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Performance of Nine Different Types of PV Modules in the Tropical Region

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***Abstract*—**With growth of PV market in tropical region, it is necessary to investigate the performance of different types of PV technology under the tropical weather conditions. Singapore Polytechnic was funded by Economic Development Board (EDB) to set up a solar PV test-bed for the research on performance of different types of PV modules in the country. The PV test-bed installed the nine different types of PV systems that are integrated to power utility grid for monitoring and analyzing their operating performances. This paper presents the 12 months operational data of nine different PV systems and analyses on performances of installed PV systems using energy yield and performance ratio. The nine types of PV systems under test have shown their energy yields ranging from 2.67 to 3.36 kWh/kW_p and their performance ratios (PRs) ranging from 70% to 88%.

***Keywords*—**Monocrystalline, Multicrystalline, Amorphous Silicon, Cadmium Telluride and thin film PV.

I. Introduction

SOLAR Photovoltaic (PV) technology for terrestrial applications has the potential to play a major role in achieving energy sustainability and solving global warming problem. Singapore is a tropical country that is rich of solar energy resource. The solar photovoltaic that converts the sunlight directly to electricity helps the country to deploy solar energy for electricity generation so as to reduce its dependency of imported primary energy resource in future.

To date, the different types of solar PV technologies have been developed for terrestrial applications ranging from consumers' products, stand-alone PV system to large utility grid-tied PV system. In the tropical region, fixed PV systems consisting of flat type modules are more widely accepted than tracking PV systems that consist of flat type or contractor type modules due to high diffuse radiation and high humidity [1]. The flat type PV modules available in the market are primarily based on semiconductor materials and can be classified as two main categories: Silicon and non-silicon.

Although the PV manufacturers already provide system designers and integrators with technical specifications of their PV products under Standard Testing Conditions(STC) and Nominal Operating Cell Temperature(NOCT) conditions, the performance of different types of solar PV modules may vary from place to place depending on the operational conditions in-situ [2]-[5]. Therefore, it is necessary to set up a test-bed in Singapore to perform the test on different types of commercial solar PV modules and evaluate their performances under the tropical weather conditions. As the energy yield of a PV system also rely on its installation, the test-bed needs to conduct experiments on the PV systems with the same type of PV modules that are installed with different orientations and tilted angles. Under the support of Singapore Economic Development Board (EDB), Singapore Polytechnic spent two years to set up a solar PV test-bed in its campus which consisted of 9 different types of PV systems as listed in Table I. All PV systems were completed and put in operation in March 2010 and have been operating successfully since then.

This paper presents the operational results of all systems in a year by analyzing and comparing their performances under the tropical weather conditions. The results shown help to understand the operation of different PV systems in Singapore.

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TABLE I
NINE TYPES OF SOLAR PV SYSTEMS UNDER TESTING

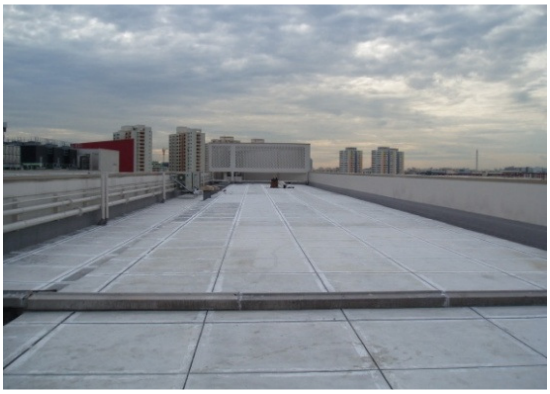
PV module	Producer	Capacity of PV Array(kWp)
HIT-205NKHB1(mono-facial HIT)	Sanyo	$1.23kW_p$
ES-124(triple junction a-Si)	Unisolar	$1.116kW_p$
HIT-200DN2-1(bifacial HIT)	Sanyo	$1.20kW_p$
ND-120T1D(mc-Si)	Sharp	$1.32kW_p$
SW175(c-Si)	Solar world	$1.225kW_p$
FS-275(CdTe)	First solar	$1.20kW_p$
MA100T2(single junction a-Si)	Mitsubishi	$1.20kW_p$
PHX-90(microcrystalline)	Phoenix solar	$1.35kW_p$
SPWR-215(all back c-Si)	Sunpower	$1.29kW_p$

II. Construction of Solar PV Test Bed

A. Conditions of PV Test Bed

The PV test-bed was located on the rooftop of a teaching building in the campus of Singapore Polytechnic as depicted in Fig. 1. Fig. 1 (a) shows the rooftop of the teaching block before installation of PV systems, while Fig. 1 (b) presents the all PV systems installed on the rooftop.

