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Task 6. PHOTOVOLTAICS EVALUATION

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PHOTOVOLTAICS EVALUATION

Solar photovoltaic (PV) performance is dependent on cell materials, module design, inverter technology and integration, and environment (solar radiation, temperature, cloud shadowing, etc.). The intent of this project, which is a continuation of previous ONR-funded work in this area, is to characterize performance and durability of different PV and inverter technologies under differing environmental conditions. Data has been gathered on PV system performance and environmental factors at a variety of installations around Hawaii using several manufacturers’ products and system architectures. The PV systems under test represent grid-connected, residential and small-scale commercial systems.

The project leverages work completed under US Department of Energy (US DOE) funding (DE-FC26-06NT42847 and DE-EE0003507) that included the installation of three PV test platforms located on Hawaii Island, Maui and Oahu, the development of a first-generation data acquisition system (DAS), and critical data management and analysis tools. Results of these efforts were reported in [1] for PV test platforms and test protocols and in [2] for the data management and analysis tools, as well as analysis of two years of data. Under ONR HEET09 [3], two additional test locations were completed on Oahu and Kauai, hosting grid-connected PV systems on Hawaii Project Frog classrooms, and two-year performance results were analyzed for the Oahu site. Test locations were developed to host new combinations of PV systems and a new DAS was designed to streamline long-term monitoring of grid-connected PV systems. This work has created a framework of knowledge on PV test platform design, installation, testing, instrumentation and data analysis methodologies.

Accomplishments under ONR HEET10 funds fall in the following four categories:

1. Development of test protocols and data collection methodologies for new test instrumentation.
2. Installation of a carport-based PV test platform in South Maui.
3. Advancement of data analysis tools, including an innovative dissociation of DC performance ratio (PR) into current and voltage performance.
4. Detailed analysis of a month of performance data from the Maui site and a year of data from UH Manoa.

Acronyms used herein are listed in a summary table at the end of this report.
6.1 Development of test protocols and data collection methodologies

Based on earlier research, a variety of new instrumentation and test equipment was deemed necessary for inclusion in the new test platform on Maui. This included new sensors for measuring incident solar radiation (a spectroradiometer and pyranometer), an IV tracer, an AC power meter, and a switching mechanism that allows measurement of open circuit voltage and short circuit current. These instruments were initially installed at the UH Manoa campus test site – on the roof of Holmes Hall – to develop test protocols and refine data management tools necessary to collect the datasets and transfer them to the data server. This site was originally developed as part of a program called the Green Holmes Hall Initiative, and will thus be referred to as GHHI. In the process of these developments, approximately one year of environmental conditions and performance data were collected for the two grid-connected PV systems at GHHI. IV curves were collected for both PV technologies. Analysis of these data will be presented in Section 6.4.

New sensors: Spectroradiometer, Diffuse/Global pyranometer

To enhance the level of data available on incident solar radiation, a critical element in understanding PV performance, a spectroradiometer and a masked pyranometer were installed. These devices measure the light spectrum and irradiance distribution between direct and diffuse light. An EKO MS-700 spectroradiometer and a Delta-T SPN1 Sunshine pyranometer were selected for their ability to operate in remote areas and in the plane of the PV modules. Both sensors were installed at GHHI and integrated into the DAS (Figure 6.1). The sensors were tested for software and hardware stability. The spectroradiometer uses a shutter, resulting in a full reading taking from 0.5 up to 10 seconds, depending on the overall irradiance. It then uses serial communication to send data to the on-site DAS controller. To ensure a constant sampling rate and to minimize risk of overwriting data, the spectroradiometer was programmed to take readings every 15 seconds. The global/diffuse pyranometer produces analog signals for both the global and diffuse irradiance. These signals are converted to digital, collected at 40Hz and averaged to 1Hz by the controller.
**IV Tracer**

We utilize an IV tracer to collect complete performance characteristics (IV curves) of individual PV modules, which in turn allows the quantification of that performance in the absence of system losses (such as those due to operation of PV modules with inverters and optimizers or due to combining PV modules in strings (mismatch loss)). An IV tracer with multiple inputs, the Daystar Multi-tracer, was selected and installed at GHHI (Figure 6.2) to test its operation in a semi-protected outdoor environment. A structure was built that suspends the IV tracer load bank and control unit beneath the existing solar array. This was done to protect the top of the unit from sun and rain while at the same time ensuring that the unit would not damage the roof. A more permanent outdoor cabinet was used for the eventual test location in Maui (Figure 6.2 - right). Programmed Cron jobs were developed to automate the transfer of data files from the IV tracer to the HNEI data server via secure VPN.
Figure 6.2: IV tracer installed on the rooftop of GHII (left) and at the Maui test site in a weather-tight outdoor cabinet (right).

**AC power meter**

An AC power meter was used to compare the AC performance of the grid-connected PV systems and evaluate the efficiency and reliability of the inverters and optimizers. The Electro Industries MP200 AC Power meter was selected to measure inverter output. The meter is designed to measure eight 3-phase systems, and each phase can be individually monitored for a total of 24 single-phase systems. It was configured to monitor the output of eleven PV systems operating at the Maui test platform, gathering information (AC active and reactive power, voltage and current) on ten single-phase inverters and one 3-phase microinverter system. DAS software and data management tools were developed to collect these AC measurements and transfer the data to the UH server.

**Switching: DAS ability to measure $I_{SC}$ and $V_{OC}$**

DC measurement boxes were developed to measure PV system or module performance in normal operation (i.e., connected to the grid). These boxes are designed to collect one-second DC voltage, DC current, voltage-to-ground, back-of-the-module temperature, and an auxiliary DC voltage selected to allow connection of analog sensors such as pyranometers. Essential parameters for evaluating optical and thermal performance of modules are short-circuit current ($I_{SC}$) and open-circuit voltage ($V_{OC}$). Although these are routinely monitored by the IV tracer, additional instrumentation was developed and integrated with the DAS to measure these parameters without the need for an IV tracer, to reduce hardware costs for future test platforms.
At fixed intervals, switches disconnect the PV module from the microinverter, measure $V_{OC}$ and $I_{SC}$, and reconnect, within approximately 15 milliseconds. This feature was tested and validated at the UH Manoa test site on two polycrystalline PV modules operating with Enphase microinverters.

6.2 Installation of the Maui Test Platform

Planning for a PV test bed located at the Maui Economic Development Board (MEDB) has been underway for several years. Issues related to the approval for interconnection of this system by the local utility have caused substantial delays, but the permit for installation was issued on November 17, 2015. Planning and design considerations for this test platform were presented in the HEET09 report [3]. The installation of the PV systems began in January 2016, and was completed by HNU Energy under subcontract to MEDB. Under HEET10, HNEI personnel installed the DAS and provided guidance to the PV installer. The PV system, including modules, inverters, DAS and IV tracer was commissioned on February 4, 2016.

