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PV performance evaluation and simulation-based energy yield prediction for tropical buildings

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Abstract

Air pollution and climate change increased the importance of renewable energy resources like solar energy in the last decades. Rack-mounted PhotoVoltaics (PV) and Building Integrated PhotoVoltaics (BIPV) are the most common photovoltaic systems which convert incident solar radiation on façade or surrounding area to electricity. In this paper the performance of different solar cell types are evaluated for tropical weather of Singapore. As a case study, the on-site measured data of PV systems implemented in a zero energy building in Singapore, is analyzed. Different types of PV systems (silicon wafer and thin film) have been installed on rooftop, façade, car park shelter, railing and etc. The impact of different solar cell generations, arrays environmental conditions (no shading, dappled shading, full shading), orientation (South, North, East or West facing) and inclination (between PV module and horizontal direction) are investigated on performance of modules. In the second stage of research, the whole PV systems in the case study are simulated in EnergyPlus energy simulation software with several PV performance models including Simple, Equivalent one-diode and Sandia. The predicted results by different models are compared with measured data and the validated model is used to provide the simulation-based energy yield predictions for wide ranges of scenarios. It has been concluded that orientation of low-slope rooftop PV has negligible impact on annual energy yield but in case of PV external sun shade, the east façade and panel slope of 30-40 ° are the most suitable location and inclination.

Keywords – Photovoltaic system; Building Integrated PhotoVoltaics; Tropics; PV performance model; Low-slope rooftop PV; PV external sunshade

1. Introduction

Emerging new technologies of on-site renewable energy production system keeps alive the dream of zero energy buildings (ZEB). ZEBs involve two strategies, minimizing the required energy by using energy efficient technologies and adopting renewable energies to meet the remaining energy needs [1]. In this context, Photovoltaics (PV) is one of the most promising renewable energy technologies in achieving sustainable building design [2,3]. Modern technologies of solar cells with lower cost and higher efficiency increased the feasibility of BIPV in real residential and commercial buildings. Based on Swanson’s law, the price of solar cells decreases 20 % by each doubling the global manufacturing capacity. This trend in price of solar cells will increase the applications of solar panels in small sized residential and general buildings. The forecasts of solar systems installation market have shown that the total capacity of BIPV will increase to 2000 MW in 2015 compared to 250 MW in 2010 [4]. While photovoltaics efficiency and manufacturing costs have not reached the point to replace the conventional power generation facilities, a broad range of suitable policies have been implemented to unlock the considerable potential of solar energy [5].

Solar panels could be integrated into façade and roof of building in design stage as Building Integrated PV (BIPV) or as a retrofit added to Building after construction which called Building Applied PV (BAPV). There are various geometrical considerations for installing PV systems. In addition to the installation slope and azimuth angle, the real application of the BIPV system should take into account the influence of shading caused by the surroundings [6]. A BIPV system as a shading is useful not only for the power generation, but also for shading to reduce cooling load. BIPV compared to rack-mounted PV system is more aesthetically pleasant and cost effective. There is saving potential of materials in the integration of PV in building and also eliminating the PV module-mounting structure. On the other hand rack mounted systems are easier to install and operate the maintenance service. In the last years by decreasing the price of solar cells in the market, the application of BIPV, BAPV and rack-mounted PV have been growing in tropical cities as well as other climates. BIPV windows have been proposed by many as an innovative and emerging glazing technology in the buildings [7,8]. In a relevant study, Redweik et al. [9] showed that although the annual irradiation on vertical facades is lower than that of more favourable surfaces (roofs), due to their very large areas, the solar potential of facades is relevant for the overall solar potential of a building.

2. PV System for Tropical Buildings

Tropical regions on earth are mostly surrounding the equator and their main characteristics are year-around high humidity and temperature with significant amount of rainfall. The cloudy sky is the main characteristic of tropical weather which affects the type of radiation on PV system in this climate. In this condition, the direct sunlight scattered by cloud particles in atmosphere and strikes the PV panel mostly as diffused light. It is known that the PV panels are more efficient under direct sunlight and their efficiency drop in cloudy weather. Singapore weather which classified as tropical rainforest has been chosen in this investigation to evaluate the performance of PV panels for tropics. The median cloud cover is around 90 % and type of precipitation is mostly thunder-storms with higher probability in the afternoon. The statistics shows that the installed capacity of grid - connected solar PV systems in Singapore household and non-household applications reached to 6 MWp in 2011[10].

It is known that PV system without battery in building may not necessarily decrease the peak load of the building. Depending on functionality of building, the peak energy demand may not coincide with the PV system peak output. PV system effect on energy demand is more pronounced in office building than in residential building, especially in countries or states with no Feed in Tariff (FiT) for on-site renewable energies like in Singapore. The reason is that the peak demand of building falls in daylight time for office spaces but for residential building is mostly during night which is out of PV system output period.

The productivity and efficiency of different solar cells have been assessed by many researchers in tropical climates. High humidity, ambient temperature, rainfall and diffuse sunlight all around the year are the main challenges for cells energy production in this climate. In tropical Bangalore, Aaditya et al. [11] observed higher average monthly efficiencies at fixed slope BIPV rooftop concurrently with lower system outputs and vice-versa. This observation justified by interplay between solar insolation, cell and ambient temperature. In another study under Malaysia’s weather, Amin et al. [12] collected performance related parameters for different solar cells and They found crystalline silicon and amorphous cells more efficient respectively in sunny and cloudy days. Similar study in Thailand [13] showed that amorphous silicon has the highest average annual array performance ratio (0.92 %) compared to poly crystalline (0.83 %) and hybrid silicon (0.87 %). Wittkopf et al. [14] also determined similar performance ratio (0.81 %) for the poly crystalline roof-top PV system at a zero energy building in Singapore. Performance ratio defined as the ratio of the actual to reference yield which determined based on the module in-plane irradiation to the reference point irradiance. The efficiency of PV modules is strongly affected by their operating temperature. Typically for every 1°C increase of module temperature, there is a ~0.45% drop of module efficiency for crystalline silicon modules [15]. The detrimental effect of temperature on the performance of a PV cell, particularly those which are silicon based is well documented. In another study, Ye et al. [16] compared the PV module temperature variation in Singapore with those in non-tropical regions and proposed useful guidelines for PV installation, especially for tropics.

Based on an official handbook [17] for solar PV, a typical rooftop solar PV system in Singapore annually yield 1100 to 1250 kWh/kWp/yr using crystalline PV modules, and 1200 to 1450 kWh/kWp/yr for amorphous thin film. However the findings of another research project [18] which conducted by Solar Energy Research Institute of Singapore (SERIS) did not confirm the postulation of higher PV yield of single junction a-Si over c-Si for Singapore weather. In the latter research, Heterojunction thin film solar cells like Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe) and a-Si tandem showed the highest average daily PV energy yield over an eight months period. Uncertainty in environmental conditions, inverter technology, arrangements of solar cells in modules and also modules in PV arrays are the main sources of discrepancies between findings of different studies. An accurate and validated performance evaluation tool, in which the details of module operating condition are taken into account, could be a better reference for this comparison. In this study, at first the whole PV data for a case study (ZEB) in Singapore have been investigated in details. In the second stage, the predictions of different PV performance models are compared with the measured on-site data to identify the most appropriate model. The selected model is used to predict the annual energy yield of low-slope Rooftop and sun shade PV for buildings in Singapore.

3. Research Methodology and Objectives

The aim of this research is to assess the implementation, feasibility and practical implications of PV modules and in particular on-site PV systems in tropical weather of Singapore. In order to have a better understanding of PV performance in this type of weather, one year data of a case study (Zero Energy Building) in Singapore have been analyzed. The performance of implemented BIPV and BAPV systems in Singapore's first Zero Energy Building (ZEB) have been investigated based on various sensors data installed on systems. Different classes of pyronometers, solar irradiation sensors, module temperature sensor, ambient temperature sensor, anemometers and inverter models have been installed on PV systems. The field sensors which their data have been used in this study are listed in Table 1 including their technical details. The annual PV energy yield and daily profile of output power and cell temperature of different types and brands of first and second generation solar cells are studied in details. The effect of different parameters like type of solar cells, location, orientation, inclination and environmental conditions (shadows) are considered on output power of each PV arrays.

Table 1 Field sensors of PV monitoring system and their technical details

Parameters	Field Sensor	Precision
Solar Irradiance	SMA Irradiance Sensor, Sunny Sensor Box	±8 % for 0-1500 w/m^2
Module Cell Temperature	Pt 100, SMA Tempsensor-Module	± 0.5 °C, in range of -20 °C to +110 °C
Output Power and Energy Values	PV Inverter Sunny Boy and Sunny Mini Central	tolerance of up to ± 3 %
Module Efficiency	- (propagated error)	Calculated error up to ± 11 %

In the second stage of the study, the geometry of building and details of PV arrays have been simulated in EnergyPlus energy simulation software (an energy analysis and thermal load simulation program). There are different ways for integrating EnergyPlus heat transfer surfaces and solar panels heat balance equations to calculate the cell temperature. The most common PV performance models which are incorporated into EnergyPlus are Simple, Equivalent One-Diode and Sandia models. In Simple PV performance model, a constant efficiency assumed during whole range of solar irradiation and cell temperature effect has not been taken into account. Equivalent One-Diode model is known as four or five parameters TRNSYS (TRaNsient SYstem Simulation Program, an energy simulation program) model for photovoltaics in which modules modeled using an equivalent one-diode circuit. The list of parameters which incorporated into EnergyPlus input file for each brand and model of PV module includes short circuit current, open circuit voltage, voltage at maximum power, current at maximum power, temperature coefficient of short circuit current, temperature coefficient of open circuit voltage, number of cells in series per module, cell temperature at NOCT (Nominal Operating Cell Temperature) condition, and module area [19]. In addition, the Sandia model is incorporated which is based on empirical coefficients assembled by Sandia National Laboratory for each specific type and brand of PV modules. The many empirical coefficients for each PV module have been found in System Advisor Model (SAM) database provided by National Renewable Energy Laboratory (NREL).

It is known that the optimum angle of solar panels at each location on the earth is close to the value of that location latitude or slightly lower [20,21]. It is also the case for rooftop PV in tropical buildings which are mostly located near to the equator and the panels are preferred to be horizontal (0 ° as latitude of equator). However, the situation is a bit more complicated for the optimum slope of external shading PV or PV glass which are located on the façade. Getting a better understanding on the impact of solar panel angle on annual energy yield of different types of solar cells is one of the objectives of this study.

Empirical and non-empirical models have been used by many researchers in the literature to predict the annual energy yield of solar panels [22,23]. Several PV performance models like Equivalent one-diode and Sandia models have been incorporated into EnergyPlus energy simulation software to model PV arrays on different sites and the results are validated with experimental data [24]. The required input parameters, location, and inclination of each installed arrays in ZEB have been incorporated into EnergyPlus as input file. The daily profile of output power, cell temperature and also annual energy yield of modules have been predicted with different PV performance models and compared to measured on-site data. With a certified accurate PV performance model, the efforts have been taken to provide guidelines of annual PV yield for different generation, location, orientation and inclination of PV arrays in tropical weather of Singapore.

