Actual Performances of PV Panels in the Local Environment

Final Report

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Executive Summary

Hong Kong is one of the most densely populated regions in the world. The large population results in a serious energy demand in modern life. Fortunately, Hong Kong possesses pretty good solar energy resource. However, solar photovoltaic (PV) installation in Hong Kong is still limited. The Hong Kong SAR Government has estimated to have about 1-1.5% of electricity supply from solar PV by 2030. In order to meet this challenge, a detailed study on performance comparisons of different solar PV panels has being conducted.

This study is to identify and compare the working performance of commercially available solar PV panel types under Hong Kong weather conditions. The objectives of this study are to identify suitable PV technologies for wide applications in Hong Kong to provide a reference for the public for selection of right solar PV panels.

According to statistics, poly-crystalline and mono-crystalline silicon solar PV panels are now dominating PV panel supply market for solar PV power generation projects in the world due to their cheaper prices, higher energy efficiency and reliable performance for power generation. However, thin-film PV panels are still sharing a few percentages of the PV market as thin-film technology has its advantages of higher energy efficiency for lower incident solar radiation, different colors and other special characteristics. Based on the market conditions, five different types of solar PV panels were selected for comparisons in this study including mono-crystalline silicon (mono-Si), poly-crystalline silicon (poly-Si), amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIGS) and Cadmium Telluride (CdTe) solar PV panels.

An on-site test system was installed in a farm in the New Territories to obtain the actual energy performance of the selected solar PV modules. The whole year's data was collected from the solar PV power generation system. The annual energy output of the PV system from Oct 10th 2018 to Oct 9th 2019 is 1916.1 kWh. The maximum daily energy output is 10.6 kWh on Nov 30th 2018. The annual energy outputs of the mono-Si 305W, mono-Si 300W, poly-Si 280W, poly-Si 275W, a-Si 140W, a-Si 130W, CIGS 140W, CIGS 115W, CdTe 107.5W and CdTe 80W PV modules are 337.5 kWh, 313.2 kWh, 299 kWh, 292.5 kWh, 131.4 kWh, 122.4 kWh, 132.3 kWh, 121.4 kWh, 134.7 kWh and 76.7 kWh, respectively. The Mono-Si 305W PV module has the highest energy efficiency and performs the best out of the ten tested PV modules, while the CdTe 107.5W PV module has the highest energy output per nominal peak watt (Wp) due to its high efficiency and better performance for low solar radiation and high temperature. Another reason for the better annual energy output per Wp might be because of the enlarged normal power of the panel, say 0-5% enlargement. In terms of energy output per square meter, the mono-Si technology performs the best, followed by the CdTe, Poly-Si, CIGS and a-Si PV panels.

Computer simulations of the ten PV modules' energy performance are conducted to evaluate the energy performance of different types of PV panels when they are integrated in building facades for a typical meteorological year in Hong Kong. The energy generations of the PV modules reach peak values at a tilt angle of 20^{o}, but there is only 0.5% difference of annual power generation for a tilt angle from 14^{o} to 22^{o}. Comparing with the optimal tilt angle, the annual energy output will decrease by 4.8%, 1.2%, 1%, 4.2%, 9.5%, 16.7%, 25.8%, 36% and 46.3% for a tilt angle of

0^{o}, 10^{o}, 30^{o}, 40^{o}, 50^{o}, 60^{o}, 70^{o}, 80^{o} and 90^{o}, respectively. The energy generations of PV modules achieve their maximum values at an azimuth angle of 180^{o}, i.e. facing south. Comparing to the optimal azimuth, the annual energy output will decrease by 17.9%, 15.7%, 9.6%, 3.3%, 1.7%, 7.3% and 14.1% for an azimuth angle of 0^{o}, 45^{o}, 90^{o}, 135^{o}, 225^{o}, 270^{o} and 315^{o}, respectively.

An economic analysis of five types of solar PV systems was made after the components' costs and installation costs were assumed when they are installed on a building roof without any shading. The payback time of the solar PV system with mono-Si PV panels is the shortest. Poly-Si and mono-Si PV panels are still the best choice for local solar PV projects although the annual power output per Wp of the CdTe PV panel tested on the test rig performed the best as it is still not known whether CdTe PV panels can be used for a long time reliably and whether CdTe PV panels can be massively produced.

1. Background of this study

Hong Kong is one of the most densely-populated regions in the world. According to the Census and Statistics Department of the Hong Kong SAR Government, the population of Hong Kong is estimated to be 7.52 million in mid-2019 [1]. The large population results in a serious energy demand in modern life. However, the Hong Kong Energy Statistics Annual Report indicated that energy supplies in Hong Kong are almost derived from external sources [2].

Renewable energy ("RE") is one of practical and affordable solutions to our energy needs. According to the International Renewable Energy Agency, renewables could supply 80% of the world's electricity by 2050. Although Hong Kong does not have favorable conditions for large-scale commercialized RE power generation, the government will apply RE on a wider and large scale by 2030 [3] (Hong Kong's Climate Action Plan). Based on the currently mature and commercially available technologies, Hong Kong has about 3-4% of realizable RE potential arising from wind, solar and waste-to-energy. The government continues to spearhead to apply RE in more systematic manner. In the meantime, the government is striving to create favourable conditions for distributed RE such as feed-in tariff and RE certificate.

Hong Kong possesses pretty good solar energy resources. The annual solar irradiation in Hong Kong is about 1400 kWh/m^2, which is much better than that in Germany (1000 kWh/m^2). As shown in Figure 1, power generation from photovoltaics (PV) amounts to cover approximately 7.2 percent of Germany' net electricity consumption in 2017 [3]. This result reveals the great potential of adopting PV technology in Hong Kong.

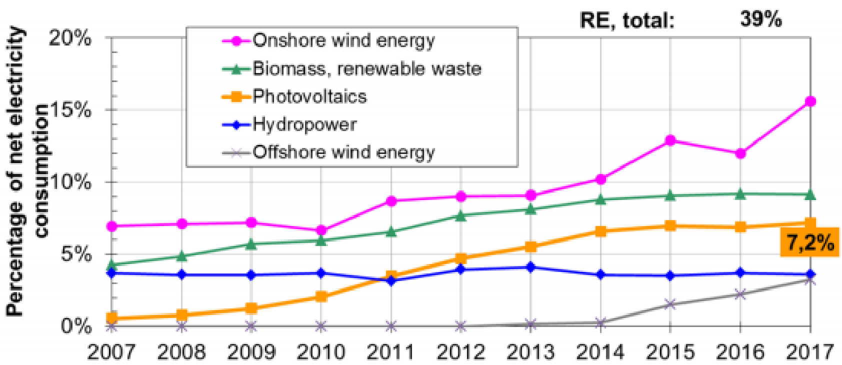


Figure 1 Percentage renewable energy in net electricity consumption (final energy) for Germany[3]

Currently, the photovoltaic installation in Hong Kong is limited, less than 6.29MWp in capacity as at the end of March 2017 [4]. The government estimated to have about 1-1.5% of electricity supply from PV by 2030. In order to meet this challenge, a detailed study on performance comparisons of different solar PV panels has been conducted. This report presents the final study results of this project.

2. Aims and objectives

This study is to investigate the actual performances of commercially available PV panels in local environment with a bid to providing a reference for the public.

This study is organized as follows: the technological reviews of PV technologies are conducted first. According to the technology and market development, five types of commercially available PV technologies are selected for on-site performance test. Then, the performances of the five different types of PV panels are compared through experiments. After that, computer simulation models of PV panels are developed and validated with the experimental data. At last, the performances of different types of PV panels are compared through computer simulations of different tilting angles and orientations for applications in building. Two panels from different manufacturers for each type are chosen so that the performance of the same type of PV panels from different manufacturers can be compared and reliable data can be collected.

3. Technological review of solar PV

Solar PV can directly convert sunlight into electricity by PV cells built with a layer of semi-conducting materials. As shown in Figure 2, solar PV technologies could be classified into three generations: the first generation includes devices that use silicon wafers; the second generation involves thin-film technologies; the third generation covers organic, dye-sensitized cells and other technologies that are emerging [5] in recent years. There are many types of solar PV technologies in laboratories and in the markets, but the most popular PV technologies used on land for large-scale applications include mono and poly crystalline silicon and thin-film solar PV technologies.

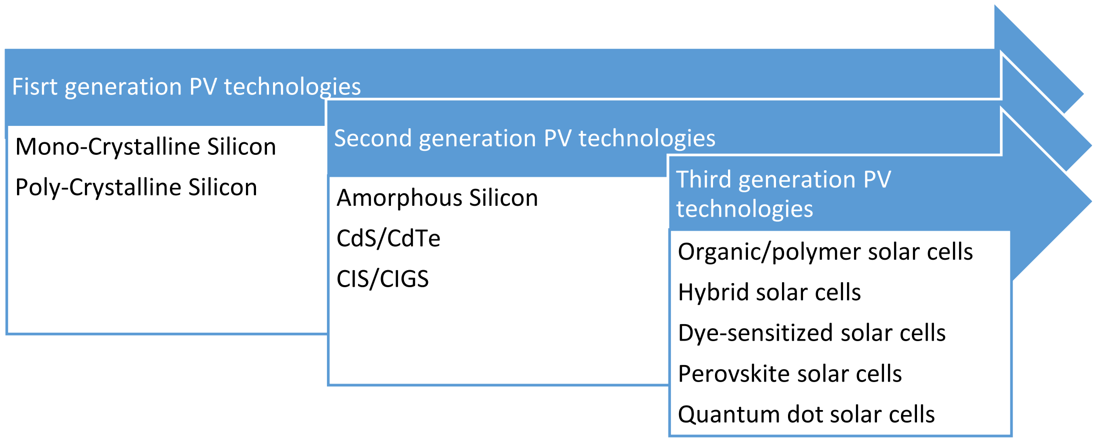


Figure 2 Development of PV technologies

3.1 First generation PV technologies

The first-generation PV technology is wafer-based silicon cells, including mono-crystalline PV and multi-crystalline PV. Typical module efficiency of mono- and multi-crystalline PV panels is around 19% and17% respectively.

3.2 Second generation PV technologies

In order to minimize material usage, second generation solar PV technologies, i.e. thin-film PV panels, are developed. This type of PV panels mainly comprises of amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIGS) and Cadmium Telluride (CdTe) solar cells. Typical efficiency of a-Si, CIGS and CdTe panels is around 9.8%, 13.5% and 14.5%, respectively.

3.3 Third generation PV technologies

Subsequently, the third generation solar PV technology is developed which are potentially able to overcome the "Shockley-Queisser limit". Emerging photovoltaics include organic solar cell, dye-sensitized solar cell, perovskite solar cell, quantum dot solar cell, etc. However, these technologies are not commercial yet for large-scale production due to their reliability and lifetime problems. Typical efficiency of organic solar cell, dye-sensitized solar cell and perovskite solar cell is around 8%, 11% and 13%, respectively.

3.4 Current status and selected PV panels

Solar cell efficiency is a key lever for PV cost reduction: for a given output power, a higher solar cell efficiency directly translates into a smaller and therefore less expensive PV system for reducing the levelized cost of electricity output. A higher power generation rate per unit area is also important in urban environments where space is limited. The development of PV materials is experiencing an enormous growth, and efficiency records are continually broken. Figure 3 shows the solar energy conversion efficiencies of best research solar cells worldwide for various photovoltaic technologies since 1976 [8]. For crystalline silicon, the best research-cell efficiency of mono-crystalline silicon is 26.1%, while that of poly-crystalline silicon is 22.8%. For thin-film PV technologies, the best research-cell efficiencies of CIGS and CdTe are 23.4% and 22.1%, while the best efficiency of a-Si is only 14.0%.

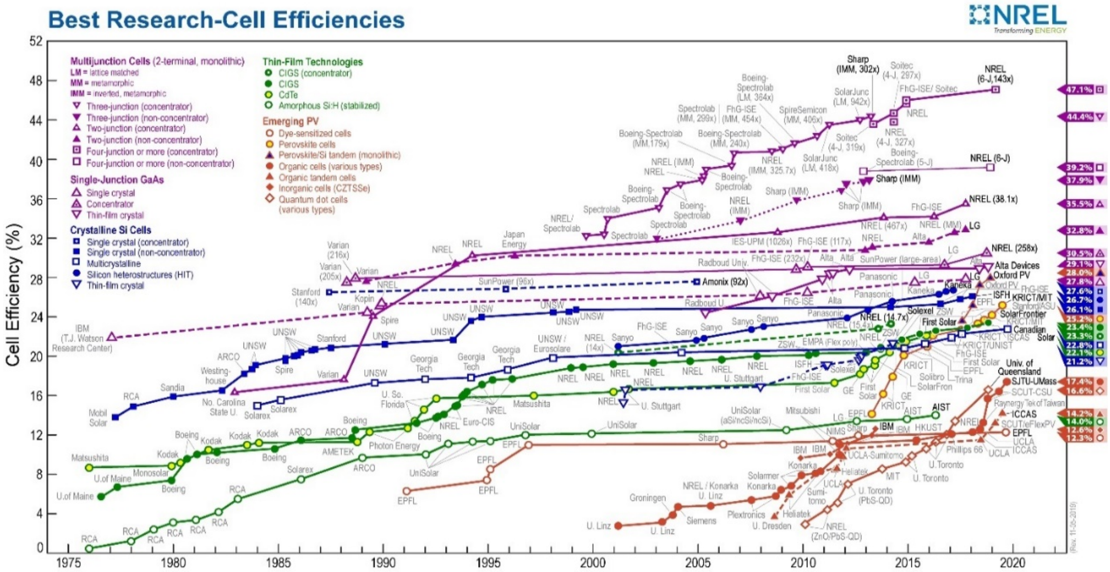


Figure 3 Best research-cell efficiencies[8]

As shown in Figures 4 to 6, the PV market is rapidly growing in the 21st century[10]. Crystalline silicon technology accounts for 95 percent of worldwide deployment in 2017, while thin-film technologies hold about 5 percent. Because of the cheaper prices, higher energy efficiency and reliable performance of poly-crystalline and mono-crystalline silicon PV panels, they are now dominating the PV panel supply market for solar PV power generation projects in the world. Thin-film technologies continue to lose market share and their peak market shares occur in the 1980s due to the consumer in indoor market (e.g. calculators) and again in 2009 during a period of silicon shortage. The market share of amorphous silicon has dropped since 2000. In 2017, CdTe and CIGS are sharing the thin-film market with a percentage of 51% and 42%.

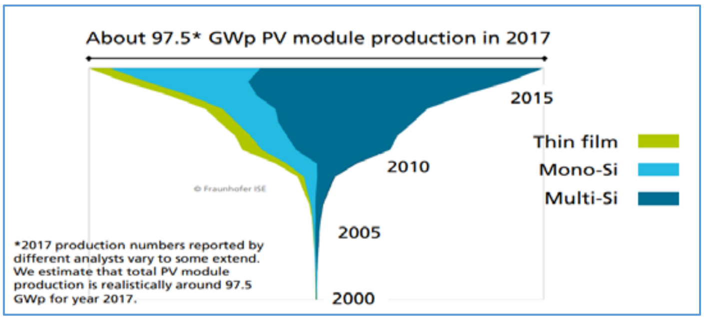


Figure 4 Global annual PV production by technology[10]

In conclusion, poly-crystalline and mono-crystalline silicon PV panels are now dominating PV panel supply market for solar PV power generation projects in the world due to their cheaper prices, higher energy efficiency and reliable performance for power generation. However, thin-film PV panels are still sharing a few percentages of the PV market due to its advantages of higher energy efficiency for lower incident solar radiation. Based on the above review of solar PV technologies, five different types of solar PV panels were selected for comparison in this study including mono-crystalline silicon, poly-crystalline silicon, amorphous silicon, CIGS, and CdTe PV panels. The advantages and disadvantages of the selected PV technologies are shown in Table 1.

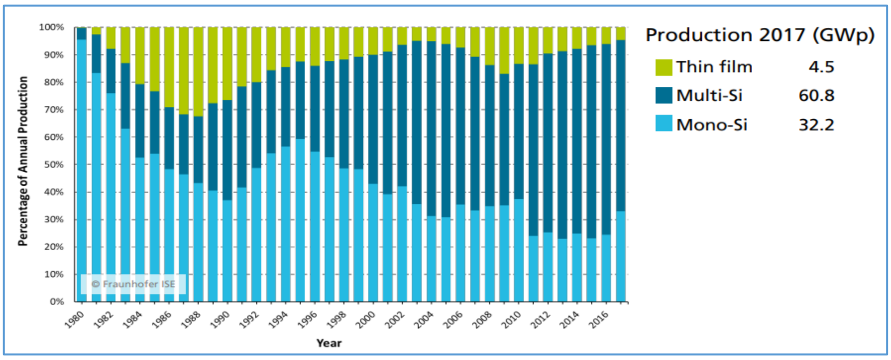


Figure 5 Percentage of global annual PV production by technology[10]

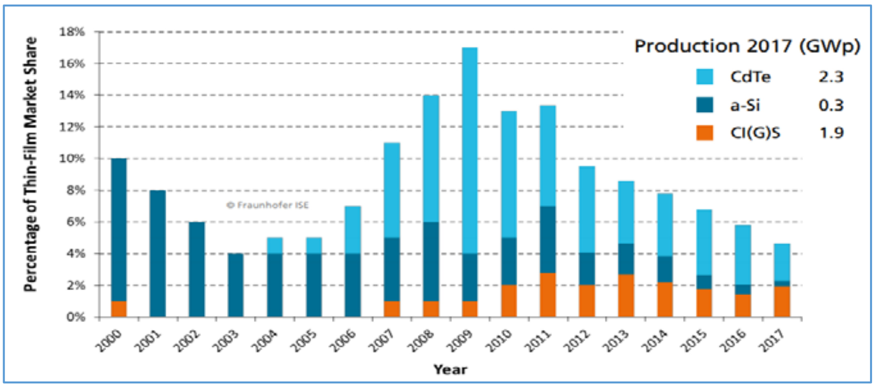


Figure 6 Market share of thin-film technologies[10]

Table 1 Advantages and disadvantages of solar PV technologies

PV technologies	Advantage	Disadvantage
Mono-crystalline silicon	Higher efficiency than poly-Si	Higher cost than poly-Si
Poly-crystalline silicon	Lower cost than mono-Si	Lower efficiency than mono-Si
Amorphous silicon	Low temperature coefficient[1] Better performance under diffuse light conditions	Low efficiency
CIGS	Medium efficiency Lower cost compared with other thin-film solar cells Bandgap tunability	Scarcity of Indium Long-time reliability has not been tested
CdTe	Higher efficiency compared with other thin-film solar cells	Te is scarce Cd is toxic

[1] As solar panel's temperature increases, the power output of the solar panel decreases. A low temperature coefficient means the influence of temperature on the power output is low.

4. Research methodology

In the first stage of this study, five different types of solar PV technologies are selected for performance comparisons. As shown in Figure 7, both on-site experiment and computer simulation will be conducted. Two PV panels from two different manufacturers for each type of PV technology were purchased and installed in a farm in the New Territories for one-year measurement. All the ten PV panels were facing south with a tilt angle of 22°. The measured data are then used to validate a computer simulation model. After validation, the simulation model, the System Advisor Model (SAM) will be used to manipulate the annual energy performance assessment of the ten typical solar PV panels for a typical meteorological year in Hong Kong at different orientations and tilt angles.

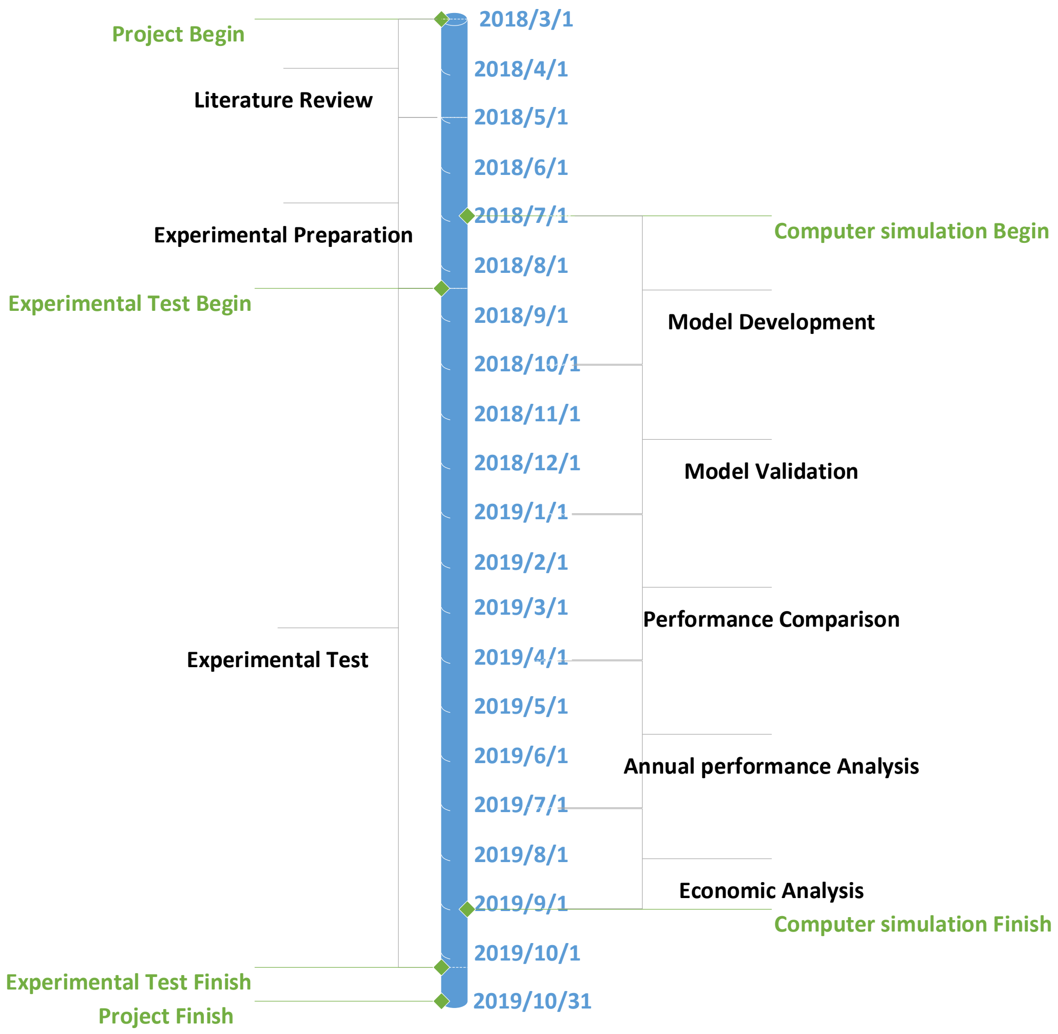


Figure 7 Research framework of the project

5. Technical specifications of the selected PV panels

During March 2018 and May 2018, the ten PV modules from different manufacturers are purchased. The specifications of the purchased five types of commercially available solar PV panels (two panels for each type) are shown in Table 2.

Table 2 Specifications of the ten selected commercially available PV panels

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
Model	Brand A 305W	Brand B 300 W	Brand C 280 W	Brand B 275 W	Brand D 140 W	Brand E 130 W	Brand E 140 W	Brand F 115W	Brand G 107.5 W	Brand H 80 W
Nominal Power (W)	305	300	280	275	140	130	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 (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 (V)	33.0	32.41	31.61	31.36	32.2	54	86.5	29.7	68.6	94.1
Maximum system voltage (V)	1000 (IEC)	1000 (IEC) 1000 (UL)	1000/ 1500 DC (IEC)	1000 (IEC) 1000 (UL)	N/A	1000	1000 (IEC) 600 (CSA/ UL)	1000 (IEC) 600 (UL)	1000 V (class Ⅱ) 1500 V (class 0)	N/A
Module Efficiency (%)	18.7	18.0	17.1	16.5	9.6	9.1	14.9	12.0	14.9	11.1
Weight (kg)	18.2	18.8	18.2	18.8	18.3	25	16.5	2.7	12	11.8
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

6. Experimental study

6.1 The test rig

In order to obtain the actual energy performance of the selected solar PV modules, an on-site test system was installed in a farm in the New Territories. Figure 8 shows the PV modules mounted on the test rig on a roof. The tilt angles of PV modules are 22^o, and the azimuths are 180^o. The schematic diagram of the grid-connected PV system is shown in Figure 9. Because of the difference of I-V characteristics, the PV modules can’t be connected directly in a circuit. Thus, 10 mini power optimizers and an inverter are utilized to form a circuit to make sure that each solar panel can generate its maximum power at any time. Firstly, ten PV modules are separately connected to ten power optimizers. The power optimizer is a DC/DC converter which is connected to each PV module and replaces traditional solar junction box. The power optimizers could increase the energy output from PV systems by constantly tracking the maximum power point (MPPT) of each module individually. Furthermore, the power optimizers could monitor the performance of each module and communicate performance data to an energy management system for enhanced, cost-effective module-level maintenance. The power optimizer could also automatically shut down modules' DC voltage whenever the inverter or grid power is shut down. Secondly, the power optimizers are connected to the inverter. The inverter could convert the DC power into 220V AC power. The inverter includes a proprietary data monitoring receiver which could aggregate the power optimizer performance data from each PV module. At last, the inverter is connected to the connection box. During the interval period of testing, the I-V curves of the PV panels could also be measured with an I-V curve tracer. Figure 10 shows the ten optimizers and inverter in the plant room.

Figure 8 The test rig on a building roof in the farm

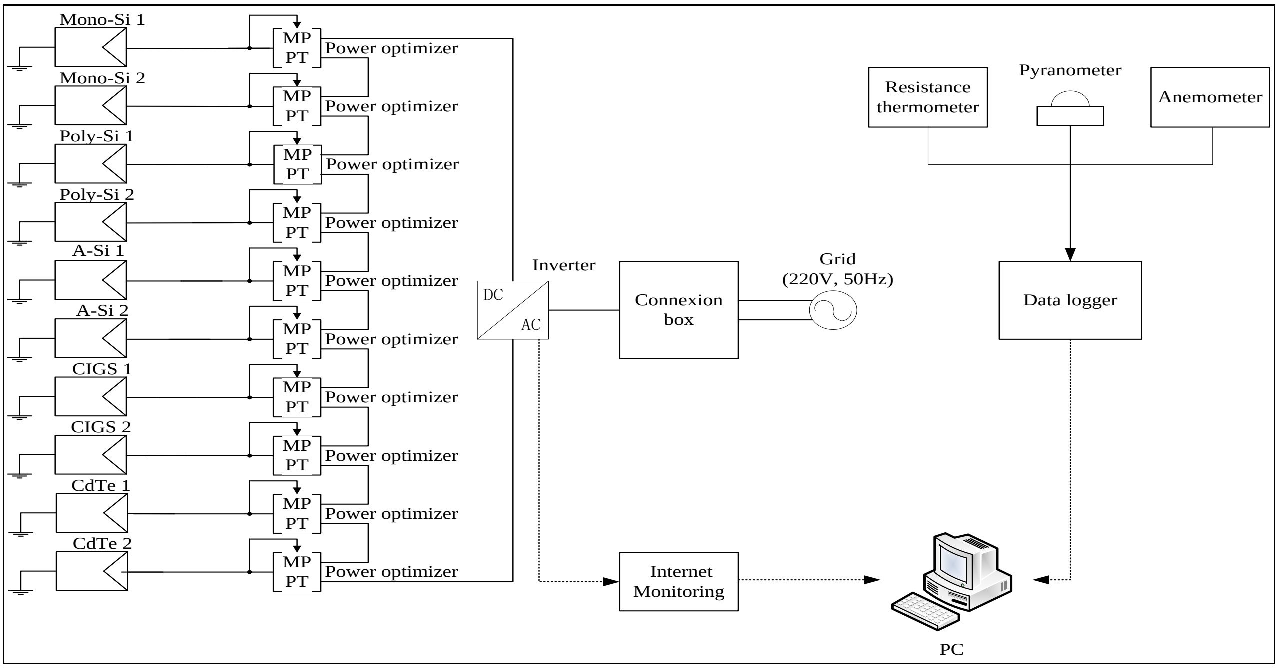


Figure 9 Schematic diagram of the PV performance testing system

Apart from the energy performance data acquisition system, the PV performance testing system also includes a weather data acquisition system. As shown in Figure 11, an outdoor temperature and humidity sensor is adopted to measure the ambient temperature and humidity. Figure 12 shows the anemometer which is used to measure the wind speed. Two pyranometers are employed to measure available solar radiation on the PV modules as shown in Figure 13. The obtained data will be collected by a portable data logger as shown in Figure 14. The data obtained from the weather data acquisition system could be used as the weather condition when the simulation model is validated with test data. The simulation results will be compared with the energy performance data obtained from the energy performance data acquisition system. The main experimental instruments and their specifications are listed in Table 3.