Test platform description

The test platform is located on a carport at the MEDB in Kihei, South Maui (Figure 6.3). The platform consists of 15 grid-connected PV systems rated to up to 2kW each, selected to provide side-by-side comparison of 10 PV module brands/types and 3 system architectures – string inverters, string inverter with optimizers, and microinverters. The full carport-based test platform consists of 108 modules and 10 inverters, comprising a total power of 22 kW. The carport roof is at an angle of 20°, facing 197°N azimuth – slightly west of due south. The latitude, longitude and altitude of the test site are 20.7°N, 156.4°W and 60 meters, respectively.
Figure 6.3: HNEI PV test platform commissioned in February 2016 in South Maui.

Table 6.1 provides the description of the PV systems, including PV manufacturer, model number, maximum power and efficiency at standard test conditions (STC), the number and technology of the PV modules, and the auxiliaries (inverters and optimizers) used with each. The last column in the table indicates the acronym used for each PV system in the analysis section, with the first 2 letters indicating the PV module technology and the last letter the system architecture (M: microinverter, S: String, O: string with optimizers).

One module of each brand/type is tested individually with the IV tracer. Performance results for those modules are reported with the first 2 letters of the acronym indicating the PV module technology and the last letter denoting the IV tracer, (I).

Table 6.1: PV systems in operation at the Maui PV test platform, South Maui.

<table>
<thead>
<tr>
<th>PV Panels</th>
<th>Rated Power [W]</th>
<th>η [%]</th>
<th>PV Technology</th>
<th># of PV Auxiliaries</th>
<th>Acronym</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET Solar ET-P660250BB</td>
<td>250</td>
<td>15.4</td>
<td>Polycrystalline</td>
<td>2</td>
<td>Enphase M215-60-2LL-S22/S23 (2) ETM</td>
</tr>
<tr>
<td>Model</td>
<td>Efficiency</td>
<td>Voltage</td>
<td>Type</td>
<td>Inverter Type</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------------</td>
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<td>---------------</td>
<td>---------------------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>First Solar FS-377 (2/9)</td>
<td>77.5</td>
<td>10.8</td>
<td>Cadmium telluride (CdTe)</td>
<td>Sunny Boy SMA-2000HF (1)</td>
<td>FSS</td>
</tr>
<tr>
<td>Kyocera KD245GX-LFB</td>
<td>245</td>
<td>14.6</td>
<td>Polycrystalline</td>
<td>Enphase M215-60-2LL-S22/S23 (2)</td>
<td>KYM</td>
</tr>
<tr>
<td>LG LG255S1C-G3 MONO</td>
<td>255</td>
<td>15.5</td>
<td>Monocrystalline</td>
<td>Enphase M215-60-2LL-S22/S23 (2)</td>
<td>LGM</td>
</tr>
<tr>
<td>Panasonic VBHN240SA06</td>
<td>240</td>
<td>19.0</td>
<td>Monocrystalline, n-type with heterojunction intrinsic thin layer (HIT)</td>
<td>ABB MICRO-0.25-I-OUTD-US-208 (8)</td>
<td>PAM</td>
</tr>
<tr>
<td>Solar Frontier SF170-S (2/4)</td>
<td>170</td>
<td>13.8</td>
<td>Copper indium gallium selenide (CIGS)</td>
<td>Sunny Boy SMA-2000HF (1)</td>
<td>SFS</td>
</tr>
<tr>
<td>Solarworld SW260 POLY</td>
<td>260</td>
<td>15.5</td>
<td>Polycrystalline</td>
<td>Enphase M215-60-2LL-S22/S23 (8)</td>
<td>SWM</td>
</tr>
<tr>
<td>Sunpower SPR-245NE-WHT-D</td>
<td>240</td>
<td>19.7</td>
<td>Monocrystalline, n-type, rear contact</td>
<td>ABB MICRO-0.25-I-OUTD-US-208 (8)</td>
<td>SPM</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sunny Boy SMA-2000HF (1)</td>
<td>SPO</td>
</tr>
</tbody>
</table>
A sequence of photographs of the test platform, taken during installation, is shown in Figure 6.4. These include (a) the string inverters, AC monitoring, internet connection hardware and HNEI DAS controller, (b) the IV tracer cabinet with conduits to carry DC cabling to the PV modules tested individually, located southeast of the carport, (c) the weather station and solar sensors and, (d) the DC measurement boxes located below the PV modules on the underside of the carport.
Figure 6.4: The Maui PV test platform during installation, including string inverters, HNEI AC instrumentation, internet connection hardware and DAS controller (a), the IV tracer (b), the weather station and solar sensors (c) and the DC measurement boxes located below the PV modules (d).

Data from the DC measurement boxes, weather station, spectroradiometer, AC monitoring, and IV tracer are collected by the DAS controller. On commissioning, operation of the data management system was verified, such that data files are transferred automatically to the server at UH Manoa through a safe VPN connection. In the initial weeks after commissioning, a slight time-synchronization issue was discovered in the recorded data. This was corrected on April 2, 2016. The analysis in Section 6.4 focuses on one month of data collected immediately following this correction.

A manual for the DAS was written to document its features, theory of operation, and a description of the hardware and software. Standard Operating Procedures (SOPs) were developed to ensure all PV systems and DAS maintenance is conducted safely, with emphasis on electrical equipment and working safely at height.

Maintenance and Calibration

Regular site visits will be conducted for maintenance of PV systems and calibration of the DAS. During an upcoming visit, HNEI will also conduct tests and troubleshooting guided by observations from the first months of data analysis, and initiate the collection of $I_{_{SC}}$ and $V_{_{OC}}$ with the DAS, as described previously.

In order to ensure data quality, the maintenance plan includes re-calibration when necessary, in accordance with detailed HNEI procedure. Each measurement box is calibrated individually using custom-built calibration equipment. When complete, new calibration coefficients are entered into the DAS controller. All data points from the calibration process are archived for long-term analysis of measurement drift. The calibrator (Figure 6.5) works with two power supplies, each generating different levels of known voltages and currents and applying them to the inputs of a measurement box. The hardware is capable of simulating a voltage input of -650V to +650V, a current input up to 10 A, and a temperature sensor. Internal relays in the calibrator connect and disconnect these inputs in sequence to automate the calibration process. A computer is connected to store the applied signal and the signal read by the measurement box. These data are used to calculate a scaling factor and offset used for conversion from signal to measurement.
Figure 6.5: The custom built calibrator, with a) front view showing connection plate, digital multimeter and two power supplies, and b) its portable cabinet to facilitate use at multiple locations.

