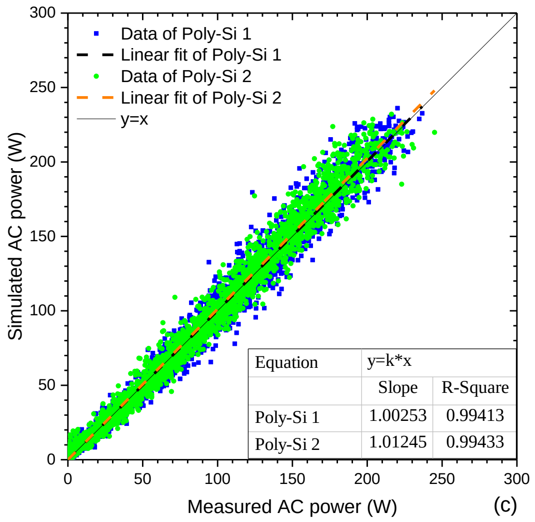


Fig. 6 Comparison between simulated results and measured data for the Poly-Si PV modules
(a) Simple efficiency model (b) Temperature correction model (c) One-diode model

Table 4 Summary of the PV module models for poly-Si PV modules

PV module	PV module model	Indicators		
		R^2	rMBE (%)	rRMSE (%)
Poly-Si 1	Simple efficiency model	0.954	15.0	35.0
	Temperature correction model	0.990	5.7	16.3
	One-diode	0.992	2.4	14.8
Poly-Si 2	Simple efficiency model	0.952	15.2	35.8
	Temperature correction model	0.992	5.6	16.0
	One-diode model	0.992	1.3	14.8

5.4 Results of the a-Si PV modules

Figure 7 compares the measured data and the simulated results calculated by three different models for the two a-Si PV modules. Table 5 summarizes the evaluation indicator values of different PV module models for a-Si PV modules. The simple efficiency model overestimated the power generation of a-Si 1 PV module and a-Si 2 PV module by 30.5% and 30.6%, respectively.

The rMBE and rRMSE of the three PV module models are out of the accuracy level for predicting the performance of a-Si PV modules. The rMBEs of a-Si 1 and a-Si 2 PV modules are larger than 10%, which means the energy output of the a-Si PV modules is overestimated by more than 10%. The rRMSEs of a-Si 1 PV module are larger than 30%, while the rRMSEs of a-Si 2 PV module are in the range of 20% to 30%. According to the calculated rMBE and rRMSE, the accuracy of the one-diode model is the highest among the three models for a-Si PV modules.