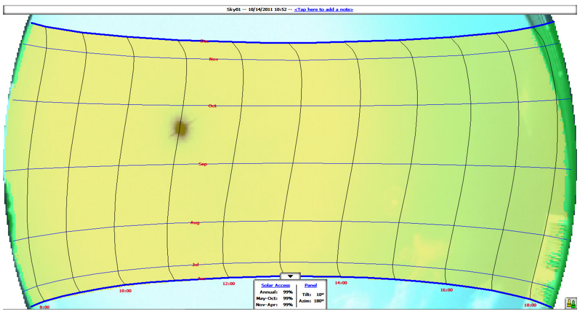
Solar assessment was conducted to investigate the availability of solar irradiance and partial shadow in the area where the PV systems were installed for site testing. Fig. 2 shows the sun path and the orthogonal sun path diagram for partial shadow analyses.



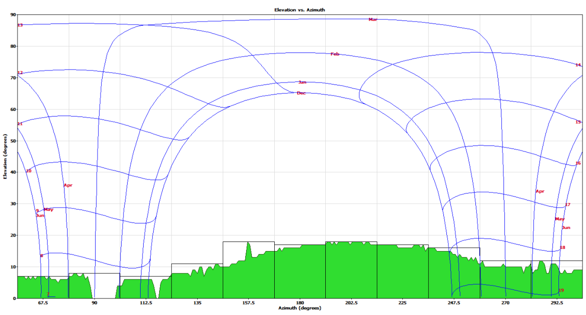
(a) Before installation of PV systems

(b) After installation of PV systems

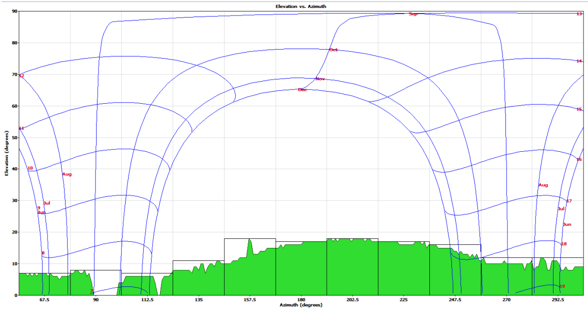
Fig. 1 The PV test-bed for experiments on different types of PV modules



(a) The sun path measured at central of rooftop



(b) The partial shadows from Dec-Mar-Jun



(c) The partial shadows from Jun-Sep-Dec

Fig. 2 Solar assessment conducted on the site of PV test-bed

B. Configuration of PV Systems

In the design of PV test-bed, all PV systems are grid-tied and adopt the same system structure. Fig. 3 illustrates the primary circuit of each system, while Fig. 4 presents the secondary measurement circuit to monitor the operational performance of PV systems. Although horizontal installation of PV modules is theoretically recommended referring to the sun path on the equator, the PV modules under testing were installed to face to due South with titled angle of 12° to clean the surface of modules by rainwater. The grid-tied inverter used for PV system is SMA SB1100 (1.1kW inverter equipped with low frequency (LF) isolation transformer that was selected to minimize the DC current injection to the grid and also accommodate grounding requirement of certain PV modules like Sun Power back-contact c-Si module for positive grounding and Mitsubishi single junction a-Si module for negative grounding.

The system operation is monitored and sampled by data acquisition unit installed in the inverter and the electrical data together with solar irradiance and ambient temperature are transmitted to Sunny Boy control Plus for data collecting and then sent to a personal computer (PC) for data logging and analyses through a RS485 network.

Main technical parameters of PV modules for nine PV systems installed in the test-bed are illustrated in Table II. All PV arrays except MA100T2 (single junction a-Si) and PHX-90 (microcrystalline) consist of one string. The PV array equipped with MA100T2 modules has 6 strings of PV modules connected in parallel, while the PV array with PHX-90 has 3 strings in parallel.