An early maintenance issue discovered after system commissioning was an apparent problem with one of the PV modules. The Solar Frontier module connected to the IV tracer showed signs of operating issues. This module will be inspected and replaced, if necessary.

A second issue that will be investigated in the near future is the power factor (PF) measured on PV systems using single-phase inverters (10 systems – from SMA, SolarEdge and ABB). These systems have a PF of 0.86, while the 3-phase microinverter system (Enphase) has a PF close to 1, as expected by datasheet specifications. Tests will be conducted to individually operate each single-phase PV system, in order to evaluate whether the low PF is related to the interaction of multiple PV systems on the same electrical panel.

Shading analysis

The Maui Brewing Company, located on the property immediately south of the PV test platform, is planning to install a large PV system in their parking lot. The proposed PV system consists of five carports, two of which will cause some degree of shading on the HNEI test platform. Based on preliminary assessment of development plans and topography (the brewery site is approximately 8 feet higher than the MEDB site), the new carports will partially shade the test platform during the months of October through March. This would not only affect power production of the test system, but also add unfortunate complexity to future data analysis. Shading analysis was done with Sketchup, a freeware 3D visualization tool. CAD models of relevant structures were built and placed in the locations indicated in the brewery carport plan.
The view of the two proposed carports expected to shade the test platform is shown in Figure 6.6. Although HNEI is not aware of current laws that would preclude construction of these carports in the specified locations, HNEI and MEDB are working with Maui Brewing in hopes of minimizing this impact.

Figure 6.6: Initial shading analysis in Maui Brewery’s planned PV installation.

6.3 Advancement of Data Analysis Methodology

Innovative approaches to PV performance data analysis were developed to enhance the value of the data collected at the Maui and GHHI sites, and others around the state. Two of these are discussed here as they relate to the results presented in Section 6.4. First, data are binned according to angle of incidence (AOI), allowing for direct comparison of results from different locations. Second, an important aspect of the HNEI approach to performance analysis is to separate the DC performance ratio (PR), typically used in the literature, into current and voltage performance, primarily to isolate optical from thermal performance. This methodology is discussed here, and, will be described in detail in an upcoming journal article.

Matlab tools were developed to extract data from files on the UH server to develop a database of parameters of interest. NetCDF [4] format, which supports the creation, access, and sharing of array-oriented scientific data, was utilized for this database. From the raw data, parameters of interest were developed, such as DC power of each module, string and system calculated from current and voltage measurements, AC power produced by each PV system evaluated from selected per-phase power measurements, and direct beam (DB) irradiance (difference between
global (G) and diffuse (DF) irradiance. Information related to sun position (calculated as in [5]) is also added to the database, including the angle-of-incidence (AOI) (the angle between the normal to the PV modules and the sun direction), the air mass (AM) (the thickness of the atmosphere crossed by the sun’s rays), and the top-of-the-atmosphere irradiance estimated in the plane-of-array (XTRPOA), which leads to the clearness index (CI) using equation (1). Data collected by the spectroradiometer is analyzed and the solar spectrum characterized using the average photon energy (APE) index, calculated as in equation (2), by dividing the integrated incident spectral irradiance by the integrated photon flux density [6].

\[
CI = \frac{G}{XTR_{POA}}, \quad APE = \frac{\int_a^b G(\lambda) d\lambda}{q \int_a^b \Phi(\lambda) d\lambda},
\]

CI is the clearness index; G is the global irradiance collected in the plane-of-array (POA), measured by the thermopile pyranometer [Wm\(^{-2}\)]; XTRPOA is the top-of-the-atmosphere irradiance estimated in the POA [Wm\(^{-2}\)]; APE is the average photon energy [eV]; \(\lambda\) is the wavelength of the light [nm]; \(G(\lambda)\) is the incident spectral irradiance for a specific wavelength [Wm\(^{-2}\)nm\(^{-1}\)]; q is the electronic charge [=1.6e\(^{-19}\) C]; \(\Phi(\lambda)\) is the incident spectral photon flux density for a specific wavelength [m\(^2\)s\(^{-1}\)nm\(^{-1}\)]; a, b, are the upper and lower wavelength limits of the measured spectrum relative to the spectroradiometer wavelength sensitivity [nm].

Diurnal and daily analysis

A useful means to examine diurnal changes in PV performance is to average the results by angle of incidence (AOI). For each recorded day, data were analyzed as follows:

1. Full day averages – including only data with AOI<70\(^{\circ}\) to limit error due to directional response of the solar sensors. These data are used as the daily average values of various performance parameters. Monthly and yearly values are calculated using these daily values.

2. Binned by AOI – to examine the variation of the diurnal cycle, data are binned by AOI from 0\(^{\circ}\) to 70\(^{\circ}\) using 10\(^{\circ}\) bins (except for the first interval from 0\(^{\circ}\) to 5\(^{\circ}\), then every 10\(^{\circ}\) from 5\(^{\circ}\) to 75\(^{\circ}\)). Results were calculated dissociating mornings from afternoons, using as midday the time when sun direction is closest to normal to the PV surface. These bins correspond to periods of time that vary from 20 to 40 minutes depending on AOI and time of the year.

AOI is a useful binning parameter because it allows analysis of PV loss due to reflection [7] and because it allows a characterization of performance that is independent of PV module orientation and location. The top-of-the-atmosphere solar resource (XTRPOA), used in the calculation of CI (equation 1), increases with decreasing AOI (higher sun angle) and is constant at fixed AOI over the course of the year. The CI per AOI, as a function of global irradiance G, collected at GHHI in 2015, is shown in Figure 6.7. Morning values are shown in cool colors and afternoon in warm colors. The daily averages are represented with black crosses. G is generally increasing with
decreasing AOI. At fixed AOI, CI increases when G increases, which is also generally true in the daily averages. The analysis per AOI allows the addition of a dimension (CI) to the plots presented in the next section, in which various parameters are plotted as a function of G. As will be shown below, there is high correlation between CI and spectral energy. Further, plotting per AOI provides a helpful visualization of operating conditions, such as potential operating issues related to the inverter.

Figure 6.7: Clearness index CI per angle of incidence AOI as a function of global irradiance G at UH Manoa test site for the full year 2015.