4. Performance Evaluation of a Case Study in Singapore

4.1 Overal Installed PV System in ZEB

The Zero Energy Building (ZEB) is retrofitted from an existing building. Converted from a three-storey former workshop, ZEB houses offices, classrooms and a resource centre. The ZEB is a zero energy building because the building produces enough energy to run itself. The building aims to produce enough energy to power the building, through a combination of green building technology, clever building design that takes advantages of natural ventilation and lighting, and the harnessing of solar energy. To achieve the self-sufficient energy, the building is powered by a broad spectrum of grid-tied and standalone solar panels installed at many locations in the building. Surplus power generated by these solar panels distributed to the rest of BCA Academy buildings. If insufficient power is produced, then grid supply will provide for ZEB, so that user comfort and function are never compromised.

Various brands of poly-crystalline silicon, mono-crystalline silicon, heterojunction with intrinsic thin layer (HIT), amorphous thin film, copper indium gallium (di) selenide (CIGS) PV modules have been installed on rooftop, linkway, car park shelter, sunshade, railing and other locations in the building. In overall, 1540 m^2 of PV modules with peak system power of 190 kWp have been implemented in the building to produce about 207 MWh electricity each year. Different types of sensors including 36 solar irradiation sensors, one ambient temperature sensors, 9 Pyranometers, 6 Anemometers, 21 cell temperature sensors and 37 power meters on Invertors are installed on PV systems. A software platform has been developed to collect and monitor the real-time measured data and also export them into text files.

The energy yield of different solar cells installed in ZEB varies based on their location, orientation, inclination, and also environmental and shading conditions. The fluctuations in annual energy yield of PV system in ZEB over 39 months of installation from October 2009 to December 2012 are shown in Fig.1. The annual PV yield of arrays ranges between 600 to 1200 kWh/yr and the type of solar cells, shading condition and arrangement of modules in an array are the key factors. The roof top arrays produced the highest electricity per peak watt of installed PV modules because of their exposure to sunlight in the whole day. Also in general, the east-oriented arrays with lower inclination were the most productive PV modules during 39 months of operation. The reason of this fact could be higher probability of rainfall in afternoon which affects the average daily radiation striking west-oriented arrays. The other source of variation is different arrangement of modules in northern rooftop arrays compared to southern ones which degraded their produced annual energy.

Fig. 1 here

The details of energy consumption and production of building for different months over the year are shown in Fig. 2. Evaluation of ZEB data at 2012 shows that the BIPV energy production was 5 % more than building energy consumption which confirms the claim of net zero energy building. In total PV systems produced 201 MWh electricity in this year which is slightly lower than expected energy yield for a typical year (207 MWh).

Fig. 2 here

The average daily profile of PV supply, city grid supply and energy consumption for weekdays and weekends over January 2012 are shown in Fig. 3-4. The daily profile of PV supply and city power grid supply to ZEB is different from weekdays to weekends and holidays. During the week, the building is mostly occupied by employees and it has uniform energy consumption during office hours. On the other hand in the weekends, the building is mostly empty and energy demand is much lower which means more energy saving of produced energy by PV systems.

Fig. 3& 4 here

4.2 Daily Profile of Efficiency, Output power and Cell Temperature

The measured output power, efficiency and cell temperature of arrays in ZEB brought the chance of getting a better understanding of module performance during the day. The yearly average daily profile of output power and efficiency together with solar cell temperature variations for a PolyCrystalline Silicon array are shown in Fig. 5-6. With the same amount of radiation on solar panel, its efficiency varies from morning to afternoon due to different cell temperature. This variation mainly depends on the thermal mass of PV modules, day/night temperature range and also other environmental conditions. The nominal power (peak power) of this array is 6.84 kWp, however its actual output power does not exceed 3.5 kW in a normal day. As expected, cell temperature is higher in afternoon which causes a small decrease in produced energy of modules compared to morning output energy. It is also observed that around 9 AM, the efficiency of module is close to standard test condition (25 °C, 1.5 Air Mass, 1000 W/m^2) efficiency which is 13.7 %. This value drops to 12 % during the noon and also in afternoon due to higher cell temperature.

Fig. 5 & 6 here

The other interesting graphs which have been generated based on the measured data in this case study, are the yearly average daily profile of arrays actual power. The deviation of the on-site produced energy of PV arrays from their nominal capacity depends on their façade direction, inclination, orientation, shading and other environmental conditions. As a sample, the maximum and average daily profiles of a roof top PolyCrystalline and sunshade Amorphous PV arrays are shown in Fig. 7-8. The maximum capacity of roof top array is around 7 kW which is close to its nominal capacity. However, the maximum power of the Sunshade array which is located on west façade is around 0.7 kW and is lower than its nominal capacity (1.044 kWp). The peak capacity mostly happens around noon for rooftop array but for sunshade array on west facade, the peak point happens in the afternoon when it receives the highest solar irradiation.

Fig. 7 & 8 here

5. Validation of PV Performance Models

An accurate modeling tool for predicting the energy yield of solar system could be useful in recognizing the optimum location, orientation and inclination of on-site PV systems in buildings. It is also applicable in recognizing the financial potential of solar panels by determining the Return of Investment (ROI) for new buildings or retrofits. The whole PV systems installed in ZEB have been simulated in EnergyPlus to consider the most realistic shading conditions for panels. This prediction tool could be used to have an estimation of annual PV yield and also to identify the optimum location, orientation and inclination of PV modules. The 3D model of the zero energy building has been generated in 3D modeling program of SketchUp. Geometrical dimensions of building and solar panels have been modeled based on the available data in the building drawing, PV manufacturer's technical catalogues and also actual building on-site measured data. The legacy OpenStudio Plug-in for SketchUp have been used to create EnergyPlus input file based on defined boundary conditions, thermal loads and other parameters. This modeling tool is capable of predicting the shadow zones at different times and days in the year which is the dominant factor for estimating the annual PV yield. The shadow shapes of the modeled building and solar panels for different hours during the day are shown in Fig. 9.

Fig. 9 here

The results of simulations are compared with measured data in terms of instantaneous DC output power of arrays and cell temperature for different solar panels. The comparison of predicted results of Simple, Equivalent one-diode and Sandia performance model with measured data for a PolyCrystalline array is shown in Fig. 10-11. The percentage deviation of measured power with predicted values (from 12 pm to 5 pm) ranges between 37-69 %, 21-53 %, 37-59 %, respectively for Simple, one-diode and Sandia models. In the same timespan, the deviation for temperature values is in the range of 0.9-5.5 %, 3.4-7.2 %, respectively for one-diode and Sandia models. In overall the one-diode and Sandia model can capture more accurate results in contrast with Simple model but there is still rooms for improvement. By implementing actual weather data of a specific year instead of IWEC (International Weather for Energy Calculation) weather data and also considering other sources of on-site energy loss in PV systems more accurate results could be achieved.

Fig. 10 & 11 here

6. Simulation-based Energy Yield Prediction

Having a validated PV performance model brings the opportunity of predicting the annual energy yield of PV systems at design stage of the building construction process. With this mindset, low-slope rooftop and sunshade solar panels have been simulated for tropical weather of Singapore. Three types of Mono-Crystalline, Poly-Crystalline and Amorphous solar cells have been modeled in EnergyPlus with Equivalent one-diode performance model. For each cell type, three different popular brands in the market have been chosen to cover the variations in energy yield of different products. In overall 9 brands (A-I) have been picked up for the simulations and the input parameters for one-diode are taken from the technical catalogues of these products.

The findings of the modeling on low-slope rooftop PV systems (Table 2) have shown that poly-crystalline modules are the most productive solar types for this climate. This conclusion matches with findings of Walsh et al. [18] in which the multi-Si wafer based solar cells have chosen as Singapore module. The effect of orientation for these low-slope (15 °) modules is negligible and east-oriented modules produce slightly higher energy. In terms of variation between different brands, Amorphous solar cells has more diverse range of PV yields in contrast to silicon wafer types. This fact shows the importance of selecting the right brand with appropriate characteristics like short circuit current, open circuit voltage, and etc.

Table 2 Predicted annual PV energy yield (DC) of low-slope Rooftop PV in Singapore

Low-slope Rooftop PV (15°)	Mono-Crystalline Brands			Poly-Crystalline Brands			Amorphous Brands		
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
East-Oriented	1330	1329	1331	1491	1375	1456	1392	1327	1080
North-Oriented	1325	1324	1326	1487	1370	1452	1380	1316	1073
South-Oriented	1322	1322	1323	1484	1368	1449	1372	1308	1070
West-Oriented	1320	1320	1321	1481	1365	1446	1379	1315	1071

In the case of sunshade modules, different ranges of façade direction and panel slope have been modeled in EnergyPlus. The outcomes of these simulations (Table 3) have shown that PolyCrystalline sunshade on east façade with slopes in range of 30-45 ° is the most productive location and inclination for this climate. The reason for this fact could be explained by considering the combination effects of radiation intensity, cell temperature, and higher probability of rainfall in afternoon for Singapore weather. The variation of annual energy yield as a function of PV external sun shade slope could be clearly seen in Fig. 12. It shows that east and west façade are the best locations for external shading and the peak point of energy yield happens in the range of 30-40 °.

Table 3 Predicted annual PV energy yield (DC) of PV Sun Shade in Singapore

PV Sun Shade (slope and dir.)	Mono-Crystalline Brands			Poly-Crystalline Brands			Amorphous Brands		
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**

0 ° slope (Hor.)	**E**	789	770	776	893	806	868	660	629	560
	N	784	788	796	915	826	890	679	647	575
	S	753	757	765	881	794	857	638	607	548
	W	746	750	757	872	787	848	640	610	544
15 ° slope	**E**	903	887	893	1020	926	993	807	769	666
	N	867	871	878	1004	910	977	781	745	649
	S	835	839	846	970	878	944	736	701	619
	W	860	863	869	995	902	969	791	743	644
30 ° slope	**E**	956	945	950	1083	985	1055	873	832	715
	N	891	894	900	1031	934	1004	795	758	663
	S	859	862	869	997	902	970	752	716	634
	W	915	918	924	1056	959	1028	850	802	690
45 ° slope	**E**	949	944	948	1086	986	1057	846	806	704
	N	861	864	868	1003	906	976	725	690	622
	S	831	835	839	971	876	945	687	654	596
	W	913	916	921	1057	958	1029	813	775	678
60 ° slope	**E**	887	887	891	1030	930	1002	740	704	639
	N	778	782	787	920	824	894	591	562	536
	S	756	760	764	895	801	869	565	537	516
	W	858	861	865	1002	904	975	710	676	614

Fig. 12 here

7. Conclusion

In this paper the performance of implemented PV system in a case study (ZEB) for tropics have been investigated based on on-site measured data of output power, cell temperature, and solar irradiation sensor. The whole set of arrays in ZEB have been simulated in EnergyPlus under different PV performance models including Simple, Equivalent one-diode and Sandia. The results of simulation have been compared with yearly average daily profile of output power and cell temperature and the most accurate model has been used to provide the annual energy yield under different scenarios. The outcomes of this research could be integrated in the following points,

- ✓ On-site solar cell temperature of panels is mostly higher in the afternoon which slightly reduces the array output power compared to the morning with the same amount of irradiation in-plain.
- ✓ The efficiency of modules is close to the standard test condition (in technical catalogue of panel) in the morning but when it passes through noon and afternoon, the efficiency drops because of higher cell temperature.
- ✓ For this climate, the maximum generated power of rooftop arrays is close to their nominal capacity in some days, however sunshade arrays maximum power never reaches to their nominal capacity during the year.
- ✓ Comparison of modeling results with measured data has shown the Equivalent one-diode and Sandia model could fairly predict the yearly average actual output power of modules but there is still room for improvement by implementing more realistic weather data and considering other sources of energy loss in panels.