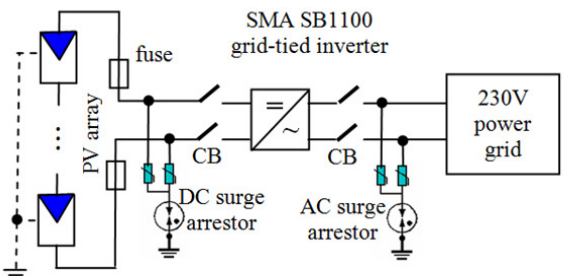


Fig. 3 The structure of PV systems

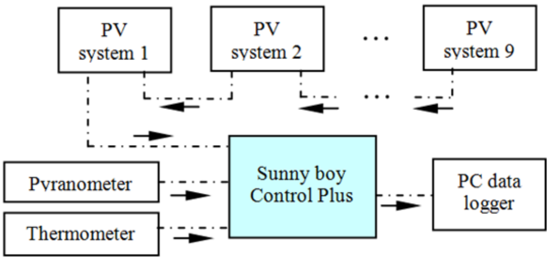


Fig. 4 The data acquisition system

III. Performances of Nine Types of PV Systems

The performance of a PV system depends on its solar radiation input and energy output under the operating conditions. According to IEC standard, two important parameters, e.g. system energy yield and system performance ratio (PR), are implemented to evaluate and compare the performances of PV systems [6]-[8] and are defined in terms of

$$\text{system energy yield} = \frac{\text{system energy ouput}\,(kWh)}{\text{installed power capacity}\,(kW_p)} \quad (1)$$

and

$$\text{system Performance Ratio}(PR) = \frac{\dfrac{\text{system energy ouput}(kWh)}{\text{installed power capacity}(kW_p)}}{\dfrac{\text{in-plane actual irradiation}(kWh)}{\text{reference irradiance}(kW)}} \quad (2)$$

The solar irradiance falling on the solar PV systems was measured by the pyranometer installed at the PV test-bed and acquired by the data logger every 5 minutes. Based on the collected data from March 2010 to Feb 2011, the monthly solar irradiation for analyses on the PV systems under testing can be figured out. The irradiations in each month at the test-bed are presented in Fig. 5. Two high peak radiation periods occurred around March and September respectively, while two low radiation peaks around June and December respectively. The measured results nicely match with the theoretical radiation changes on the Equator caused by the motion of the Earth around the Sun. Based on the data captured by the pyranometer in a year; the average daily solar irradiation is 4.05kWh/m^2/day. The average daily performance analyses given below refer to the measured irradiations on the site of PV test-bed.

The PV test-bed was set up and completed in Feb. 2010. Since then, all PV systems installed in the test bed have been operating reliably and maintaining stable energy output to the power grid. The operation of PV systems were monitored by measuring solar energy input, DC inputs to the inverter (voltage, current, power & energy) and AC outputs to grid (voltage, current, power & energy). The software program was developed to process the operational data for evaluating the system performances.

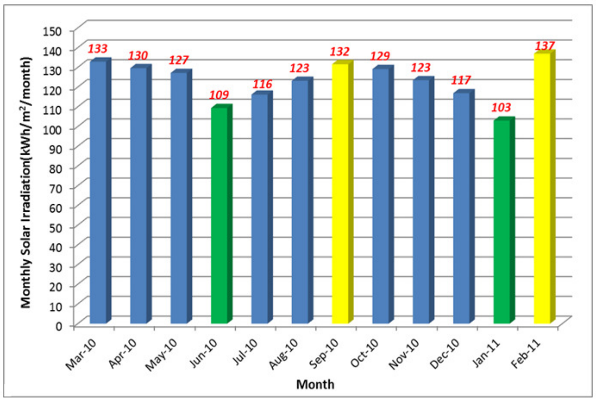


Fig. 5 Solar irradiations measured at the solar PV test-bed

The performance of each PV system is depicted by its energy yield and performance ratio (PR) that are defined in (1) and (2) respectively. The energy yields and PRs of all nine PV systems are calculated and presented in Figs. 6 and 7. It is noticeable that system energy yields change from 2.67kWh/kW$_p$ (Uni-Solar triple junction a-Si module) to 3.36kWh/kW$_p$ (Sanyo bifacial HIT module) and the system PRs range from 70% (Uni-Solar triple junction a-Si module) to 88% (Sanyo bifacial HIT module). Based on our experiments, all PV systems except triple junction a-Si have the PR values higher than 75%. The better performance of bifacial HIT modules results from additional radiation reflected from the ground to the cells on its back side. As for the mono-facial PV system, Mitsubishi single junction a-Si has the best performance.