Performance Ratio, optical and thermal performance

For each period of analysis, the average for all measured and computed data is calculated, and the irradiance, power and current are integrated over time to calculate the energy collected. The following methodology focuses on the DC performance of the PV modules. The solar energy received by the PV modules during a certain period of time is referred to as solar yield [Wh/m²]. The energy produced by the PV modules is often referred to as PV yield [Wh]. From the energy results, the performance ratio (PR) and the current performance (IP) are calculated using equations (3) and (4) below. The PR relates the module’s operating efficiency to the theoretical efficiency indicated in the manufacturer’s specifications, evaluated at STC. PR is calculated by dividing the PV energy yield by the solar yield, both normalized to STC (3). The current performance IP is calculated similarly, except that PV current, rather than power, is integrated (4). The average operating voltage is divided by the STC maximum point voltage for the PV
system to obtain the normalized voltage VN, also referred to as voltage performance (as shown in equation (5)).

\[
PR = \frac{Y_{PV}}{P_{MP,STC}} \times \frac{G_{STC}}{Y_{SUN}} \quad \text{with} \quad Y_{PV} = \int_{\Delta t} P_{PV} \cdot dt \quad \text{and} \quad Y_{SUN} = \int_{\Delta t} G \cdot dt,
\]

\[
IP = \frac{\int_{\Delta t} I_{PV} \cdot dt}{I_{MP,STC}} \times \frac{G_{STC}}{\int_{\Delta t} G \cdot dt}, \quad (4)
\]

\[
VN = \frac{V_{PV}}{V_{MP,STC}}. \quad (5)
\]

PR is the DC performance ratio of the PV module or system; \(Y_{PV}\) and \(Y_{SUN}\) are the PV and solar yield, [Wh] and [Whm\(^{-2}\)] respectively, the energy calculated integrating the power of the PV modules \(P_{PV}\) [W] and the irradiance \(G\) measured by the thermopile pyranometer [Wm\(^{-2}\)] for the period of analysis \(\Delta t\) [hour]; \(IP\) is the current performance calculated integrating the operating current \(I_{PV}\) [A] over the period of analysis and divided by the STC current at maximum power \(I_{MP,STC}\) [A] and by the normalized solar yield; \(VN\) is the normalized voltage evaluated averaging the operating voltage \(V_{PV}\) [V] over the period of analysis normalized by the STC maximum power voltage \(V_{MP,STC}\) [V].

For PV modules tested individually with the IV tracer, additional electrical characteristics, \(V_{OC}\) and \(I_{SC}\), are monitored. This information will soon also be available for PV modules operating with microinverters, due to the previously discussed switching capabilities of the DAS. As with the calculation of current performance (IP) and normalized voltage (VN) at the maximum power point, \(IP_{SC}\) and \(VN_{OC}\) are calculated as follows:

\[
IP_{SC} = \frac{\int_{\Delta t} I_{SC} \cdot dt}{I_{SC,STC}} \times \frac{G_{STC}}{\int_{\Delta t} G \cdot dt}, \quad (6)
\]

\[
VN_{OC} = \frac{V_{OC}}{V_{OC,STC}}. \quad (7)
\]

where \(IP_{SC}\) is the short-circuit current performance calculated integrating the short-circuit current \(I_{SC}\) [A] over the period of analysis \(\Delta t\) [hour] and divided by the STC short-circuit current \(I_{SC,STC}\) [A] and by the normalized solar yield; \(VN_{OC}\) is the normalized \(V_{OC}\) calculated averaging the open-circuit voltage \(V_{OC}\) [V] normalized by the STC open-circuit voltage \(V_{OC,STC}\) [V].

For all of these performance parameters, the specifications indicated in the manufacturer's datasheet were used for normalization. This means that the analysis results include the normalization error due to slight differences between the actual performance of each PV module and the specifications from the datasheet. Each PV module has a unique performance that is
determined during the manufacturing process and is evaluated by the manufacturers. The STC flash test results (FTR) of each individual PV module are usually available upon request. The FTR were collected for each PV module in test at MEDB, averaged per PV system, and compared to the datasheet specifications, leading to a normalization error estimated at ±4%. Unfortunately, one PV manufacturer did not share the FTR and another has no results on the \( I_{SC} \) and \( V_{OC} \). Thus, to provide information on all tested PV systems and modules, the performance results normalized by FTR (which limits the impact of normalization error) are not presented in the analysis contained in Section 6.4.

In our approach, the DC performance ratio (PR) was split into current performance (IP) and normalized voltage (VN). The difference between PR and the product of IP and VN was estimated to be below 1% for all periods of analysis. This small difference is a result of the small variation of the voltage in comparison to the current during the periods of analysis, even when considered on a daily basis. The IP is highly correlated to the \( I_{SC} \) as shown in the following section. The \( I_{SC} \) provides the average values of \( I_{SC} \) that characterize the optical performance of the PV modules, which is sensitive to the intensity, incident angle and spectral content of the irradiance, temperature, soiling and shading [8, 9]. In the analysis that follows, results from the PV systems and modules tested in Maui and Oahu are presented in terms of DC performance, including PR, VN, IP and its correlation with \( I_{SC} \), as these parameters relate to PV module brand/type and operating conditions. This approach allows improved understanding relative to earlier methods by isolating optical from thermal performance.

### 6.4 PV System Performance Analysis

The instrumentation and analysis techniques discussed in preceding sections were used to characterize the diurnal and day-to-day variation of the environmental conditions and resulting DC performance of the PV systems. The DC performance of grid-connected PV systems is affected by the performance of the PV modules and by system losses related to combining PV modules into strings (mismatch loss), and potential operating issues with the inverters or optimizers. A diagnostic approach was taken to calculate system losses by comparing the performance of grid-connected systems to unconnected modules, tested individually with the IV tracer. Results are presented below for the PV test platform in Maui, as well as for a one-year dataset from UH Manoa. These results form the basis of a journal article now in preparation, as well as a recently completed UH Master’s thesis [10].

Performance Analysis from Maui Test Site

Results presented here are for the month of April 2016 (including 25 days beginning after correction of a data time sync issue). The analysis focuses initially on the diurnal variation of PV
performance, followed by monthly averages, detailing PR, VN, IP and its relationship to IPsc, to examine performance differences between PV technologies in varying operating conditions. The impact of system loss, especially loss due to operating issues in which microinverters limit maximum module power output at high irradiance, is examined.

Diurnal performance variation

The DC performance of the Cadmium Telluride (CdTe) PV system, as an example representative of the results obtained for all PV modules and systems at the test site, without the issue of inverter saturation, is shown in Figure 6.8. PR, IP and VN are plotted versus G. In addition, VN is plotted as a function of AT. The graphs indicate the performance calculated per day, per AOI, differentiating morning (cool colors) and afternoon (warm colors) performance. Daily performance (black crosses) shows the variability among analyzed days during the period (April 2016).

DC PR of the CdTe PV system, as a function of G, is shown in Figure 6.8a. G is generally increasing with decreasing AOI, as seen previously in Figure 6.7, which also showed that at fixed AOI, CI increases with increasing G. The PR values are highly distributed, ranging between 83% and 107%. The PR is lower in the mornings than in the afternoons, especially for AOI above 55°. The daily average PR is distributed between 94% and 101%. Performance numbers above 100% are possible, since PR is computed according to values specified by the manufacturer at STC. In addition to normalization error, actual environmental conditions differ from STC.