- ✓ The simulation-based energy yield predictions of low-slope rooftop PV have shown that available product of PolyCrystalline in the market are better choice than Monocrystalline and single junction amorphous silicon and the effect of orientation in these modules is negligible for this climate.
- ✓ The simulation-based energy yield predictions of external sun shade PV have shown that east façade with panel slope angle of 30-40 ° is the most productive location and inclination for this climate.

The outcomes of this research have shown the potential of building energy simulation and PV performance prediction model at design stage of building construction projects. Since the importance of life cycle cost is increasing in the decision making process of building construction project, a more accurate and realistic simulation tools could help designers to have more reliable return of investment (ROI) for solar panels in buildings.

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List of Figures:

Fig. 6 Yearly average profile of output power and cell temperature for a Poly-Crystalline as a function of solar irradiation

Fig. 7 Yearly average daily profile of generated power for a rooftop PV array, including error bars

Fig. 8 Yearly average daily profile of generated power for a west façade sunshade PV array, including error bars

Fig. 9 Shadow shapes of the main buildings and solar panels on 7th of July under clear sky (from 8 AM to 5 PM)

Fig. 10 Comparison of measured generated power with simulated results by different PV performance models

Fig. 11 Comparison of measured cell temperature with simulated results by different PV performance models

Fig. 12 Predicted annual energy yield of sun shade system as a function of slope angle and façade direction

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Abstract

Air pollution and climate change increased the importance of renewable energy resources like solar energy in the last decades. Rack-mounted PhotoVoltaics (PV) and Building Integrated PhotoVoltaics (BIPV) are the most common photovoltaic systems which convert incident solar radiation on façade or surrounding area to electricity. In this paper the performance of different solar cell types are evaluated for tropical weather of Singapore. As a case study, the on-site measured data of PV systems implemented in a zero energy building in Singapore, is analyzed. Different types of PV systems (silicon wafer and thin film) have been installed on rooftop, façade, car park shelter, railing and etc. The impact of different solar cell generations, arrays environmental conditions (no shading, dappled shading, full shading), orientation (South, North, East or West facing) and inclination (between PV module and horizontal direction) are investigated on performance of modules. In the second stage of research, the whole PV systems in the case study are simulated in EnergyPlus energy simulation software with several PV performance models including Simple, Equivalent one-diode and Sandia. The predicted results by different models are compared with measured data and the validated model is used to provide the

simulation-based energy yield predictions for wide ranges of scenarios. It has been concluded that orientation of low-slope rooftop PV has negligible impact on annual energy yield but in case of PV external sun shade, the east façade and panel slope of 30-40 ° are the most suitable location and inclination.

***Keywords* – Photovoltaic system; Building Integrated PhotoVoltaics; Tropics; PV performance model; Low-slope rooftop PV; PV external sunshade**

1. Introduction

Emerging new technologies of on-site renewable energy production system keeps alive the dream of zero energy buildings (ZEB). ZEBs involve two strategies, minimizing the required energy by using energy efficient technologies and adopting renewable energies to meet the remaining energy needs [1]. In this context, Photovoltaics (PV) is one of the most promising renewable energy technologies in achieving sustainable building design [2,3]. Modern technologies of solar cells with lower cost and higher efficiency increased the feasibility of BIPV in real residential and commercial buildings. Based on Swanson's law, the price of solar cells decreases 20 % by each doubling the global manufacturing capacity. This trend in price of solar cells will increase the applications of solar panels in small sized residential and general buildings. The forecasts of solar systems installation market have shown that the total capacity of BIPV will increase to 2000 MW in 2015 compared to 250 MW in 2010 [4]. While photovoltaics efficiency and manufacturing costs have not reached the point to replace the conventional power generation facilities, a broad range of suitable policies have been implemented to unlock the considerable potential of solar energy [5].

Solar panels could be integrated into façade and roof of building in design stage as Building Integrated PV (BIPV) or as a retrofit added to Building after construction which called Building Applied PV (BAPV). There are various geometrical considerations for installing PV systems. In addition to the installation slope and azimuth angle, the real application of the BIPV system should take into account the influence of shading caused by the surroundings [6]. A BIPV system as a shading is useful not only for the power generation, but also for shading to reduce cooling load. BIPV compared to rack-mounted PV system is more aesthetically pleasant and cost effective. There is saving potential of materials in the integration of PV in building and also eliminating the PV module-mounting structure. On the other hand rack mounted systems are easier to install and operate the maintenance service. In the last years by decreasing the price of solar cells in the market, the application of BIPV, BAPV and rack-mounted PV have been growing in tropical cities as well as other climates. BIPV windows have been proposed by many as an innovative and emerging glazing technology in the buildings [7,8]. In a relevant study, Redweik et al. [9] showed that although the annual irradiation on vertical facades is lower than that of more favourable surfaces (roofs), due to their very large areas, the solar potential of facades is relevant for the overall solar potential of a building.

2. PV System for Tropical Buildings

Tropical regions on earth are mostly surrounding the equator and their main characteristics are year-around high humidity and temperature with significant amount of rainfall. The cloudy sky is the main characteristic of tropical weather which affects the type of radiation on PV system in this climate. In this condition, the direct sunlight scattered by cloud particles in atmosphere and strikes the PV panel mostly as diffused light. It is known that the PV panels are more efficient under direct sunlight and their efficiency drop in cloudy weather. Singapore weather which classified as tropical rainforest has been chosen in this investigation to evaluate the performance of PV panels for tropics. The median could cloud cover is around 90 % and type of precipitation is mostly thunder-storms with higher probability in the afternoon. The statistics shows that the installed capacity of grid -connected solar PV systems in Singapore household and non-household applications reached to 6 MWp in 2011[10].

It is known that PV system without battery in building may not necessarily decrease the peak load of the building. Depending on functionality of building, the peak energy demand may not coincide with the PV system peak output. PV system effect on energy demand is more pronounced in office building than in residential building, especially in countries or states with no Feed in Tariff (FiT) for on-site renewable energies like in Singapore. The reason is that the peak demand of building falls in daylight time for office spaces but for residential building is mostly during night which is out of PV system output period.

The productivity and efficiency of different solar cells have been assessed by many researchers in tropical climates. High humidity, ambient temperature, rainfall and diffuse sunlight all around the year are the main challenges for cells energy production in this climate. In tropical Bangalore, Aaditya et al. [11] observed higher average monthly efficiencies at fixed slope BIPV rooftop concurrently with lower system outputs and vice-versa. This observation justified by interplay between solar insolation, cell and ambient temperature. In another study under Malaysia's weather, Amin et al. [12] collected performance related parameters for different solar cells and They found crystalline silicon and amorphous cells more efficient respectively in sunny and cloudy days. Similar study in Thailand [13] showed that amorphous silicon has the highest average annual array performance ratio (0.92 %) compared to poly crystalline (0.83 %) and hybrid silicon (0.87 %). Wittkopf et al. [14] also determined similar performance ratio (0.81 %) for the poly crystalline roof-top PV system at a zero energy building in Singapore. Performance ratio defined as the ratio of the actual to reference yield which determined based on the module in-plane irradiation to the reference point irradiance. The efficiency of PV modules is strongly affected by their operating temperature. Typically for every 1°C increase of module temperature, there is a ~0.45% drop of module efficiency for crystalline silicon modules [15]. The detrimental effect of temperature on the performance of a PV cell, particularly those which are silicon based is well documented. In another study, Ye et al. [16] compared the PV module temperature variation in Singapore with those in non-tropical regions and proposed useful guidelines for PV installation, especially for tropics.

Based on an official handbook [17] for solar PV, a typical rooftop solar PV system in Singapore annually yield 1100 to 1250 kWh/kWp/yr using crystalline PV modules, and 1200 to 1450 kWh/kWp/yr for amorphous thin film. However the findings of another research project [18] which conducted by Solar Energy Research Institute of Singapore (SERIS) did not confirm the postulation of higher PV yield of single junction a-Si over c-Si for Singapore weather. In the latter research, Heterojunction thin film solar cells like Copper Indium Gallium Selenide (CIGS), Cadmium Telluride (CdTe) and a-Si tandem showed the highest average daily PV energy yield over an eight months period. Uncertainty in environmental conditions, inverter technology, arrangements of solar cells in modules and also modules in PV arrays are the main sources of discrepancies between findings of different studies. An accurate and validated performance evaluation tool, in which the details of module operating condition are taken into account, could be a better reference for this comparison. In this study, at first the whole PV data for a case study (ZEB) in Singapore have been investigated in details. In the second stage, the predictions of different PV performance models are compared with the measured on-site data to identify the most appropriate model. The selected model is used to predict the annual energy yield of low-slope Rooftop and sun shade PV for buildings in Singapore.

3. Research Methodology and Objectives

The aim of this research is to assess the implementation, feasibility and practical implications of PV modules and in particular on-site PV systems in tropical weather of Singapore. In order to have a better understanding of PV performance in this type of weather, one year data of a case study (Zero Energy Building) in Singapore have been analyzed. The performance of implemented BIPV and BAPV systems in Singapore's first Zero Energy Building (ZEB) have been investigated based on various sensors data installed on systems. Different classes of pyronometers, solar irradiation sensors, module temperature sensor, ambient temperature sensor, anemometers and inverter models have been installed on PV systems. The field sensors which their data have been used in this study are listed in Table 1 including their technical details. The annual PV energy yield and daily profile of output power and cell temperature of different types and brands of first and second generation solar cells are studied in details. The effect of different parameters like type of solar cells, location, orientation, inclination and environmental conditions (shadows) are considered on output power of each PV arrays.

Table 1 Field sensors of PV monitoring system and their technical details

Parameters	Field Sensor	Precision
Solar Irradiance	SMA Irradiance Sensor, Sunny Sensor Box	±8 % for 0-1500 w/m^2
Module Cell Temperature	Pt 100, SMA Tempsensor-Module	± 0.5 °C, in range of -20 °C to +110 °C
Output Power and Energy Values	PV Inverter Sunny Boy and Sunny Mini Central	tolerance of up to ± 3 %
Module Efficiency	- (propagated error)	Calculated error up to ± 11 %

In the second stage of the study, the geometry of building and details of PV arrays have been simulated in EnergyPlus energy simulation software (an energy analysis and thermal load simulation program). There are different ways for integrating EnergyPlus heat transfer surfaces and solar panels heat balance equations to calculate the cell temperature. The most common PV performance models which are incorporated into EnergyPlus are Simple, Equivalent One-Diode and Sandia models. In Simple PV performance model, a constant efficiency assumed during whole range of solar irradiation and cell temperature effect has not been taken into account. Equivalent One-Diode model is known as four or five parameters TRNSYS (TRaNsient SYstem Simulation Program, an energy simulation program) model for photovoltaics in which modules modeled using an equivalent one-diode circuit. The list of parameters which incorporated into EnergyPlus input file for each brand and model of PV module includes short circuit current, open circuit voltage, voltage at maximum power, current at maximum power, temperature coefficient of short circuit current, temperature coefficient of open circuit voltage, number of cells in series per module, cell temperature at NOCT (Nominal Operating Cell Temperature) condition, and module area [19]. In addition, the Sandia model is incorporated which is based on empirical coefficients assembled by Sandia National Laboratory for each specific type and brand of PV modules. The many empirical coefficients for each PV module have been found in System Advisor Model (SAM) database provided by National Renewable Energy Laboratory (NREL).