Figure 10 The optimizers and inverter

Figure 11 Temperature and humidity sensor

Figure 12 Anemometer

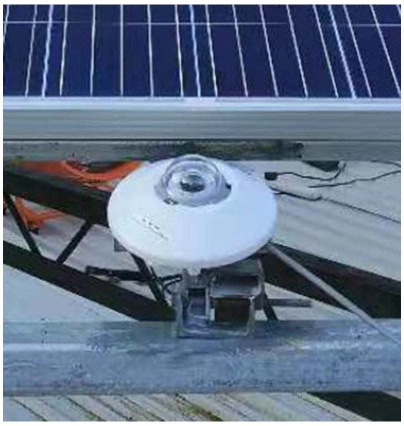


Figure 13 Pyranometer

Figure 14 Weather data acquisition system

Data collection from the solar PV power generation system started from Aug 15th 2018. The PV system has been working very well with a total solar energy output of 2242 kWh until Oct 9th 2019. However, the measurement of the flexible CIGS solar PV panel was interrupted for a short time period due to the damage by the Typhoon Mangkhut. The broken PV panel was replaced on October 9th 2018. Figure 15 shows the daily energy output of the PV system from Oct 10th 2018 to Oct 9th 2019. The annual energy output of the PV system is 1916.1 kWh. The maximum daily energy output is 10.6 kWh on November 30th 2018.

Table 3 The main experimental instruments and their specifications

Equipment	**Function**	**Manufacturer and model**	**Accuracy/sensitivity**	**Quantity**
Power optimizer	Tracking Max power point	SolarEdge P405	Rated input DC power: 405W Maximum input DC voltage: 125 V MPPT operating range: 12.5-105V	10
Inverter	Converting DC to AC power, data recording and communication	SolarEdge SE2200H	Maximum DC Power: 3400 W; European weighted efficiency: 98.3%	1
Pyranometer	Solar irradiation measurements	EKO instruments (MS-802)	Sensitivity: about 7 $\mu V/(W/m^2)$; Non-linearity < 0.2% (at 1000 W/m^2)	2
Temperature and humidity sensor	Ambient temperature and humidity measurements	Star sensors (CWS18)	Temperature: ± 0.5 °C; Humidity: ± 2%RH	1
Anemometer	Wind speed measurements	Zhonghuan Tig (EL15-1C)	Wind speed:± 0.3 m/s (≤10 m/s); ± (0.3v) (>10 m/s);	1
I-V curve checker	I-V Curve test	EKO instruments (MP-160)	Measuring range: Current: 0.03, 0.3, 3, 10 A; Voltage: 3, 30, 300 V; Power: Max.300 W;	1
Data Logger	Data collection	Graphtec (GL840 Midi Data Logger Wireless)	The minimum resolutions are 1 μV and 0.1 °C	1

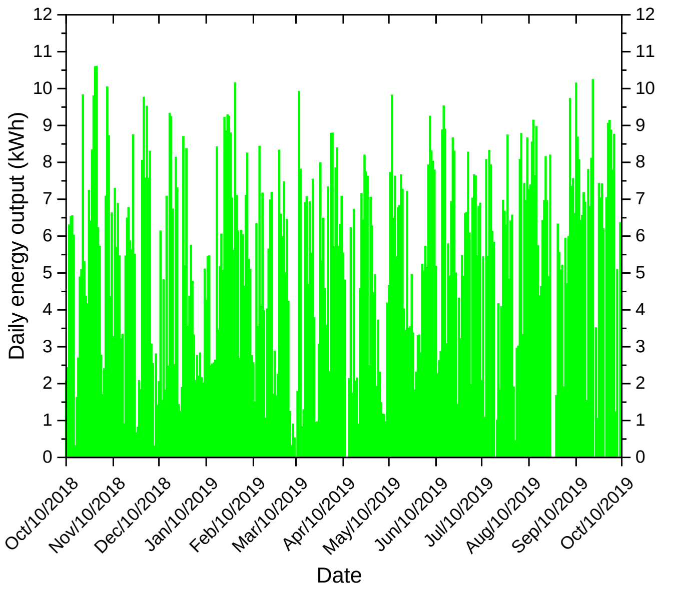


Figure 15 Daily energy output of the PV system

6.2 Calibration of the power output from optimizers by I-V curve tests

In order to verify whether the PV modules work at their maximum power points through the 10 optimizers, an I-V curve test was conducted on Nov 29th 2018. Figure 16 shows the test instrument, EKO MP-170 I-V curve checker. The device can enable the operator to perform accurate I-V performance measurements and inspection of PV modules or arrays on site. In this study, it is used to evaluate the performance of the 10 PV modules and systems by measuring their I-V curve characteristics to make sure that the maximum power is generated from each solar PV panel.

Figure 16 EKO MP-170 I-V curve checker

Figures 17 to 21 show the I-V curve test results. The tests were conducted under four different levels of solar radiation from 300W to 1000W for each solar PV panel. The red points are the currents and voltages recorded by the optimizer/inverter of the system, while the black points and lines indicate the I-V curves measured by the I-V checker. The principle of the I-V checker measurement is based on the capacitive electronic load method, which means that it is a compact measurement device with a wide measuring range (voltage, current and power). When checking the I-V characteristic of each solar PV panel, the PV module was disconnected for a short time from the grid and was connected to the I-V checker. The working status of the PV panel is then compared between the data measured by the I-V Checker and the data recorded by the data acquisition system of the system as soon as the solar PV panel was disconnected for the solar PV panel concerned. The comparison results show that the maximum power points tracked by the optimizers/inverter are all very close to the maximum power points detected by the I-V curve checker. It demonstrates that the PV panels did produce their maximum power at any time. The calibration exercise is very successful.

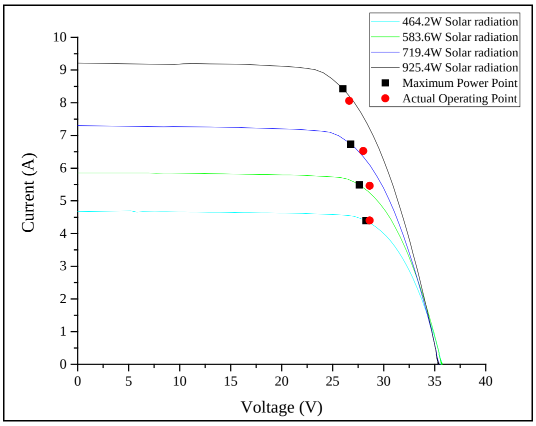
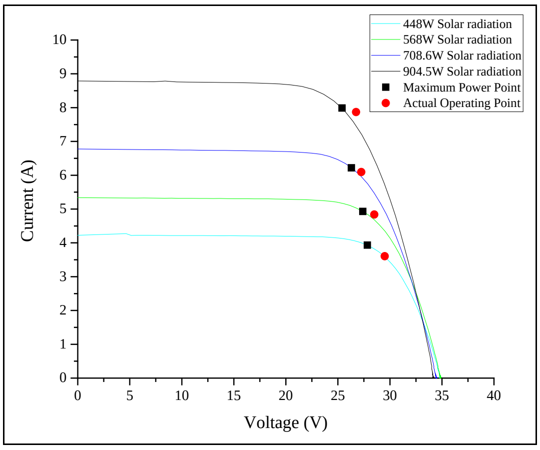


Figure 17 Maximum power point comparisons for the Mono-Si 305W PV module (Left) and the Mono-Si 300W PV module (right)



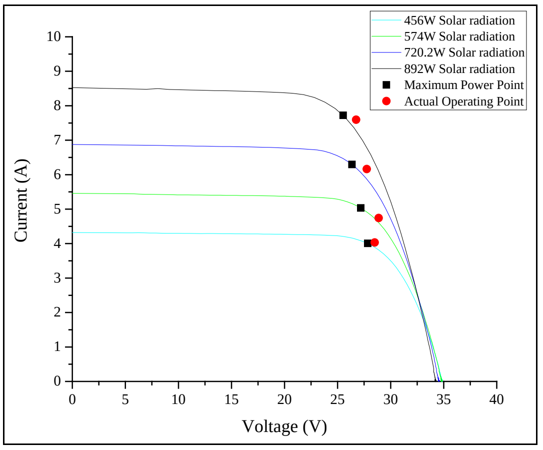
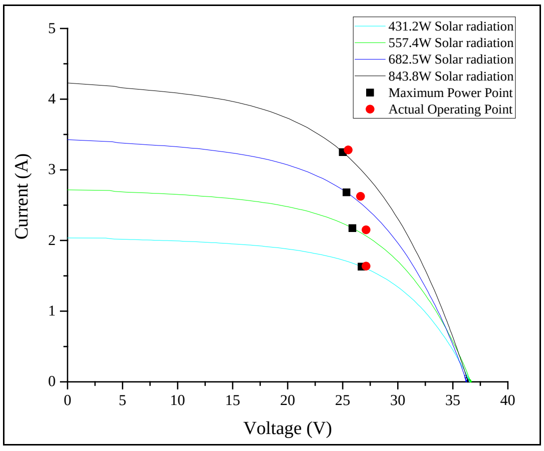


Figure 18 Maximum power point comparisons for the Poly-Si 280W PV module (Left) and the Poly-Si 275W PV module (right)



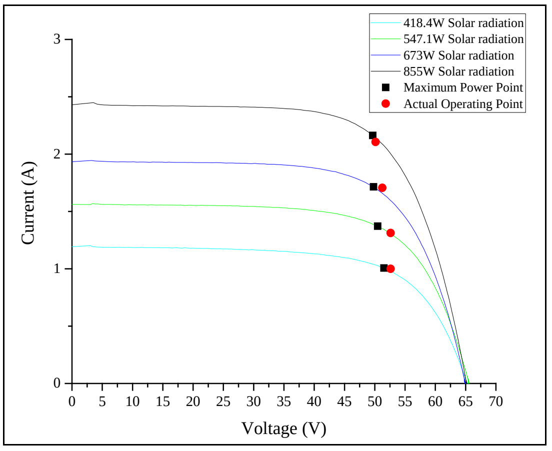


Figure 19 Maximum power point comparisons for the A-Si 140W PV module (Left) and the A-Si 130W PV module (right)

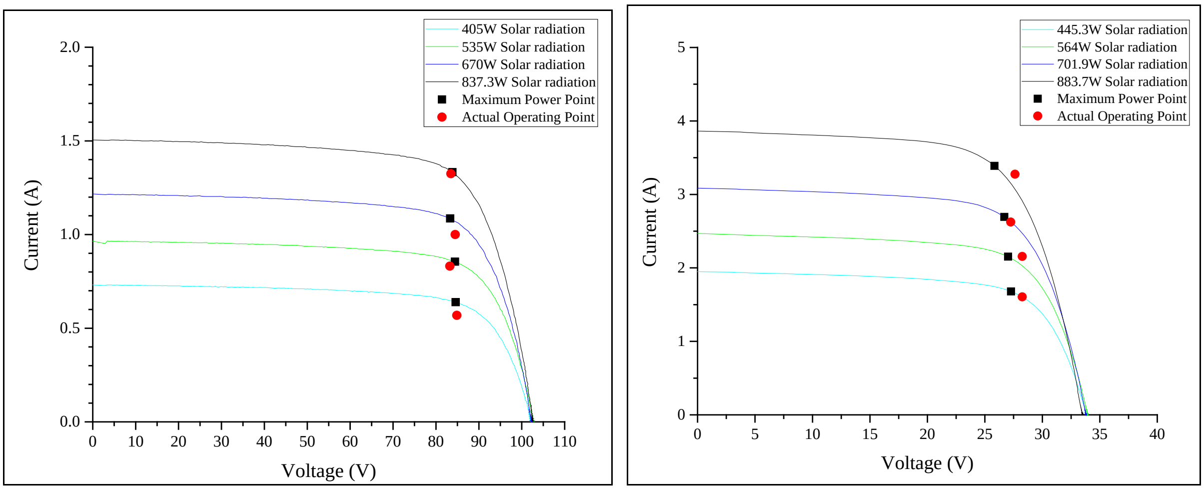


Figure 20 Maximum power point comparisons for the CIGS 140W PV module (Left) and the CIGS 115W PV module (right)

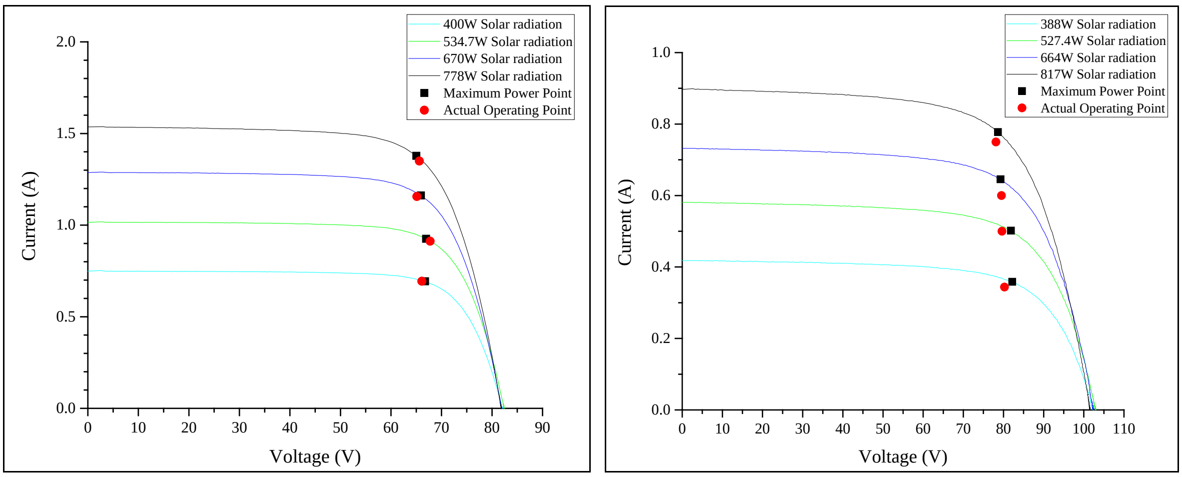


Figure 21 Maximum power point comparisons for the CdTe 107.5W PV module (Left) and the CdTe 80W PV module (right)

6.3 Data analysis of the solar PV system

The system performance data is collected to analyze the energy performance of the ten solar PV panels and the performance data are shown in Appendix A. The actual energy output test results of the PV system (Table A1) showed that the Mono-Si 305W PV module has the highest energy efficiency and performs the best out of the ten tested PV modules, while the CdTe 107.5W PV module has the highest energy output per peak watt installation capacity. In terms of energy output per square meter, the mono-Si technology performs the best, followed by the CdTe, Poly-Si, CIGS and a-Si PV panels.

The test revealed that September has the monthly peak energy output. The detailed monthly energy outputs are listed in Tables A2-A4 of Appendix A and are plotted in Figures A1-A3 in Appendix A. In summer, the energy outputs of Jun-Sept are outperformed and the daily energy outputs are plotted in Figures A4-A6 in Appendix A. It is found that the Mono-Si 305W PV module performs best in daily energy output and the daily energy output per square meter, while the CdTe 107.5W PV module performs best in daily energy output per peak watt (Wp). The maximum daily energy output occurred on Oct 30th 2018. The lower temperature and good solar resource result in the excellent energy output. More power generation per Wp from the CdTe panel is due to its high efficiency and better performance for low solar radiation and high temperature. Another reason for the better annual energy output per Wp might be because of the enlarged normal power of the panel, say 0-5% enlargement of the Nominal Power of the panel.

In order to have a better understanding of the performance of the PV modules under different weather conditions, the measuring period is further classified to sunny days, partly cloudy days and cloudy days. Some typical days are selected to represent each condition. The weather on Oct 30th 2018 and Nov 6th 2018 was sunny and their maximum solar radiations are nearly 1000W/m^2, so that they are selected to represent the sunny days. The weather on Nov 2nd 2018 and Nov 3rd 2018 was selected to represent cloudy days and their maximum solar radiations are less than 350 W/m^2. On Oct 31st 2018 and Nov 1st 2018, although the maximum solar radiations were nearly 800 W/m^2, the solar radiations had abrupt changes at noon. Thus, they are used to represent partly cloudy days.

Figures A7 to A18 in Appendix A show the hourly energy outputs on the typical days for each weather conditions. Tables A6 to A8 in Appendix A show the daily energy output on typical sunny day (Oct 30th 2018), typical partly cloudy day (Oct 31st 2018) and typical cloudy day (Nov 2nd 2018) respectively. It is found that the trends of the hourly energy outputs are proportional to the available solar radiation. The maximum hourly energy output occurred on sunny days. On sunny days, partly cloudy days and cloudy days, the mono-Si 305W PV module generates the maximum hourly energy output and the maximum hourly energy output per square meter. The CdTe 107.5W PV module performs best in hourly energy output per peak watt (Wp) on sunny days, partly cloudy days and cloudy days.

The hourly average energy conversion efficiencies on typical sunny days, typical partly cloudy days and typical cloudy days are shown in Figures A16 to A18 in Appendix A respectively. The working efficiencies of the PV modules are lower than their efficiencies in standard test conditions because the temperatures of the PV modules in working condition are usually higher than 25 ^oC in Hong Kong. It was found that the changes in efficiencies of mono-Si and poly-Si are greater than those of the thin-film PV modules. Table A9 in Appendix A shows the average conversion efficiency in typical days. The efficiencies of mono-Si and poly-Si PV modules in sunny days are lower than their efficiencies in partly cloudy days and cloudy days. It is also observed that the daily average energy conversion efficiency of the CdTe 107.5W PV module is getting close to the daily average energy conversion efficiency of the mono-Si 300W PV module, which can demonstrate the excellent performance of the CdTe 107.5 PV module in terms of daily average energy conversion efficiency.

6.4 Influence of environmental conditions on solar PV electricity output

The PVUSA (Photovoltaics for Utility Scale Applications) was adopted to evaluate climate influence on energy performance of PV panels. The method is based on collecting solar, meteorological, and system power output data for a time period and regressing the system output data against a combination of irradiance, wind speed, and ambient temperature, variables in the form of the following equation.

$$P_{DC} = G_{POA} * (a + bG_{POA} + cT_{amb} + dWS)$$

where P_{DC} is the DC power output, W; G_{POA} is the total solar irradiance in the POA (Plan of Array), W/m^2; T_{amb} is the ambient temperature, ^{o}C; WS is the wind speed, m/s; *a*, *b*, *c* and *d* are regression coefficients.

Table 4 gives the regression coefficients of the PVUSA model for the tested PV modules. Figures 22 to 31 show the comparison between the measured power generations of the PV modules and the POA irradiance and the comparison between the measured power generations of the PV modules and the simulated power generations based on the PVUSA model. The power generation has a strong relationship to the POA irradiance, however, the relationship to wind speed and ambient temperature is not obvious. Generally, the power generation increases with the increase of the wind speed, while the power generation decreases with the increase of the ambient temperature.

Table 4 Regression coefficients of the PVUSA model for the PV modules

PV module	a	b	c	d
Mono-Si 305W	3.1162E-01	-3.3306E-05	-1.1217E-03	1.8176E-03
Mono-Si 300W	2.9122E-01	-3.2760E-05	-1.1033E-03	1.7878E-03
Poly-Si 280W	2.8018E-01	-3.1360E-05	-1.0562E-03	1.7114E-03
Poly-Si 275W	2.7177E-01	-3.0800E-05	-1.0373E-03	1.6808E-03
A-Si 140W	1.2562E-01	-1.8424E-05	-6.2049E-04	1.0054E-03
A-Si 130W	1.2376E-01	-1.0556E-05	-3.5551E-04	5.7606E-04
CIGS 140W	1.3527E-01	-1.2544E-05	-4.2246E-04	6.8454E-04
CIGS 115W	1.1505E-01	-1.2236E-05	-4.1209E-04	6.6774E-04
CdTe 107.5W	1.1817E-01	-1.0234E-05	-3.4467E-04	5.5848E-04
CdTE 80W	7.1531E-02	-4.7936E-06	-1.6144E-04	2.6159E-04

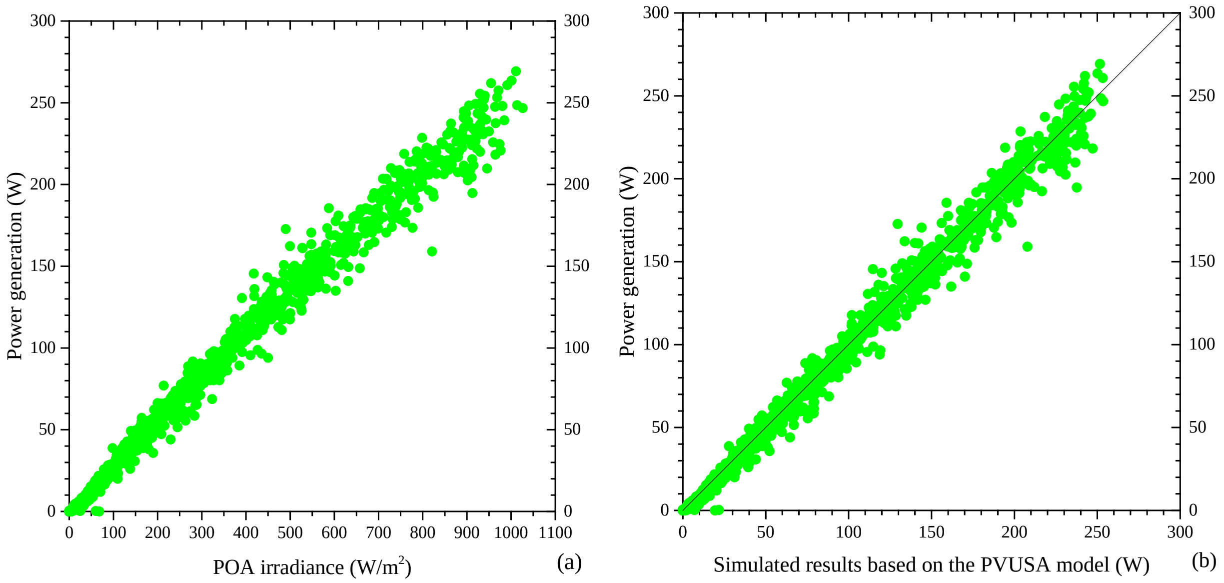


Figure 22 Comparison between the power generation of Mono-Si 305W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

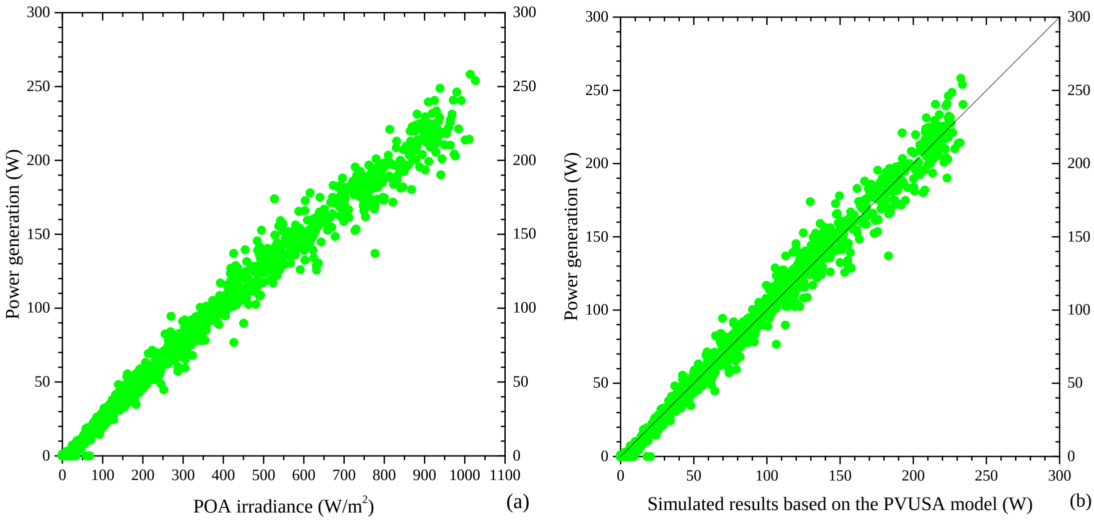


Figure 23 Comparison between the power generation of Mono-Si 300W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

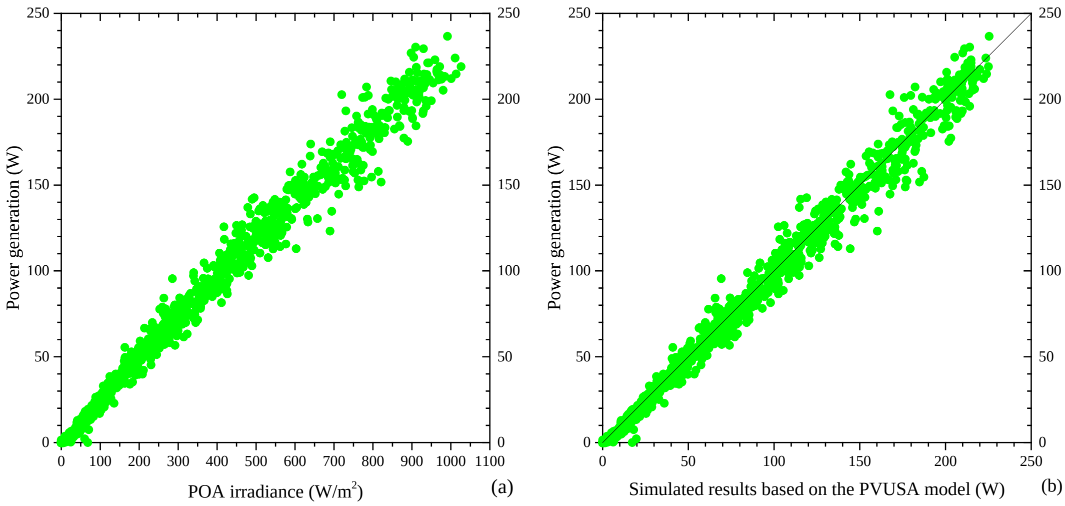


Figure 24 Comparison between the power generation of Poly-Si 280W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

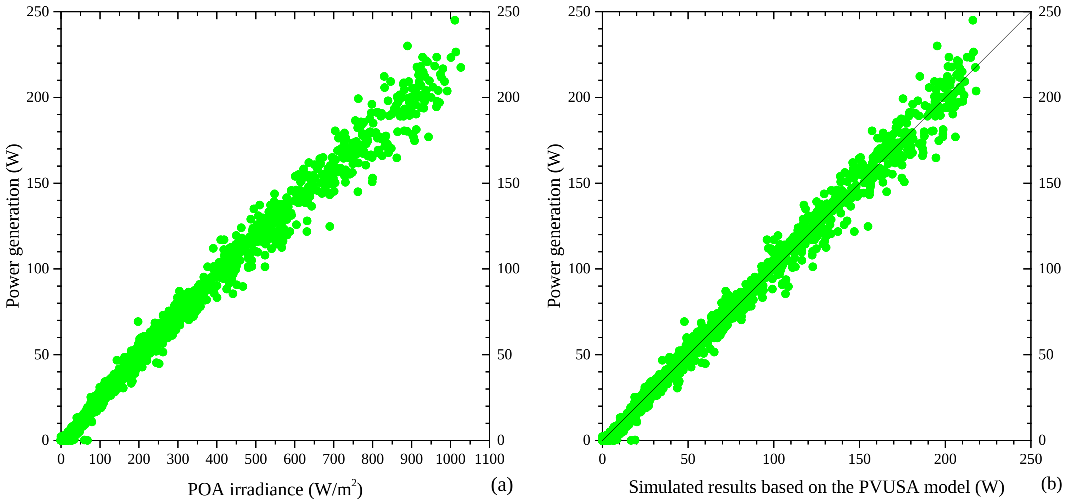


Figure 25 Comparison between the power generation of Poly-Si 275W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

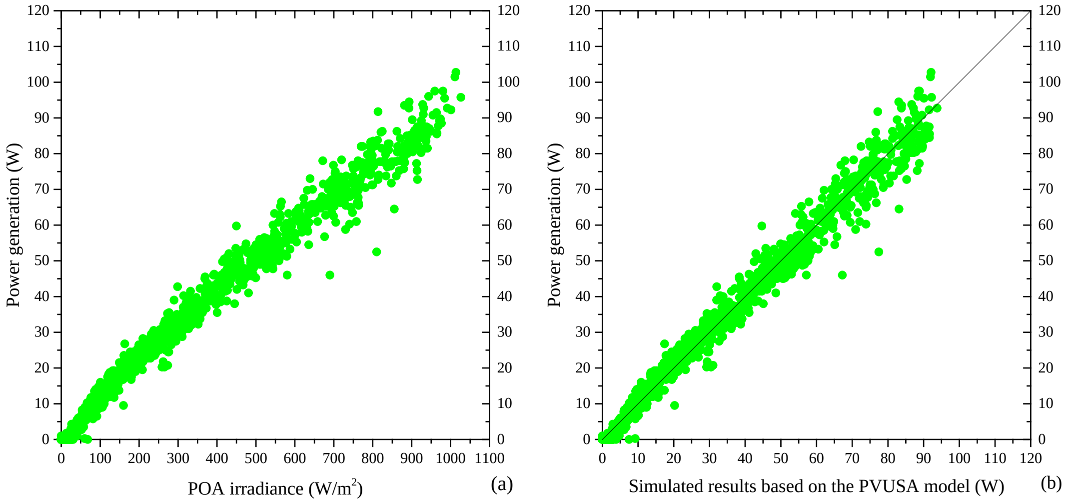


Figure 26 Comparison between the power generation of A-Si 140W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