IP, binned by AOI, as a function of G, is shown in Figure 6.8b. IP is lower in the morning than in the afternoon. At fixed high AOI, IP tends to decrease with increasing G or CI. Daily IP values vary within a small range between 102 and 105%. IP behavior is very similar to that of PR, binned by AOI. IP varies by more than 25% during the day, and is largely responsible for lower PR in the mornings than the afternoons.

Subsequent plots show the VN versus G (Figure 6.8c) and AT (Figure 6.8d). VN generally decreases with increasing G. VN decreases with increasing AT at all AOI except for a few VN values recorded at low irradiance below 0.15 kWm⁻². Daily VN varies most notably with changing AT, with values ranging between 92 and 98%. VN shows less diurnal variability than IP, at around 10-12%. In addition to diurnal variation in irradiance, other environmental conditions change during the day, with a tendency to higher CI and DB, lower DF and lower AT in the mornings, as compared to the afternoons. These changing atmospheric conditions explain the variation of IP, and therefore PR, during the day and are a focus for future investigation. Variability in daily average performance shows a trend opposite to diurnal variation, with a very small range in IP values (3%) and larger range in VN (7%).
IP is highly correlated to $IP_{SC}$ and is also impacted by operating issues that may affect the grid-connected PV systems. IP, binned by AOI, as a function of $IP_{SC}$, for a monocrystalline PV module tested with the IV tracer (LGI), and for the same module operating with a microinverter (LGM), are presented in Figure 6.9. For the module tested with the IV tracer (left frame), IP is
linearly proportional to $I_{PSC}$ at all AOI, and in daily average. This observation holds true for all PV modules tested with the IV tracer. In comparison, for the module operating with the microinverter (right frame), IP is mostly linear with $I_{PSC}$ but with low values at low AOI (midday), which impacts the performance during the portion of the day when the most energy is collected, which in turn impacts the daily performance. These lower performance values are due to inverter saturation meaning that PV power is greater than the maximum DC input of the inverter, which can convert only part of the available power. Inverter saturation has an important impact on IP at low AOI ($<35^\circ$), also affecting VN (higher values) and lowering PR (not shown). All PV systems using the Enphase microinverters at Maui suffer from inverter saturation. Despite selecting PV modules with STC rated power within the range advised by the microinverter datasheet (between 240W and 270W), the microinverters limit the PV module output at high irradiance. Conditions in Maui are characterized by high irradiance levels, with average irradiance reaching 1.1kWm$^{-2}$. Thus, in some Hawaii locations, solar conditions may dictate the use of a lower PV power than inverter specifications might suggest, to limit this loss due to inverter saturation.

**Figure 6.9:** Current performance IP of the monocrystalline PV module with the IV tracer (LGI, left) and operating with a microinverter (LGM, right) as a function of the short-circuit current performance $I_{PSC}$ of the PV module (LGI). Impact of inverter saturation visible by low IP values at low AOI, affecting the daily average performance.

**Solar resource and environmental conditions**

As mentioned previously, the site on Maui has a high solar resource, characterized by global irradiation of 6.4 kWhm$^{-2}$ received per day in the POA, 73% of which is from DB and 27% from
DF (scattered, reflected). The monthly average CI is estimated at 0.66. The spectrum energy averages 1.92eV, which is higher than the energy of the reference spectrum (AM1.5G), which is characterized by an APE of 1.88eV when using our instrument’s spectral sensitivity range. This means that the solar spectrum at the site is rich in low wavelengths compared to the reference spectrum. Daytime AT averaged 27°C in April 2016, varying between 25°C and 29°C, with one cooler day at 21°C.

Comparison of PV technologies and test conditions

Monthly averages of DC performance obtained at MEDB during April 2016, on all instrumented PV systems, including the results of the modules tested with the IV tracer, are presented here. These results emphasize DC performance of individual modules, since only one module in each PV system that employs a microinverter or optimizer is instrumented. For the string inverter systems, the results reflect the performance of the strings of PV modules. To ensure that sampling time was not impacting the results, datasets synchronized with IV tracer measurements, with a sampling time of 3 minutes, were selected for analysis. The impact of sampling time is minor on the daily average results, with the difference estimated to be below 0.8% when comparing results using a 1-second dataset versus a 3-minute dataset.

Monthly PR, IP and VN, calculated using datasheet specifications for normalization, are presented in Figure 6.10. PR is plotted on the x-axis, with IP and VN on the y-axis. The best performing PV systems are thus located on the right side of the graph. The data collected by the IV tracer are in blue squares for VN and red diamonds for IP, while green circles and yellow triangles correspond to performance of the PV modules in grid-connected operation. PV system acronyms are as defined previously in Table 2. PR ranges between 86% and 97%, depending on PV modules and test conditions. The best performing grid-connected system/module is the SFS CIGS system, with a PR of 97%, while the second tested CIGS system, STS, is one of the poorer performers, with a PR of 87%. The second best performer is the CdTe FSS system, with a PR of 96%. Following that system are the HIT PAM/PAS systems, with PR between 91% and 92% and the Sunpower modules, with PR between 89% and 90%. Systems with PR below 88.5% include the polycrystalline (ETM, KYM and SW), the CIGS STS, the multicrystalline LGM and the bifacial multicrystalline SUM. IP is estimated at 90% for the CIGS system STS and 104% for the CdTe. For all other PV systems, IP is between 95% and 101%. VN is lowest, at 88%, for the polycrystalline from SW, increasing to above 96% for the 2 tested CIGS systems. The remaining systems show VN between 89% and 94%.

The performance of the PV modules tested with the IV tracer (blue squares and red diamonds) is generally higher by ~1%, as compared to the grid-connected systems. The CIGS module FS exhibited operating issues, which decrease the performance by up to 4% in PR, as compared to the grid-connected PV system. This module will be inspected and likely replaced in the near future. The CdTe PV module is the best performer with a PR at 97%, followed by the HIT at 92.5%. The rest of the PV modules have a PR between 89% and 90% except for the CIGS STI
at 88% and the polycrystalline SWI at 87%. The PV systems tested with the Enphase microinverters (ETM, KYM, LGM and SWM) exhibit the highest IP difference between test conditions, with differences from 0.9% to 2.9% in IP, affecting the PR by up to 2.2%. These results suggest low impact of test conditions on DC performance of the PV modules operating at MEDB and limited impact of system loss (around 1%), which increases slightly in the case of inverter saturation to ~2% in the monthly average.