It is known that the optimum angle of solar panels at each location on the earth is close to the value of that location latitude or slightly lower [20,21]. It is also the case for rooftop PV in tropical buildings which are mostly located near to the equator and the panels are preferred to be horizontal (0 ° as latitude of equator). However, the situation is a bit more complicated for the optimum slope of external shading PV or PV glass which are located on the façade. Getting a better understanding on the impact of solar panel angle on annual energy yield of different types of solar cells is one of the objectives of this study.

Empirical and non-empirical models have been used by many researchers in the literature to predict the annual energy yield of solar panels [22,23]. Several PV performance models like Equivalent one-diode and Sandia models have been incorporated into EnergyPlus energy simulation software to model PV arrays on different sites and the results are validated with experimental data [24]. The required input parameters, location, and inclination of each installed arrays in ZEB have been incorporated into EnergyPlus as input file. The daily profile of output power, cell temperature and also annual energy yield of modules have been predicted with different PV performance models and compared to measured on-site data. With a certified accurate PV performance model, the efforts have been taken to provide guidelines of annual PV yield for different generation, location, orientation and inclination of PV arrays in tropical weather of Singapore.

4. Performance Evaluation of a Case Study in Singapore

4.1 Overal Installed PV System in ZEB

The Zero Energy Building (ZEB) is retrofitted from an existing building. Converted from a three-storey former workshop, ZEB houses offices, classrooms and a resource centre. The ZEB is a zero energy building because the building produces enough energy to run itself. The building aims to produce enough energy to power the building, through a combination of green building technology, clever building design that takes advantages of natural ventilation and lighting, and the harnessing of solar energy. To achieve the self-sufficient energy, the building is powered by a broad spectrum of grid-tied and standalone solar panels installed at many locations in the building. Surplus power generated by these solar panels distributed to the rest of BCA Academy buildings. If insufficient power is produced, then grid supply will provide for ZEB, so that user comfort and function are never compromised.

Various brands of poly-crystalline silicon, mono-crystalline silicon, heterojunction with intrinsic thin layer (HIT), amorphous thin film, copper indium gallium (di) selenide (CIGS) PV modules have been installed on rooftop, linkway, car park shelter, sunshade, railing and other locations in the building. In overall, 1540 m^2 of PV modules with peak system power of 190 kWp have been implemented in the building to produce about 207 MWh electricity each year. Different types of sensors including 36 solar irradiation sensors, one ambient temperature sensors, 9 Pyranometers, 6 Anemometers, 21 cell temperature sensors and 37 power meters on Invertors are installed on PV systems. A software platform has been developed to collect and monitor the real-time measured data and also export them into text files.

The energy yield of different solar cells installed in ZEB varies based on their location, orientation, inclination, and also environmental and shading conditions. The fluctuations in annual energy yield of PV system in ZEB over 39 months of installation from October 2009 to December 2012 are shown in Fig.1. The annual PV yield of arrays ranges between 600 to 1200 kWh/yr and the type of solar cells, shading condition and arrangement of modules in an array are the key factors. The roof top arrays produced the highest electricity per peak watt of installed PV modules because of their exposure to sunlight in the whole day. Also in general, the east-oriented arrays with lower inclination were the most productive PV modules during 39 months of operation. The reason of this fact could be higher probability of rainfall in afternoon which affects the average daily radiation striking west-oriented arrays. The other source of variation is different arrangement of modules in northern rooftop arrays compared to southern ones which degraded their produced annual energy.

Fig. 1 here

Comment [E1]: Revised (colors replaced with patterns)

The details of energy consumption and production of building for different months over the year are shown in Fig. 2. Evaluation of ZEB data at 2012 shows that the BIPV energy production was 5 % more than building energy consumption which confirms the claim of net zero energy building. In total PV systems produced 201 MWh electricity in this year which is slightly lower than expected energy yield for a typical year (207 MWh).

Fig. 2 here

Comment [E2]: Revised (colors replaced with patterns)

The average daily profile of PV supply, city grid supply and energy consumption for weekdays and weekends over January 2012 are shown in Fig. 3-4. The daily profile of PV supply and city power grid supply to ZEB is different from weekdays to weekends and holidays. During the week, the building is mostly occupied by employees and it has uniform energy consumption during office hours. On the other hand in the weekends, the building is mostly empty and energy demand is much lower which means more energy saving of produced energy by PV systems.

Fig. 3& 4 here

Comment [E3]: Revised (colors replaced with patterns)

4.2 Daily Profile of Efficiency, Output power and Cell Temperature

The measured output power, efficiency and cell temperature of arrays in ZEB brought the chance of getting a better understanding of module performance during the day. The yearly average daily profile of output power and efficiency together with solar cell temperature variations for a PolyCrystalline Silicon array are shown in Fig. 5-6. With the same amount of radiation on solar panel, its efficiency varies from morning to afternoon due to different cell temperature. This variation mainly depends on the thermal mass of PV modules, day/night temperature range and also other environmental conditions. The nominal power (peak power) of this array is 6.84 kWp, however its actual output power does not exceed 3.5 kW in a normal day. As expected, cell temperature is higher in afternoon which causes a small decrease in produced energy of modules compared to morning output energy. It is also observed that around 9 AM, the efficiency of module is close to standard test condition (25 °C, 1.5 Air Mass, 1000 W/m^2) efficiency which is 13.7 %. This value drops to 12 % during the noon and also in afternoon due to higher cell temperature.

Fig. 5 & 6 here

Comment [E4]: Revised (a separate curve markers have been specified for clarification)

The other interesting graphs which have been generated based on the measured data in this case study, are the yearly average daily profile of arrays actual power. The deviation of the on-site produced energy of PV arrays from their nominal capacity depends on their façade direction, inclination, orientation, shading and other environmental conditions. As a sample, the maximum~~, minimum~~ and average daily profiles of a roof top PolyCrystalline and sunshade Amorphous PV arrays are shown in Fig. 7-8. The maximum capacity of roof top array is around 7 kW which is close to its nominal capacity. However, the maximum power of the Sunshade array which is located on west façade is around 0.7 kW and is lower than its nominal capacity (1.044 kWp). The peak capacity mostly happens around noon for rooftop array but for sunshade array on west facade, the peak point happens in the afternoon when it receives the highest solar irradiation.

Fig. 7 & 8 here

Comment [E5]: Revised (the minimum curve has been removed from the graphs)

5. Validation of PV Performance Models

An accurate modeling tool for predicting the energy yield of solar system could be useful in recognizing the optimum location, orientation and inclination of on-site PV systems in buildings. It is also applicable in recognizing the financial potential of solar panels by determining the Return of Investment (ROI) for new buildings or retrofits. The whole PV systems installed in ZEB have been simulated in EnergyPlus to consider the most realistic shading conditions for panels. This prediction tool could be used to have an estimation of annual PV yield and also to identify the optimum location, orientation and inclination of PV modules. The 3D model of the zero energy building has been generated in 3D modeling program of SketchUp. Geometrical dimensions of building and solar panels have been modeled based on the available data in the building drawing, PV manufacturer's technical catalogues and also actual building on-site measured data. The legacy OpenStudio Plug-in for SketchUp have been used to create EnergyPlus input file based on defined boundary conditions, thermal loads and other parameters. This modeling tool is capable of predicting the shadow zones at different times and days in the year which is the dominant factor for estimating the annual PV yield. The shadow shapes of the modeled building and solar panels for different hours during the day are shown in Fig. 9.

Fig. 9 here

The results of simulations are compared with measured data in terms of instantaneous DC output power of arrays and cell temperature for different solar panels. The comparison of ~~predictions of three PV performance models of~~predicted results of Simple, Equivalent one-diode and Sandia performance model ~~are compared~~ with measured data for a PolyCrystalline array is shown in Fig. 10-11. The percentage deviation of measured power with predicted values (from 12 pm to 5 pm) ranges between 37-69 %, 21-53 %, 37-59 %, respectively for Simple, one-diode and Sandia models. In the same timespan, the deviation for temperature values is in the range of 0.9-5.5 %, 3.4-7.2 %, respectively for one-diode and Sandia models. ~~It can be seen that~~ In overall the one-diode and Sandia model ~~could~~ can capture more accurate results in contrast with Simple model but there is still rooms for improvement. By implementing actual weather data of a specific year instead of IWEC (International Weather for

Comment [E6]: Further elaboration provided for the shadow shapes of the building

Energy Calculation) weather data and also considering other sources of on-site energy loss in PV systems more accurate results could be achieved.

Fig. 10 & 11 here

Comment [E7]: Revised (Markers are used for better clarification)

6. Simulation-based Energy Yield Prediction

Having a validated PV performance model brings the opportunity of predicting the annual energy yield of PV systems at design stage of the building construction process. With this mindset, low-slope rooftop and sunshade solar panels have been simulated for tropical weather of Singapore. Three types of Mono-Crystalline, Poly-Crystalline and Amorphous solar cells have been modeled in EnergyPlus with Equivalent one-diode performance model. For each cell type, three different popular brands in the market have been chosen to cover the variations in energy yield of different products. In overall 9 brands (A-I) have been picked up for the simulations and the input parameters for one-diode are taken from the technical catalogues of these products.

The findings of the modeling on low-slope rooftop PV systems (Table 2) have shown that poly-crystalline modules are the most productive solar types for this climate. This conclusion matches with findings of Walsh et al. [18] in which the multi-Si wafer based solar cells have chosen as Singapore module. The effect of orientation for these low-slope (15 °) modules is negligible and east-oriented modules produce slightly higher energy. In terms of variation between different brands, Amorphous solar cells has more diverse range of PV yields in contrast to silicon wafer types. This fact shows the importance of selecting the right brand with appropriate characteristics like short circuit current, open circuit voltage, and etc.

Table 2 Predicted annual PV energy yield (DC) of low-slope Rooftop PV in Singapore

Low-slope Rooftop PV (15°)	Mono-Crystalline Brands			Poly-Crystalline Brands			Amorphous Brands		
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**
East-Oriented	1330	1329	1331	1491	1375	1456	1392	1327	1080
North-Oriented	1325	1324	1326	1487	1370	1452	1380	1316	1073
South-Oriented	1322	1322	1323	1484	1368	1449	1372	1308	1070
West-Oriented	1320	1320	1321	1481	1365	1446	1379	1315	1071

In the case of sunshade modules, different ranges of façade direction and panel slope have been modeled in EnergyPlus. The outcomes of these simulations (Table 3) have shown that PolyCrystalline sunshade on east façade with slopes in range of 30-45 ° is the most productive location and inclination for this climate. The reason for this fact could be explained by considering the combination effects of radiation intensity, cell temperature, and higher probability of rainfall in afternoon for Singapore weather. The variation of annual energy yield as a function of PV external sun shade slope could be clearly seen in Fig. 12. It shows that east and west façade are the best locations for external shading and the peak point of energy yield happens in the range of 30-40 °.