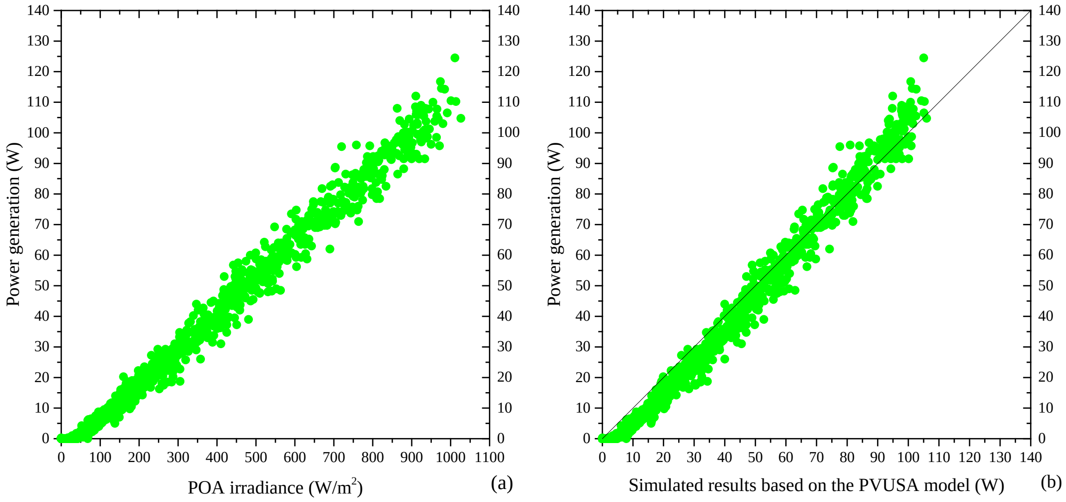


Figure 27 Comparison between the power generation of A-Si 130W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

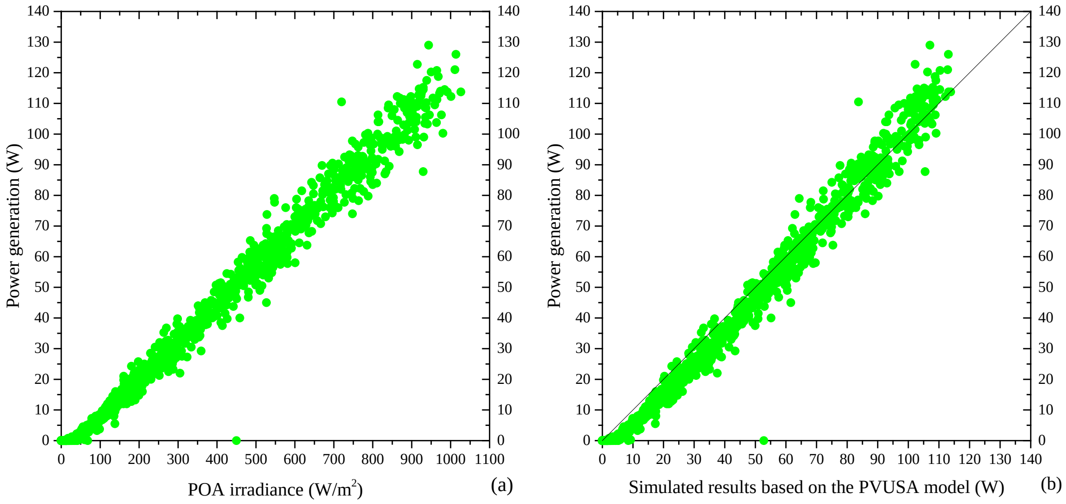


Figure 28 Comparison between the power generation of CIGS 140W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

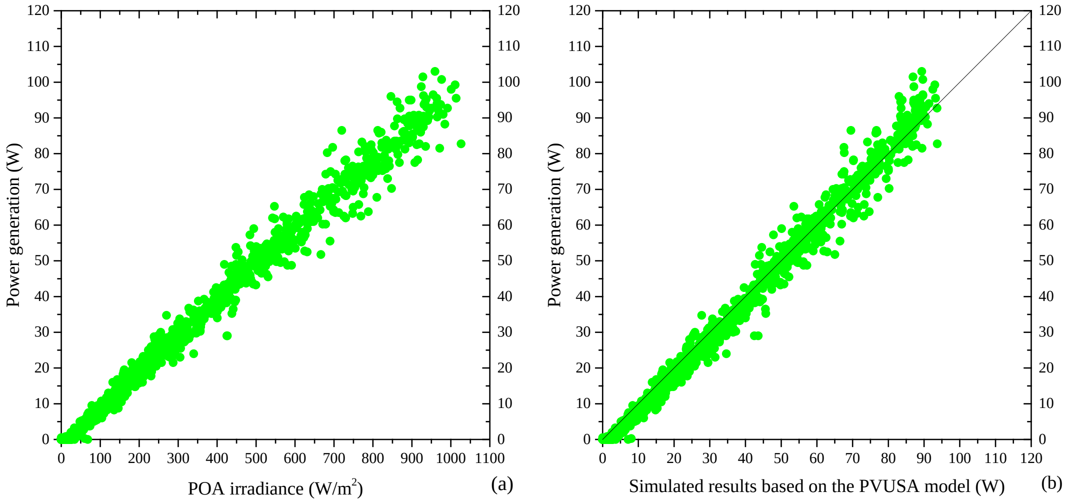


Figure 29 Comparison between the power generation of CIGS 115W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

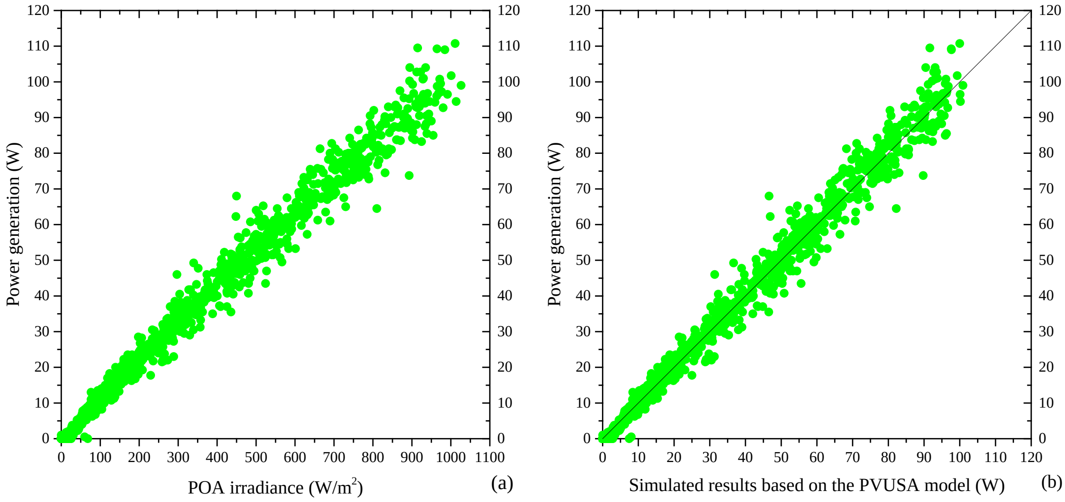


Figure 30 Comparison between the power generation of CdTe 107.5W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

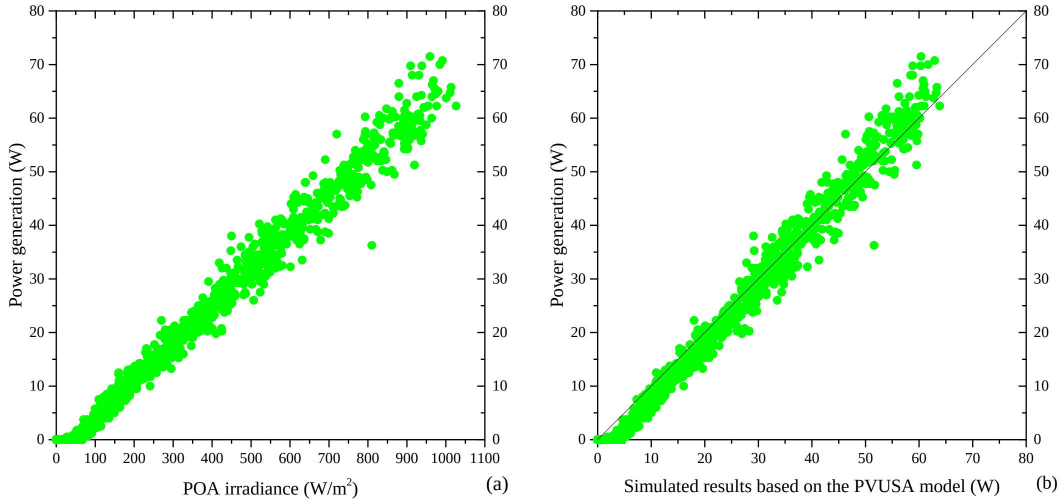


Figure 31 Comparison between the power generation of CdTe 80W PV module and (a) POA irradiance, (b) simulated results based on the PVUSA model

7. Simulation study

7.1 Simulation model

For better understanding of energy performance in different tiling angles under local conditions, the simulation software, System Advisor Model (SAM) as shown in Figure 32, is used to evaluate the energy performance of different types of PV panels.

In the SAM, five different module performance models could be selected, including simple efficiency module model, California Energy Commission (CEC) performance model with module database, CEC performance model with user-entered specifications, Sandia PV array performance model with module database, and IEC single diode model. For this study, the CEC performance model with user-entered specifications is selected. By inputting the technical specifications of the selected PV modules and weather data, the energy performance of the solar panel would be generated.

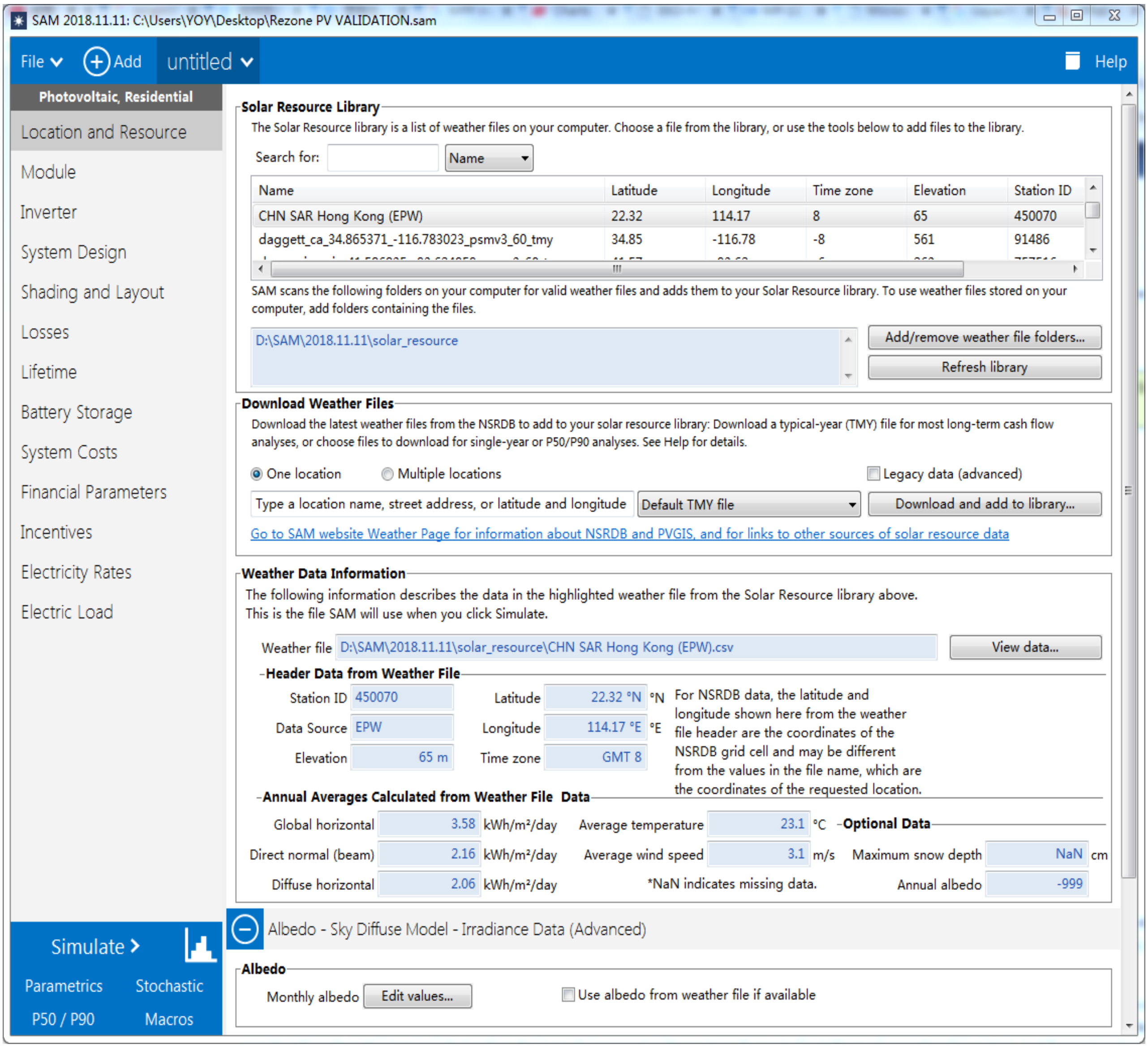


Figure 32 Main software window of the system advisor model

7.2 Model validation

The simulation model developed in SAM is then verified with the actual testing results to ensure its accuracy. After verification, the simulation models are used to estimate the energy performance for each type of PV panels for a typical meteorological year in Hong Kong.

The simulation model is verified with the experimental data collected from the farm between Oct 10th 2018 and Nov 11th 2018. Figure 33 shows the comparison between the measured and simulated power generation of Mono-Si PV modules for example. More results on the comparisons are showed in Figures B1 to B10 in Appendix B. The coefficient of variation of the Root Mean Square Error (CV(RMSE)) is adopted to evaluate the error between simulation results and experimental results. The values of RMSE are obtained with the following equation:

$$\mathrm{CV(RMSE)} = \frac{\sqrt{\left(\sum_{i=1}^{N}(m_i - s_i)^2/N\right)}}{\bar{m}} \tag{4}$$

where m_i and s_i are the measured and simulated data for the instance "i", respectively; N is the number of data points; $\bar{m}$ is the average value of all measured data.

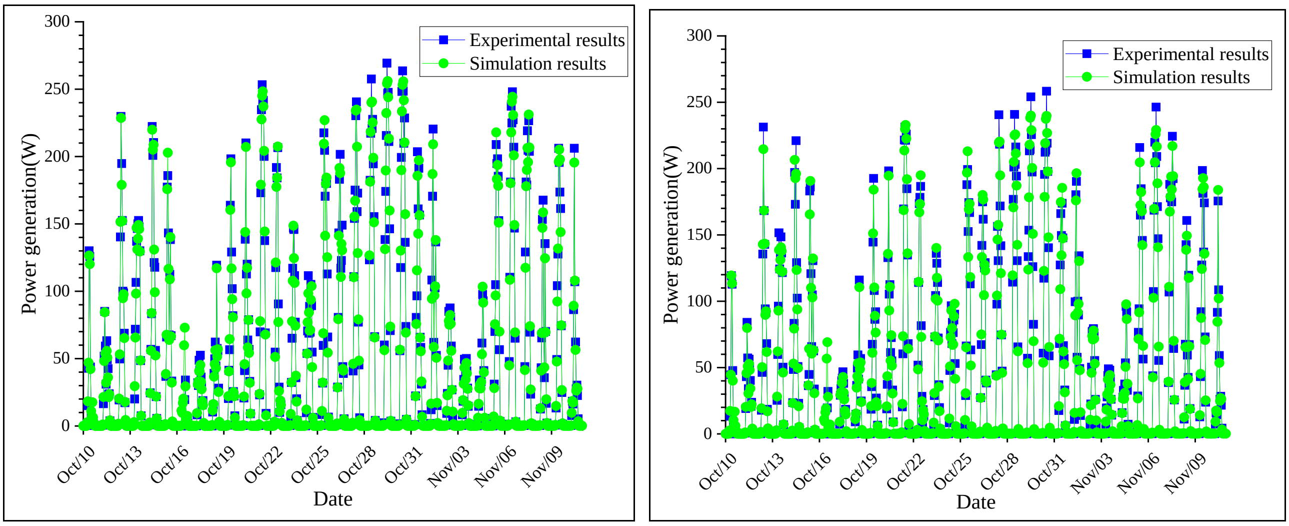


Figure 33 Comparison between the measured and simulated power generation of the Mono-Si 305W PV module (left) and the Mono-Si 300W PV module (right)

The CV(RMSE)s of the PV performance simulation models of the solar PV modules are listed in Table 10. According to ASHRAE guideline 14 [12], a simulation model is regarded to be acceptable if the CV(RMSE) is lower than 30%. It can be found that the CV(RMSE)s are lower than 30%, which means that the simulation results agree very well with the experimental results. Thus, the simulation model could be used to evaluate the performance of the solar PV modules under different weather conditions.

Table 10 CV(RMSE)s of PV performance simulation models

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
CV(RMSE)	7.8%	8.3%	7.2%	7.1%	7.1%	14.2%	10.7%	7.5%	6.8%	10.2%

7.3 Simulation results

Figures C1 to C10 in Appendix C show the simulation results of the annual energy generation of the PV modules with different tilt angles and orientations. The energy generations of the PV modules reach peak values at a tilt angle of 20°. The power generations of PV modules decrease slightly from tilt angle of 20° to 30°, but fall drastically after the tilt angle of 40°. The optimal tilt angle of PV modules are found to be 20 degree, but 0.5% difference of annual power generation is found from a tilt angle of 14° to 22° depending on local latitude and weather. Comparing to the optimal tilt angles (20°), the annual energy output will decrease by 4.8%, 1.2%, 1%, 4.2%, 9.5%, 16.7%, 25.8%, 36% and 46.3% for a tilt angle of 0°, 10°, 30°, 40°, 50°, 60°, 70°, 80° and 90° respectively. The energy generations of PV modules achieve their maximum values at an azimuth angle of 180°, i.e. facing south. Comparing to the optimal azimuth, the annual energy output will decrease 17.9%, 15.7%, 9.6%, 3.3%, 1.7%, 7.3% and 14.1% for an azimuth of 0 °, 45 °, 90°, 135°, 225°, 270° and 315°, respectively.

Table 5 shows the simulation results of annual energy output of different PV modules. Mono Si-305W and CdTe 107.5W have the highest energy output per square meter and the highest energy output per peak watt (Wp), respectively. The CdTe 107.5W PV module has the highest energy output per peak power (kWh/Wp) among the ten PV modules because of its lower temperature coefficient, higher efficiency when solar radiation is weak and enlarged nominal peal power rate.

Table 5 Simulation results of annual energy output (azimuth=180°, tilt angle=22°)

Solar PV module	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Annual Energy output (kWh)	354.1	334.4	316.7	310.6	142.6	136.8	146.6	129.4	143.2	81.3
Energy output per square meter (kWh/m^2)	215.9	200.2	193.1	186.0	98.3	95.7	156.0	134.8	198.9	112.9
Energy output per peak power (kWh/Wp)	1.16	1.11	1.13	1.13	1.02	1.05	1.05	1.12	1.33	1.02

9. Economic analysis

The PV market is changing rapidly. The economic comparisons of different PV technologies are conducted based on the estimated PV installation costs and energy output.

The installation cost of a PV system includes the cost of PV module, inverter, other hardware, soft costs and profit. Since labor cost is high in Hong Kong compared with the mainland, the soft cost and profit is dominated in the PV system cost. According to an example provided by CLP, the market price of a PV system is nearly 30~50 HKD/W in total [15]. Table 6 shows the estimated installation cost in HK for different type of PV panels. The prices of PV modules and inverters are derived from the average prices in China. The prices of other hardware[2] are about the same, while the soft costs and profit[3] are inversely proportional to the efficiency of PV modules. The lower efficiency of the PV module is, the higher the soft cost and profit is. According to the calculation, the total cost of a mono-Si PV system is the lowest, and the total cost of an a-Si PV system is the highest.

Table 6 Estimated installation cost of a PV system in Hong Kong (HKD/Wp)

Items	Mono-Si	Poly-Si	A-Si	CIGS	CdTe
PV module	2.8	2.6	4.5	5.0	5.0
Inverter	1.4	1.4	1.4	1.4	1.4
Other hardware	10.0	10.0	10.0	10.0	10.0
Soft cost and profit	15.0	15.0	30	18.6	18.6
Total cost	29.2	29.0	45.9	35.0	35.0

Table 7 gives the payback time of a PV system with the same installing capacity. For each technology, the PV module which has a higher value of energy output per peak power is used for the evaluation.

Table 7 The payback time of PV system with the same installing capacity (1kWp)

Items	Mono-Si	Poly-Si	A-Si	CIGS	CdTe
Initial cost (HKD)	29,200	29,000	45,900	35,000	35,000
Energy output per peak power (kWh/Wp)	1.16	1.13	1.02	1.05	1.33
Annual income (HKD)[4]	5,800	5,650	5,100	5,250	6,650
Payback time (years)	5	5.1	9.0	6.7	5.3
Economic benefit in 15 years (HKD)	57,800	55,750	30,600	43,750	64,750

However, since the available area for PV system installation is limited. The Mono-Si PV module which has the highest efficiency can reach the highest capacity. Table 8 shows the economic benefit of the PV systems with the same area of 10 m^2. It is found that the mono-Si PV PV system performs the best in the economic benefit in 15 years. The economic benefits of the CdTe PV system and poly-Si PV system are slightly lower than the mono-Si PV system. However, since the CdTe PV technology is still new, its long-time reliability/degradation performance and massive production need to be further verified in future.

Table 8 Economic benefits of the PV systems with the same area (10m^2)

[2] Other hardware includes costs of cable, cable connection, steel support, switches, combiner boxes, monitor system and so on.
[3] Soft costs and profit include labor costs, project coordination fee, operating overhead, supply chain costs, permitting, interconnection and inspection costs, as well as contractor's profits.
[4] The Feed-in Tariff (FiT) rates to be adopted at the launch of the FiT Scheme are set at: (a) $5 for ≤10kW; (b) $4 for >10kW to ≤200kW; and (c) $3 for >200kW to ≤1MW.

Items	Mono-Si	Poly-Si	A-Si	CIGS	CdTe
Efficiency of PV module (%)	18.7	17.1	9.6	14.9	14.9
Available capacity (kWp)	1.87	1.71	0.96	1.49	1.49
Initial cost (HKD)	54,604	49,590	44,064	52,150	52,150
Energy output per square meter (kWh/m^2)	215.9	193.1	98.3	156.0	198.9
Annual income (HKD) [5]	10,795	9,655	4,915	7,800	9,945
Payback time (years)	5.1	5.1	9.0	6.7	5.2
Economic benefit in 15 years (HKD)	107,321	95,235	29,661	64,850	97,025

10. Conclusions

This final report presents a review of the technological development of solar photovoltaic panels, the experimental results of the on-site tests and the energy performance simulations of the solar PV panels for integration in buildings for local weather conditions. Based on the detailed study results, the main conclusions are summarized as follows:

(1) The technology review of current solar PV technologies shows that crystalline silicon solar PV modules are dominating the solar PV supply market in the world and account for 95 percent of worldwide deployment, while thin-film technologies only contribute to the installation for about 4.5 percent in 2017.

(2) According to the data collected on-site from the solar PV system between Oct 10th 2018 and Oct 9th 2019, the annual energy outputs per installation peak power capacity of the five different types of solar PV panels follow the following sequence:

$P_{CdTe} > P_{Mono\text{-}Si} > P_{Poly\text{-}Si} > P_{CIGS} > P_{a\text{-}Si}$

(3) According to the data collected on-site from the solar PV system between Oct 10th 2018 and Oct 9th 2019, the annual energy outputs per square meter of the five different types of solar PV panels follow the following sequence:

$P_{Mono\text{-}Si} > P_{CdTe} > P_{Poly\text{-}Si} > P_{CIGS} > P_{a\text{-}Si}$

(4) A detailed energy performance simulation of the five types of solar PV panels for application in building facades has been completed. It is found that the optimal tilt angle of the PV system is 20^o, but 0.5% difference of annual power generation is found from a tilt angle of 14^o to 22^o depending on different annual weather conditions. For different optimal tilt angles, the annual energy outputs are given in Appendix C for different orientations so that local industry/developers/engineers/users of solar PV applications can easily use the data for their solar PV projects in the future.

(5) An economic analysis of five types of solar PV systems were made after the components' costs and installation costs were assumed. The payback time of the solar PV system with mono-Si PV panels is the shortest. Poly-Si and mon-Si PV panels are still the best choice for local solar PV projects although the annual power output per Wp of the CdTe PV panel tested on the test rig performed the best as it is still not known whether CdTe PV panels can be used for a long time reliably and whether CdTe PV panels can be massively produced. The CdTe PV panel cost is still more expensive.

12. References

[1] Census and Statistics Department of Hong Kong. https://www.censtatd.gov.hk/hkstat/sub/so20.jsp.

[2] Census and Statistics Department of Hong Kong. Hong Kong Energy Statistics Annual Report (2017 Edition), Hong Kong, April 30 2018.

[3] Fraunhofer ISE. Recent Facts about Photovoltaics in Germany, download from www.pv-fakten.de, version of July 20, 2018.

[4] Meinhardt (M&E) Ltd. Study Report of Photovoltaic (PV) Applications and PV Potential on Building Rooftops in Hong Kong. 2019.

[5] Lacerda JS, van den Bergh JCJM. Diversity in solar photovoltaic energy: Implications for innovation and policy. Renewable & Sustainable Energy Reviews. 2016;54:331-40.

[6] El Chaar L, Lamont LA, El Zein N. Review of photovoltaic technologies. Renewable & Sustainable Energy Reviews. 2011;15:2165-75.

[7] Sampaio PGV, Gonzalez MOA. Photovoltaic solar energy: Conceptual framework. Renewable & Sustainable Energy Reviews. 2017;74:590-601.

[8] NREL. https://www.nrel.gov/pv/assets/pdfs/best-research-cell-efficiencies.20191106.pdf. November 6, 2019.

[9] Polman A, Knight M, Garnett EC, Ehrler B, Sinke WC. Photovoltaic materials: Present efficiencies and future challenges. Science. 2016;352.

[10] Fraunhofer ISE. PHOTOVOLTAICS REPORT. Fraunhofer Institute for Solar Energy, Freiburg, August 27 2018.

[11] Freeman J, Whitmore J, Kaffine L, Blair N, Dobos AP. System Advisor Model: Flat Plate Photovoltaic Performance Modeling Validation Report. NREL/TP-6A20-60204: National Renewable Energy Laboratory: Albuquerque, Golden, Colorado, 2013.

[12] ASHRAE. ASHRAE Guideline 14-2014: Measurement of Energy Demand and Savings. Atlanta, GA, USA: American Society of Heating, Refrigerating and Air-Conditioning Engineers. 2014.

[13] Hegedus S. Review of photovoltaic module energy yield (kWh/kW): comparison of crystalline Si and thin film technologies. Wires Energy Environ. 2013;2:218-33.

[14] Strevel N, Trippel L, Gloeckler M. Performance characterization and superior energy yield of First Solar PV power plants in high temperature conditions. Photovoltaics International. 2012;17:148-54.

[15] https://www.clp.com.hk/zh/community-and-environment/renewable-schemes/feed-in-tariff/feed-in-tariff-residential-customers.