![Figure 6.10: Monthly average performance ratio PR (x-axis), current performance IP and normalized voltage VN (y-axis) for all PV systems (SYS) and PV modules in test with the IV tracer (IVT), at MEDB, South Maui in April 2016 (normalized using STC specifications from manufacturer’s datasheet).](image)

**Relationship between IP and IP\(_{SC}\)**

Monthly average values of IP as a function of IP\(_{SC}\) are presented in Figure 6.11 for all PV modules in test with the IV tracer except the SFI (due to operating issues affecting results). IP is highly correlated to IP\(_{SC}\). For most modules, IP\(_{SC}\) is slightly higher, by 1% to 2.5%, than IP. For the KY and ST, the IP\(_{SC}\) is similar or slightly lower than IP. The largest difference is on the CdTe module, which exhibits IP\(_{SC}\) lower than IP by 4%. These differences will be investigated further as this work moves forward. IP\(_{SC}\) varies from 91% for the CIGS STI to 103% for the
monocrystalline LGI. For the remaining modules, $\text{IP}_{\text{SC}}$ is between 97% and 101%. Thus, most of the tested PV modules exhibit high optical performance.

Figure 6.11: Monthly average current performance $\text{IP}$ as a function of short-circuit current performance $\text{IP}_{\text{SC}}$ for all PV modules tested with the IV tracer at MEDB, South Maui in April 2016 (normalized using STC specifications from manufacturer’s datasheet).

Performance Analysis from UH Manoa/GHII Test Site - 2015

The method of analysis described above was used to analyze 1 year of data collected at the PV test site located on the campus of UH Manoa. Two PV technologies are installed at this location – micromorph tandem thin film and polycrystalline, as detailed in Table 6.2, which includes the PV manufacturer, model number, maximum power and efficiency at STC, number and technology of the modules, and associated string inverters.
Table 6.2: Description of the PV arrays operating at GHHI in Oahu.

<table>
<thead>
<tr>
<th>PV Modules</th>
<th>Rated Power [W]</th>
<th>η [%]</th>
<th># of PV</th>
<th>PV Technology</th>
<th>Auxiliaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyocera KD205 (2//13)</td>
<td>250</td>
<td>13.8</td>
<td>26</td>
<td>Polycrystaline</td>
<td>Sunny Boy SMA-5000US (1)</td>
</tr>
<tr>
<td>Mitsubishi Heavy Industries MT130 (6//4)</td>
<td>130</td>
<td>8.5</td>
<td>24</td>
<td>Micromorph</td>
<td>Sunny Boy SMA-3000US (1)</td>
</tr>
</tbody>
</table>

In the analysis below, the diurnal and day-to-day variation of environmental conditions is described and correlation between atmospheric parameters established. The DC performance of the PV systems and individual modules (tested with the IV tracer) is examined to establish the primary factors affecting performance, to characterize the optical and thermal performance of the PV technologies, to estimate the performance distribution of the PV modules at this site, and to determine the impact of mismatch loss. Finally, the impact of degradation, at this 4-year old site, on the performance of the PV systems is assessed using 2011 to 2013 datasets. Part of the work presented here formed the core of a recently completed HNEI Master’s thesis [10].

IV curves were collected every minute in 2015 on the GHHI modules. The IV tracer, which was selected for testing at the final location in Maui, can test a maximum of 4 micromorph and 2 polycrystalline PV modules at any given time. At GHHI, two sets of PV modules were tested sequentially in 2015, allowing evaluation of 8 micromorph and 4 polycrystalline PV modules. The first period of testing was from February to June and the second occurred from June to November.

Environmental conditions

As observed at the Maui site, the environmental conditions at GHHI exhibit a clear diurnal variation, with higher CI, G and DB, lower DF and AT in the mornings than in the afternoons. Seasonal variations of the environmental conditions are also apparent, with AT and APE peaking in summer, and the annual cycle of solar resource peaking at the equinoxes. This site is also characterized by a high solar resource, with high irradiance levels (up to 1.1 kWm⁻²) and with a global irradiation of 5.8 kWhm⁻² received per day in the POA, with 72% from DB and 28% from DF. Daily average CI averaged 0.6 in 2015. Daytime AT averaged 26.5°C over the year, with monthly averages ranging between 24°C in March and 29°C in August. The APE averaged 1.93eV, corresponding to a spectrum rich in low wavelengths, as compared to the STC spectrum.
The variation of APE, daily and at selected AOI, is shown in Figure 6.12. Periods of missing data in January and August/September correspond to periods when the spectroradiometer was not available or the controller program was being improved for stability. During 2015, an increase in summer APE is apparent, as is the impact of AM, which reduces the spectral energy at high AOI during winter. High APE values in tropical locations and during summer months were reported in [8, 11, 12] related to AM decreasing at lower latitudes and in summer [8].

Figure 6.12: Average photon energy APE at selected AOI versus time for 2015.

A clear relationship was observed between APE and CI. APE as function of CI, at selected AOI (left) and at low AOI (right) is shown in Figure 6.13. In the right hand panel, it can be seen that since there is limited impact of AM at low AOI, the APE decreases with increasing CI, while at higher AOI, the impact of AM on APE makes that relationship less apparent. CI is related to the irradiance distribution between the DB and DF components, which are functions of atmospheric conditions such as moisture content and, particularly, cloud cover. For low CI values (CI<0.3), G consists primarily of DF, which increases APE, while for higher CI values, G consists primarily of DB, which decreases APE. For CI values above 0.7, i.e. in clear sky conditions, the APE is seen to decrease linearly with increasing CI (right frame). Midday (low AOI) CI values exhibited lower values in summer than in winter in 2015. The seasonal impact seen in midday data, when lower values of CI are observed, may be that of a higher APE in summer than in winter in 2015, while AM impact is most apparent at high AOI. A useful conclusion is that for test platforms where a spectroradiometer is not available, midday CI is a good indicator of spectral energy.
Comparison of GHHI PV technologies and test conditions

The 2015 variation of DC PR, IP and VN of the grid-connected PV systems, including daily performance and performance at all AOI, is shown in Figure 6.14. As with the Maui data, PV performance exhibits small daily variation (~10%), but important diurnal change (25-30%). The diurnal variation of PR (as seen at different AOI) is primarily due to variation in IP (20-25%), while the impact of VN on PR is considerably less. Diurnal VN variation is around 5% for the micromorph and 10% for the polycrystalline. This is related to temperature having a higher impact on the polycrystalline technology as compared to the micromorph thin film. IP decreases at high AOI, with lower performance in the mornings as compared with the afternoons. The daily IP of the micromorph PV array increases in summer, while the polycrystalline IP shows only slight variation during the year. The impact of the temperature indicated on $I_{SC}$ in the datasheet is similar (+0.06%/K) for both PV technologies. Soiling impact is also similar between the 2 PV systems, given identical maintenance schedules. Shading impacts the PV systems differently due the location of the polycrystalline behind the micromorph system. When plotting IP at low AOI, i.e. when shading is not impacting the PV systems, the difference in IP between the 2 PV technologies remains apparent, related to different spectral sensitivities of the PV technologies. The seasonal IP variation of the micromorph thin film is due to spectral enhancement related to APE, which shows similar seasonal behavior to IP, with higher values in summer [11]. Daily average VN also impacts PR variability (by 5-10%) over the course of the year, which was observed to be related to temperature.
Figure 6.14: DC performance ratio PR, current performance IP, and normalized voltage VN of the micromorph (left) and polycrystalline (right) PV systems operating at GHII in 2015, daily
and per AOI. Missing data during summer are related to the thermopile pyranometer being unavailable during a calibration period.