Table 3 Predicted annual PV energy yield (DC) of PV Sun Shade in Singapore

PV Sun Shade (slope and dir.)	Mono-Crystalline Brands			Poly-Crystalline Brands			Amorphous Brands		
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**

0 ° slope (Hor.)	**E**	789	770	776	893	806	868	660	629	560
	N	784	788	796	915	826	890	679	647	575
	S	753	757	765	881	794	857	638	607	548
	W	746	750	757	872	787	848	640	610	544
15 ° slope	**E**	903	887	893	1020	926	993	807	769	666
	N	867	871	878	1004	910	977	781	745	649
	S	835	839	846	970	878	944	736	701	619
	W	860	863	869	995	902	969	791	743	644
30 ° slope	**E**	956	945	950	1083	985	1055	873	832	715
	N	891	894	900	1031	934	1004	795	758	663
	S	859	862	869	997	902	970	752	716	634
	W	915	918	924	1056	959	1028	850	802	690
45 ° slope	**E**	949	944	948	1086	986	1057	846	806	704
	N	861	864	868	1003	906	976	725	690	622
	S	831	835	839	971	876	945	687	654	596
	W	913	916	921	1057	958	1029	813	775	678
60 ° slope	**E**	887	887	891	1030	930	1002	740	704	639
	N	778	782	787	920	824	894	591	562	536
	S	756	760	764	895	801	869	565	537	516
	W	858	861	865	1002	904	975	710	676	614

Fig. 12 here

Comment [E8]: Revised (Markers are used for better clarification)

7. Conclusion

In this paper the performance of implemented PV system in a case study (ZEB) for tropics have been investigated based on on-site measured data of output power, cell temperature, and solar irradiation sensor. The whole set of arrays in ZEB have been simulated in EnergyPlus under different PV performance models including Simple, Equivalent one-diode and Sandia. The results of simulation have been compared with yearly average daily profile of output power and cell temperature and the most accurate model has been used to provide the annual energy yield under different scenarios. The outcomes of this research could be integrated in the following points,

- ✓ On-site solar cell temperature of panels is mostly higher in the afternoon which slightly reduces the array output power compared to the morning with the same amount of irradiation in-plain.
- ✓ The efficiency of modules is close to the standard test condition (in technical catalogue of panel) in the morning but when it passes through noon and afternoon, the efficiency drops because of higher cell temperature.
- ✓ For this climate, the maximum generated power of rooftop arrays is close to their nominal capacity in some days, however sunshade arrays maximum power never reaches to their nominal capacity during the year.
- ✓ Comparison of modeling results with measured data has shown the Equivalent one-diode and Sandia model could fairly predict the yearly average actual output power of modules but there is still room for improvement by implementing more realistic weather data and considering other sources of energy loss in panels.

- ✓ The simulation-based energy yield predictions of low-slope rooftop PV have shown that available product of PolyCrystalline in the market are better choice than Monocrystalline and single junction amorphous silicon and the effect of orientation in these modules is negligible for this climate.
- ✓ The simulation-based energy yield predictions of external sun shade PV have shown that east façade with panel slope angle of 30-40 ° is the most productive location and inclination for this climate.

The outcomes of this research have shown the potential of building energy simulation and PV performance prediction model at design stage of building construction projects. Since the importance of life cycle cost is increasing in the decision making process of building construction project, a more accurate and realistic simulation tools could help designers to have more reliable return of investment (ROI) for solar panels in buildings.

8. Acknowledgment

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List of Figures:

Fig. 6 Yearly average profile of output power and cell temperature for a Poly-Crystalline as a function of solar irradiation

Fig. 7 Yearly average daily profile of generated power for a rooftop PV array, including error bars

Fig. 8 Yearly average daily profile of generated power for a west façade sunshade PV array, including error bars

Fig. 9 Shadow shapes of the main buildings and solar panels ~~at 2 pm~~on 7th of July under clear sky (from 8 AM to 5 PM)

Fig. 10 Comparison of measured generated power with s~~S~~imulated results by different PV performance models

Fig. 11 Comparison of measured cell temperature with s~~S~~imulated results by different PV performance models

Fig. 12 Predicted annual energy yield of sun shade system as a function of slope angle and façade direction

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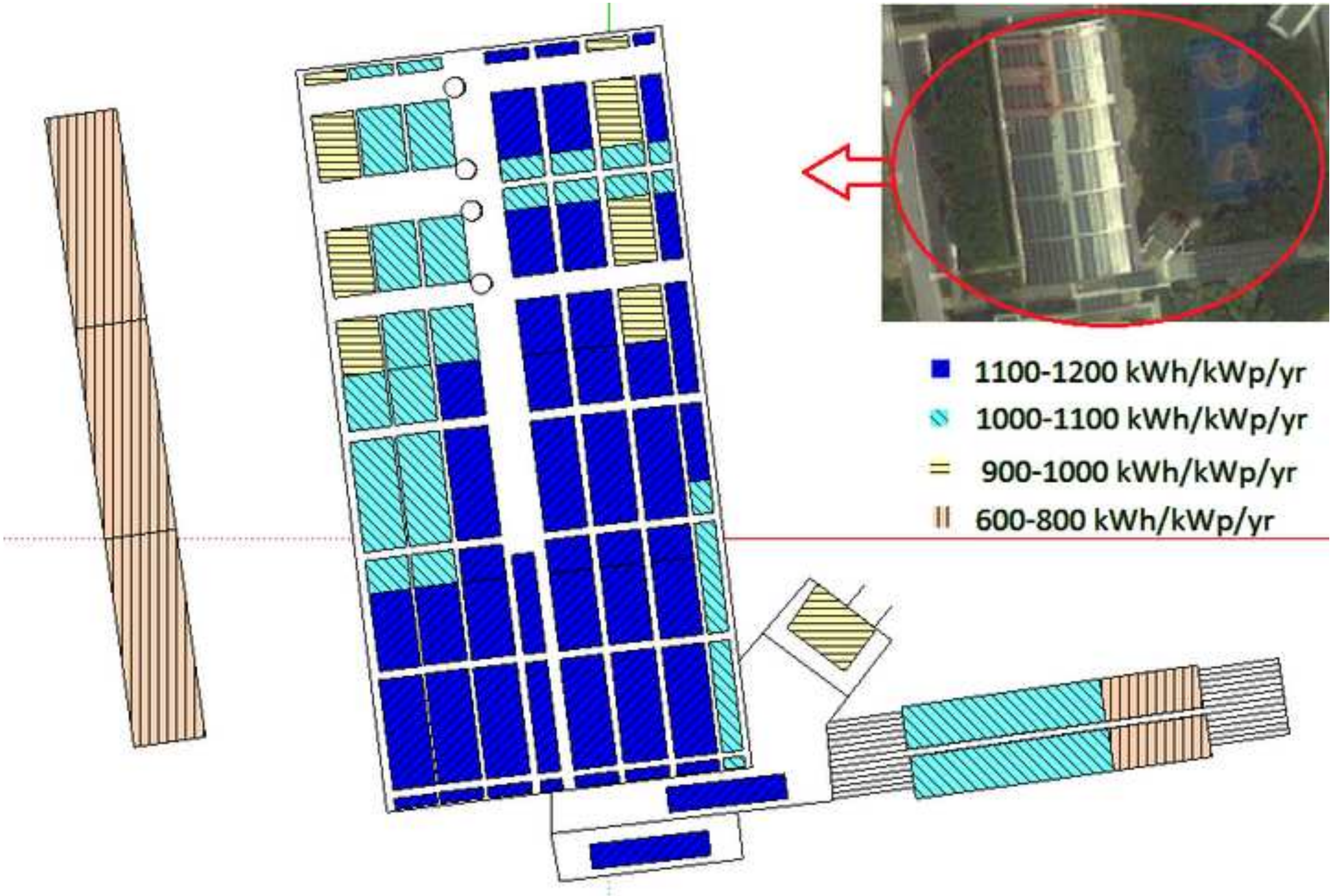

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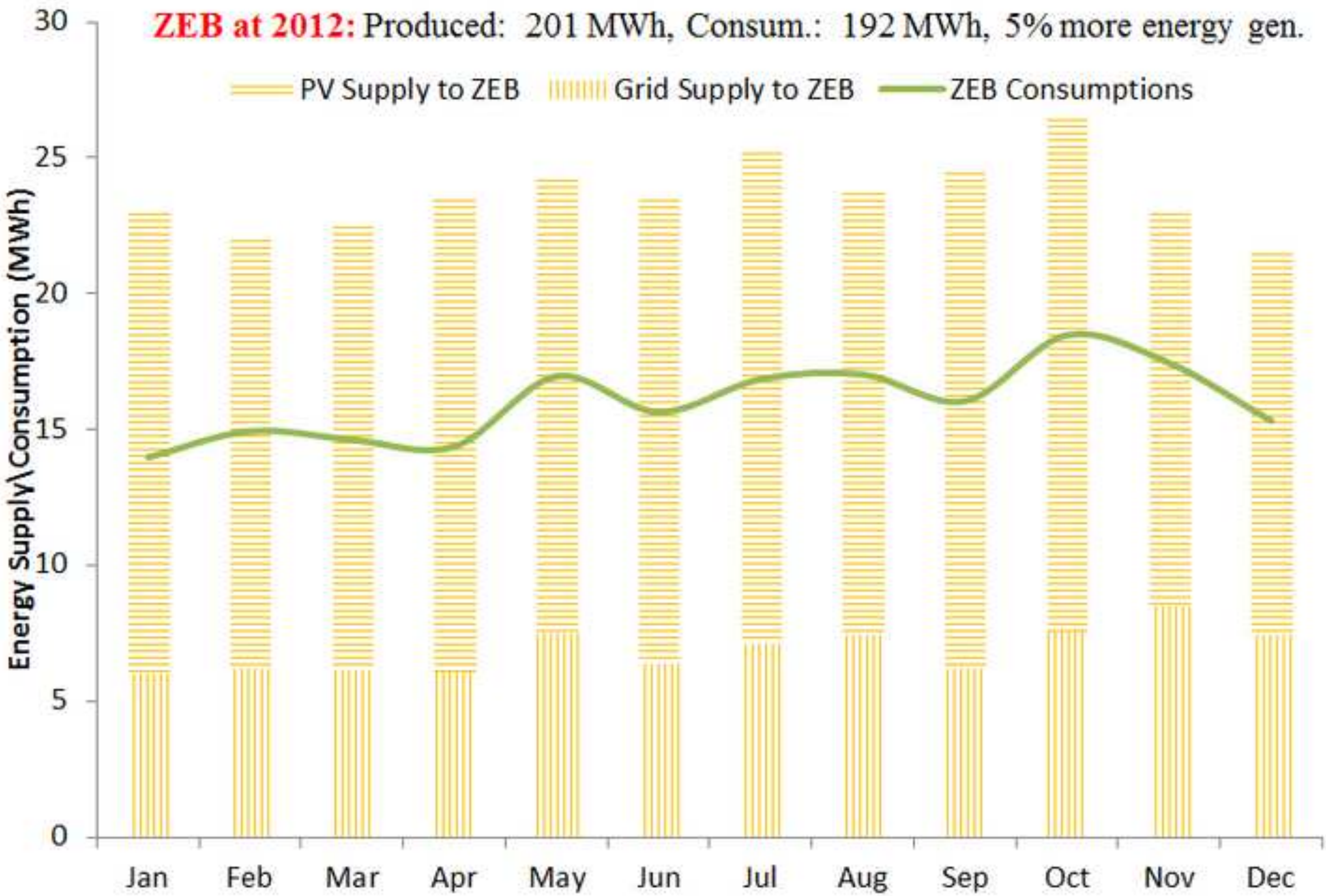