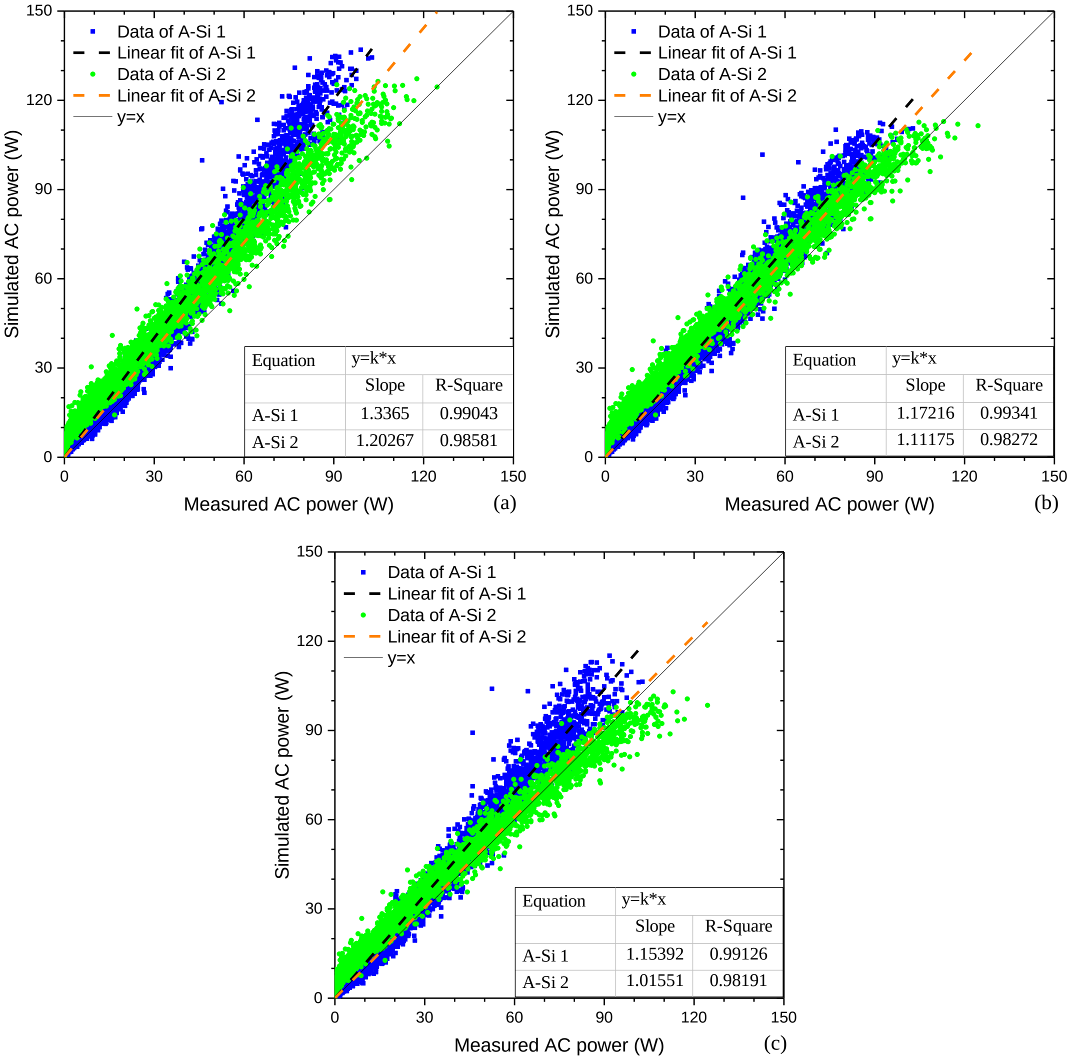


Fig. 7 Comparison between simulated results and measured data for the a-Si PV modules
(a) Simple efficiency model (b) Temperature correction model (c) One-diode model

Table 5. Summary of the PV module models for a-Si PV modules

PV module	PV module model	Indicators		
		R^2	rMBE (%)	rRMSE (%)
A-Si 1	Simple efficiency model	0.818	30.5	67.9
	Temperature correction model	0.946	17.2	37.0
	One-diode model	0.951	14.5	35.4
A-Si 2	Simple efficiency model	0.920	30.6	51.9
	Temperature correction model	0.956	22.8	38.6
	One-diode model	0.975	12.3	28.9

5.5 Results of the CIGS PV modules

Figure 8 compares the measured data and the simulated results calculated by three different models for the two CIGS PV modules. Table 6 summarizes the evaluation indicator values of different PV module models for the CIGS PV modules. The simple efficiency model overestimated the power generation of CIGS 1 PV module and CIGS 2 PV module by 30.1%

and 16.7%, respectively.

The rMBEs and rRMSE of all the three PV module models for CIGS 1 PV module are larger than 10% and 30%, while the rMBEs and rRMSE of the temperature correction model and one-diode model for CIGS 2 PV module are within 10% and 30%, respectively. Overall, the accuracy of the one-diode model is the highest. The rMBE of the one-diode model were 17.1% and 4.5% for the two CIGS PV modules, and rRMSE were 31.2% and 16.4%, respectively.