Appendix A: Experimental results of the PV energy output

Table A1 Actual energy output (from Oct 10th 2018 to Oct 9th 2019)

Solar PV panel	**Mono-Si 305W**	**Mono-Si 300W**	**Poly-Si 280W**	**Poly-Si 275W**	**A-Si 140W**	**A-Si 130W**	**CIGS 140W**	**Flexible CIGS 115W**	**CdTe 107.5W**	**CdTe 80W**
Annual Energy output (kWh)	337.5	313.2	299	292.5	131.4	122.4	132.3	121.4	134.7	76.7
Energy output per m^2 (kWh/m^2)	206.4	187.5	182.8	175.1	90.4	85.6	140.8	126.3	187.1	106.6
Energy output per Wp (Wh/Wp)	1106.4	1043.9	1067.8	1063.6	938.4	941.9	945.2	1055.9	1253.1	959.1
Module Efficiency (%)	18.7	18.0	17.1	16.5	9.6	9.1	14.9	12.0	14.9	11.1

Table A2 Monthly Energy Output (from Oct 10th 2018 to Oct 9th 2019) (unit: kWh)

Solar PV panel	**Mono-Si 305W**	**Mono-Si 300W**	**Poly-Si 280W**	**Poly-Si 275W**	**A-Si 140W**	**A-Si 130W**	**CIGS 140W**	**Flexible CIGS 115W**	**CdTe 107.5W**	**CdTe 80W**
Oct-18	21.9	20.6	19.4	19.1	8.7	8.5	9.1	8	8.9	5.1
Nov-18	26.4	24.6	23.5	23.1	10.3	10.1	10.9	9.5	10.6	6.1
Dec-18	26.6	25	23.6	23.3	10.2	10.1	10.9	9.6	10.6	6.1
Jan-19	28.4	26.6	25.2	24.8	10.6	10.6	11.7	10.2	11.2	6.5
Feb-19	23.6	22	20.9	20.6	9	8.6	9.4	8.4	9.4	5.2
Mar-19	24.2	22.5	21.4	21.1	9.1	8.5	9.4	8.5	9.5	5.3
Apr-19	27.3	25.4	24.2	23.7	10.4	9.6	10.5	9.6	10.8	6.1
May-19	24.1	22.4	21.5	21.1	9.8	8	8.7	8.4	9.8	5.2
Jun-19	30.9	28.6	27.6	26.9	12.5	11	11.7	11.1	12.6	7.1
Jul-19	29.1	27	26	25.3	11.8	10.2	11	10.5	11.8	6.7
Aug-19	30.2	27.8	26.7	26	12.1	10.8	11.5	10.9	12	6.9
Sep-19	35	31.8	30.5	29.2	13.2	12.9	13.7	13.1	13.7	8
Oct-19	9.7	8.9	8.5	8.3	3.8	3.7	3.9	3.7	3.8	2.3

Table A3 Monthly Energy Output per square meter (from Oct 10th 2018 to Oct 9th 2019) (unit: kWh/m^2)

Solar PV panel	**Mono-Si 305W**	**Mono-Si 300W**	**Poly-Si 280W**	**Poly-Si 275W**	**A-Si 140W**	**A-Si 130W**	**CIGS 140W**	**Flexible CIGS 115W**	**CdTe 107.5W**	**CdTe 80W**
Oct-18	13.4	12.3	11.9	11.4	6	5.9	9.7	8.3	12.3	7.1
Nov-18	16.1	14.7	14.4	13.8	7.1	7.1	11.6	9.9	14.7	8.5
Dec-18	16.3	15	14.4	13.9	7	7.1	11.6	10	14.8	8.5
Jan-19	17.4	15.9	15.4	14.8	7.3	7.4	12.4	10.6	15.5	9
Feb-19	14.4	13.2	12.8	12.3	6.2	6	10	8.7	13.1	7.2
Mar-19	14.8	13.5	13.1	12.6	6.3	5.9	9.9	8.9	13.2	7.3
Apr-19	16.7	15.2	14.8	14.2	7.2	6.7	11.1	10	14.9	8.5
May-19	14.7	13.4	13.2	12.7	6.7	5.6	9.2	8.7	13.7	7.3
Jun-19	18.9	17.1	16.9	16.1	8.6	7.7	12.5	11.6	17.5	9.9
Jul-19	17.8	16.2	15.9	15.2	8.1	7.1	11.7	10.9	16.4	9.3
Aug-19	18.5	16.7	16.3	15.6	8.3	7.5	12.2	11.3	16.7	9.6
Sep-19	21.4	19	18.6	17.5	9.1	9	14.6	13.7	19	11.2
Oct-19	6	5.3	5.2	5	2.6	2.6	4.1	3.8	5.3	3.2

Table A4 Monthly Energy Output per peak power (from Oct 10th 2018 to Oct 9th 2019) (unit: Wh/Wp)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Oct-18	71.8	68.5	69.3	69.3	61.8	65.2	65.1	69.4	82.4	63.8
Nov-18	86.6	82	83.9	84	73.7	77.6	78	82.9	98.4	76.8
Dec-18	87.4	83.3	84.3	84.7	72.7	77.8	78.2	83.3	98.9	76.5
Jan-19	93	88.8	89.9	90.1	75.5	81.2	83.4	88.5	104	81.1
Feb-19	77.2	73.3	74.7	74.8	64	66.1	67.2	72.9	87.6	65
Mar-19	79.3	75.1	76.6	76.6	65.2	65.2	66.8	74	88.6	65.9
Apr-19	89.4	84.6	86.4	86.3	74.5	74	74.7	83.6	100.1	76.2
May-19	79	74.8	76.9	76.9	69.8	61.2	61.9	72.8	91.5	65.4
Jun-19	101.3	95.4	98.6	97.9	88.9	84.5	83.9	96.7	117.3	89.3
Jul-19	95.6	89.9	92.7	92.1	84.5	78.6	78.5	91.5	109.7	83.4
Aug-19	99	92.7	95.2	94.5	86.5	83	82.1	94.4	111.9	86.5
Sep-19	114.8	106	108.9	106.2	94.3	99.3	97.7	114.1	127.5	100.5
Oct-19	32	29.7	30.4	30.2	26.9	28.2	27.8	31.8	35.2	28.8

Table A5 Monthly Average Conversion Efficiency (from Oct 10th 2018 to Oct 9th 2019) (unit: %)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Oct-18	15.8	14.6	14	13.7	7	7	11.5	9.8	14.6	8.4
Nov-18	15.8	14.4	14	13.7	6.9	6.9	11.3	9.7	14.4	8.3
Dec-18	16.3	15	14.5	14.1	7	7.1	11.7	10	14.8	8.5
Jan-19	16.4	15.1	14.5	14.2	6.9	7	11.7	10	14.7	8.5
Feb-19	16.2	14.8	14.4	14	6.9	6.8	11.3	9.8	14.7	8.1
Mar-19	16.2	14.8	14.4	14	6.9	6.5	10.9	9.7	14.5	8
Apr-19	16.1	14.6	14.2	13.8	6.9	6.5	10.7	9.6	14.4	8.1
May-19	16.1	14.7	14.4	14	7.3	6.1	10.1	9.5	14.9	7.9
Jun-19	15.5	14	13.8	13.4	7	6.3	10.2	9.5	14.4	8.1
Jul-19	15.4	13.9	13.7	13.3	7	6.2	10.1	9.4	14.1	8
Aug-19	15.4	13.9	13.6	13.1	7	6.3	10.2	9.4	13.9	8
Sep-19	15	13.5	13.2	12.8	6.6	6.4	10.3	9.4	13.5	8
Oct-19	15.1	13.5	13.2	12.7	6.6	6.5	10.5	9.6	13.3	8.1

Table A6 Typical Daily Energy Output (unit: kWh)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Sunny day	1787.3	1676	1586.8	1555	667.5	740.5	798.3	671.3	706.5	438
Partly cloudy day	1075.8	1012.3	955.5	938	417.5	410	440.3	389.8	425.3	239
Cloudy day	502.3	477	448	441	212.5	160	177.8	170.5	205.5	94.3

Table A7 Typical Daily Energy Output per square meter (unit:Wh/m^2)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Sunny day	1093	1003.6	970.4	931.1	459	517.8	849.1	698.3	981.3	608.3
Partly cloudy day	657.9	606.1	584.4	561.7	287.1	286.7	468.3	405.5	590.6	331.9
Cloudy day	307.2	285.6	274	264.1	146.1	111.9	189.1	177.4	285.4	130.9

Table A8 Typical Daily Energy Output per peak power (unit: Wh/Wp)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Sunny day	5.9	5.6	5.7	5.7	4.8	5.7	5.7	5.8	6.6	5.5
Partly cloudy day	3.5	3.4	3.4	3.4	3	3.2	3.1	3.4	4	3
Cloudy day	1.6	1.6	1.6	1.6	1.5	1.2	1.3	1.5	1.9	1.2

Table A9 Average Conversion Efficiency in typical days

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Sunny day	15.7	14.4	13.9	13.5	6.6	7.4	12.2	10	14.1	8.7
Partly cloudy day	16.5	15.2	14.6	14.2	7.2	7.2	11.7	10.1	14.8	8.3
Cloudy day	16.8	15.6	15	14.6	8	6.1	10.3	9.7	15.6	7.1

Table A10 Maximum Daily Energy Output per month (from Oct 10^{th} 2018 to Oct 9^{th} 2019) (Wh)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 107.5W	CdTe 80W
Oct-18	1787.3	1676	1586.8	1555	667.5	742.3	801	671.3	706.5	442
Nov-18	1699	1572.8	1491.8	1463.5	643.8	707.3	759	625.5	682.5	425.3
Dec-18	1604.3	1500.3	1423.8	1398.8	603.8	666.8	709.5	604.8	641.3	399.3
Jan-19	1723.5	1607.8	1526.8	1501.3	621	708.5	773.3	647.3	681	422
Feb-19	1442.5	1333.8	1279.5	1253	532	574.3	625.3	533.5	578	349.8
Mar-19	1708.5	1582	1505	1476	609.8	671.3	729.3	626.3	665.8	409.8
Apr-19	1515	1401.3	1341	1313.3	556.5	588.3	629.3	551.5	598.5	364.8
May-19	1677.5	1549	1481.5	1452.3	635.5	653.3	692	611	672.5	408.3
Jun-19	1619.3	1493.8	1439.5	1402	634	626.8	667	601.3	654.5	399
Jul-19	1511.5	1381.8	1319.5	1287.3	593.5	561	602.3	543.8	593.8	359.8
Aug-19	1582	1447.3	1385.8	1357	614	587.8	626.5	571.3	615.5	374.3
Sep-19	1753	1614	1531.8	1498.5	675.5	688.8	720.8	672.3	689.5	430.5
Oct-19	1585.5	1451.8	1382.5	1343	597.5	597.8	638.5	595.8	601.5	372.3

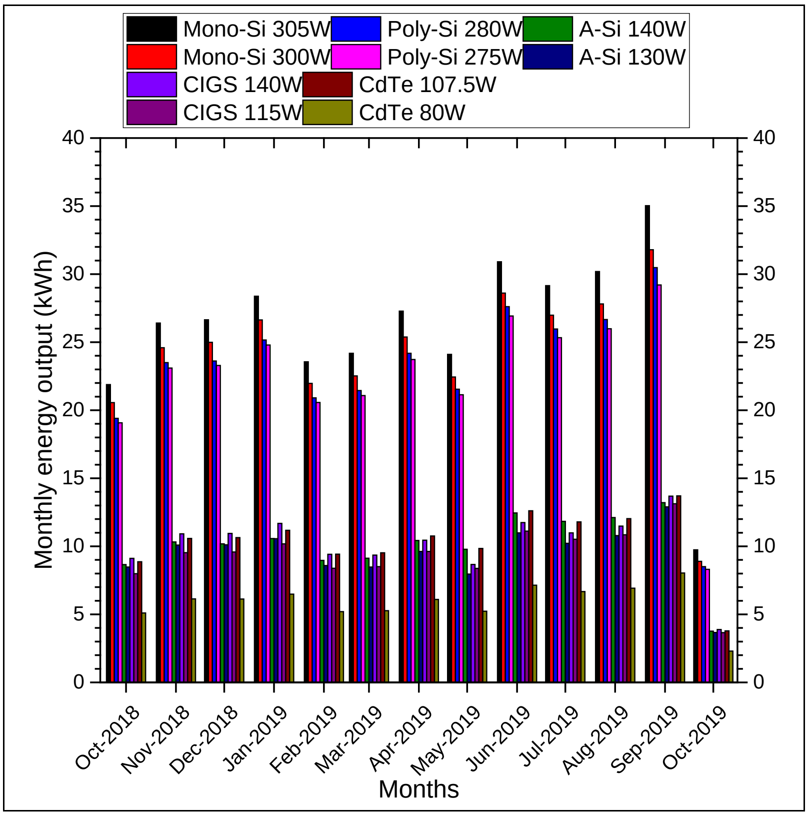


Figure A1 Monthly energy outputs of the PV panels
(from Oct 10th 2018 to Oct 9th 2019)

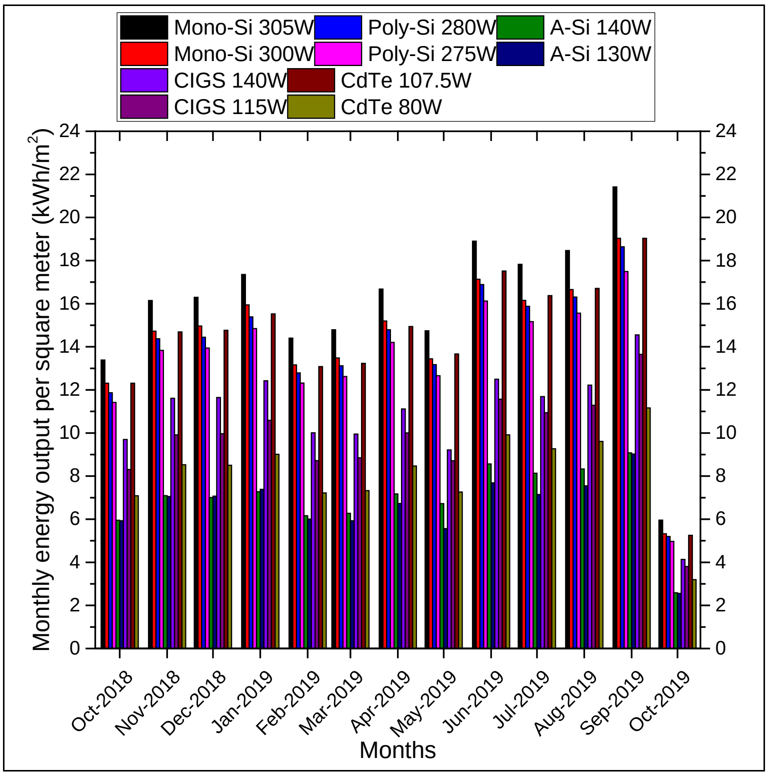


Figure A2 Monthly energy outputs per square meter of the PV panels
(from Oct 10th 2018 to Oct 9th 2019)

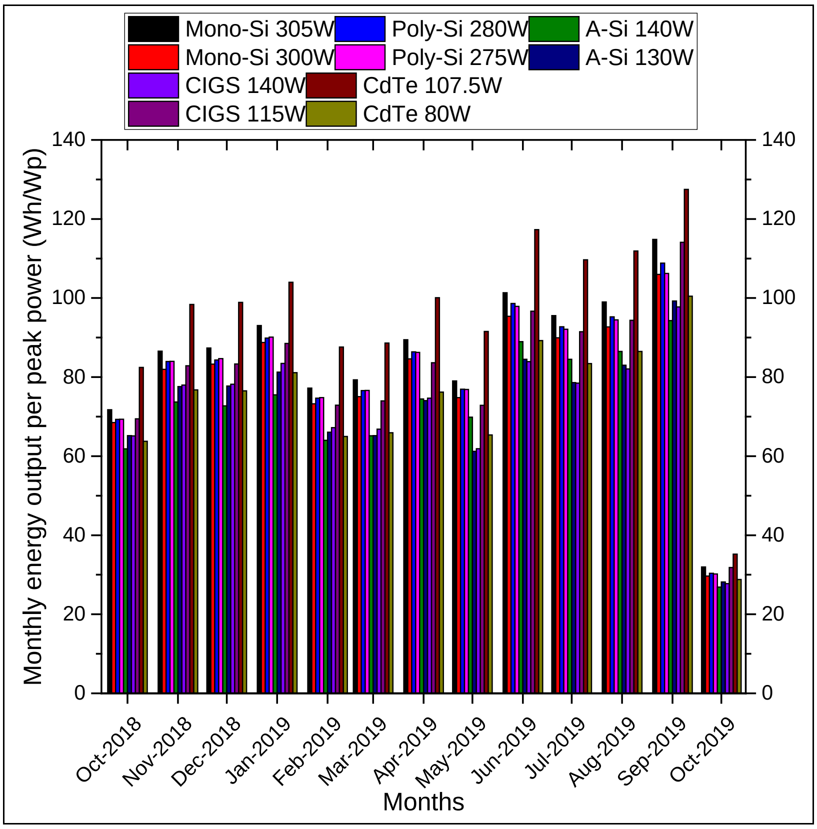


Figure A3 Monthly energy outputs per peak power of the PV panels (from Oct 10th 2018 to Oct 9th 2019)

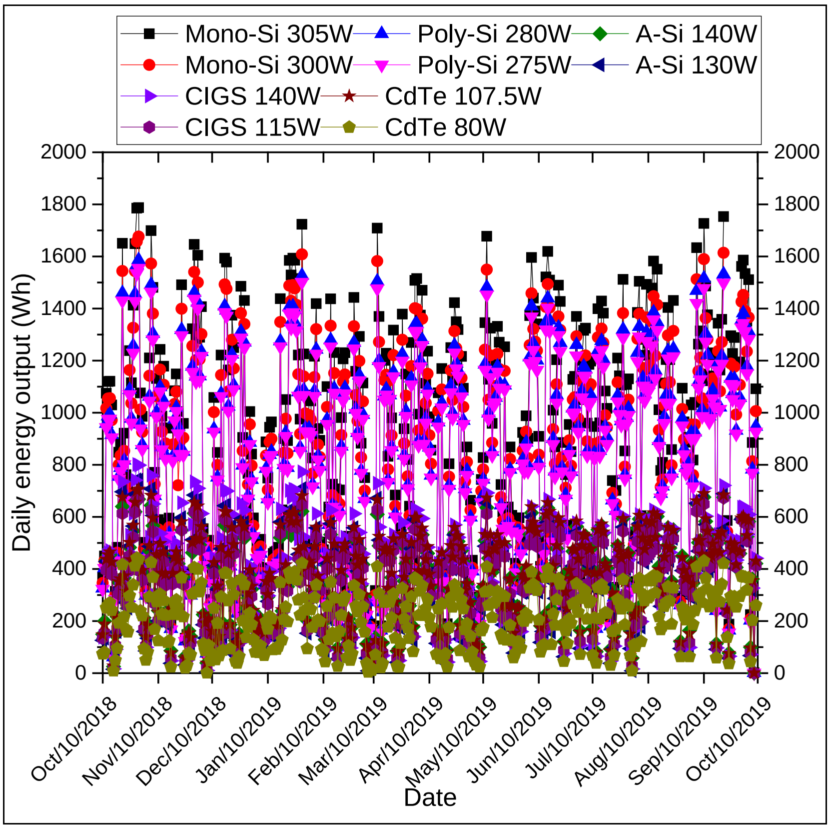


Figure A4 Comparisons of daily energy outputs (from Oct 10th 2018 to Oct 9th 2019)

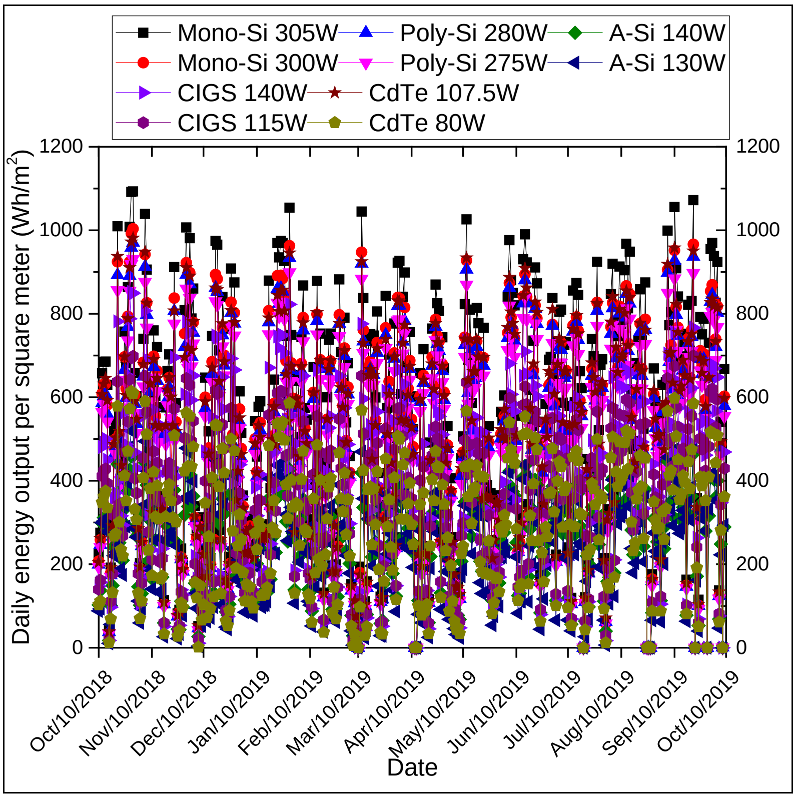


Figure A5 Comparison of daily energy output per square meter (from Oct 10th 2018 to Oct 9th 2019)

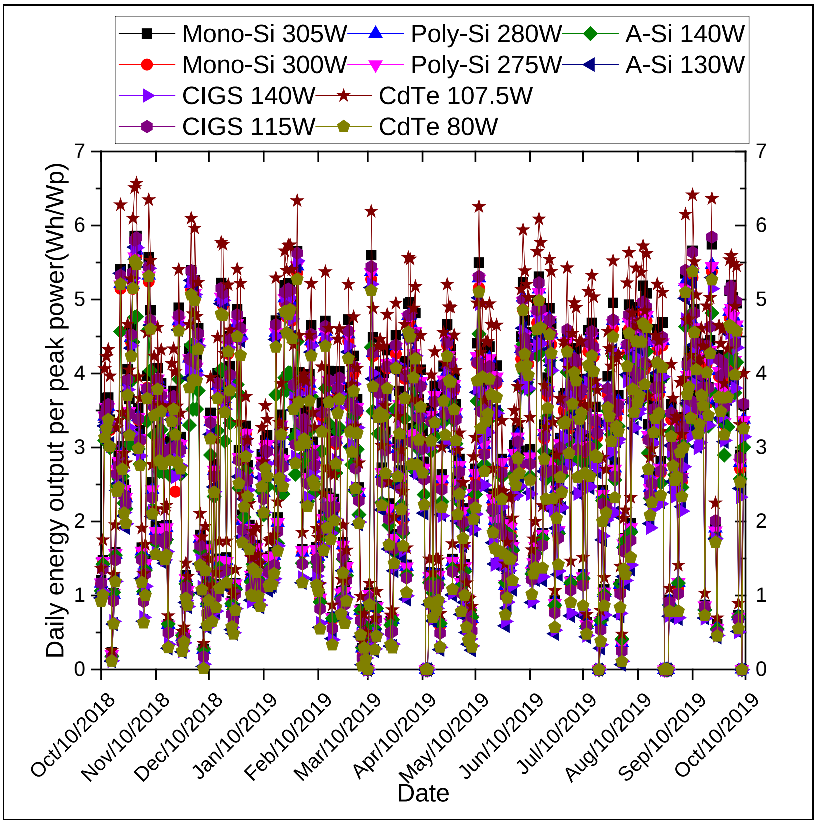


Figure A6 Comparison of daily energy output per peak power (From Oct 10th 2018 to Oct 9th 2019)

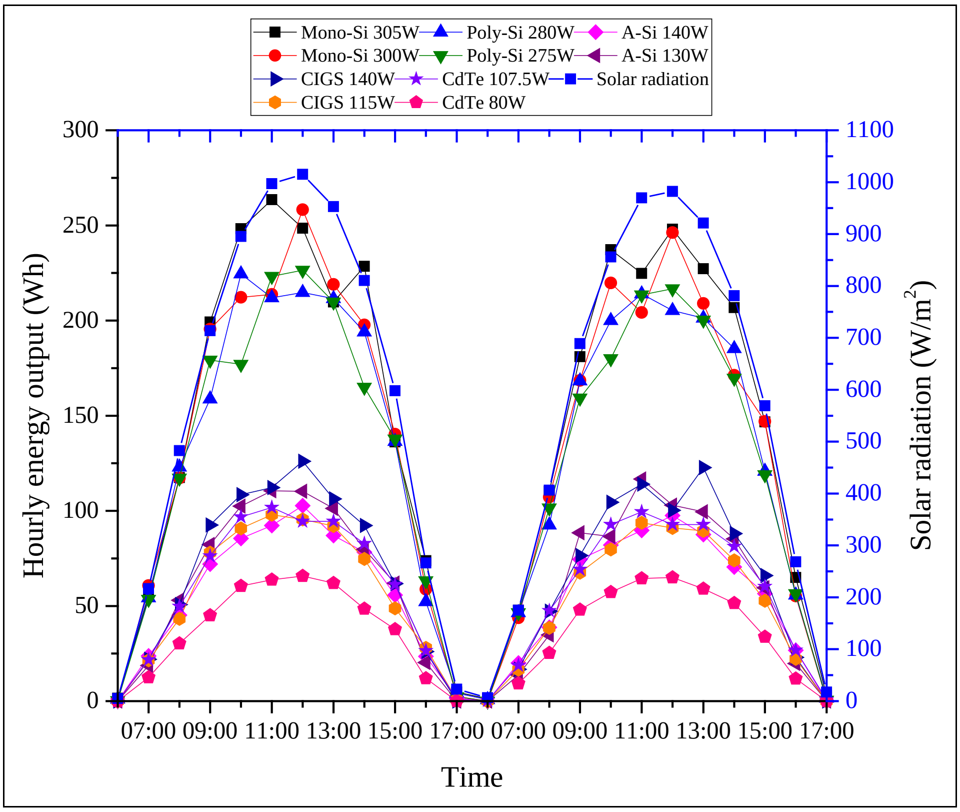


Figure A7 Hourly energy output on typical sunny days (Oct 30th 2018 and Nov 6th 2018)

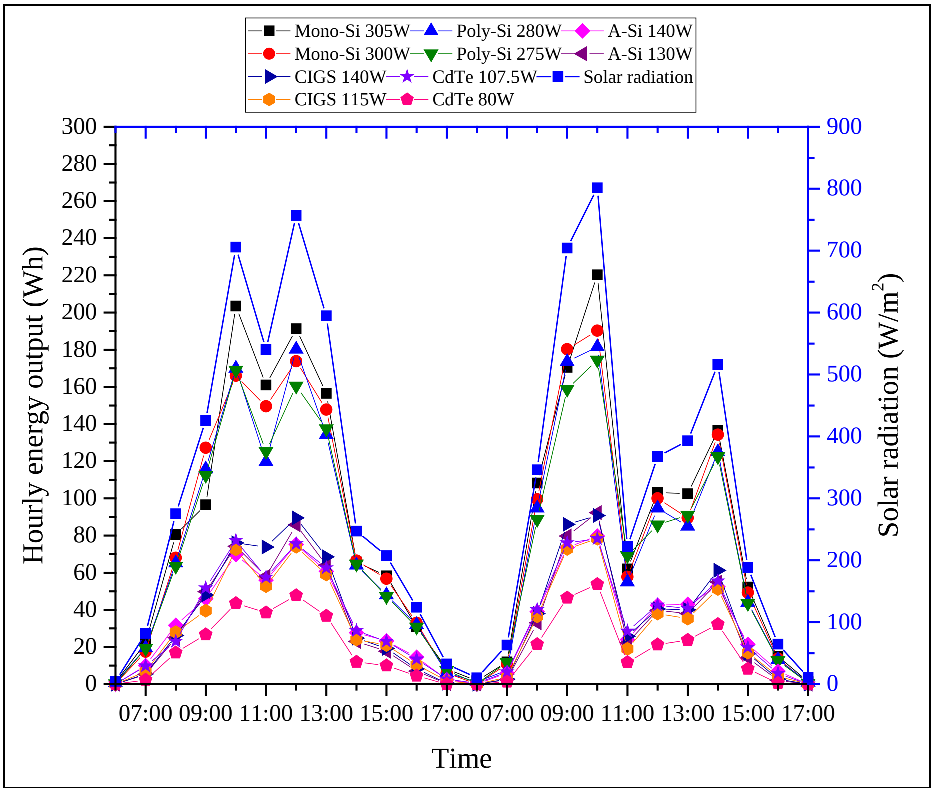


Figure A8 Hourly energy output on typical partly cloudy days (Oct 31st 2018 and Nov 1st 2018)