The yearly average DC performance for each PV system and each PV module tested in 2015 is presented in Table 6.3. Results for the PV modules individually tested with the IV tracer provide an estimate of the performance distribution of the modules constituting the PV systems. Performance comparisons between PV system and individual PV modules provide information on system losses. There is no inverter saturation observed on these systems, as there was in Maui. Rather, system losses are attributed to mismatch loss, related to combining modules in series and parallel. The micromorph PR average for 2015 is 87%, while PR for individual modules varies between 86 and 90%. The polycrystalline PV system has an annual average PR of 91%, with individual module PR averages slightly higher (92-94%). IP is high (105%) for the micromorph PV system, which represents the lower IP values of the individual PV modules (one module has lower IP ~99%, but the remainder of the modules show IP above 104%). IP of the polycrystalline system is approximately 98%, which is lower than the poorest performing PV module in that system. VN is higher for the polycrystalline system, with values around 92%, than for the micromorph, which reaches only 82%. For both technologies, the system VN corresponds to the maximum VN of the individual modules. The PR and IP are lower and VN higher for the PV systems, as compared to the individually tested modules. When combining PV modules in string, the current of the poorest performing module limits the string current. As the rest of the PV modules operate at current lower than their maximum power current, the operating voltage is increased leading to higher VN. The mismatch loss is related to performance distribution (especially for current) and to the arrangement of PV modules in strings (micromorph system has 6 parallel strings of 4 modules in series; polycrystalline has 2 parallel strings of 13 modules). The performance distribution of the modules constituting these systems, in terms of PR, is ~4% for the micromorph and ~2% for the polycrystalline. The mismatch loss, evaluated by comparing the performance of the best performing module in the PV system, is ~3% for both PV systems.

Table 6.3: Yearly average PR, IP and VN for both PV systems in 2015.

<table>
<thead>
<tr>
<th></th>
<th>Micromorph</th>
<th>Polycrystalline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PV System</td>
<td>PV modules</td>
</tr>
<tr>
<td>PR</td>
<td>86.9%</td>
<td>86-90%</td>
</tr>
<tr>
<td>IP</td>
<td>105.1%</td>
<td>99-110%</td>
</tr>
<tr>
<td>VN</td>
<td>82.3%</td>
<td>73-82%</td>
</tr>
</tbody>
</table>
Regarding the low VN for the micromorph PV modules, we previously reported, in [2], PR degradation of the micromorph system over the 2 years from commissioning in December 2010 to the end of 2012. The variation of daily average PR, VN and IP of both PV systems, from 2011 to 2013, is shown in Figure 6.15. The micromorph degradation is visible on the plot of system voltage, while IP remains relatively constant over the same period for both PV arrays. Seasonal spectral enhancement of IP on the micromorph observed in 2015 is not apparent during 2012 and 2013. This is related to the fact that midday CI, highly related to spectral energy, does not exhibit seasonal variation in 2012 and 2013, as in 2015, and supports our analysis of the seasonal variation of APE related to midday CI values, with AM impact limited to high AOI. Additional data collection and analysis are necessary to develop more robust seasonal statistics, particularly since 2015 was characterized by an atypically hot summer.

![Figure 6.15](image)

**Figure 6.15:** Daily average performance ratio PR (a), voltage VN (b) and current IP (c) performances during the first years of operation at GHHI, showing that PR degradation is visible on VN of the micromorph PV system (blue) while no degradation is observed on the polycrystalline system (green).

As observed in Maui, there is a linear relationship between IP and IP\(_{SC}\) at all AOI. The daily IP averaged for the complete period of testing in 2015 is plotted as a function of IP\(_{SC}\) average in Figure 6.16, for all modules tested with the IV tracer. The results from the modules tested in Maui are included for comparison. For the GHHI polycrystalline modules, the average IP\(_{SC}\) values vary between 99% and 100% and are slightly higher than IP. For the micromorph, IP\(_{SC}\) is lower than IP with values between 102% and 105%, except for one module with an IP\(_{SC}\) of 98%, leading to low IP of 99%. Optical performance is high at GHHI, particularly for the micromorph, which is enhanced by the light spectrum of the location. There is an important current performance distribution of modules within the same brands/types. Performance
distribution depends on initial performance, which can be evaluated with FTR, and degradation, which at GHHI particularly affected the micromorph modules. More extensive testing than in the past is now done to evaluate PV modules during the manufacturing process, which reduces this performance variability among like modules.

When comparing the performance results at GHHI to those from Maui, the Kyocera polycrystalline modules have similar PR, IP and VN. The micromorph PV system has high IP (105%), similar to the CdTe technology, and a VN lower than all other tested PV modules due the 2-year long degradation (micromorph VN was 87-88% at commissioning in 2010). The correlation between IP and IP$_{SC}$ is similar for the micromorph and the CdTe tested at MEDB, with IP$_{SC}$ significantly lower than IP, while for most PV modules, IP$_{SC}$ is similar to or slightly lower than IP. More investigation is needed to understand the correlation between IP and IP$_{SC}$ among various PV technologies. The micromorph PV modules exhibit high IP (up to 110%) and IP$_{SC}$ (up to 105%) values, and are sensitive to the seasonal variation of the spectral energy in 2015. The micromorph technology is enhanced by the location’s light spectrum, which is rich in low wavelengths.

Figure 6.16: Daily average current performance IP as a function of the short-circuit current performance IP$_{SC}$ of the micromorph and polycrystalline PV modules tested with the IV tracer at GHHI in 2015 and for the PV modules tested at Maui/MEDB in April 2016.
6.5 Conclusions

Important milestones were achieved in our understanding of the performance of grid-connected PV systems operating in Hawaii. DC performance is affected by varying environmental conditions, PV technology, and variations among like modules introduced in the manufacturing process. DC performance of PV systems is also affected by system losses related to combining PV modules into strings (mismatch loss) and due to the potential operating issues with the inverters and optimizers. Test protocols and analysis tools were developed to streamline data collection and better characterize module performance, and to identify and quantify the impact of system architectures and losses. Methodologies and instrumentation were developed at the UH campus site (GHHI), for incorporation into a new test site located on the island of Maui.

