Assessment of Operation and Performance for Grid-connected PV Systems

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Introduction

The performance ratio (PR) has been used to compare PV modules operating in different environments, but it does not provide enough information to understand the performance variability. Current modelling tools provide additional insights if the module reference data set is available, but there are still uncertainties in terms of the effects of spectral energy, angle-of-incidence and degradation [1]. A PV test platform, commissioned on the island of Maui in February 2016, has been used to conduct side-by-side comparison of 15 grid-connected PV systems and 10 different PV modules. A new energy rating analysis is proposed to elucidate the performance differences between PV modules which can lead to better match the PV technology to the environment.

Objectives

Develop an improved energy rating analysis
- to better understand performance differences between PV technologies
- to differentiate the effects of the operating conditions from environmental conditions without complex modelling

Methods

Test Protocols:
- 15 PV systems including 10 PV technologies and 3 system architectures (Table 1, Fig. 1)
- IV tracer collecting IV curves on each individual PV module providing detailed module performance and short-circuit current used to calculate the optical performance
- High accurate, high resolution monitoring and data acquisition system

Fig. 1: PV test platform commissioned in February 2016 in Kihei, Maui. Lat: 20.7ºN, Long:156.4ºW, Alt: 60 meters, Tilt: 20º, Azim: 197ºN

Energy rating analysis: (Equations)
- Performance ratio (1) dissociated into current (2) and voltage (3) performance: $\mathrm{PR} \approx \mathrm{IP} \times \mathrm{VN}$
- Optical performance IP_{SC} (4) calculated from short-circuit current (I_{SC}), includes spectral and temperature effects [2]
- Daily performance calculated using dataset with angle-of-incidence below 70º (high accuracy of solar sensors)
- Irradiance (G) measured with a secondary standard pyranometer
- Solar spectrum monitored by a spectroradiometer to determine the average photon energy (APE)

Equations

1) Performance Ratio

$$\mathrm{PR} = \frac{\int_{\Delta t} P_{PV} \cdot dt}{P_{MP,STC}} \times \frac{G_{STC}}{\int_{\Delta t} G \cdot dt}$$

2) Voltage Performance

$$\mathrm{VN} = \frac{\overline{V_{PV}}}{V_{MP,STC}}$$

3) Current Performance

$$\mathrm{IP} = \frac{\int_{\Delta t} I_{PV} \cdot dt}{I_{MP,STC}} \times \frac{G_{STC}}{\int_{\Delta t} G \cdot dt}$$

4) Optical Performance

$$IP_{SC} = \frac{\int_{\Delta t} I_{SC} \cdot dt}{I_{SC,STC}} \times \frac{G_{STC}}{\int_{\Delta t} G \cdot dt}$$

P_{PV}, V_{PV}, I_{PV} operating power, voltage, and current of the system or module
$P_{MP,STC}$, $V_{MP,STC}$, $I_{MP,STC}$, $I_{SC,STC}$ datasheet specifications at standard test conditions (STC)

Table 1: Description of the grid-connected PV systems in operation at MEDB, Maui. PV modules and auxiliaries (inverters, optimizers, microinverters).

PV type	PV technology	Rated power [W]	η [%]	# of PV	Auxiliaries	System label
S1	Standard p-type polycrystalline	250	15.4	2	Micro1 (2)	S1M
S2	Standard p-type polycrystalline	250	15.2	2	Micro1 (2)	S2M
S3	Standard p-type polycrystalline	260	15.5	8	Micro1 (8)	S3M
				8	String1 (1), Optimizer1 (8)	S3O
				8	String2 (1)	S3S
S4	Standard p-type monocrystalline	265	16.5	2	Micro1 (2)	S4M
H1	High efficient n-type monocrystalline with heterojunction intrinsic thin layer (HIT)	240	19.0	8	Micro2 (8)	H1M
				8	String2 (1)	H1S
H2	High efficient n-type monocrystalline with rear contact	245	19.7	8	Micro2 (8)	H2M
				8	String2 (1), Optimizer2 (4)	H2O
				8	String2 (1)	H2S
H3	High efficient n-type monocrystalline, Bifacial Hybrid Cell Technology	300	18.2	2	Micro2 (2)	H3M
C1	Copper indium gallium selenide (CIGS)	145	13.3	10	String2 (1)	C1S
C2	CIGS	170	13.8	8	String2 (1)	C2S
D1	Cadmium telluride (CdTe)	77.5	10.8	18	String2 (1)	D1S

Results

- Mostly sunny environment, high spectral energy (APE), warm ambient temperatures (AT) (Table 2)
- Low seasonal variation due to location and orientation of PV test platform (Fig. 2-a and 2-b)
- Current performance (IP) increases in overcast conditions and decreases in case of soiling and shading (Fig. 2-e)
- IP proportional to optical performance
- Voltage performance (VN) sensitive to AT, ≈ thermal performance (Fig. 2-d)
- $\mathrm{PR} \approx \mathrm{IP} \times \mathrm{VN}$ (Fig. 2-c), difference between PR and $(\mathrm{IP} \times \mathrm{VN})$ < 1%
- Similar module performances for all crystalline PR 86-92%, VN 87%-93%, IP 95-100% (Fig. 4)
- High IP 104% for CdTe, VN 92%, PR 95%

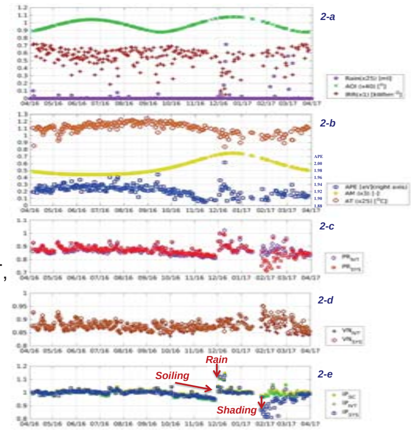

Fig. 2: Variation of the environmental conditions (a, b) and of the daily performances (c: PR, d: VN, e: IP) for a PV system (S3S) and module (S3) during the first year of operation (April 2016 – March 2017).

- High VN >96% for both CIGS but different IP (C1 90%, C2 98%) and PR (C1 88%, C2 97%)
- Comparison system and module performances: Normalization error[2], system losses, differing operating conditions (soiling, shading)

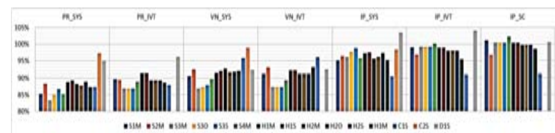

Fig. 4: First-year average performances (PR, VN, IP, and IP_{SC}) of all PV systems (SYS) and PV modules (IVT)

Table 2: Yearly average environmental conditions

Parameters	Irradiation	AT	APE[1]
Unit	$kWhm^{-2}$	ºC	eV
Average	5.6	27.5	1.92
Standard deviation	1.1	1.9	0.02

[1] APE_{STC} = 1.88 eV
[2] Normalization error relative to non-uniform performances of PV modules with same datasheet specifications

Conclusions

New energy rating analysis :
- Provides insights on optical and thermal performances
- Current performance helps differentiate the effects of the environmental and operating conditions and can support spectral effect analysis

PV performances in Maui:
- Thin films outperforming crystalline modules [3, 4] due to high current performance for CdTe and high voltage performance for CIGS
- Small performance difference between standard and high efficient crystalline modules
- Significant performance difference between CIGS. Low performer exhibits low optical performance and low current performance in overcast conditions

Next: Impact of environmental conditions on PV performances and identification of best PV technologies to specific environmental conditions

References

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