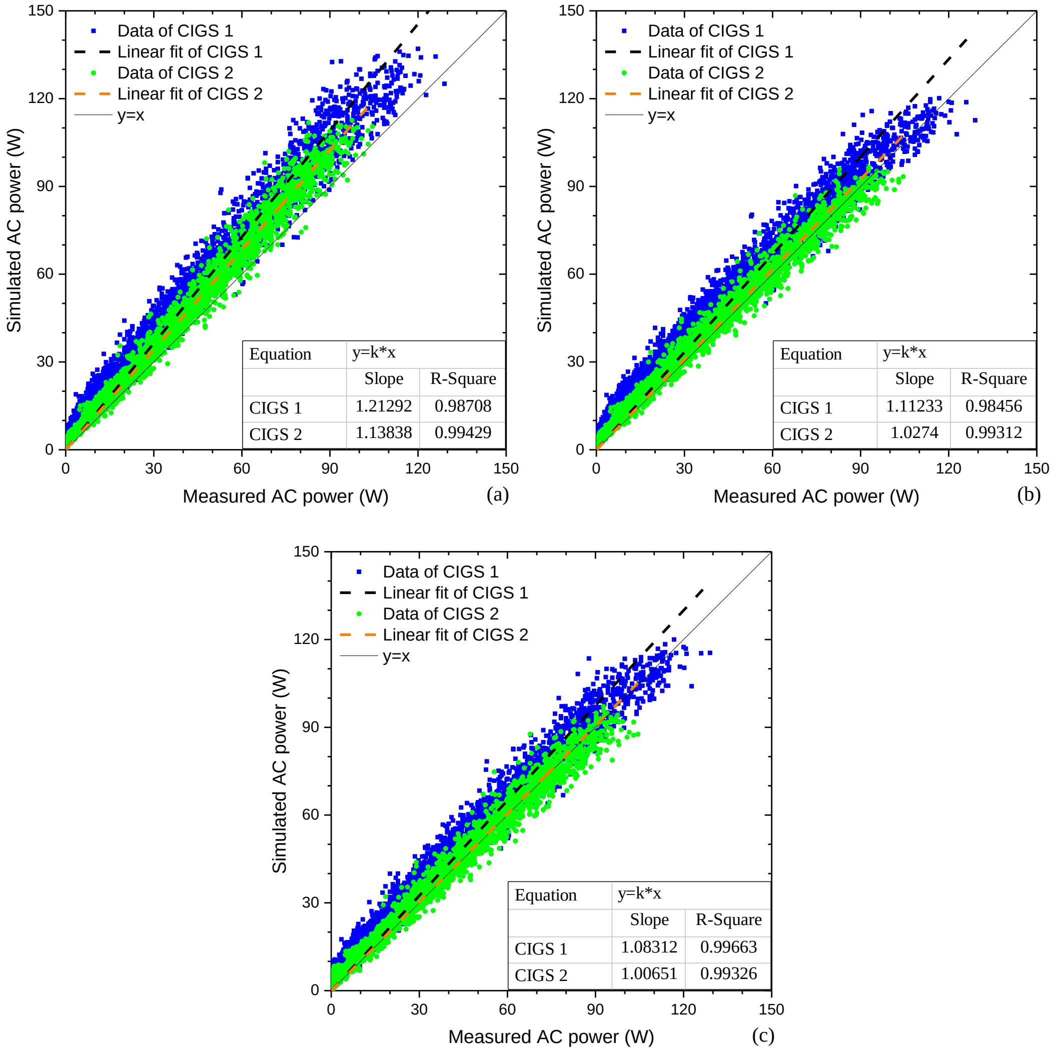


Fig. 8 Comparison between simulated results and measured data for the CIGS PV modules (a) Simple efficiency model (b) Temperature correction model (c) One-diode model

Table 6 Summary of the PV module models for CIGS PV modules

PV module	PV module model	Indicators		
		R^2	rMBE (%)	rRMSE (%)
CIGS 1	Simple efficiency model	0.915	30.1	52.3
	Temperature correction model	0.958	21.4	36.8
	One-diode model	0.970	17.1	31.2
CIGS 2	Simple efficiency model	0.964	16.7	32.2
	Temperature correction model	0.989	7.5	17.7
	One-diode model	0.991	4.5	16.4

5.6 Results of the CdTe PV modules

Figure 9 compares the measured data and the simulated results calculated by three different models for the two CdTe PV modules. Table 7 summarizes the evaluation indicator values of different PV module models for CdTe PV modules. The simple efficiency model underestimated the power generation of CdTe 1 PV module by 2.0%, while overestimated the CdTe 2 PV module by 28.0%.