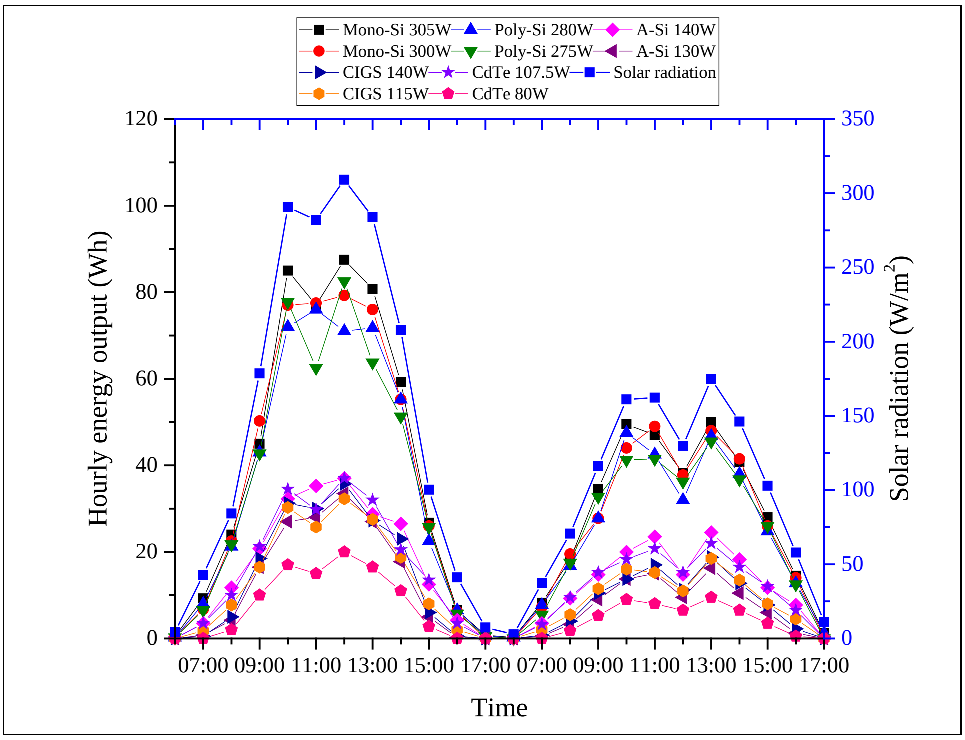


Figure A9 Hourly energy output on typical partly cloudy days
(Nov 2nd 2018 and Nov 3rd 2018)

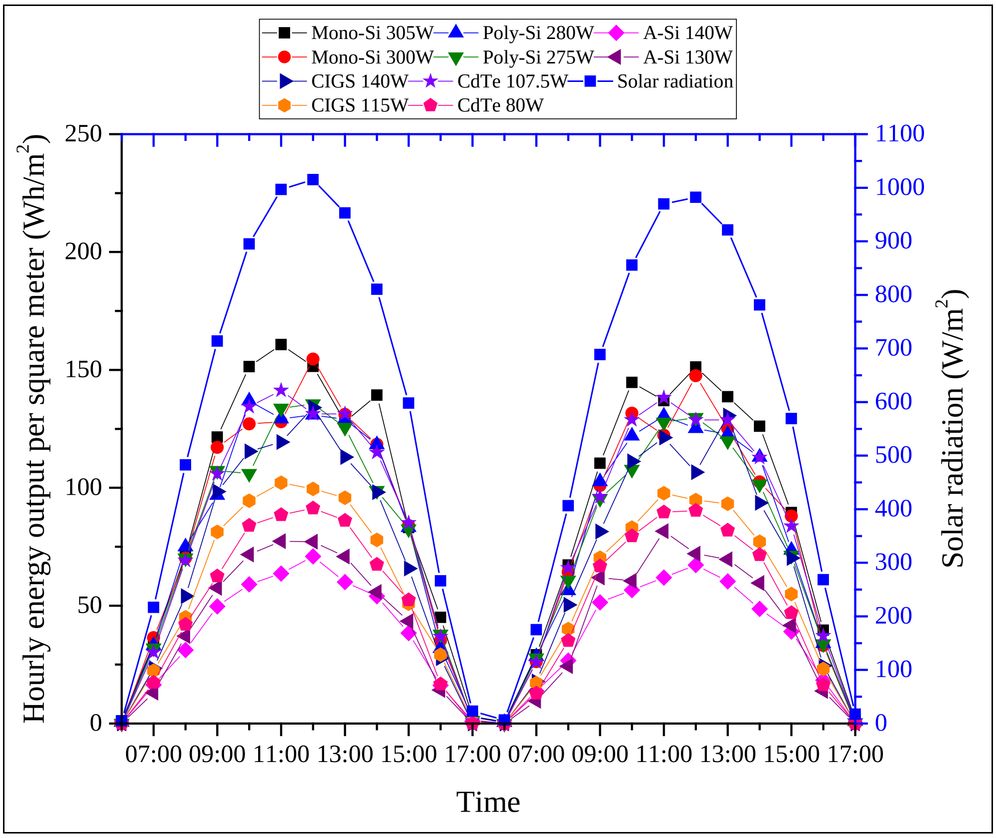


Figure A10 Hourly energy output per square meter on typical sunny days
(Oct 30th 2018 and Nov 6th 2018)

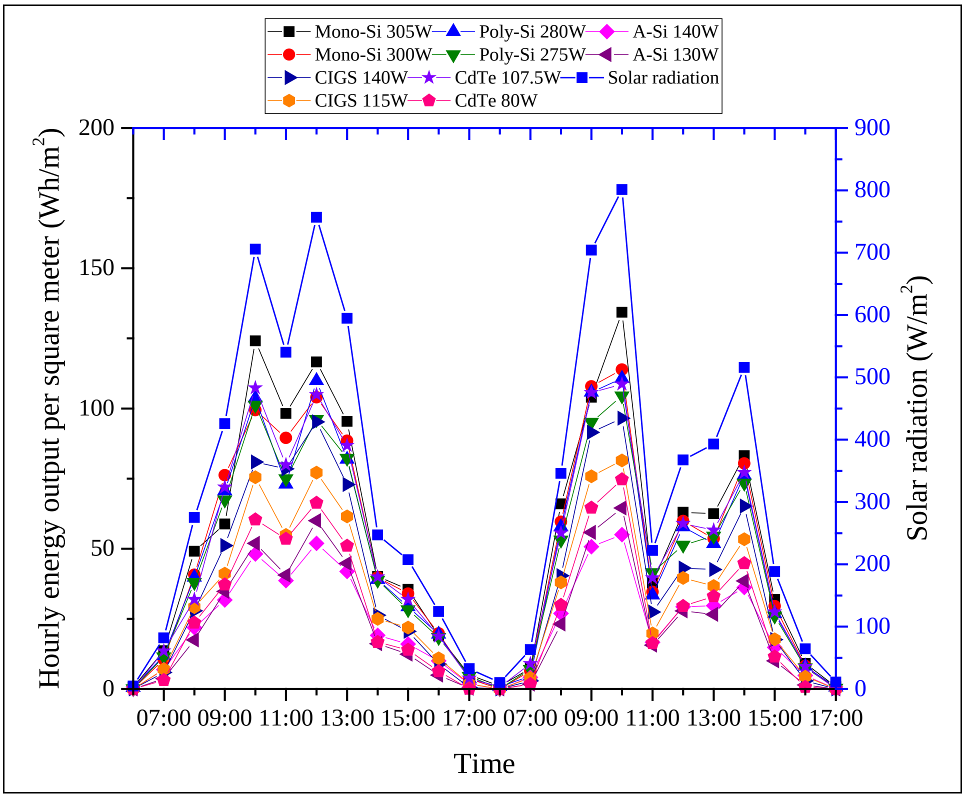


Figure A11 Hourly energy output per square meter on typical partly cloudy days (Oct 31st 2018 and Nov 1st 2018)

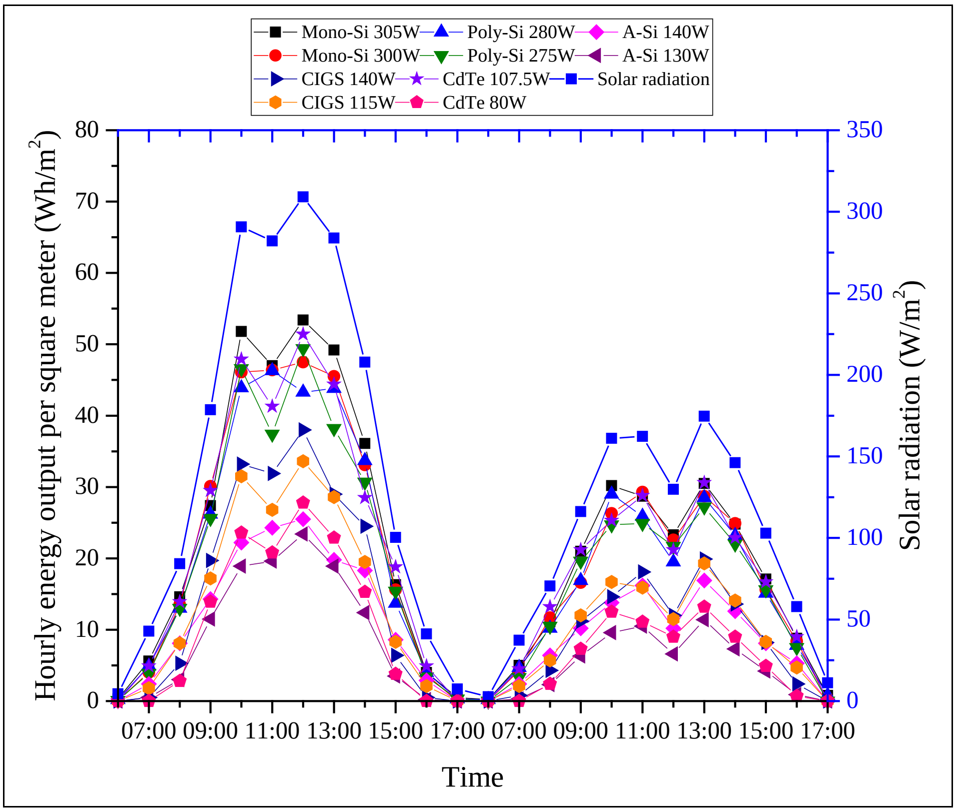


Figure A12 Hourly energy output per square meter on typical cloudy days (Nov 2nd 2018 and Nov 3rd 2018)

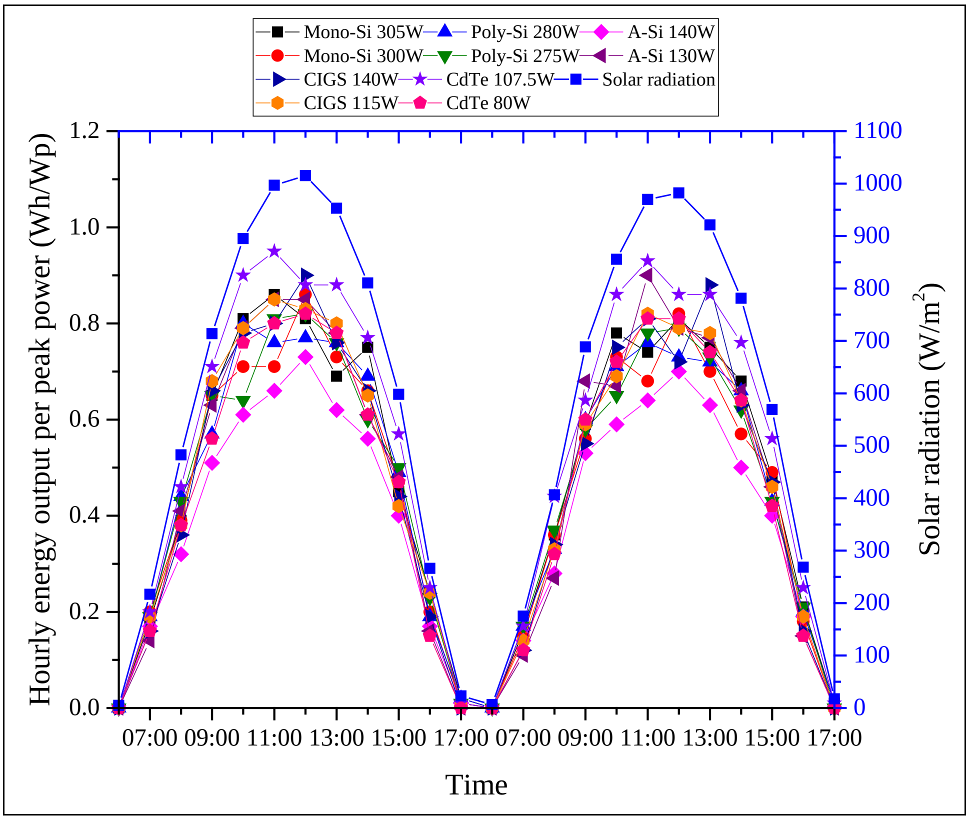


Figure A13 Hourly energy output per peak power on typical sunny days (Oct 30th 2018 and Nov 6th 2018)

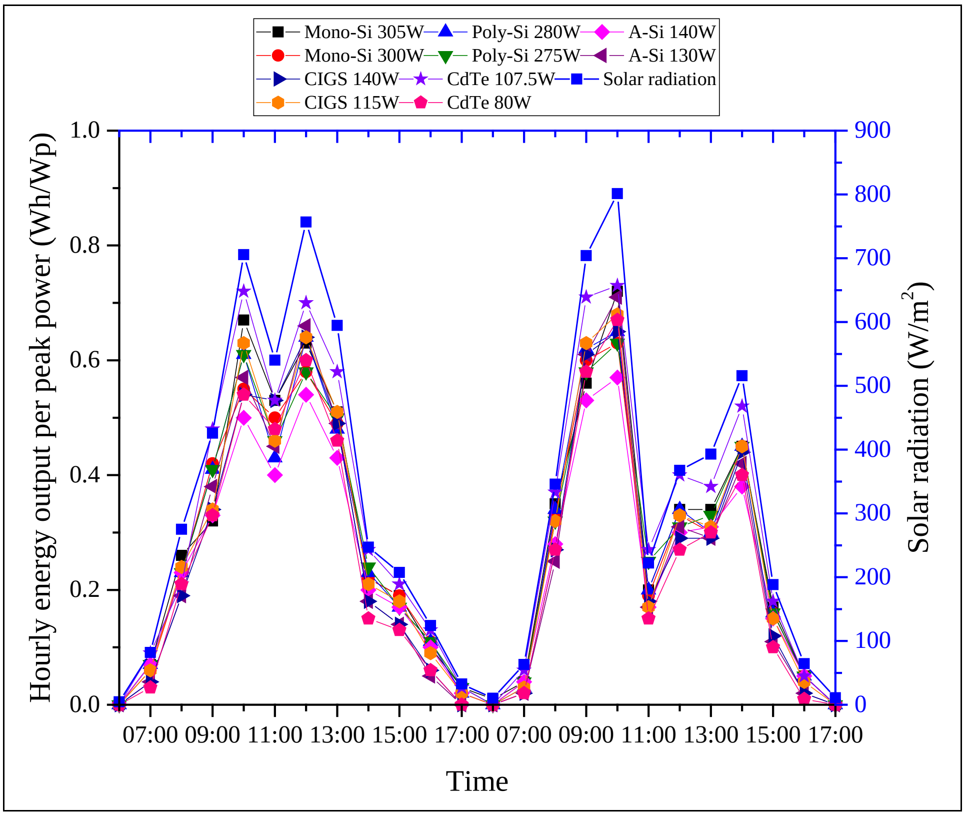


Figure A14 Hourly energy output per peak power on typical partly cloudy days (Oct 31st 2018 and Nov 1st 2018)

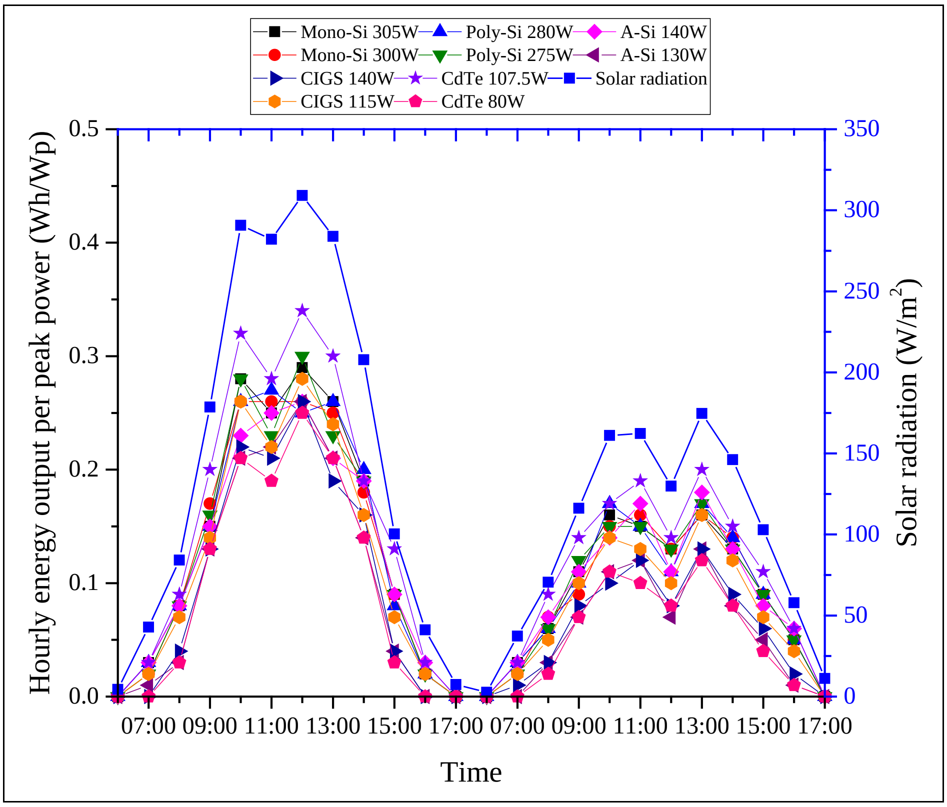


Figure A15 Hourly energy output per peak power on typical cloudy days (Nov 2nd 2018 and Nov 3rd 2018)

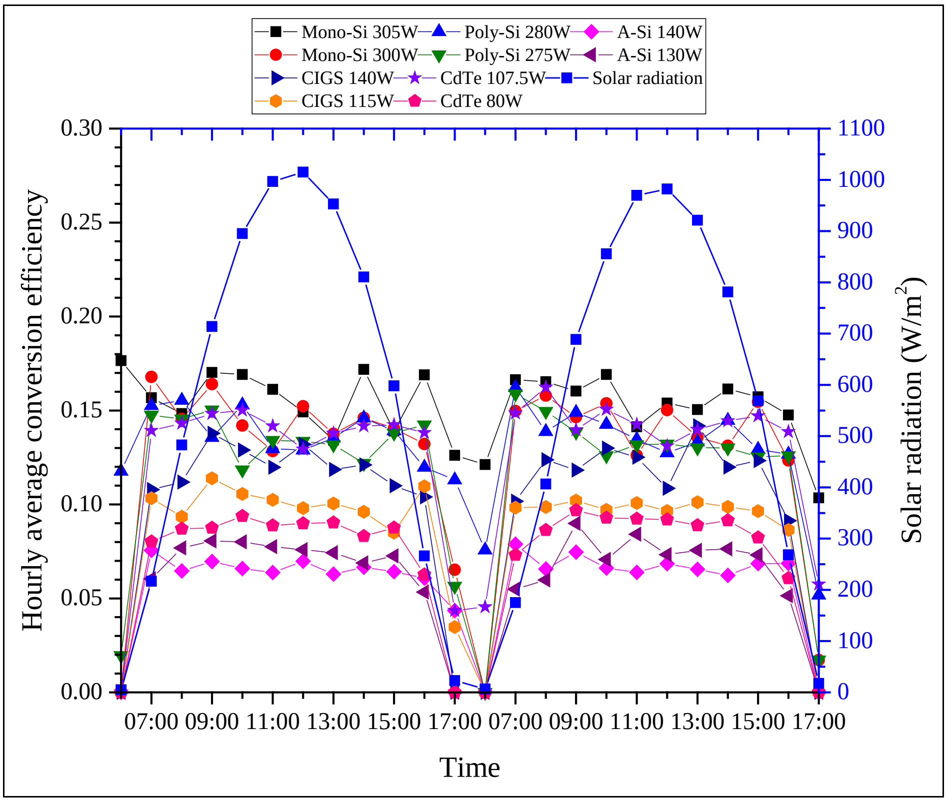


Figure A16 Hourly average conversion efficiency of PV modules on typical sunny days (Oct 30th 2018 and Nov 6th 2018)

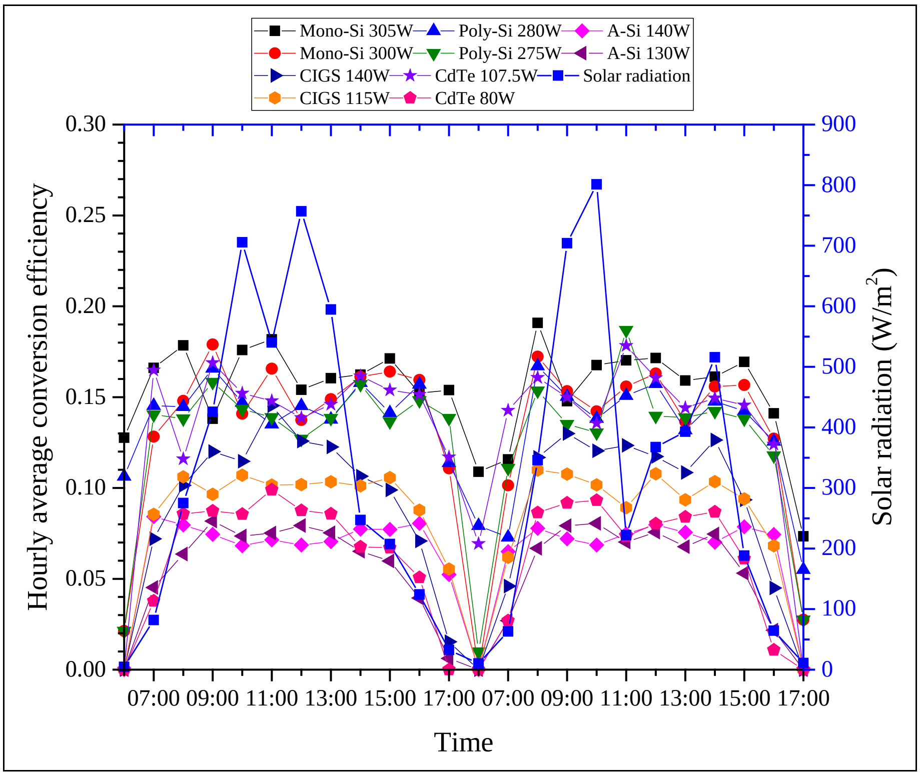


Figure A17 Hourly average conversion efficiency of PV modules on typical partly cloudy days (Oct 31st 2018 and Nov 1st 2018)

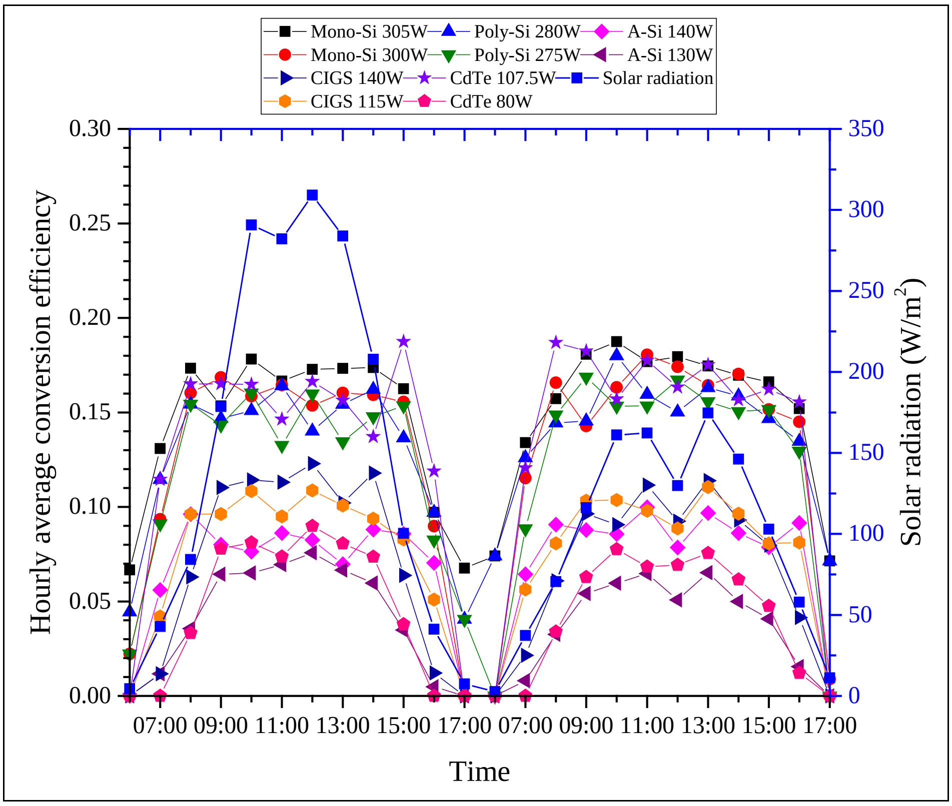


Figure A18 Hourly average conversion efficiency of PV modules on typical cloudy days (Nov 2nd 2018 and Nov 3rd 2018)

Appendix B: Comparison between experimental results and simulation results

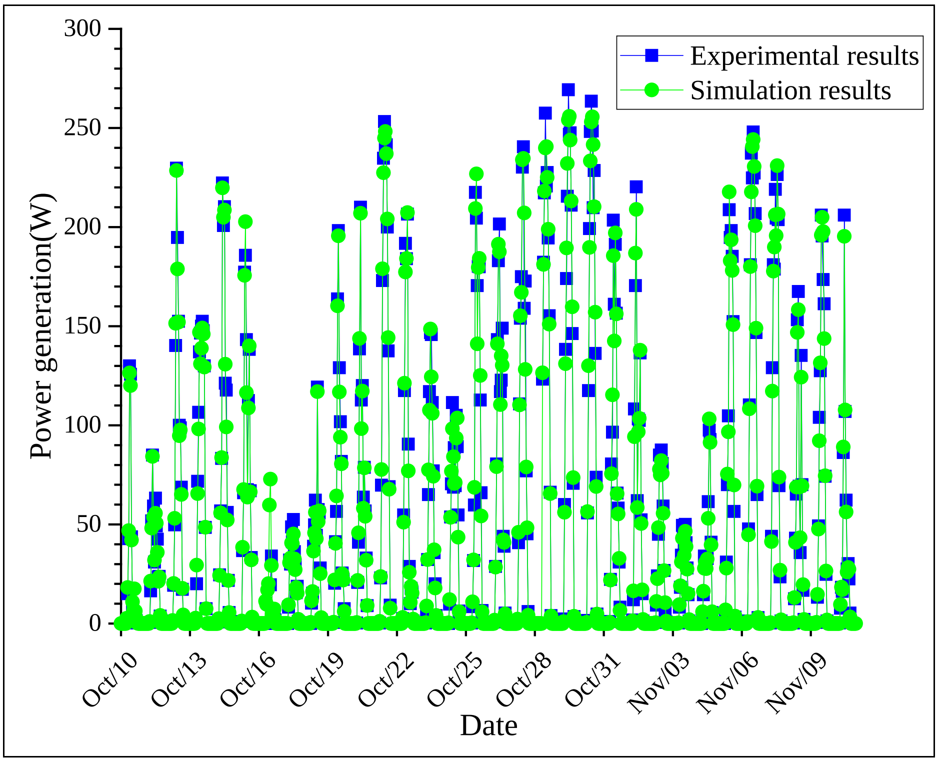


Figure B1 Comparison between the measured and simulated power generation of the Mono-Si 305W PV module

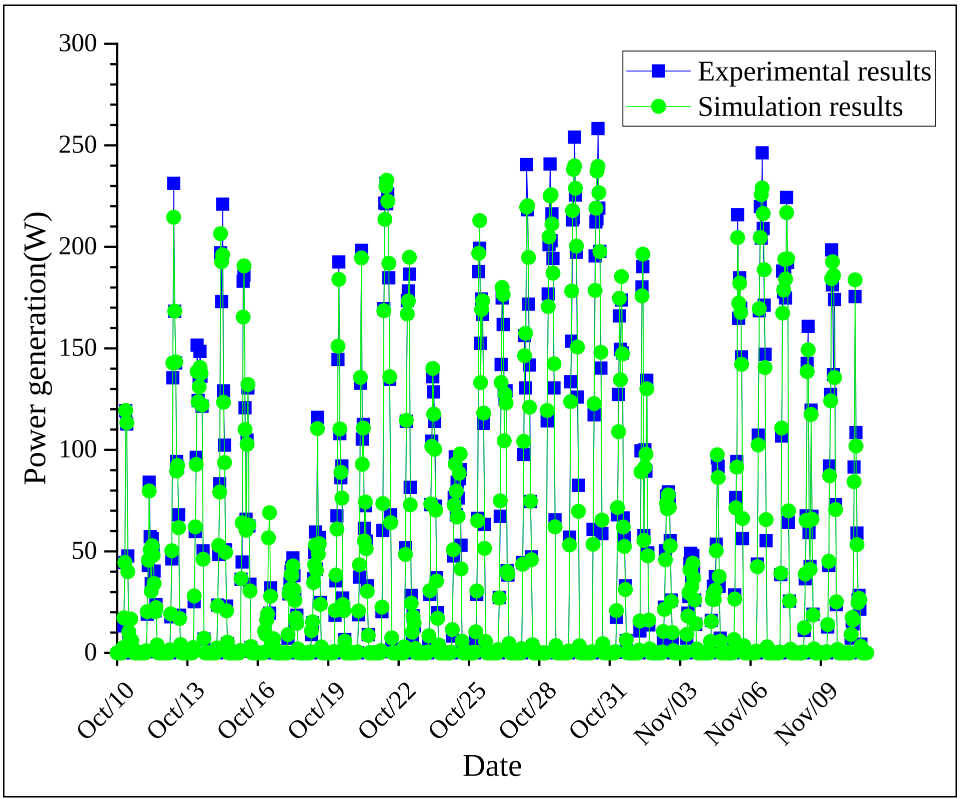


Figure B2 Comparison between the measured and simulated power generation of the Mono-Si 300W PV module