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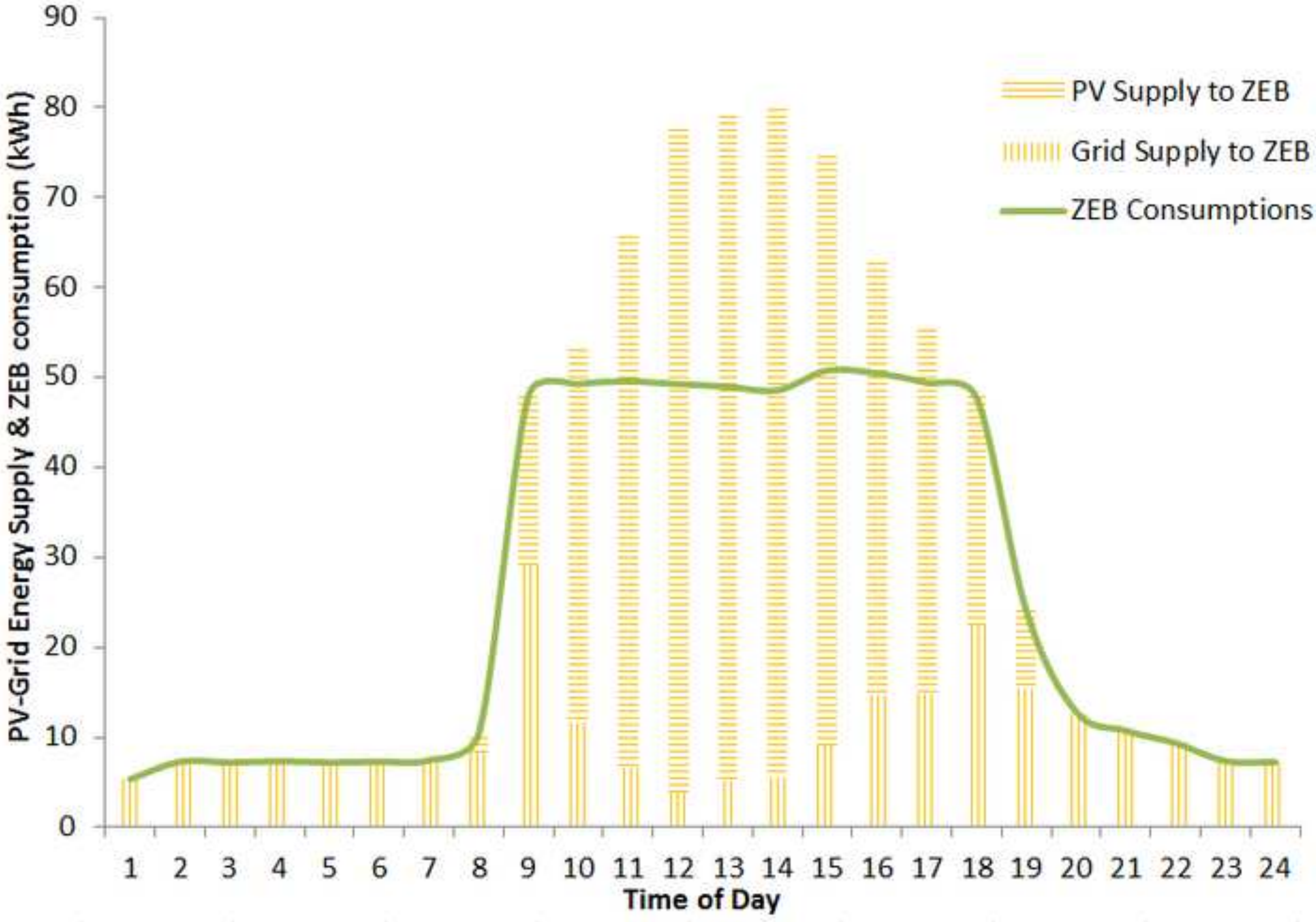

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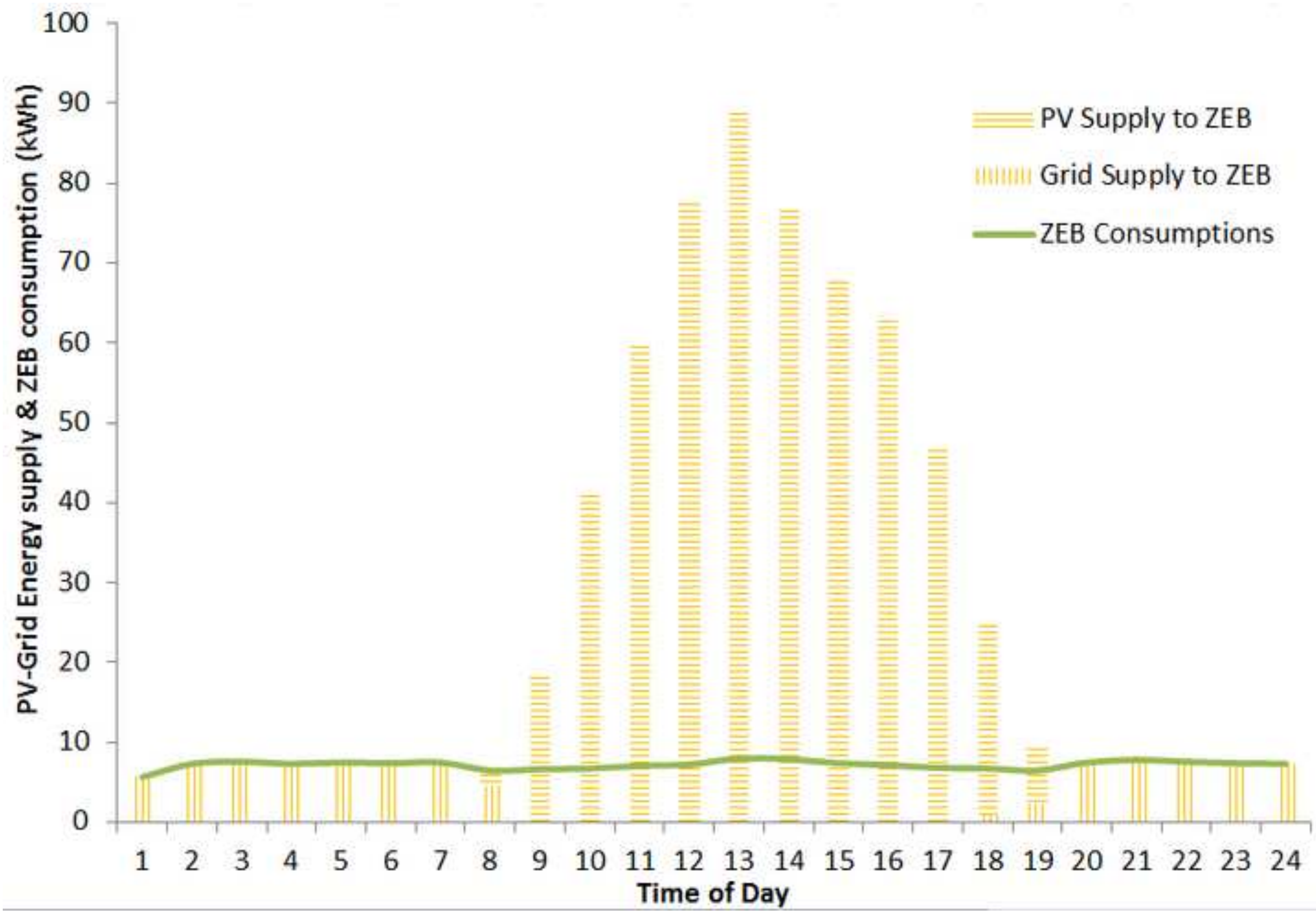

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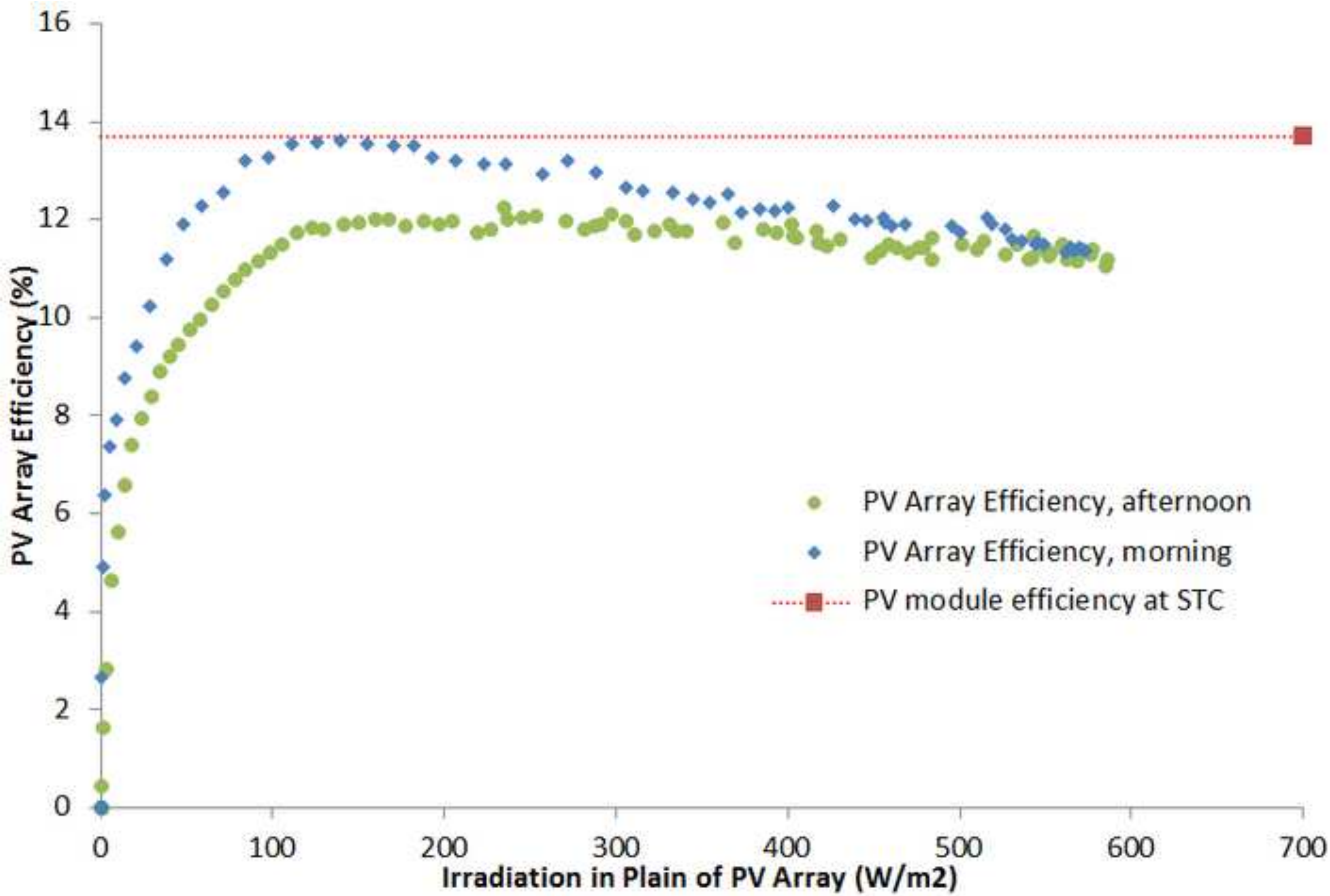