Although the power output was underestimated, the lowest rMBE and rRMSE are calculated to be -2.0% and 16.1% for the simple efficiency model. The power output of the CdTe 2 PV module was overestimated by all three models, the lowest rMBE and rRMSE were achieved by the one-diode model with a result of 19.2% and 33.3%, respectively. Among the three models, the accuracy of the simple efficiency model is the highest for CdTe 1 PV module, while the accuracy of the one-diode model is highest for the CdTe 2 PV module. The results may caused by the outstanding performance of the CdTe PV module in warm climates, and the power output is higher than estimated value. This is consistent with other literature [40].

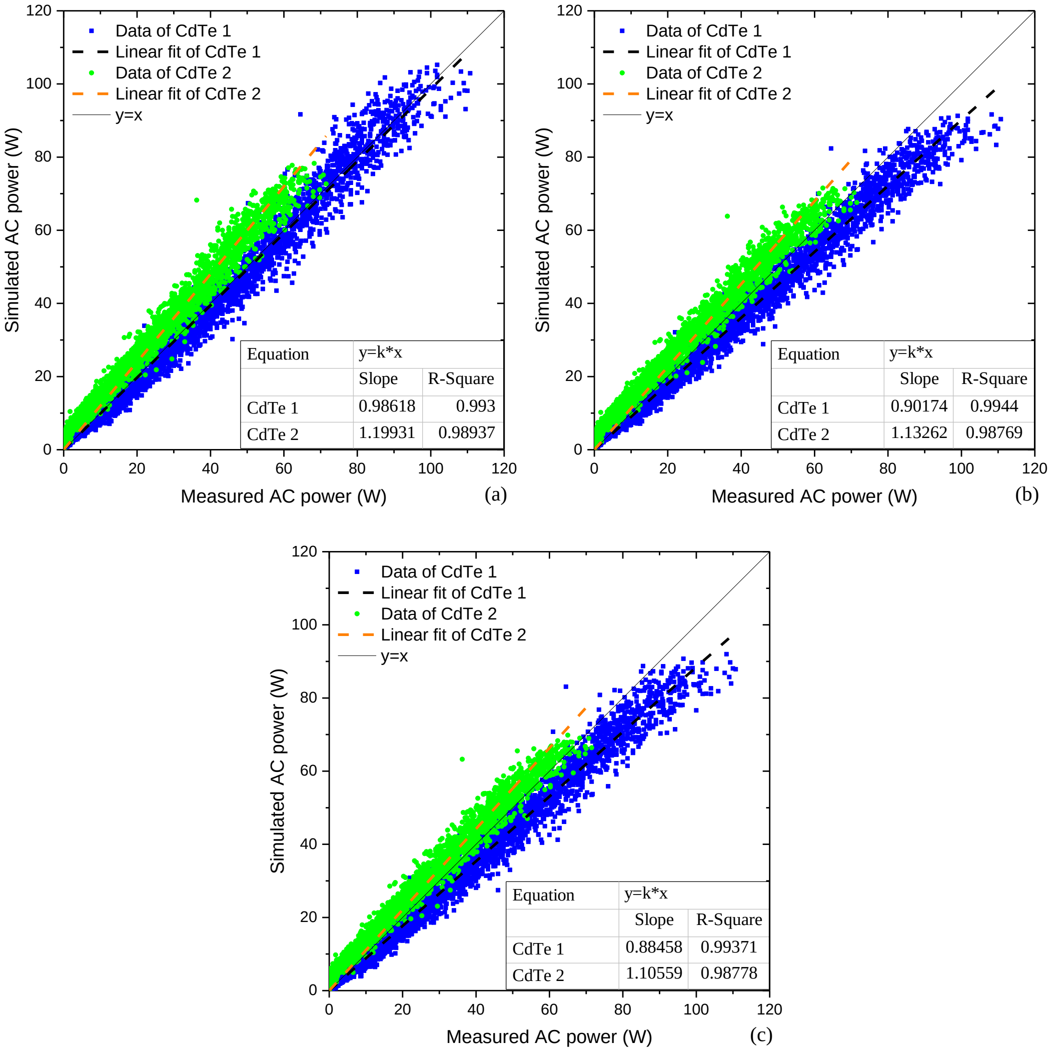


Fig. 9 Comparison between simulated results and measured data for the CdTe PV modules
(a) Simple efficiency model (b) Temperature correction model (c) One-diode model