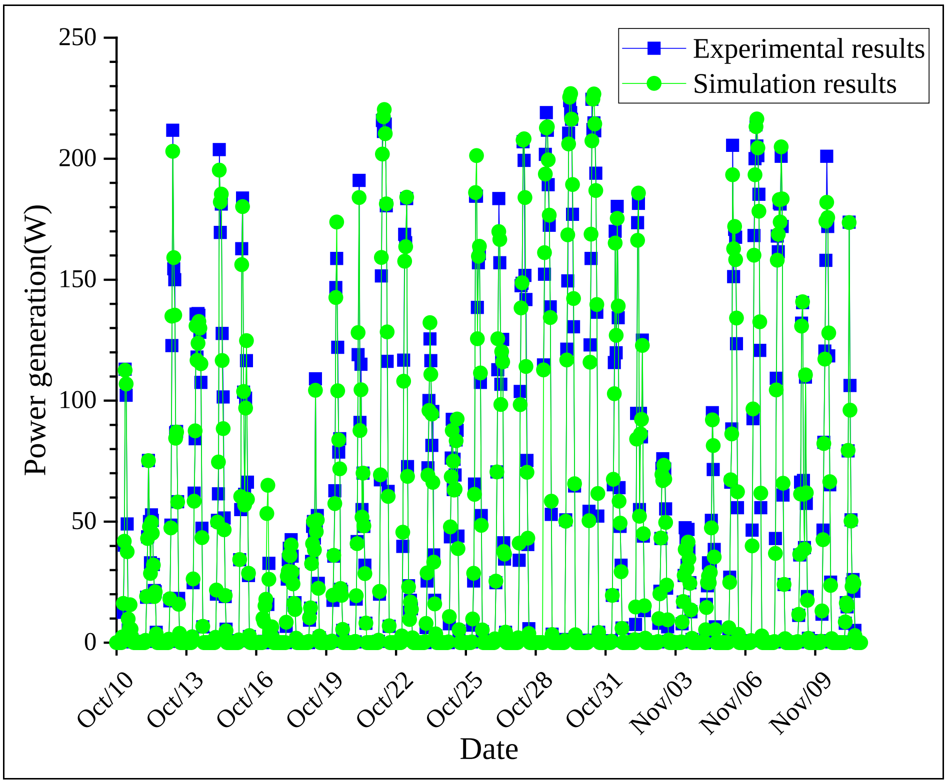


Figure B3 Comparison between the measured and simulated power generation of the Poly-Si 280W PV module

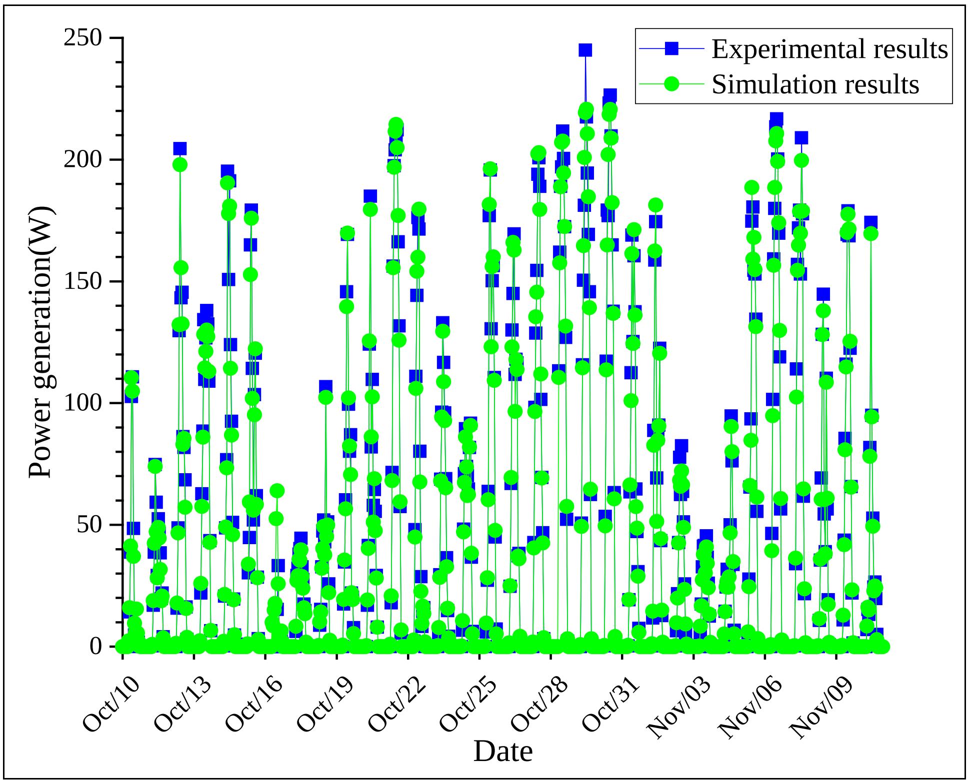


Figure B4 Comparison between the measured and simulated power generation of the Poly-Si 275W PV module

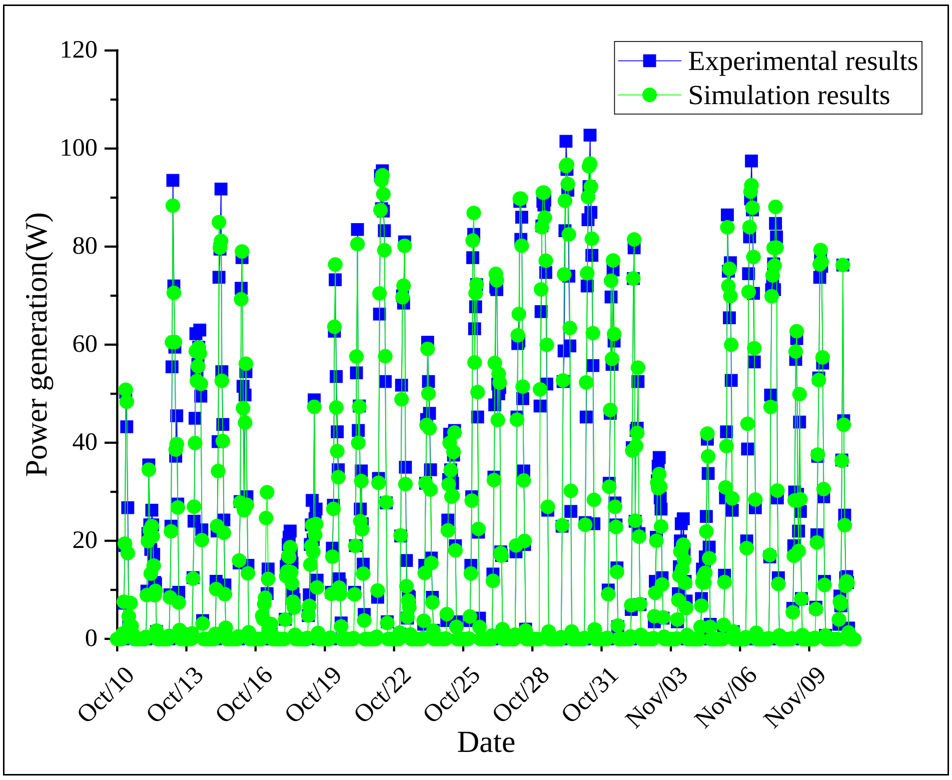


Figure B5 Comparison between the measured and simulated power generation of the A-Si 140W PV module

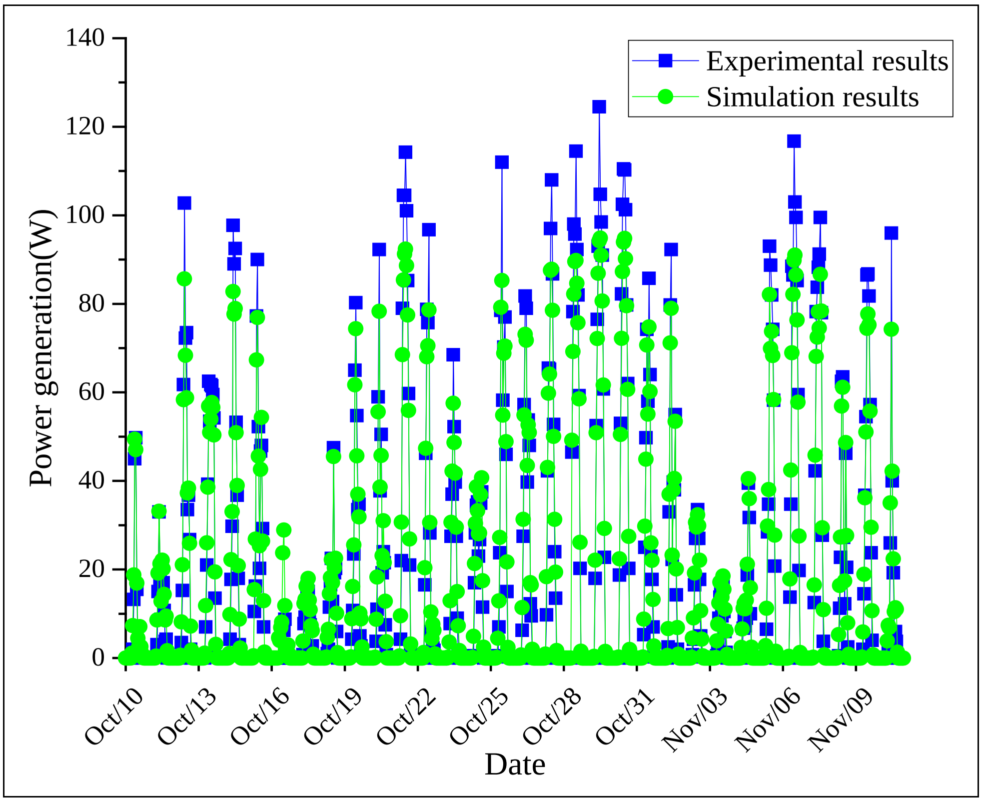


Figure B6 Comparison between the measured and simulated power generation of the A-Si 130W PV module

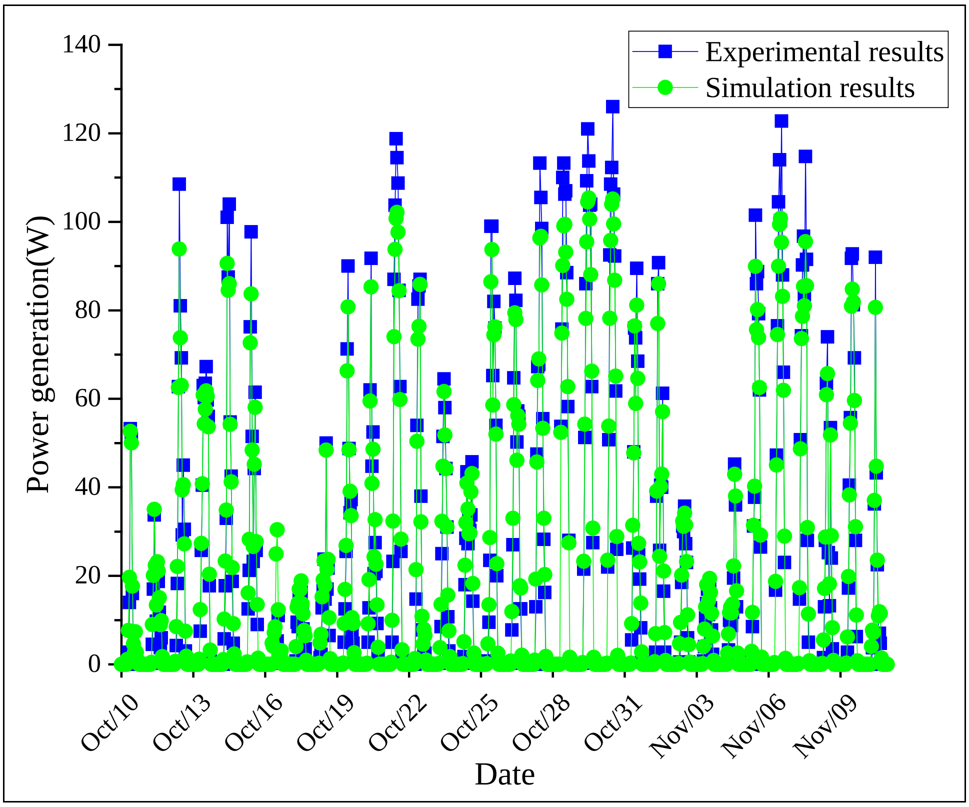


Figure B7 Comparison between the measured and simulated power generation of the CIGS 140W PV module

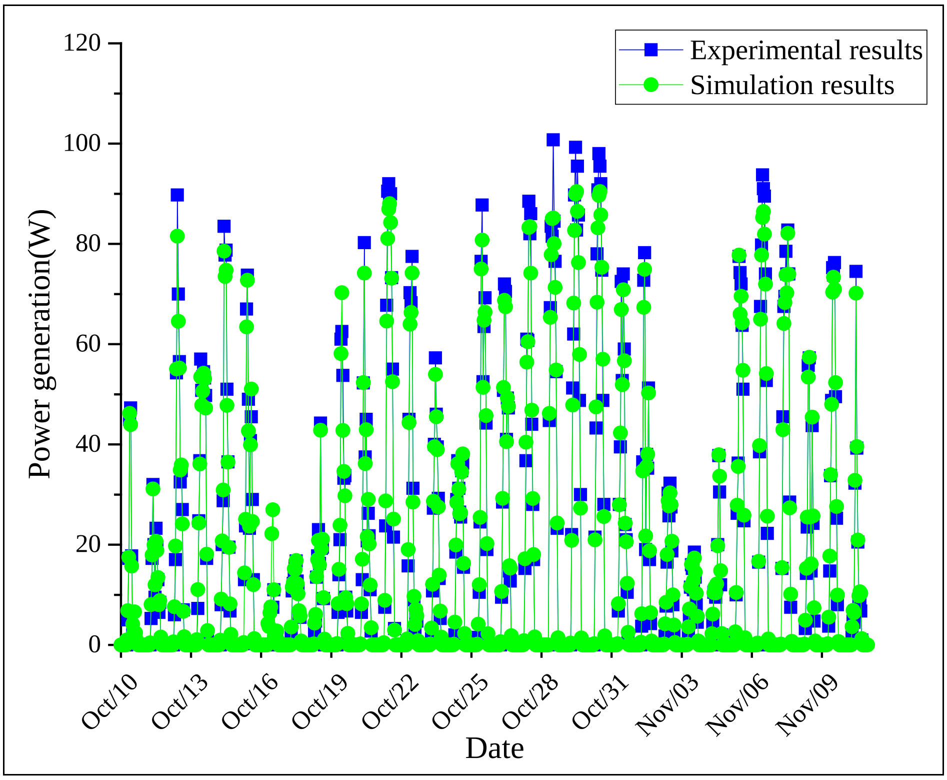


Figure B8 Comparison between the measured and simulated power generation of the CIGS 115W PV module

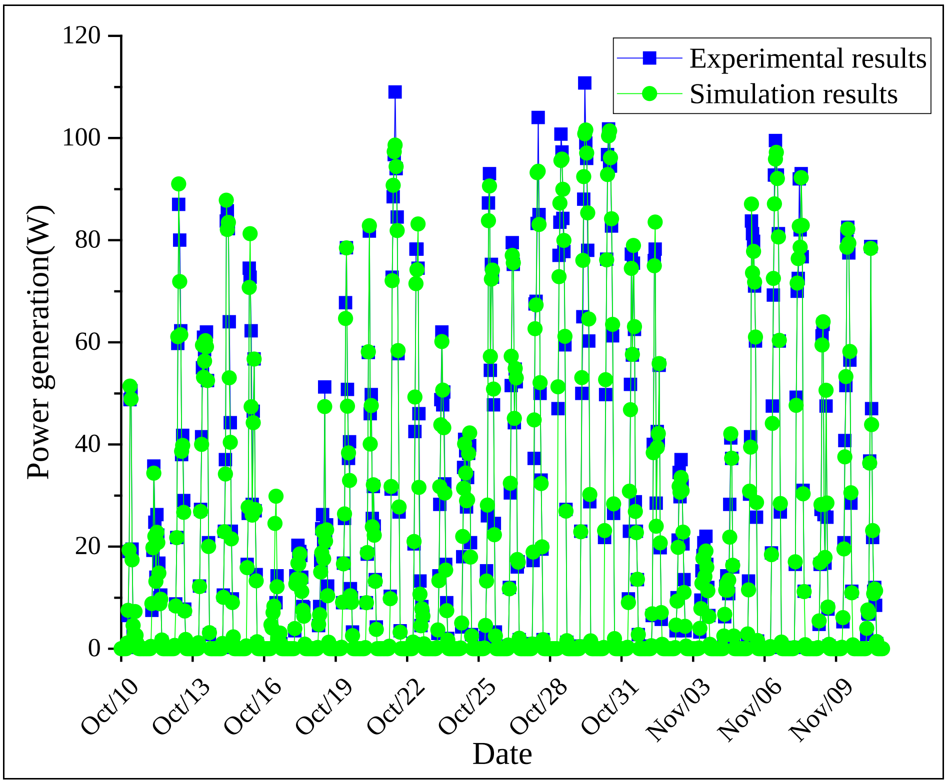


Figure B9 Comparison between the measured and simulated power generation of the CdTe 107.5W PV module

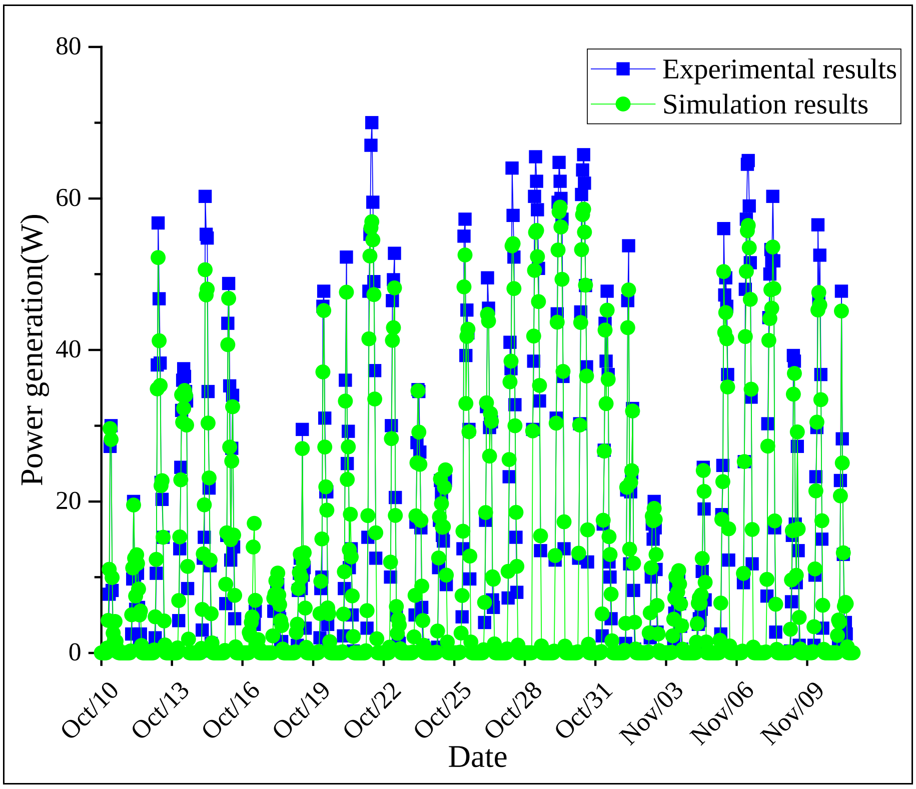


Figure B10 Comparison between the measured and simulated power generation of the CdTe 80W PV module

Appendix C: Simulation results of PV output for different tilt angles and orientations

Table C1 Annual energy output of the Mono-Si 305W PV module

No.	**Tilt angle (º)**	**Azimuth (º)/facing direction**	**Annual energy output of PV panel (kWh)**	**Annual energy output per square meter (kWh/m^2)**	**Annual energy output per peak power (kWh/Wp)**
1	0	N.A.	337.5	206.4	1.11
2	10	0/N	320.7	196.1	1.05
3	10	45/NE	323.8	198	1.06
4	10	90/E	333.8	204.1	1.09
5	10	135/SE	344.7	210.8	1.13
6	10	180/S	350.2	214.2	1.15
7	10	225/SW	347.4	212.5	1.14
8	10	270/W	337.7	206.5	1.11
9	10	315/NW	326.5	199.7	1.07
10	20	0/N	296	181	0.97
11	20	45/NE	302.9	185.3	0.99
12	20	90/E	323.2	197.6	1.06
13	20	135/SE	343.8	210.2	1.13
14	20	180/S	354.3	216.7	1.16
15	20	225/SW	349.1	213.5	1.14
16	20	270/W	330.5	202.1	1.08
17	20	315/NW	308.3	188.5	1.01
18	30	0/N	264.8	161.9	0.87
19	30	45/NE	277	169.4	0.91
20	30	90/E	307.3	187.9	1.01
21	30	135/SE	335.9	205.4	1.1
22	30	180/S	350.1	214.1	1.15
23	30	225/SW	343.3	210	1.13
24	30	270/W	317.4	194.1	1.04
25	30	315/NW	284.3	173.9	0.93
26	40	0/N	230.2	140.8	0.75
27	40	45/NE	248.4	151.9	0.81
28	40	90/E	287.7	176	0.94
29	40	135/SE	321.4	196.6	1.05
30	40	180/S	338.3	206.9	1.11
31	40	225/SW	330.5	202.1	1.08
32	40	270/W	299.5	183.2	0.98
33	40	315/NW	256.8	157	0.84
34	50	0/N	198.7	121.5	0.65
35	50	45/NE	219.5	134.2	0.72
36	50	90/E	265.2	162.2	0.87
37	50	135/SE	301.5	184.4	0.99
38	50	180/S	319.6	195.4	1.05

39	50	225/SW	311.8	190.7	1.02
40	50	270/W	278	170	0.91
41	50	315/NW	228	139.4	0.75
42	60	0/N	170.6	104.4	0.56
43	60	45/NE	192.2	117.6	0.63
44	60	90/E	240.8	147.3	0.79
45	60	135/SE	276.9	169.3	0.91
46	60	180/S	294.2	179.9	0.96
47	60	225/SW	287.8	176	0.94
48	60	270/W	253.8	155.2	0.83
49	60	315/NW	200.5	122.6	0.66
50	70	0/N	145	88.7	0.48
51	70	45/NE	167.9	102.7	0.55
52	70	90/E	215.6	131.9	0.71
53	70	135/SE	248.3	151.9	0.81
54	70	180/S	262.5	160.6	0.86
55	70	225/SW	259.3	158.6	0.85
56	70	270/W	228.5	139.7	0.75
57	70	315/NW	175.5	107.3	0.58
58	80	0/N	123	75.2	0.4
59	80	45/NE	147	89.9	0.48
60	80	90/E	190.6	116.6	0.62
61	80	135/SE	217.3	132.9	0.71
62	80	180/S	226.1	138.2	0.74
63	80	225/SW	227.7	139.2	0.75
64	80	270/W	202.5	123.8	0.66
65	80	315/NW	153.6	93.9	0.5
66	90	0/N	107.2	65.6	0.35
67	90	45/NE	129.3	79.1	0.42
68	90	90/E	166.2	101.6	0.54
69	90	135/SE	185.7	113.6	0.61
70	90	180/S	189.4	115.8	0.62
71	90	225/SW	194.9	119.2	0.64
72	90	270/W	176.4	107.9	0.58
73	90	315/NW	134.6	82.3	0.44

Table C2 Annual energy output of the Mono-Si 300W PV module

No.	Tilt angle (°)	Azimuth (°)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	318.6	190.8	1.06
2	10	0/N	302.8	181.3	1.01
3	10	45/NE	305.7	183.1	1.02
4	10	90/E	315.1	188.7	1.05
5	10	135/SE	325.4	194.8	1.08
6	10	180/S	330.6	198	1.1
7	10	225/SW	328	196.4	1.09
8	10	270/W	318.8	190.9	1.06
9	10	315/NW	308.3	184.6	1.03
10	20	0/N	279.6	167.4	0.93
11	20	45/NE	286.1	171.3	0.95
12	20	90/E	305.1	182.7	1.02
13	20	135/SE	324.6	194.4	1.08
14	20	180/S	334.5	200.3	1.12
15	20	225/SW	329.6	197.3	1.1
16	20	270/W	312.1	186.9	1.04
17	20	315/NW	291.2	174.3	0.97
18	30	0/N	250.3	149.9	0.83
19	30	45/NE	261.8	156.7	0.87
20	30	90/E	290.2	173.8	0.97
21	30	135/SE	317.1	189.9	1.06
22	30	180/S	330.7	198	1.1
23	30	225/SW	324.2	194.1	1.08
24	30	270/W	299.7	179.5	1
25	30	315/NW	268.6	160.9	0.9
26	40	0/N	217.8	130.4	0.73
27	40	45/NE	234.8	140.6	0.78
28	40	90/E	271.8	162.7	0.91
29	40	135/SE	303.5	181.8	1.01
30	40	180/S	319.6	191.4	1.07
31	40	225/SW	312.2	186.9	1.04
32	40	270/W	282.9	169.4	0.94
33	40	315/NW	242.7	145.3	0.81
34	50	0/N	188.1	112.6	0.63
35	50	45/NE	207.6	124.3	0.69
36	50	90/E	250.6	150.1	0.84
37	50	135/SE	284.8	170.5	0.95
38	50	180/S	301.9	180.8	1.01
39	50	225/SW	294.6	176.4	0.98
40	50	270/W	262.6	157.2	0.88

41	50	315/NW	215.7	129.1	0.72
42	60	0/N	161.7	96.8	0.54
43	60	45/NE	181.9	109	0.61
44	60	90/E	227.6	136.3	0.76
45	60	135/SE	261.6	156.6	0.87
46	60	180/S	278	166.5	0.93
47	60	225/SW	271.9	162.8	0.91
48	60	270/W	239.9	143.6	0.8
49	60	315/NW	189.7	113.6	0.63
50	70	0/N	137.5	82.3	0.46
51	70	45/NE	159	95.2	0.53
52	70	90/E	203.9	122.1	0.68
53	70	135/SE	234.7	140.5	0.78
54	70	180/S	248.1	148.6	0.83
55	70	225/SW	245	146.7	0.82
56	70	270/W	216	129.3	0.72
57	70	315/NW	166.2	99.5	0.55
58	80	0/N	116.7	69.9	0.39
59	80	45/NE	139.3	83.4	0.46
60	80	90/E	180.4	108	0.6
61	80	135/SE	205.4	123	0.68
62	80	180/S	213.7	128	0.71
63	80	225/SW	215.2	128.9	0.72
64	80	270/W	191.5	114.7	0.64
65	80	315/NW	145.5	87.1	0.48
66	90	0/N	101.8	60.9	0.34
67	90	45/NE	122.6	73.4	0.41
68	90	90/E	157.3	94.2	0.52
69	90	135/SE	175.7	105.2	0.59
70	90	180/S	179.1	107.3	0.6
71	90	225/SW	184.4	110.4	0.61
72	90	270/W	167	100	0.56
73	90	315/NW	127.6	76.4	0.43

Table C3 Annual energy output of the Poly-Si 280W PV panel

No.	Tilt angle (º)	Azimuth (º)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	301.1	182.3	1.06
2	10	0/N	286	173.2	1.01
3	10	45/NE	288.8	174.9	1.02
4	10	90/E	297.8	180.3	1.05
5	10	135/SE	307.7	186.3	1.09
6	10	180/S	312.7	189.4	1.11
7	10	225/SW	310.1	187.8	1.1
8	10	270/W	301.3	182.4	1.07
9	10	315/NW	291.3	176.4	1.03
10	20	0/N	263.9	159.8	0.93
11	20	45/NE	270.2	163.6	0.96
12	20	90/E	288.4	174.6	1.02
13	20	135/SE	307.1	186	1.09
14	20	180/S	316.8	191.8	1.12
15	20	225/SW	311.9	188.8	1.1
16	20	270/W	294.9	178.6	1.04
17	20	315/NW	274.9	166.5	0.97
18	30	0/N	236.1	143	0.83
19	30	45/NE	247.1	149.6	0.87
20	30	90/E	274.2	166	0.97
21	30	135/SE	300.3	181.8	1.06
22	30	180/S	313.6	189.9	1.11
23	30	225/SW	306.9	185.9	1.09
24	30	270/W	283.2	171.5	1
25	30	315/NW	253.6	153.5	0.9
26	40	0/N	205.3	124.3	0.73
27	40	45/NE	221.5	134.1	0.78
28	40	90/E	256.7	155.4	0.91
29	40	135/SE	287.4	174	1.02
30	40	180/S	303.3	183.7	1.07
31	40	225/SW	295.7	179	1.05
32	40	270/W	267.2	161.8	0.95
33	40	315/NW	229	138.6	0.81
34	50	0/N	177.2	107.3	0.63
35	50	45/NE	195.7	118.5	0.69
36	50	90/E	236.6	143.2	0.84
37	50	135/SE	269.6	163.2	0.95
38	50	180/S	286.4	173.4	1.01
39	50	225/SW	278.8	168.8	0.99
40	50	270/W	248	150.1	0.88