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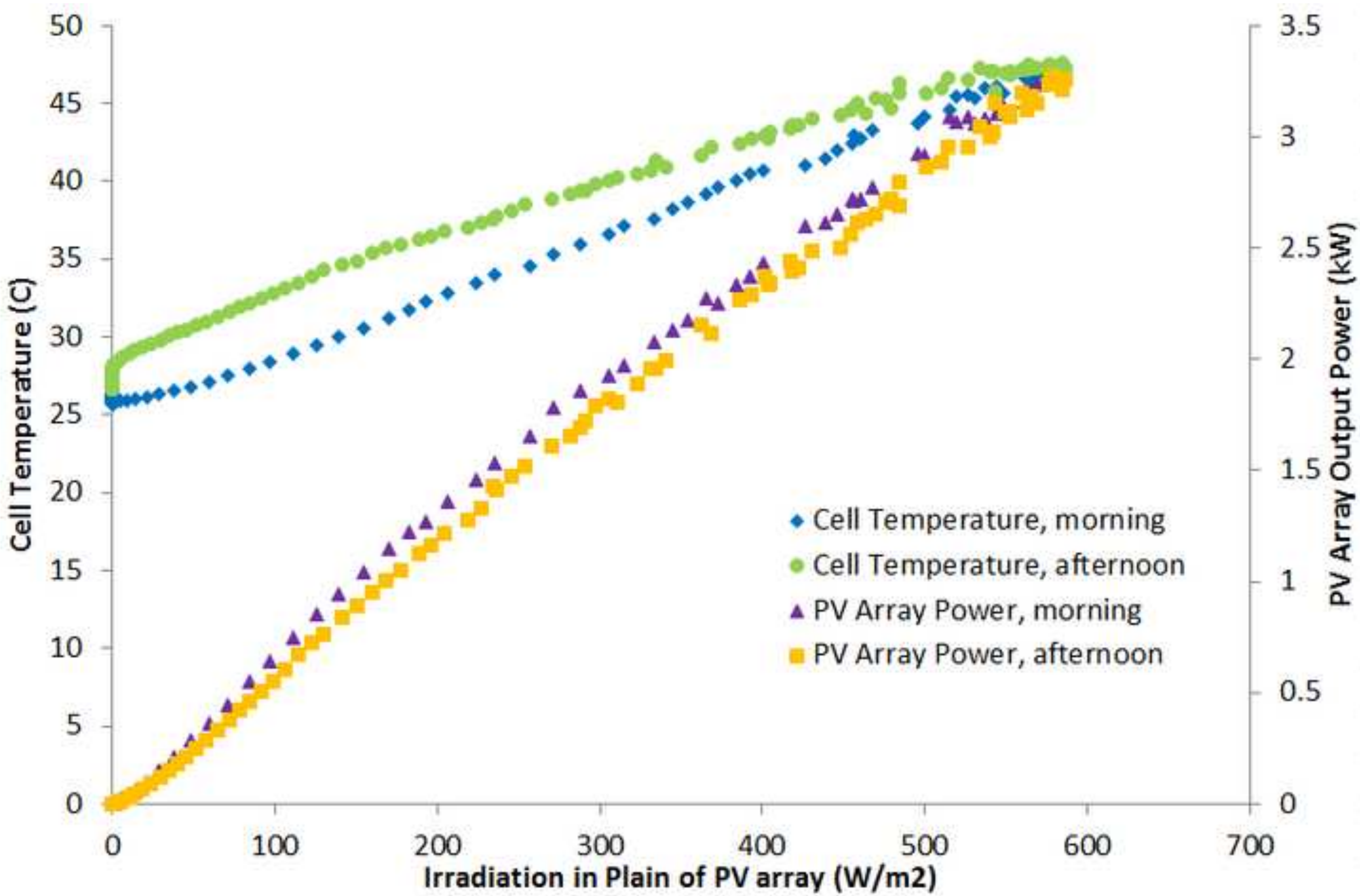

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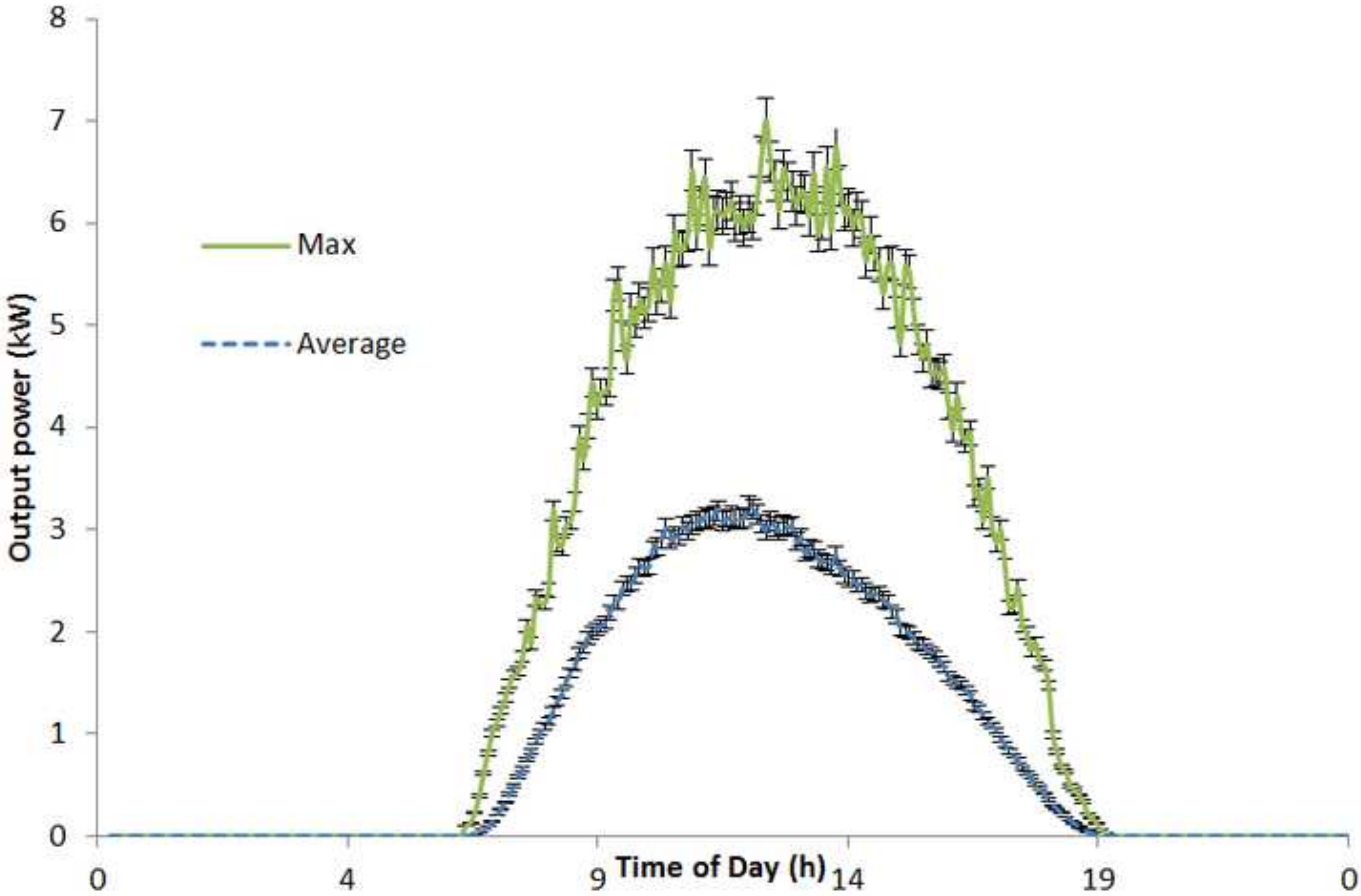

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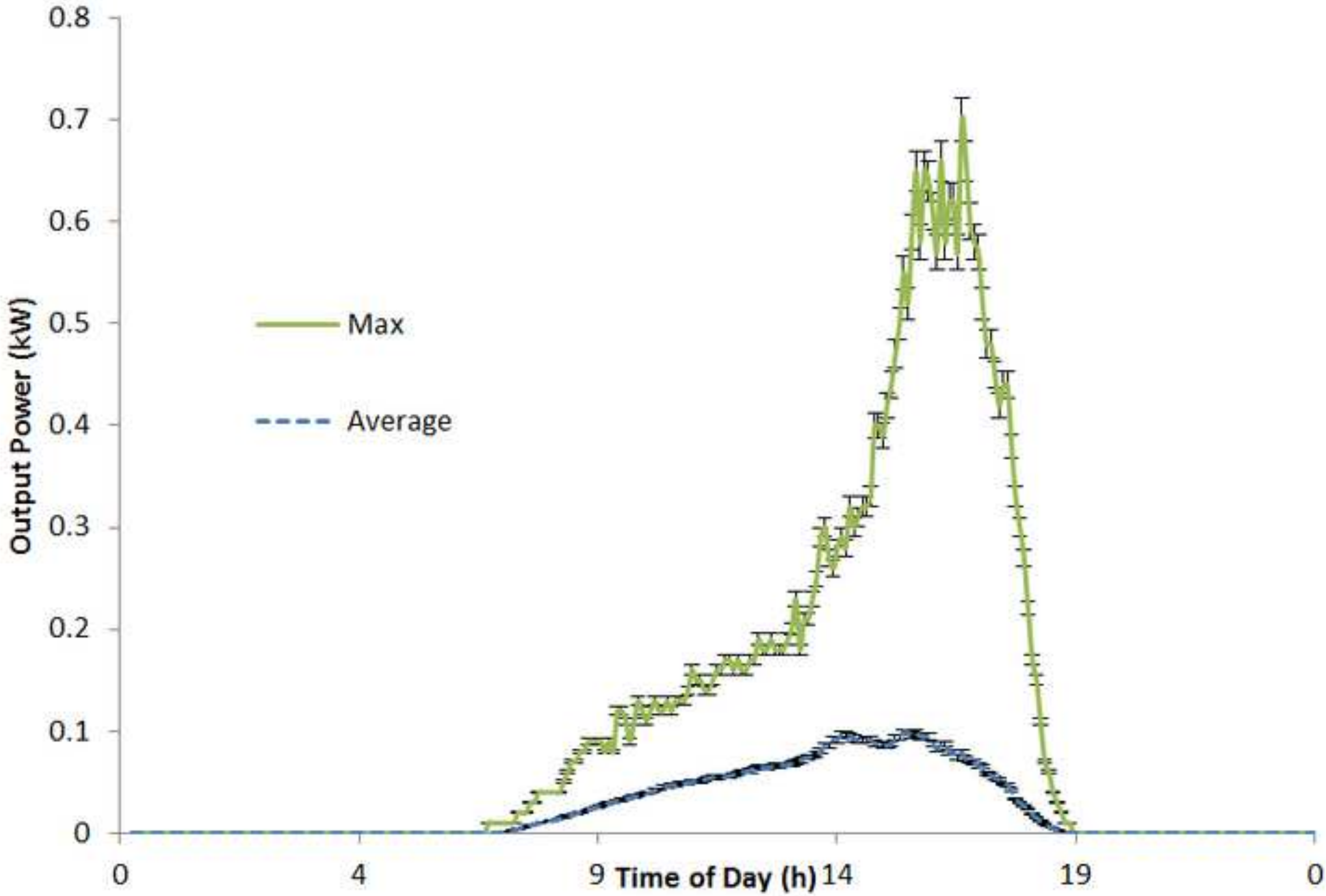