Table 7 Summary of the PV module models for CdTe PV modules

PV module	PV module model	Datasheet values		
		R^2	rMBE (%)	rRMSE (%)
CdTe 1	Simple efficiency model	0.990	-2.0	16.1
	Temperature correction model	0.980	-8.9	22.8
	One-diode model	0.975	-11.2	25.9
CdTe 2	Simple efficiency model	0.928	28.0	48.2
	Temperature correction model	0.956	22.3	37.6
	One-diode model	0.966	19.2	33.3

6. Discussions

6.1 Uncertainty analysis of PV energy output prediction

The above comparison results show smaller deviations for wafer silicon technologies and larger deviations for thin-film PV technologies. A number of uncertainties are analyzed, which contribute to the deviation between the estimated power output and the measured power output.

Firstly, the uncertainties of the PV performance models are calculated according to Equation 5 and 7. These uncertainties comes from the characteristics data of the PV modules and meteorological data which were used for the model simulation. Manufacturers are unable to produce all PV modules with the same parameters as a result of material and process variability. Usually, the power tolerance of PV modules is 0~+5W. The lower the rating power, the higher the relative error. Meanwhile, there are also uncertainties associated with the open-circuit voltage, short-circuit current, and temperature coefficients, etc. Besides, the uncertainty of the meteorological data is due to the measuring error of instruments, including pyranometers and temperature sensors. The measuring error will influence the accuracy of PV power generation prediction. Table 8 shows the uncertainties of the simple efficiency model and the temperature correction model. With more variables, the temperature correction model exhibits a higher uncertainty than the simple efficiency model.

Table 8 Uncertainties of the simple efficiency model and temperature correction model

System	Uncertainty of simple efficiency model (%)	Uncertainty of temperature correction model (%)
Mono-Si 1	2.59	6.20
Mono-Si 2	2.60	6.21
Poly-Si 1	2.68	6.13
Poly-Si 2	2.70	6.14
A-Si 1	4.09	6.35
A-Si 2	4.62	8.62
CIGS 1	4.09	7.83
CIGS 2	4.79	7.49
CdTe 1	5.06	8.10
CdTe 2	6.56	11.65

Secondly, there are uncertainties which are not considered in the PV performance model. All the mathematical algorithms in the simulation model are simplified and some factors are not taken into account. These factors include light soaking and thermal annealing effect [41], solar spectral influence [42], and long-term performance degradation [43], etc. Unlike wafer silicon PV technologies, the performances of thin-film PV module technologies are not stable due to the metastability. After reaching the stabilization point, the performance of the CIGS PV module becomes stable, while the maximum power of the a-Si and CdTe PV module is still changing [41]. In addition, solar spectral irradiance affects the power output of PV modules by varying the short circuit current of PV modules. Especially, the impact of solar spectral irradiance on the power output of a-Si and CdTe PV modules is more serious than other PV technologies due to their narrow spectral response band [44]. Finally, PV modules would experience energy degradation with various degrees as time goes [45], which further making it difficult to predict their power outputs accurately with the PV module models.

Lastly, the uncertainties on the assumption of the PV system are especially critical to the accuracy of the PV performance prediction. There are power losses resulting from PV array mismatch, PV panel soiling losses, PV shading losses, electrical line resistive losses, etc. These assumptions inputs will influence the power output estimation and are highly dependent on the users and their experience.

6.2 Comparison with other studies

Table 9 shows the findings of existing publications on the prediction accuracy of PV models.