41	50	315/NW	203.4	123.1	0.72
42	60	0/N	152.3	92.2	0.54
43	60	45/NE	171.5	103.8	0.61
44	60	90/E	214.8	130.1	0.76
45	60	135/SE	247.3	149.8	0.87
46	60	180/S	263.3	159.4	0.93
47	60	225/SW	257	155.6	0.91
48	60	270/W	226.4	137.1	0.8
49	60	315/NW	178.8	108.3	0.63
50	70	0/N	129.4	78.3	0.46
51	70	45/NE	149.8	90.7	0.53
52	70	90/E	192.3	116.5	0.68
53	70	135/SE	221.6	134.2	0.78
54	70	180/S	234.5	142	0.83
55	70	225/SW	231.4	140.1	0.82
56	70	270/W	203.7	123.4	0.72
57	70	315/NW	156.6	94.8	0.55
58	80	0/N	109.7	66.4	0.39
59	80	45/NE	131.1	79.4	0.46
60	80	90/E	170	103	0.6
61	80	135/SE	193.8	117.4	0.69
62	80	180/S	201.7	122.1	0.71
63	80	225/SW	203.1	123	0.72
64	80	270/W	180.6	109.4	0.64
65	80	315/NW	137	83	0.48
66	90	0/N	95.7	57.9	0.34
67	90	45/NE	115.4	69.8	0.41
68	90	90/E	148.2	89.8	0.52
69	90	135/SE	165.6	100.3	0.59
70	90	180/S	168.9	102.3	0.6
71	90	225/SW	173.9	105.3	0.61
72	90	270/W	157.4	95.3	0.56
73	90	315/NW	120.1	72.7	0.42

Table C4 Annual energy output of the Poly-Si 275W PV panel

No.	Tilt angle (°)	Azimuth (°)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	295.3	176.9	1.07
2	10	0/N	280.7	168.1	1.02
3	10	45/NE	283.4	169.7	1.03
4	10	90/E	292.1	174.9	1.06
5	10	135/SE	301.7	180.7	1.1
6	10	180/S	306.6	183.6	1.12
7	10	225/SW	304.1	182.1	1.11
8	10	270/W	295.5	177	1.07
9	10	315/NW	285.8	171.1	1.04
10	20	0/N	259.2	155.2	0.94
11	20	45/NE	265.2	158.8	0.96
12	20	90/E	282.9	169.4	1.03
13	20	135/SE	301.1	180.3	1.1
14	20	180/S	310.6	186	1.13
15	20	225/SW	305.8	183.1	1.11
16	20	270/W	289.3	173.2	1.05
17	20	315/NW	269.9	161.6	0.98
18	30	0/N	232	138.9	0.84
19	30	45/NE	242.7	145.3	0.88
20	30	90/E	269.1	161.1	0.98
21	30	135/SE	294.4	176.3	1.07
22	30	180/S	307.5	184.1	1.12
23	30	225/SW	301	180.2	1.09
24	30	270/W	277.9	166.4	1.01
25	30	315/NW	249	149.1	0.91
26	40	0/N	201.9	120.9	0.73
27	40	45/NE	217.7	130.4	0.79
28	40	90/E	252	150.9	0.92
29	40	135/SE	281.9	168.8	1.03
30	40	180/S	297.5	178.2	1.08
31	40	225/SW	290	173.6	1.05
32	40	270/W	262.3	157	0.95
33	40	315/NW	225	134.7	0.82
34	50	0/N	174.5	104.5	0.63
35	50	45/NE	192.5	115.3	0.7
36	50	90/E	232.3	139.1	0.84
37	50	135/SE	264.5	158.4	0.96
38	50	180/S	281	168.3	1.02
39	50	225/SW	273.5	163.8	0.99
40	50	270/W	243.4	145.8	0.89

41	50	315/NW	200	119.7	0.73
42	60	0/N	150	89.8	0.55
43	60	45/NE	168.8	101.1	0.61
44	60	90/E	211.1	126.4	0.77
45	60	135/SE	242.8	145.4	0.88
46	60	180/S	258.4	154.7	0.94
47	60	225/SW	252.3	151.1	0.92
48	60	270/W	222.4	133.2	0.81
49	60	315/NW	176	105.4	0.64
50	70	0/N	127.6	76.4	0.46
51	70	45/NE	147.6	88.4	0.54
52	70	90/E	189.1	113.2	0.69
53	70	135/SE	217.7	130.3	0.79
54	70	180/S	230.2	137.9	0.84
55	70	225/SW	227.2	136.1	0.83
56	70	270/W	200.3	119.9	0.73
57	70	315/NW	154.2	92.3	0.56
58	80	0/N	108.3	64.9	0.39
59	80	45/NE	129.3	77.4	0.47
60	80	90/E	167.3	100.2	0.61
61	80	135/SE	190.6	114.1	0.69
62	80	180/S	198.2	118.7	0.72
63	80	225/SW	199.6	119.5	0.73
64	80	270/W	177.6	106.4	0.65
65	80	315/NW	135	80.9	0.49
66	90	0/N	94.5	56.6	0.34
67	90	45/NE	113.8	68.1	0.41
68	90	90/E	146	87.4	0.53
69	90	135/SE	163	97.6	0.59
70	90	180/S	166.2	99.5	0.6
71	90	225/SW	171	102.4	0.62
72	90	270/W	155	92.8	0.56
73	90	315/NW	118.5	71	0.43

Table C5 Annual energy output of the A-Si 140W PV panel

No.	Tilt angle (º)	Azimuth (º)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	135.9	93.5	0.97
2	10	0/N	129.4	89	0.92
3	10	45/NE	130.5	89.8	0.93
4	10	90/E	134.4	92.4	0.96
5	10	135/SE	138.7	95.4	0.99
6	10	180/S	140.8	96.9	1.01
7	10	225/SW	139.7	96.1	1
8	10	270/W	135.9	93.5	0.97
9	10	315/NW	131.6	90.5	0.94
10	20	0/N	119.7	82.3	0.86
11	20	45/NE	122.4	84.2	0.87
12	20	90/E	130.2	89.6	0.93
13	20	135/SE	138.3	95.1	0.99
14	20	180/S	142.6	98	1.02
15	20	225/SW	140.4	96.6	1
16	20	270/W	133.1	91.5	0.95
17	20	315/NW	124.5	85.6	0.89
18	30	0/N	107.5	73.9	0.77
19	30	45/NE	112.2	77.2	0.8
20	30	90/E	124	85.3	0.89
21	30	135/SE	135.3	93	0.97
22	30	180/S	141.2	97.1	1.01
23	30	225/SW	138.2	95	0.99
24	30	270/W	127.9	88	0.91
25	30	315/NW	115.1	79.2	0.82
26	40	0/N	93.9	64.6	0.67
27	40	45/NE	101	69.4	0.72
28	40	90/E	116.3	80	0.83
29	40	135/SE	129.6	89.2	0.93
30	40	180/S	136.7	94	0.98
31	40	225/SW	133.2	91.6	0.95
32	40	270/W	120.9	83.1	0.86
33	40	315/NW	104.3	71.7	0.74
34	50	0/N	81.4	56	0.58
35	50	45/NE	89.5	61.6	0.64
36	50	90/E	107.4	73.9	0.77
37	50	135/SE	121.8	83.8	0.87
38	50	180/S	129.3	88.9	0.92
39	50	225/SW	125.9	86.6	0.9
40	50	270/W	112.4	77.3	0.8

41	50	315/NW	92.9	63.9	0.66
42	60	0/N	70.2	48.3	0.5
43	60	45/NE	78.7	54.1	0.56
44	60	90/E	97.8	67.2	0.7
45	60	135/SE	112	77.1	0.8
46	60	180/S	119.1	81.9	0.85
47	60	225/SW	116.3	80	0.83
48	60	270/W	102.9	70.7	0.73
49	60	315/NW	82	56.4	0.59
50	70	0/N	59.9	41.2	0.43
51	70	45/NE	69	47.5	0.49
52	70	90/E	87.8	60.4	0.63
53	70	135/SE	100.7	69.3	0.72
54	70	180/S	106.4	73.2	0.76
55	70	225/SW	105.1	72.2	0.75
56	70	270/W	92.9	63.9	0.66
57	70	315/NW	72	49.5	0.51
58	80	0/N	51	35.1	0.36
59	80	45/NE	60.6	41.7	0.43
60	80	90/E	77.9	53.6	0.56
61	80	135/SE	88.4	60.8	0.63
62	80	180/S	91.9	63.2	0.66
63	80	225/SW	92.6	63.7	0.66
64	80	270/W	82.6	56.8	0.59
65	80	315/NW	63.2	43.5	0.45
66	90	0/N	44.6	30.6	0.32
67	90	45/NE	53.5	36.8	0.38
68	90	90/E	68.2	46.9	0.49
69	90	135/SE	75.9	52.2	0.54
70	90	180/S	77.3	53.2	0.55
71	90	225/SW	79.6	54.7	0.57
72	90	270/W	72.3	49.7	0.52
73	90	315/NW	55.6	38.2	0.4

Table C6 Annual energy output of the A-Si 130W PV panel

No.	Tilt angle (^{o})	Azimuth (^{o})/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	130.5	91.3	1
2	10	0/N	124.3	86.9	0.96
3	10	45/NE	125.4	87.7	0.96
4	10	90/E	129.1	90.3	0.99
5	10	135/SE	133.1	93.1	1.02
6	10	180/S	135.2	94.6	1.04
7	10	225/SW	134.2	93.8	1.03
8	10	270/W	130.6	91.3	1
9	10	315/NW	126.4	88.4	0.97
10	20	0/N	115.1	80.5	0.89
11	20	45/NE	117.6	82.2	0.9
12	20	90/E	125.1	87.5	0.96
13	20	135/SE	132.8	92.9	1.02
14	20	180/S	136.8	95.7	1.05
15	20	225/SW	134.8	94.3	1.04
16	20	270/W	127.8	89.4	0.98
17	20	315/NW	119.6	83.6	0.92
18	30	0/N	103.3	72.3	0.79
19	30	45/NE	107.9	75.4	0.83
20	30	90/E	119.1	83.3	0.92
21	30	135/SE	129.9	90.8	1
22	30	180/S	135.5	94.7	1.04
23	30	225/SW	132.7	92.8	1.02
24	30	270/W	122.9	85.9	0.95
25	30	315/NW	110.6	77.4	0.85
26	40	0/N	90.3	63.1	0.69
27	40	45/NE	97	67.9	0.75
28	40	90/E	111.6	78.1	0.86
29	40	135/SE	124.4	87	0.96
30	40	180/S	131.2	91.7	1.01
31	40	225/SW	127.9	89.4	0.98
32	40	270/W	116.1	81.2	0.89
33	40	315/NW	100.2	70.1	0.77
34	50	0/N	78.3	54.7	0.6
35	50	45/NE	86.1	60.2	0.66
36	50	90/E	103.1	72.1	0.79
37	50	135/SE	116.9	81.8	0.9
38	50	180/S	124.1	86.8	0.95
39	50	225/SW	120.8	84.5	0.93
40	50	270/W	108	75.5	0.83

41	50	315/NW	89.3	62.5	0.69
42	60	0/N	67.6	47.2	0.52
43	60	45/NE	75.7	52.9	0.58
44	60	90/E	93.9	65.7	0.72
45	60	135/SE	107.5	75.2	0.83
46	60	180/S	114.3	79.9	0.88
47	60	225/SW	111.6	78.1	0.86
48	60	270/W	98.8	69.1	0.76
49	60	315/NW	78.8	55.1	0.61
50	70	0/N	57.6	40.3	0.44
51	70	45/NE	66.4	46.4	0.51
52	70	90/E	84.4	59	0.65
53	70	135/SE	96.6	67.6	0.74
54	70	180/S	102.1	71.4	0.79
55	70	225/SW	100.8	70.5	0.78
56	70	270/W	89.2	62.4	0.69
57	70	315/NW	69.3	48.4	0.53
58	80	0/N	49.1	34.3	0.38
59	80	45/NE	58.3	40.8	0.45
60	80	90/E	74.9	52.3	0.58
61	80	135/SE	84.9	59.3	0.65
62	80	180/S	88.1	61.6	0.68
63	80	225/SW	88.8	62.1	0.68
64	80	270/W	79.4	55.5	0.61
65	80	315/NW	60.8	42.5	0.47
66	90	0/N	42.9	30	0.33
67	90	45/NE	51.4	36	0.4
68	90	90/E	65.5	45.8	0.5
69	90	135/SE	72.8	50.9	0.56
70	90	180/S	74.1	51.9	0.57
71	90	225/SW	76.4	53.4	0.59
72	90	270/W	69.5	48.6	0.53
73	90	315/NW	53.5	37.4	0.41

Table C7 Annual energy output of the CIGS 140W PV panel

No.	Tilt angle (°)	Azimuth (°)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	139.5	148.4	1
2	10	0/N	132.6	141	0.95
3	10	45/NE	133.8	142.4	0.96
4	10	90/E	138	146.7	0.99
5	10	135/SE	142.4	151.5	1.02
6	10	180/S	144.8	154	1.03
7	10	225/SW	143.6	152.7	1.03
8	10	270/W	139.6	148.5	1
9	10	315/NW	135	143.6	0.96
10	20	0/N	122.5	130.3	0.87
11	20	45/NE	125.3	133.3	0.9
12	20	90/E	133.6	142.1	0.95
13	20	135/SE	142.2	151.2	1.02
14	20	180/S	146.6	156	1.05
15	20	225/SW	144.3	153.5	1.03
16	20	270/W	136.6	145.3	0.98
17	20	315/NW	127.5	135.6	0.91
18	30	0/N	109.7	116.7	0.78
19	30	45/NE	114.7	122	0.82
20	30	90/E	127.1	135.2	0.91
21	30	135/SE	139	147.9	0.99
22	30	180/S	145.2	154.4	1.04
23	30	225/SW	142.1	151.1	1.01
24	30	270/W	131.2	139.6	0.94
25	30	315/NW	117.7	125.2	0.84
26	40	0/N	95.6	101.6	0.68
27	40	45/NE	103	109.5	0.74
28	40	90/E	119	126.6	0.85
29	40	135/SE	133.1	141.6	0.95
30	40	180/S	140.5	149.5	1
31	40	225/SW	136.9	145.6	0.98
32	40	270/W	123.9	131.8	0.88
33	40	315/NW	106.4	113.2	0.76
34	50	0/N	82.6	87.9	0.59
35	50	45/NE	91.1	96.9	0.65
36	50	90/E	109.8	116.8	0.78
37	50	135/SE	124.9	132.8	0.89
38	50	180/S	132.7	141.2	0.95
39	50	225/SW	129.1	137.4	0.92
40	50	270/W	115	122.4	0.82

41	50	315/NW	94.6	100.6	0.68
42	60	0/N	71.1	75.6	0.51
43	60	45/NE	79.9	85	0.57
44	60	90/E	99.7	106.1	0.71
45	60	135/SE	114.6	121.9	0.82
46	60	180/S	122	129.7	0.87
47	60	225/SW	119.1	126.7	0.85
48	60	270/W	105.1	111.8	0.75
49	60	315/NW	83.3	88.6	0.59
50	70	0/N	60.5	64.3	0.43
51	70	45/NE	69.9	74.3	0.5
52	70	90/E	89.4	95.1	0.64
53	70	135/SE	102.8	109.3	0.73
54	70	180/S	108.7	115.6	0.78
55	70	225/SW	107.3	114.1	0.77
56	70	270/W	94.7	100.7	0.68
57	70	315/NW	73	77.7	0.52
58	80	0/N	51.3	54.6	0.37
59	80	45/NE	61.2	65.1	0.44
60	80	90/E	79.1	84.2	0.57
61	80	135/SE	90	95.7	0.64
62	80	180/S	93.5	99.5	0.67
63	80	225/SW	94.3	100.3	0.67
64	80	270/W	84	89.4	0.6
65	80	315/NW	64	68	0.46
66	90	0/N	44.8	47.7	0.32
67	90	45/NE	53.9	57.4	0.39
68	90	90/E	69.1	73.5	0.49
69	90	135/SE	77	81.9	0.55
70	90	180/S	78.5	83.5	0.56
71	90	225/SW	80.8	86	0.58
72	90	270/W	73.3	78	0.52
73	90	315/NW	56.1	59.7	0.4

Table C8 Annual energy output of the CIGS 115W PV panel

No.	Tilt angle (°)	Azimuth (°)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	123.1	128.1	1.07
2	10	0/N	117.1	121.9	1.02
3	10	45/NE	118.2	123	1.03
4	10	90/E	121.8	126.7	1.06
5	10	135/SE	125.7	130.8	1.09
6	10	180/S	127.7	132.9	1.11
7	10	225/SW	126.7	131.8	1.1
8	10	270/W	123.2	128.2	1.07
9	10	315/NW	119.2	124	1.04
10	20	0/N	108.3	112.7	0.94
11	20	45/NE	110.8	115.2	0.96
12	20	90/E	118	122.7	1.03
13	20	135/SE	125.4	130.5	1.09
14	20	180/S	129.3	134.6	1.12
15	20	225/SW	127.3	132.5	1.11
16	20	270/W	120.6	125.5	1.05
17	20	315/NW	112.7	117.2	0.98
18	30	0/N	97.1	101	0.84
19	30	45/NE	101.5	105.5	0.88
20	30	90/E	112.3	116.8	0.98
21	30	135/SE	122.7	127.6	1.07
22	30	180/S	128.1	133.2	1.11
23	30	225/SW	125.4	130.4	1.09
24	30	270/W	115.9	120.6	1.01
25	30	315/NW	104.1	108.3	0.91
26	40	0/N	84.7	88.1	0.74
27	40	45/NE	91.2	94.8	0.79
28	40	90/E	105.2	109.4	0.91
29	40	135/SE	117.5	122.2	1.02
30	40	180/S	124	129	1.08
31	40	225/SW	120.8	125.7	1.05
32	40	270/W	109.5	113.9	0.95
33	40	315/NW	94.2	98	0.82
34	50	0/N	73.3	76.2	0.64
35	50	45/NE	80.7	84	0.7
36	50	90/E	97.1	101	0.84
37	50	135/SE	110.3	114.8	0.96
38	50	180/S	117.2	121.9	1.02
39	50	225/SW	114	118.6	0.99
40	50	270/W	101.7	105.8	0.88

41	50	315/NW	83.8	87.2	0.73
42	60	0/N	63.1	65.7	0.55
43	60	45/NE	70.9	73.7	0.62
44	60	90/E	88.3	91.9	0.77
45	60	135/SE	101.4	105.4	0.88
46	60	180/S	107.8	112.2	0.94
47	60	225/SW	105.3	109.5	0.92
48	60	270/W	93	96.7	0.81
49	60	315/NW	73.9	76.8	0.64
50	70	0/N	53.8	55.9	0.47
51	70	45/NE	62.1	64.6	0.54
52	70	90/E	79.2	82.4	0.69
53	70	135/SE	91	94.7	0.79
54	70	180/S	96.2	100.1	0.84
55	70	225/SW	95	98.8	0.83
56	70	270/W	83.8	87.2	0.73
57	70	315/NW	64.8	67.4	0.56
58	80	0/N	45.7	47.6	0.4
59	80	45/NE	54.4	56.6	0.47
60	80	90/E	70.2	73	0.61
61	80	135/SE	79.8	83	0.69
62	80	180/S	82.9	86.3	0.72
63	80	225/SW	83.5	86.9	0.73
64	80	270/W	74.5	77.5	0.65
65	80	315/NW	56.8	59.1	0.49
66	90	0/N	39.9	41.5	0.35
67	90	45/NE	48	49.9	0.42
68	90	90/E	61.3	63.8	0.53
69	90	135/SE	68.4	71.1	0.59
70	90	180/S	69.7	72.5	0.61
71	90	225/SW	71.7	74.6	0.62
72	90	270/W	65.1	67.7	0.57
73	90	315/NW	49.9	51.9	0.43

Table C9 Annual energy output of the CdTe 107.5W PV panel

No.	Tilt angle (º)	Azimuth (º)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	136.3	189.3	1.27
2	10	0/N	129.6	180	1.21
3	10	45/NE	130.8	181.7	1.22
4	10	90/E	134.8	187.2	1.25
5	10	135/SE	139.1	193.2	1.29
6	10	180/S	141.4	196.4	1.32
7	10	225/SW	140.2	194.8	1.3
8	10	270/W	136.3	189.4	1.27
9	10	315/NW	131.9	183.2	1.23
10	20	0/N	119.8	166.3	1.11
11	20	45/NE	122.5	170.2	1.14
12	20	90/E	130.5	181.3	1.21
13	20	135/SE	138.8	192.8	1.29
14	20	180/S	143.2	198.9	1.33
15	20	225/SW	141	195.8	1.31
16	20	270/W	133.5	185.4	1.24
17	20	315/NW	124.7	173.1	1.16
18	30	0/N	107.3	149.1	1
19	30	45/NE	112.2	155.8	1.04
20	30	90/E	124.2	172.5	1.16
21	30	135/SE	135.8	188.6	1.26
22	30	180/S	141.8	196.9	1.32
23	30	225/SW	138.7	192.7	1.29
24	30	270/W	128.2	178.1	1.19
25	30	315/NW	115.1	159.9	1.07
26	40	0/N	93.5	129.9	0.87
27	40	45/NE	100.7	139.9	0.94
28	40	90/E	116.4	161.6	1.08
29	40	135/SE	130	180.6	1.21
30	40	180/S	137.2	190.6	1.28
31	40	225/SW	133.7	185.7	1.24
32	40	270/W	121.1	168.2	1.13
33	40	315/NW	104.1	144.6	0.97
34	50	0/N	80.9	112.4	0.75
35	50	45/NE	89.2	123.8	0.83
36	50	90/E	107.3	149.1	1
37	50	135/SE	122	169.5	1.14
38	50	180/S	129.6	180.1	1.21
39	50	225/SW	126.2	175.2	1.17
40	50	270/W	112.4	156.2	1.05

41	50	315/NW	92.6	128.6	0.86
42	60	0/N	69.6	96.7	0.65
43	60	45/NE	78.2	108.7	0.73
44	60	90/E	97.6	135.5	0.91
45	60	135/SE	112.1	155.7	1.04
46	60	180/S	119.2	165.6	1.11
47	60	225/SW	116.4	161.7	1.08
48	60	270/W	102.8	142.7	0.96
49	60	315/NW	81.6	113.3	0.76
50	70	0/N	59.3	82.3	0.55
51	70	45/NE	68.5	95.1	0.64
52	70	90/E	87.5	121.5	0.81
53	70	135/SE	100.5	139.7	0.94
54	70	180/S	106.3	147.6	0.99
55	70	225/SW	104.9	145.8	0.98
56	70	270/W	92.6	128.7	0.86
57	70	315/NW	71.5	99.3	0.67
58	80	0/N	50.3	69.9	0.47
59	80	45/NE	60	83.4	0.56
60	80	90/E	77.5	107.6	0.72
61	80	135/SE	88.1	122.3	0.82
62	80	180/S	91.6	127.2	0.85
63	80	225/SW	92.3	128.1	0.86
64	80	270/W	82.2	114.2	0.77
65	80	315/NW	62.7	87	0.58
66	90	0/N	43.9	61	0.41
67	90	45/NE	52.8	73.4	0.49
68	90	90/E	67.7	94	0.63
69	90	135/SE	75.4	104.8	0.7
70	90	180/S	76.8	106.7	0.71
71	90	225/SW	79.1	109.9	0.74
72	90	270/W	71.8	99.7	0.67
73	90	315/NW	55	76.4	0.51

Table C10 Annual energy output of the CdTe 80W PV panel

No.	Tilt angle (º)	Azimuth (º)/facing direction	Annual energy output of PV panel (kWh)	Annual energy output per square meter (kWh/m^2)	Annual energy output per peak power (kWh/Wp)
1	0	N.A.	77.4	107.5	0.97
2	10	0/N	73.6	102.2	0.92
3	10	45/NE	74.3	103.2	0.93
4	10	90/E	76.5	106.3	0.96
5	10	135/SE	79	109.7	0.99
6	10	180/S	80.3	111.5	1
7	10	225/SW	79.6	110.6	1
8	10	270/W	77.4	107.5	0.97
9	10	315/NW	74.9	104.1	0.94
10	20	0/N	68	94.5	0.85
11	20	45/NE	69.6	96.6	0.87
12	20	90/E	74.1	102.9	0.93
13	20	135/SE	78.8	109.5	0.99
14	20	180/S	81.3	112.9	1.02
15	20	225/SW	80	111.2	1
16	20	270/W	75.8	105.3	0.95
17	20	315/NW	70.8	98.3	0.88
18	30	0/N	61	84.7	0.76
19	30	45/NE	63.7	88.5	0.8
20	30	90/E	70.5	97.9	0.88
21	30	135/SE	77.1	107	0.96
22	30	180/S	80.5	111.8	1.01
23	30	225/SW	78.8	109.4	0.98
24	30	270/W	72.8	101.1	0.91
25	30	315/NW	65.4	90.8	0.82
26	40	0/N	53.2	73.8	0.66
27	40	45/NE	57.2	79.5	0.72
28	40	90/E	66.1	91.7	0.83
29	40	135/SE	73.8	102.5	0.92
30	40	180/S	77.9	108.1	0.97
31	40	225/SW	75.9	105.4	0.95
32	40	270/W	68.8	95.5	0.86
33	40	315/NW	59.1	82.1	0.74
34	50	0/N	46	63.9	0.57
35	50	45/NE	50.6	70.3	0.63
36	50	90/E	60.9	84.6	0.76
37	50	135/SE	69.2	96.2	0.87
38	50	180/S	73.5	102.1	0.92
39	50	225/SW	71.6	99.5	0.9
40	50	270/W	63.9	88.7	0.8

41	50	315/NW	52.6	73.1	0.66
42	60	0/N	39.6	55	0.49
43	60	45/NE	44.4	61.7	0.56
44	60	90/E	55.4	76.9	0.69
45	60	135/SE	63.6	88.3	0.79
46	60	180/S	67.6	93.9	0.85
47	60	225/SW	66.1	91.8	0.83
48	60	270/W	58.4	81.1	0.73
49	60	315/NW	46.3	64.4	0.58
50	70	0/N	33.7	46.8	0.42
51	70	45/NE	38.9	54	0.49
52	70	90/E	49.7	69	0.62
53	70	135/SE	57	79.2	0.71
54	70	180/S	60.2	83.7	0.75
55	70	225/SW	59.5	82.7	0.74
56	70	270/W	52.6	73	0.66
57	70	315/NW	40.6	56.4	0.51
58	80	0/N	28.6	39.7	0.36
59	80	45/NE	34.1	47.3	0.43
60	80	90/E	44	61.1	0.55
61	80	135/SE	49.9	69.4	0.62
62	80	180/S	51.9	72	0.65
63	80	225/SW	52.3	72.7	0.65
64	80	270/W	46.7	64.8	0.58
65	80	315/NW	35.6	49.4	0.45
66	90	0/N	24.9	34.6	0.31
67	90	45/NE	30	41.7	0.38
68	90	90/E	38.4	53.3	0.48
69	90	135/SE	42.7	59.4	0.53
70	90	180/S	43.5	60.4	0.54
71	90	225/SW	44.9	62.3	0.56
72	90	270/W	40.8	56.6	0.51
73	90	315/NW	31.3	43.4	0.39