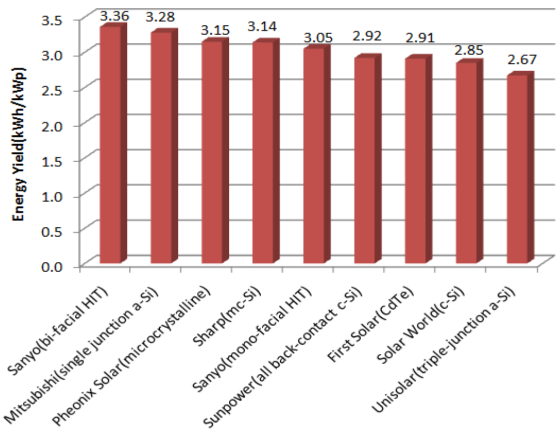


Fig. 6 Energy yields of 9 PV systems

TABLE II
TECHNICAL DATA OF NINE PV MODULES UNDER TESTING

No	PV module brand	producer	P_{max} (W_p)	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)	Voltage Temp coeff	Efficiency (%)
1	HIT-205NKHB1 (mono-facial HIT)	Sanyo	205	40.7	5.05	50.3	5.54	-0.126V/deg	16.4
2	ES-124 (triple junction a-Si)	Unisolar	124	30	4.1	42	5.1	-0.16V/K	6
3	HIT-200DN2-1 (bifacial HIT)	Sanyo	200(F) 140(B)	40.7	4.92	50.3	5.40	--	--
4	ND-120T1D(mc-Si)	Sharp	120	17.1	7.02	21.3	7.81	-0.082V/deg	12.1
5	SW175(c-Si)	Solar world	175	35.4	4.95	44.6	5.43	-0.29%/K	13.26
6	FS-275(CdTe)	First solar	75	69.4	1.08	92	1.20	-0.25%/deg	10.0
7	MA100T2(single junction a-Si)	Mitsubishi	100	108	0.93	141	1.17	-0.33%/K	6.35
8	PHX-90 (microcrystalline)	Pheonix solar	90	49.30	1.83	62.50	2.11	0.30%/K	8.5
9	SPWR-215(back contacts c-Si)	Sunpower	215	39.8	5.40	48.3	5.80	-0.1368V/deg	17.3

IV. CONCLUSIONS

The nine types of different PV modules have been tested at the PV test-bed set up in Singapore Polytechnic since March 2010. This paper presents the analytic results arising from site operational data in a year. It shows the performance ratios of nine PV systems under testing vary from 70% of PR to 88% of PR and their energy yields range from 2.67kWh/kW$_p$ to 3.36kWh/kW$_p$. Among nine PV systems, 8 PV systems except Uni-solar triple-junction a-Si PV system have their PRs higher than 75%. The annual experiments on nine PV systems conclude that the PV systems are able to maintain reliable operation in tropical area and provide satisfactory performance under the tropical weather conditions.

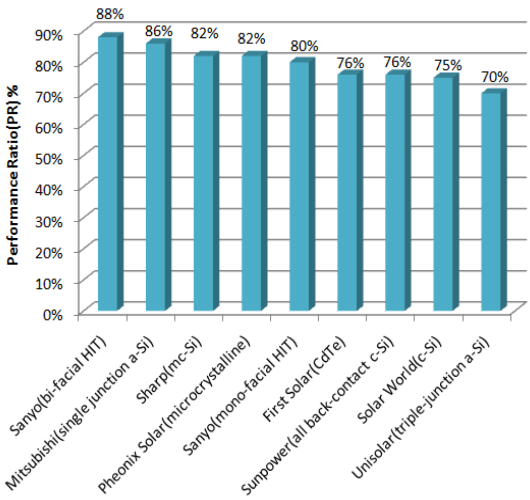


Fig. 7 Performance ratios (PR) of 9 PV systems

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