Table 9 Literature review on the PV model accuracy for energy prediction

Reference	PV technology	Findings
Torres-Ramírez et al. [12]	thin film	The accuracy of Osterwald's method and constant fill factor method for modeling the outdoor performance of the a-Si, a-Si:H/μc-Si, CIGS, and CdTe PV modules ranked from the lowest to the highest.
Boyd et al. [28]	mono-Si, poly-Si, 2-a-Si, CIS	The accuracy of the one-diode model for mono-Si and poly-Si is approximately 3% (rMBE) and 6% (rRMSE), respectively, while the differences are 6% and 10% for CIS and 20% and 27% for 2-a-Si.
Roberts et al. [31]	poly-Si	The PV performance models based on efficiency estimation tend to overestimate the power output of PV system, with an average rMBE of 5.14%, while the PV performance models based on one-diode module model tend to underestimate the power output with an average rMBE of -4.91%.
Cameron et al. [32]	crystalline silicon, a-Si, CdTe, CIS	Temperature correction model and the one-diode model could predict the energy output of crystalline silicon PV modules within about ±2%. However, differences in expected output could reach approaching 14% for other technologies.
Makrides et al. [34]	mono-Si, poly-Si, a-Si, CIGS, CdTe	The one-diode model provided the best accuracy for mono-Si, poly-Si and CIGS PV modules. The PVUSA model which is based on outdoor-measured data provided the best accuracy for a-Si and CdTe PV modules.

With the results of the present study and previous publications, the following conclusions can be drawn. The one-diode model which is based on the one-diode model could be used to predict the energy performance of mono-Si and poly-Si PV modules with the highest accuracy. The energy performance prediction of a-Si PV module is the most complicated among the five PV technologies. Studies had shown that not only the light soaking and thermal annealing effect [46], but also the spectral influence [47] has a large influence on the performance of a-Si PV modules. Although the mean bias error is larger than 10%, the one-diode model has the highest accuracy for a-Si PV modules among the three models. The CIGS PV module could also be predicted with high accuracy by using the one-diode model. The accuracy of the simple efficiency model is the highest for one of the CdTe PV modules, while the accuracy of the one-diode model is the best for the other CdTe PV module. Further study will be conducted to evaluate the impacts which influence the energy performance of thin-film PV modules to further improve the accuracy of the models for thin-film PV modules.

7. Conclusions

This study tested the energy outputs of different types of PV modules and evaluated the accuracies of three simple PV module models for predicting the power output of different PV modules based on the module datasheet values. Some highlighted conclusions are summarized as follows:

1. With the development of PV technologies, the efficiency of CdTe and CIGS PV modules are improved to be close to that of silicon PV modules. In terms of the annual energy outputs per unit area, the mono-Si PV module is the highest of the five different types of solar PV panels, and a-Si PV modules is the lowest.

2. The results show that the simple efficiency model overestimates the energy output of all the PV modules by 10% except for one of the CdTe PV modules.

3. Both the temperature correction model and the one-diode model could predict the energy output of mono-Si and poly-Si PV modules within an acceptable accuracy level. However, the one-diode model had the highest accuracy for predicting mono-Si and poly-Si PV modules. The rMBE of the one-diode model were -3.1% and 3.4% for predicting the power output of mono-Si PV modules, while the rRMSE were 15.4% and 16.8%. The rMBE of one-diode model were 2.4% and 1.3% for poly-Si PV modules, while the rRMSE were both 14.8%.

4. Although the mean bias error is larger than 10%, the one-diode model shows the highest accuracy among the three models. The large error may cause by the light soaking, thermal annealing effect and/or solar spectrum influence.

5. The one-diode model has the highest accuracy for CIGS PV modules. The rMBE of the one-diode model were 17.1% and 4.5% for the two CIGS PV modules, and rRMSE were 31.2% and 16.4%, respectively.

6. The simple efficiency model has the highest accuracy for one of the CdTe PV modules with an rMBE of -2.0%, while the one-diode model has the highest accuracy for the other CdTe PV module with an rMBE of 19.2%.

7. The accuracies of the three models for thin-film PV modules are lower than those for

Si-based PV modules. It might be caused by a lot of uncertainties.

The results of this study provide a reference for rapid prediction of the energy output of PV systems with different PV technologies. Further studies will be conducted to investigate the reasons of low accuracy and develop more accurate models for predicting the power output of thin-film PV technologies.

Credit author statement

Meng Wang: Investigation, Validation, Writing - original draft. Jinqing Peng: Methodology, Writing - review & editing, Supervision. Yimo Luo: Investigation, Writing - review & editing, Visualization. Zhicheng Shen: Investigation, Resources, Visualization. Hongxing Yang: Conceptualization, Supervision, Project administration.

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