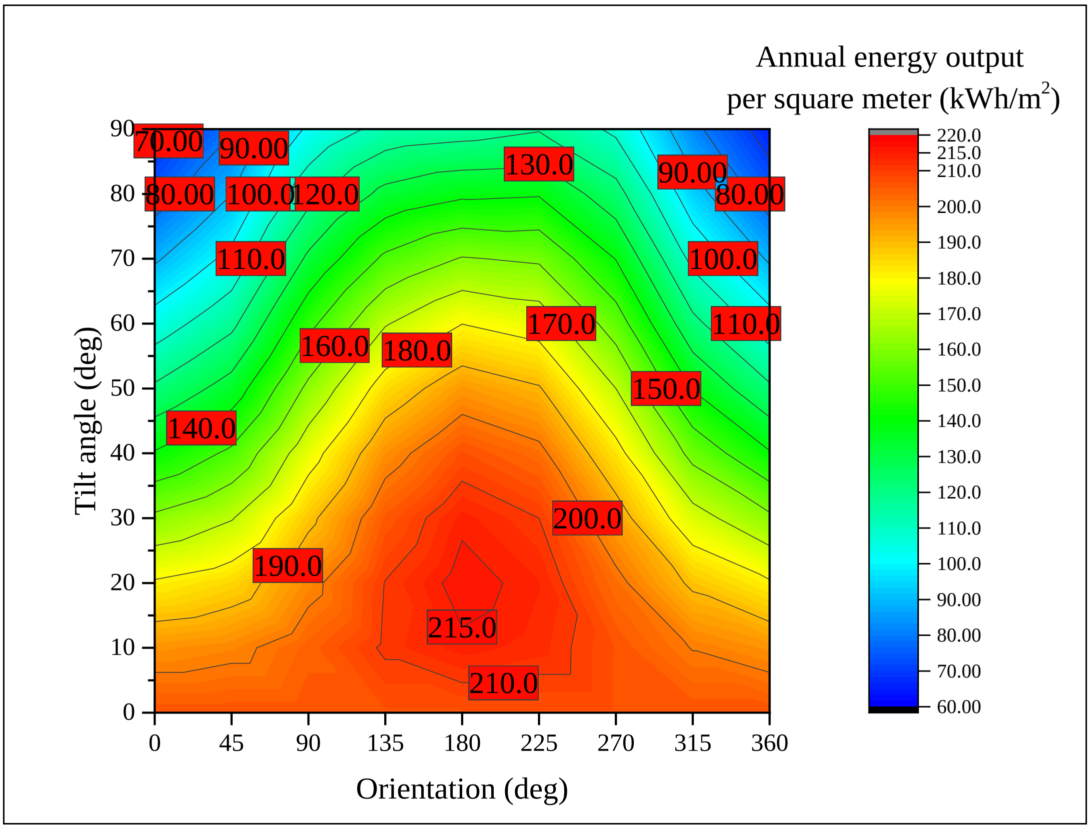


Figure C1 Annual energy outputs per square meter of the Mono-Si 305W PV module with different orientations and tilt angles

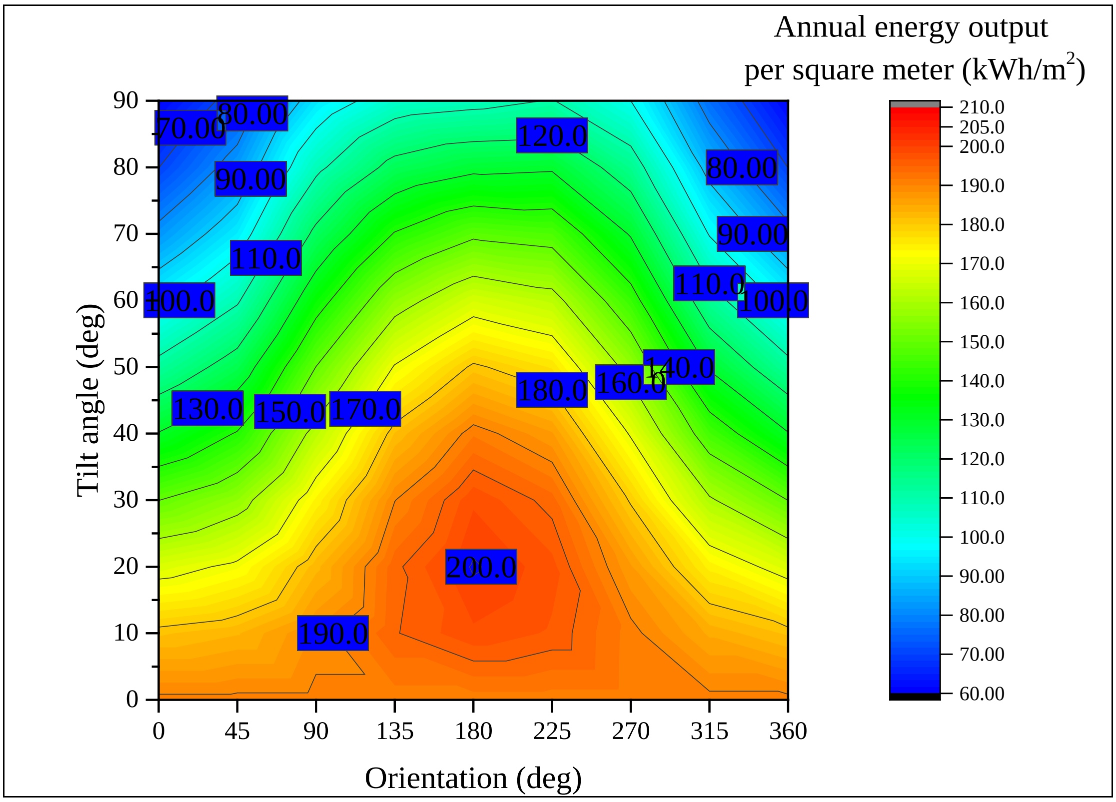


Figure C2 Annual energy outputs per square meter of the Mono-Si 300W PV module with different orientations and tilt angles

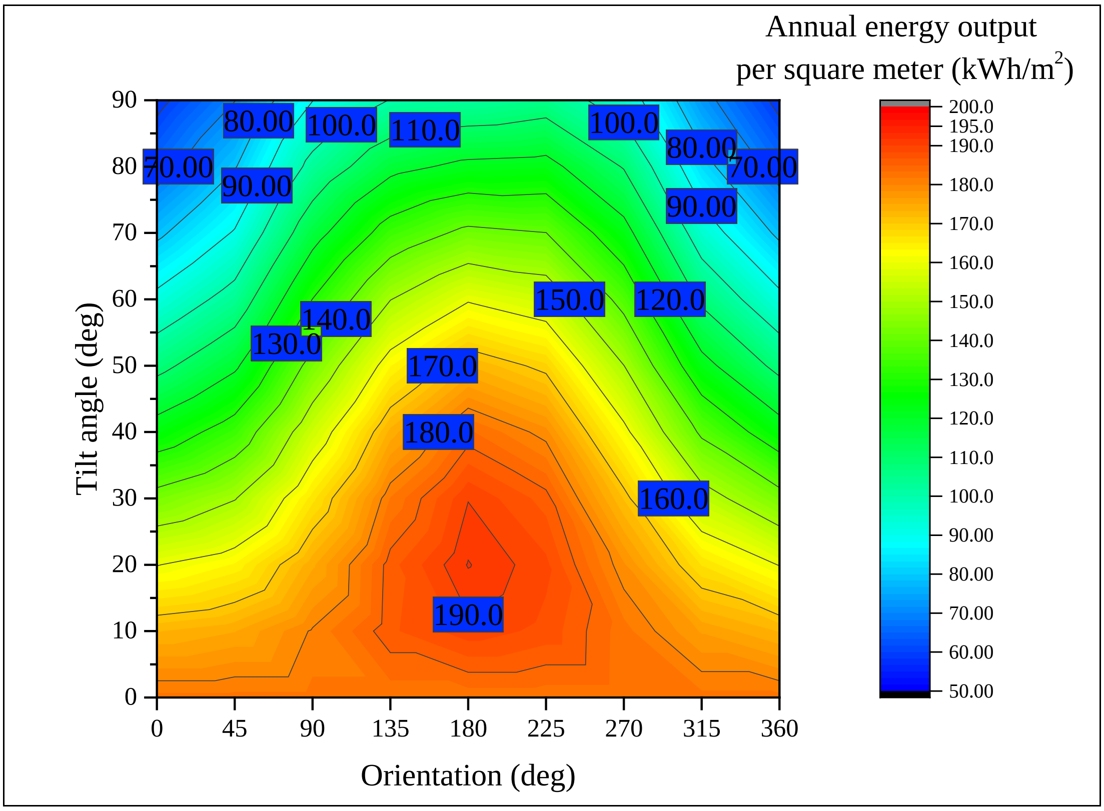


Figure C3 Annual energy outputs per square meter of the Poly-Si 280W PV module with different orientations and tilt angles

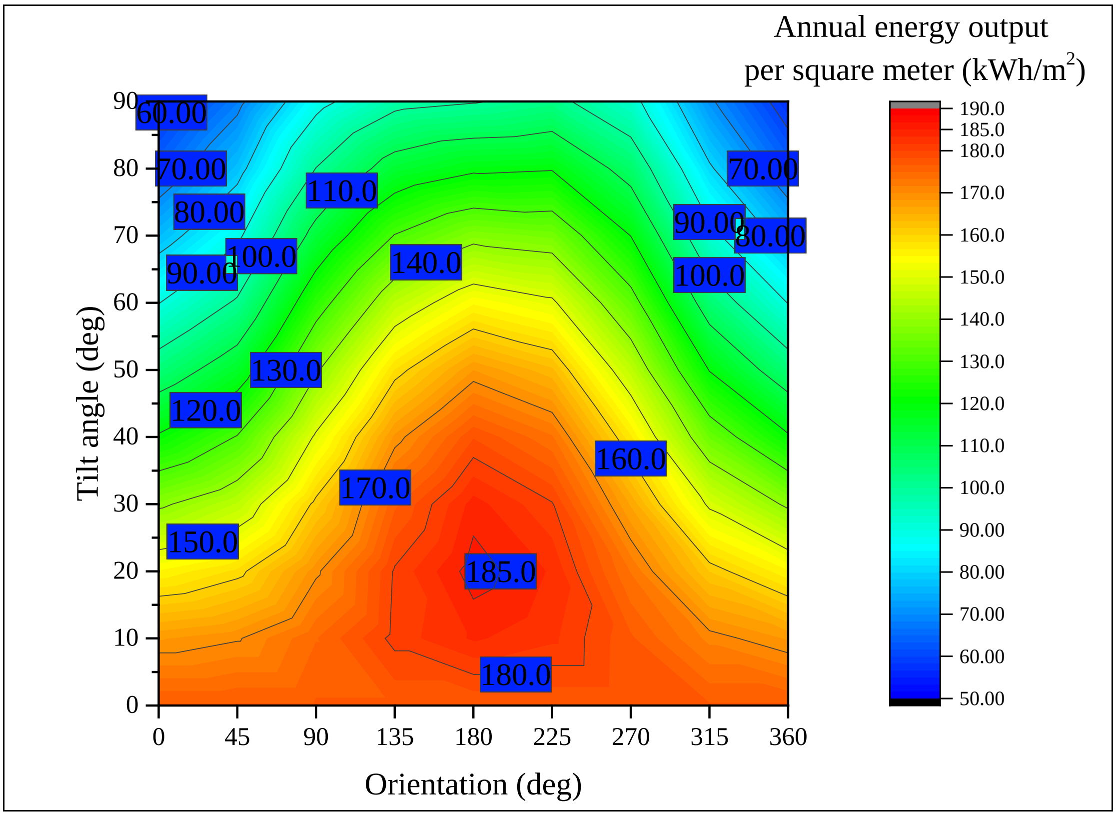


Figure C4 Annual energy outputs per square meter of the Poly-Si 275W PV module with different orientations and tilt angles

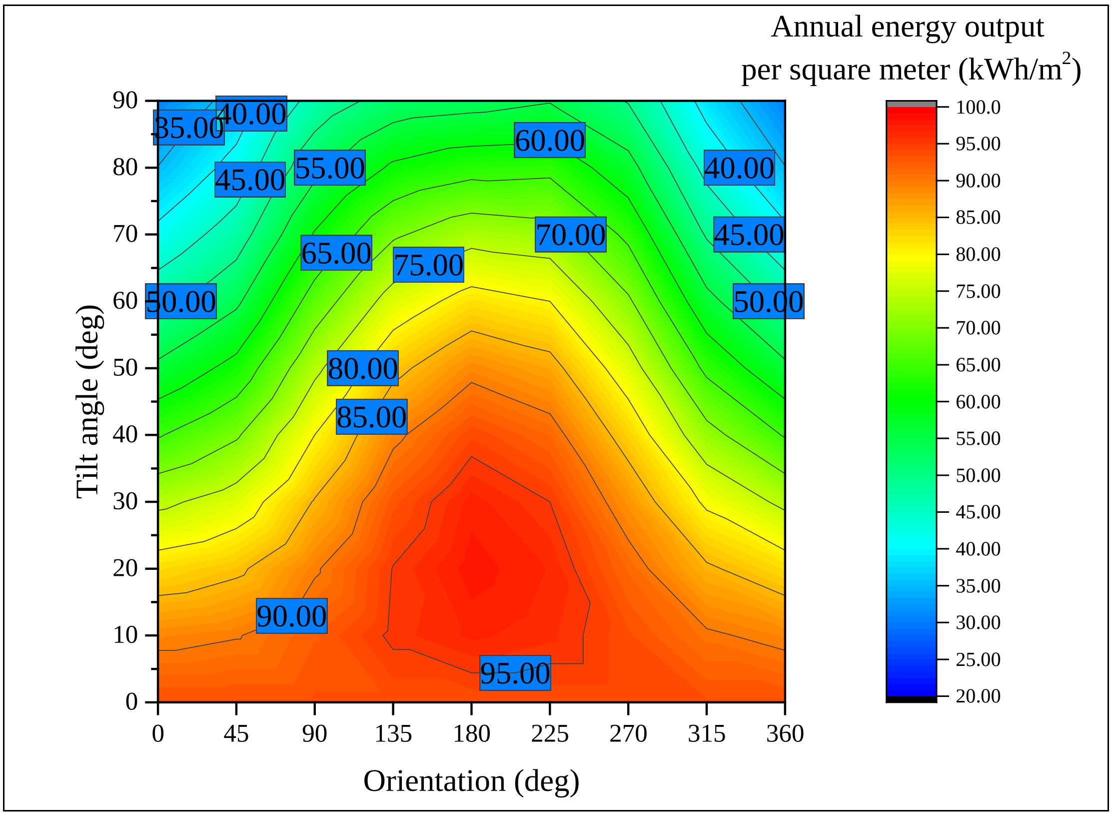


Figure C5 Annual energy outputs per square meter of the A-Si 140W PV module with different orientations and tilt angles

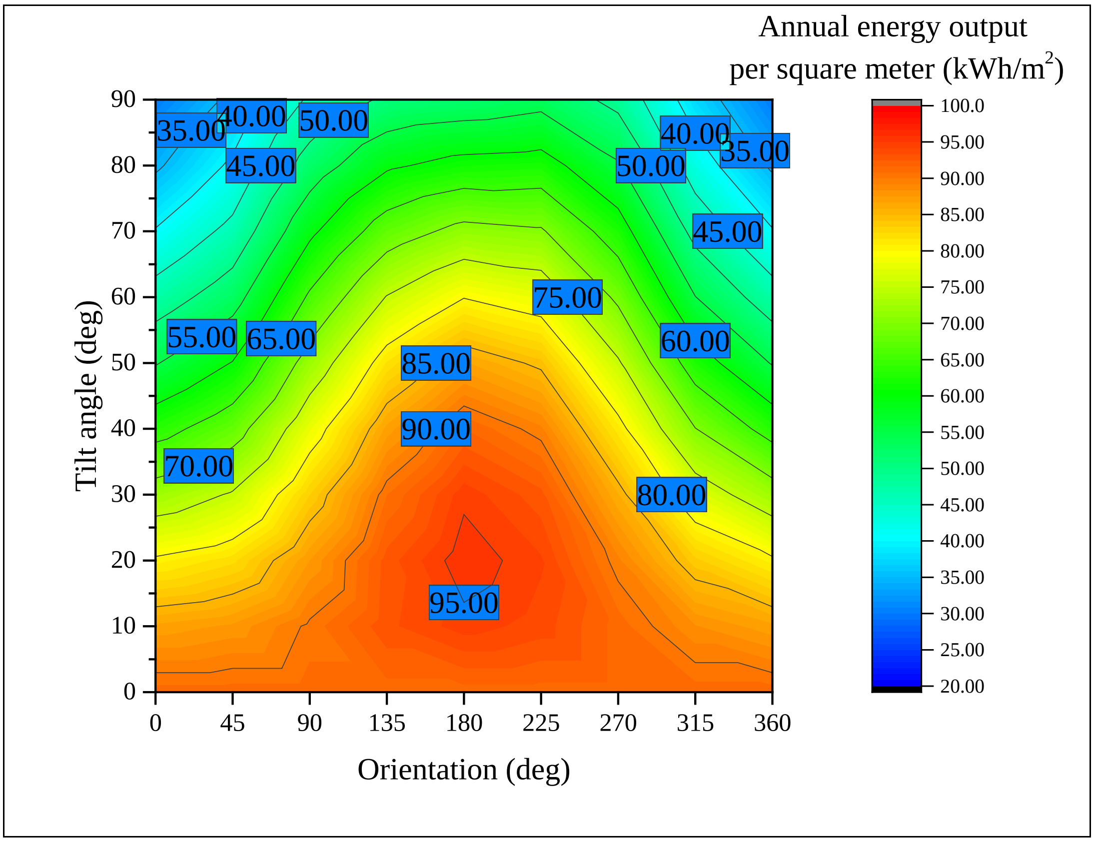


Figure C6 Annual energy outputs per square meter of the A-Si 130W PV module with different orientations and tilt angles

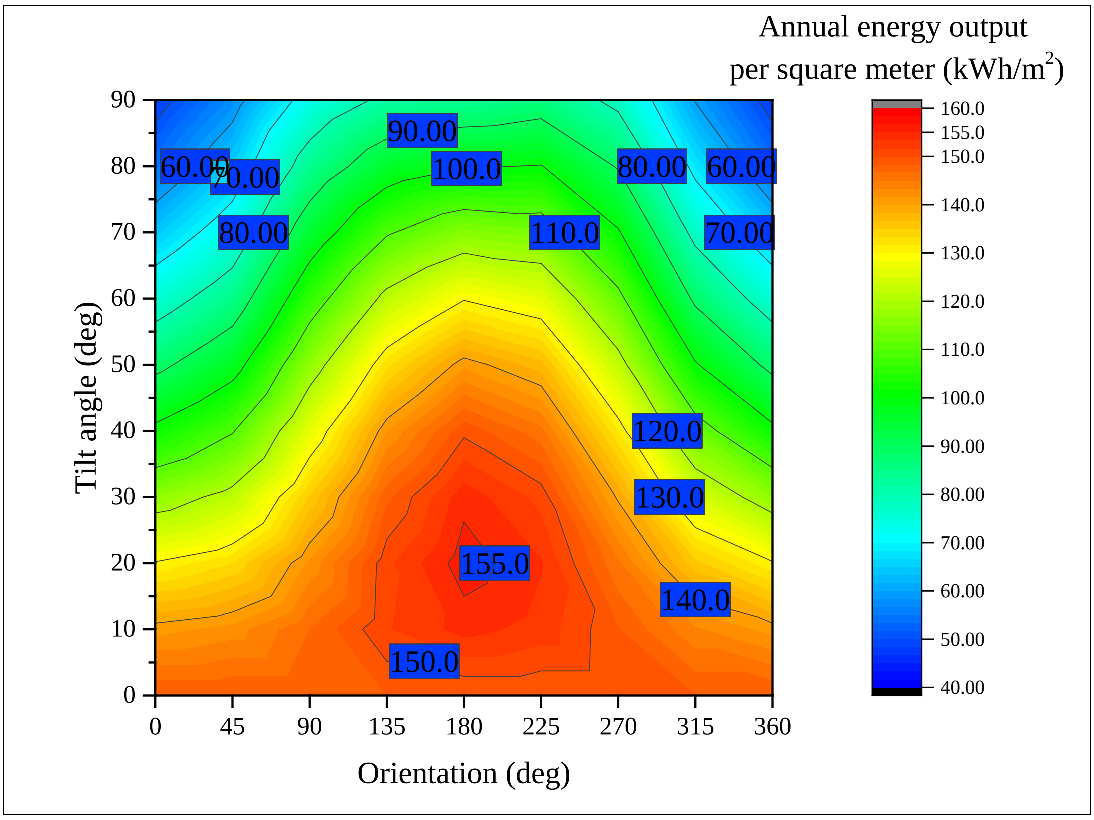


Figure C7 Annual energy outputs per square meter of the CIGS 140W PV module with different orientations and tilt angles

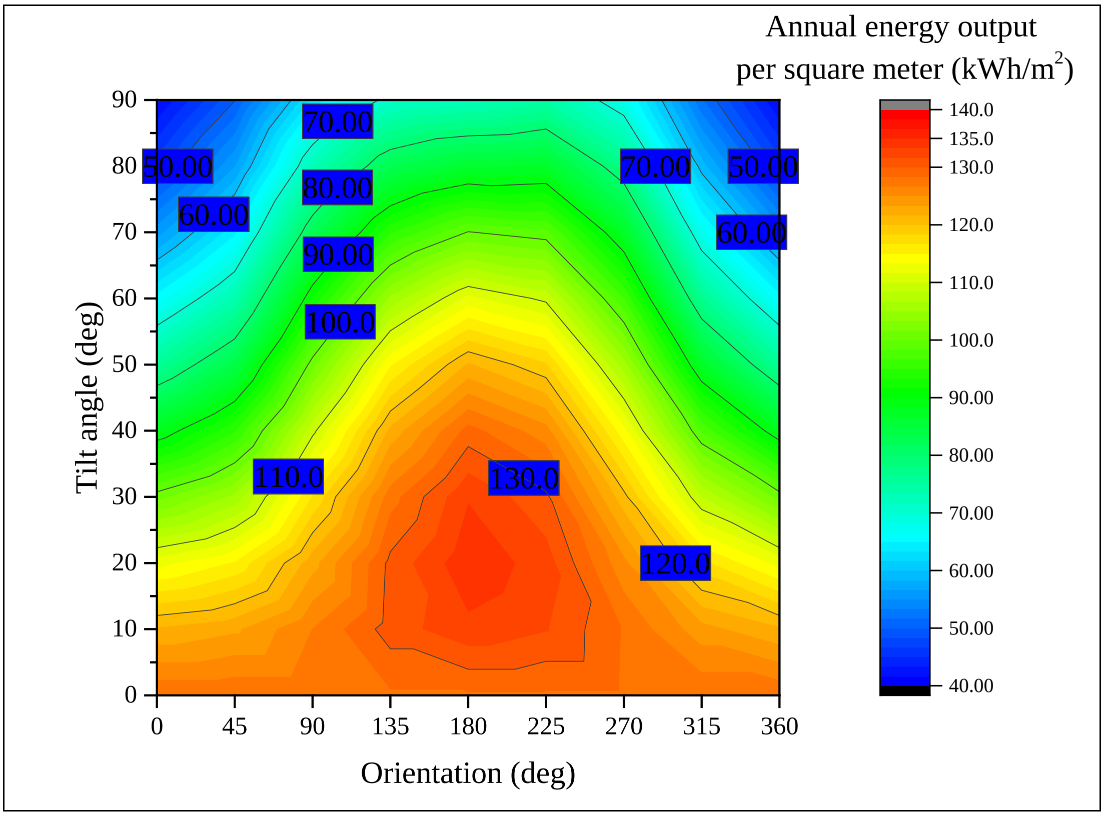


Figure C8 Annual energy outputs per square meter of the CIGS 115W PV module with different orientations and tilt angles

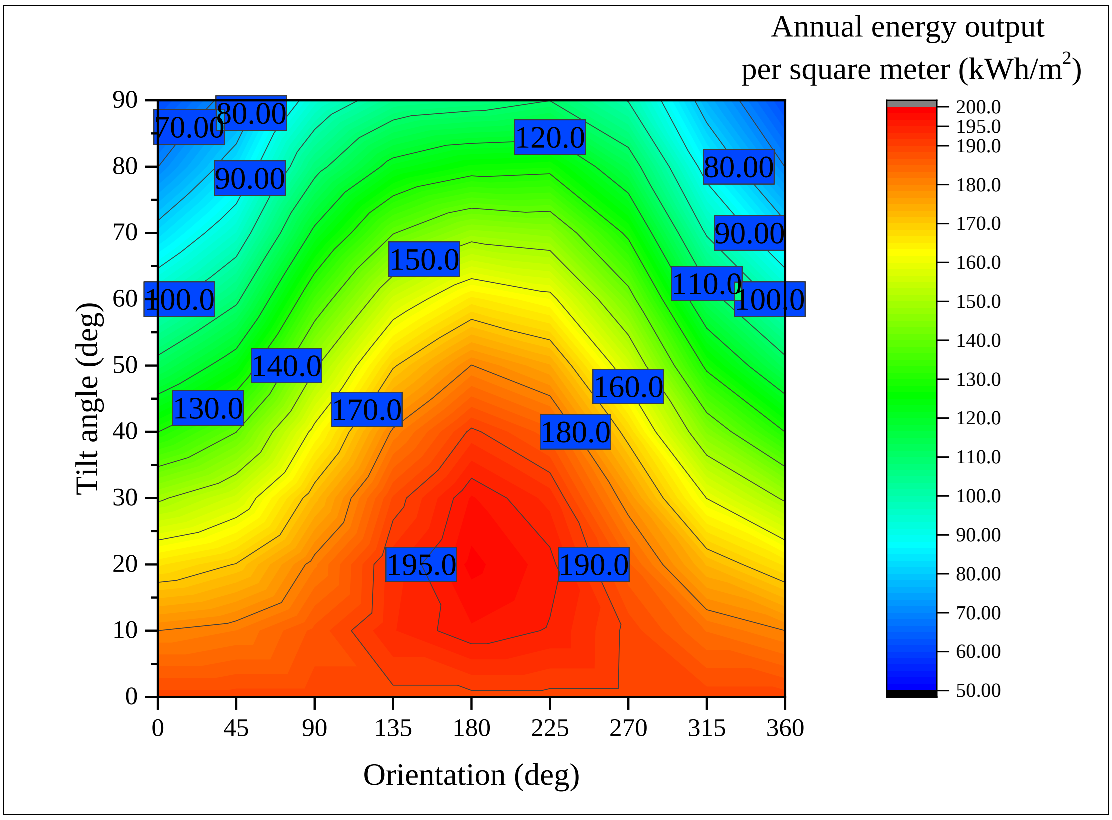


Figure C9 Annual energy outputs per square meter of the CdTe 107.5W PV module with different orientations and tilt angles

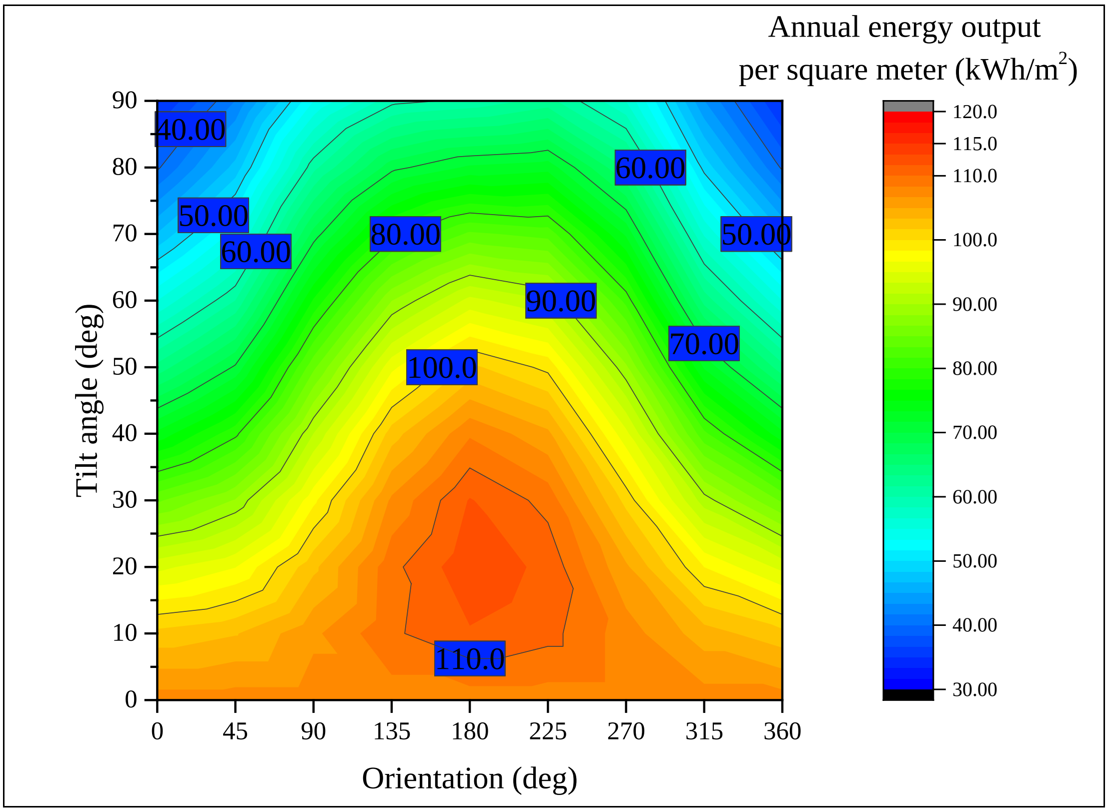


Figure C10 Annual energy outputs per square meter of the CdTe 80W PV module with different orientations and tilt angles