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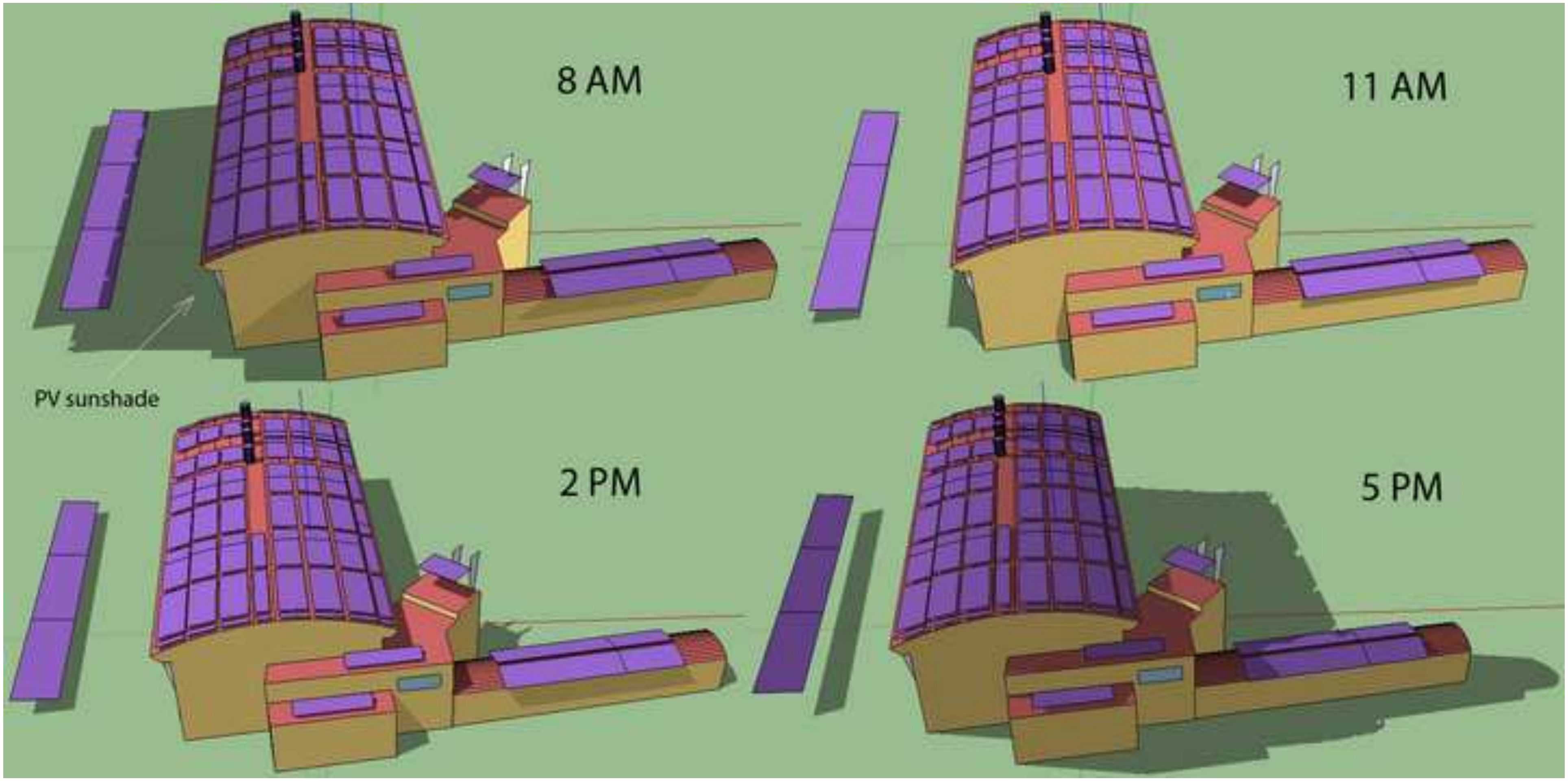

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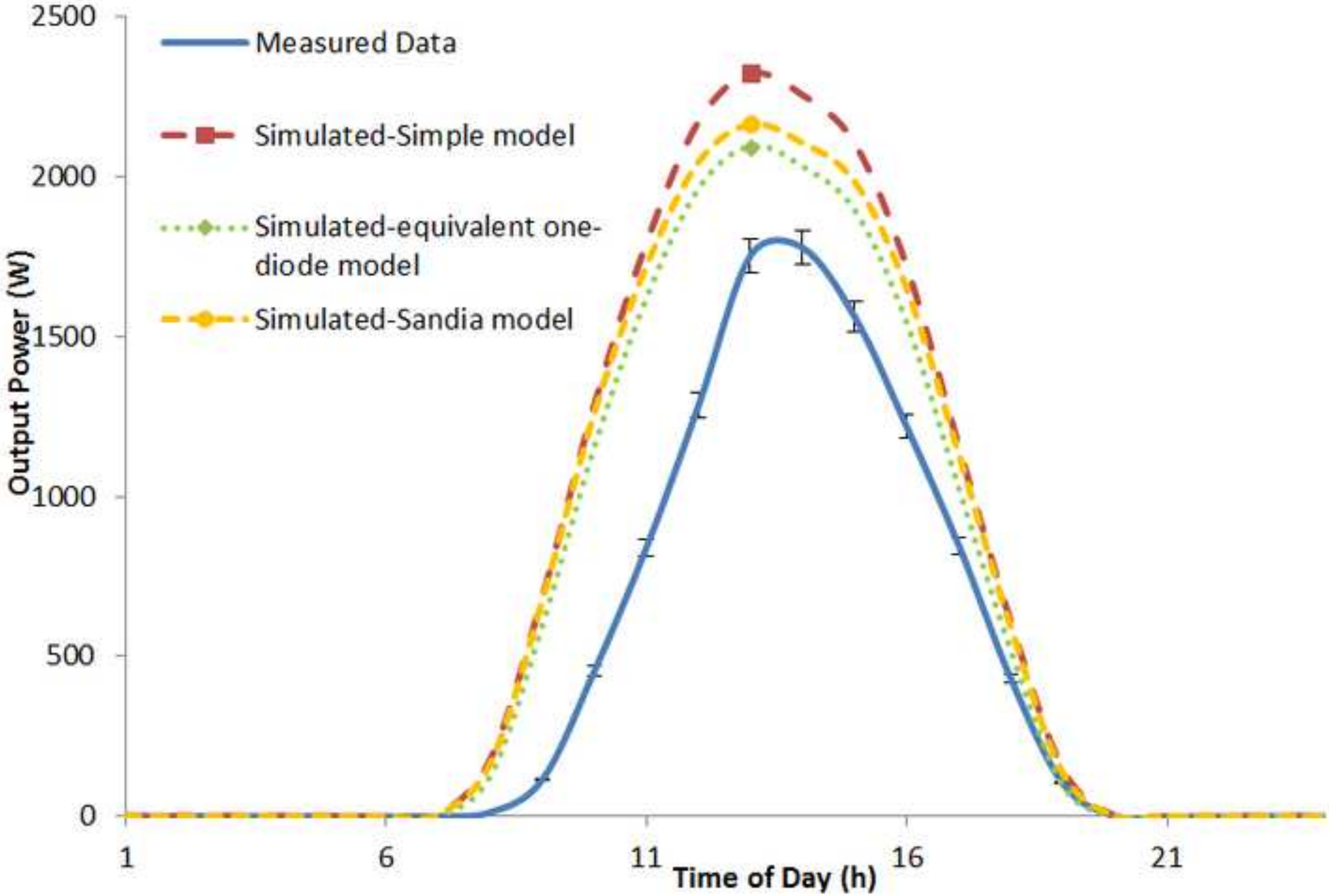

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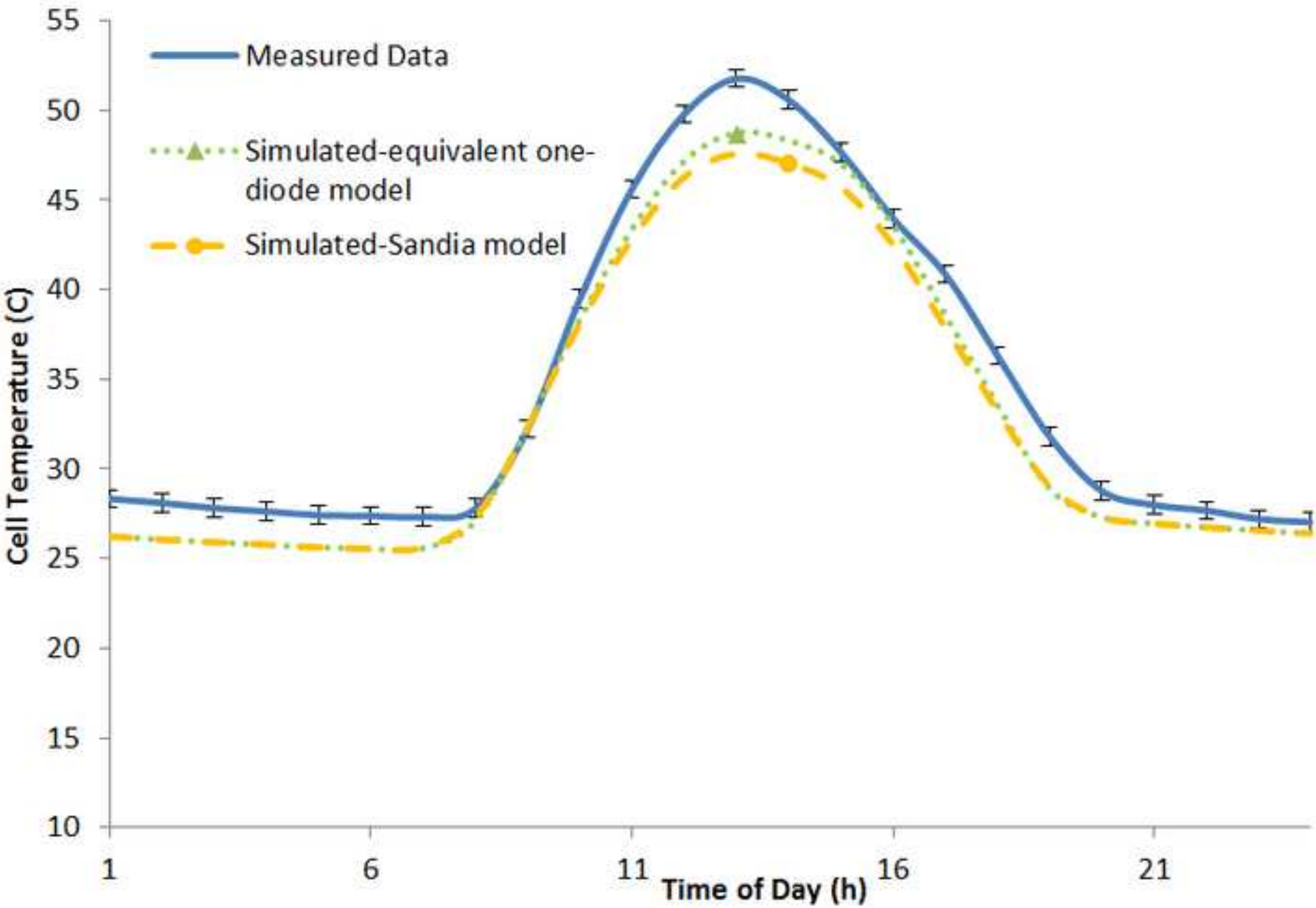

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