After considerable planning and permitting delays, the Maui test platform was commissioned in February 2016, instrumented with the new HNEI DAS and providing side-by-side operation of 15 PV systems testing 10 PV module brands/types and 3 system architectures. PV technologies in test include mono and polycrystalline, bifacial, high efficient and thin films (CdTe, CIGS and micromorph). The test platform also has the capability to collect data on individual modules through the use of an IV tracer that can record complete performance characteristics (IV curves) in the absence of system losses. System losses can then be quantified by comparing this isolated module performance with performance in grid-connected operation.

Newly developed analysis methodologies have enhanced our understanding of the diurnal and day-to-day variation of DC performance and allowed us to identify the most important environmental parameters and operating conditions. Specifically, we dissociate PR, typically used to characterize PV performance, into current performance, which is highly correlated to short-circuit current and characterizes optical performance, and voltage performance, which is primarily related to thermal conditions. Current and voltage performance are also affected by system losses and module degradation. Current performance was seen to be most sensitive to inverter saturation (with corresponding impact on PR), while voltage performance proves to be a good indicator of performance degradation. This innovative approach is useful for identifying spectral enhancement (current) as well as temperature impact and degradation (voltage) on the long-term performance of the PV systems or modules. Further, by analyzing performance at varying incident angles, we are able to assess the diurnal variation of system performance, to diagnose special operating conditions and issues (shading, reflection and inverter saturation), and to compare performance of PV systems in different locations/orientations.

Experimental results were analyzed for a month (April 2016) at the new Maui site and for a year (2015) at the UH Manoa site. Both locations are characterized by high daily average irradiation (~ 6 kWhm\(^{-2}\)). An important finding that is related to high irradiance is that, despite specifications from manufacturers, inverter saturation is likely at high sun angles in these tropical locations. This suggests that lower PV power than would normally be advised may be appropriate in such locations – for a given inverter. Also, the light spectrum in both locations is
rich in low wavelengths, as expected by the latitude. This is favorable to PV technologies that are spectrally enhanced by low wavelengths, such as the micromorph tested on Oahu.

Daily average DC performance ratio of grid-connected systems was found to be between 86% and 97%. The impact of DC system losses was below 3% at both locations, which is within the range of normalization error (±4%). PV system performance variability is thus primarily related to the selected PV modules. Optical performance of the tested PV modules varies by 14%, with most modules performing between 95 and 101%, except one low performer (91% - CIGS) and two high performers (104-105% - amorphous and CdTe). Thermal performance varies between modules by 15% with most modules performing between 87 and 94%, with higher performance (96-98%) for the two CIGS modules and degraded performance for the 4-year old micromorph system (83%). While the standard crystalline modules exhibit similar performance, the two tested CIGS modules exhibited a large difference of 10%.

Performance analysis of grid-connected PV systems operating in Hawaii will be continued, with emphasis on the data now being collected at the fully instrumented Maui test platform, and at other sites in Hawaii. Operating issues such as inverter saturation will be further diagnosed, along with the impact of soiling and shading. The AC performance of the PV systems will be analyzed to provide information on the efficiency and reliability of the inverters and optimizers. The data collected by the IV tracer will serve be used to determine the impact of environmental conditions and angle of incidence on short-circuit current, open-circuit voltage, and their correlation with the maximum operating point. These efforts will ultimately lead to the development of a performance modeling approach, suited to Hawaii and other locations, that will allow the prediction of diurnal, monthly, seasonal, and long-term variation of PV module and system performance.

**Acronyms**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternative current</td>
<td></td>
</tr>
<tr>
<td>AM</td>
<td>Air mass</td>
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</tr>
<tr>
<td>AOI</td>
<td>Angle-of-incidence</td>
<td>°</td>
</tr>
<tr>
<td>APE</td>
<td>Average photon energy</td>
<td>eV</td>
</tr>
<tr>
<td>CdTe</td>
<td>Cadmium telluride</td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td>Clearness index</td>
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<tr>
<td>CIGS</td>
<td>Copper indium gallium selenide</td>
<td></td>
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<tr>
<td>DAS</td>
<td>Data acquisition system</td>
<td></td>
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<tr>
<td>DB</td>
<td>Direct beam</td>
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<tr>
<td>DC</td>
<td>Direct current</td>
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<tr>
<td>DF</td>
<td>Diffuse irradiance</td>
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<tr>
<td>ϕ</td>
<td>Spectral photon flux density</td>
<td>m(^{-2})s(^{-1})nm(^{-1})</td>
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<tr>
<td>FTR</td>
<td>Flash test result</td>
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<tr>
<td>----------</td>
<td>----------------------------------------</td>
<td></td>
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<tr>
<td>G</td>
<td>Global irradiance</td>
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<td>GHHI</td>
<td>Green Holmes Hall Initiative</td>
<td></td>
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<tr>
<td>$G_{STC}$</td>
<td>Irradiance at STC</td>
<td>Wm⁻²</td>
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<td>HIT</td>
<td>Heterojunction intrinsic thin layer</td>
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</tr>
<tr>
<td>$I_{MP,STC}$</td>
<td>Maximum power point current at STC</td>
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</tr>
<tr>
<td>IP</td>
<td>Current performance</td>
<td>-</td>
</tr>
<tr>
<td>$I_{PV}$</td>
<td>Operating PV current</td>
<td>A</td>
</tr>
<tr>
<td>$I_{SC}$</td>
<td>Short-circuit current</td>
<td>A</td>
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<tr>
<td>$\lambda$</td>
<td>Wavelength</td>
<td>nm</td>
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<tr>
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<td>Power factor</td>
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<td>Plane of array</td>
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<td>$P_{MP,STC}$</td>
<td>Maximum power at STC</td>
<td>W</td>
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<tr>
<td>$P_{PV}$</td>
<td>Operating PV power</td>
<td>W</td>
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<tr>
<td>PR</td>
<td>Performance ratio</td>
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<td>q</td>
<td>Electronic charge</td>
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<td>STC</td>
<td>Standard test conditions</td>
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<td>Maximum power point voltage at STC</td>
<td>V</td>
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<tr>
<td>VN</td>
<td>Normalized voltage or voltage performance</td>
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<tr>
<td>VPN</td>
<td>Virtual private network</td>
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<td>Operating PV voltage</td>
<td>V</td>
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<td>Extraterrestrial irradiance</td>
<td>Wm⁻²</td>
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<td>PV energy yield</td>
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<tr>
<td>$Y_{SUN}$</td>
<td>Solar yield</td>
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**References**


