Report on PV Test Sites and Test Protocols

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Hawai‘i Distributed Energy Resource Technologies for Energy Security

Revised Task 8 Deliverable PV Test Sites and Test Protocols
plus
Subtask 11.1 Deliverables 1 and 3 Photovoltaic Systems (corrected)

By the

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1. Introduction

1.1. Objective

The Hawaiʻi Natural Energy Institute (HNEI), at the University of Hawaiʻi at Mānoa (UH), has been developing and deploying photovoltaic (PV) test beds to evaluate the performance of different PV systems under different environmental conditions on three of the Hawaiian islands. This study is intended to provide a performance comparison of the PV systems for public use, to help consumers and PV installers select the best value technologies and system configurations.

1.2. Background

Funding under this program has enabled HNEI to develop the initial prototypes of PV test beds including a test bed for side-by-side comparisons of selected PV modules, instrumentation of PV arrays, data acquisition systems, and tools for data analysis to characterize the solar resource and PV system performance. Data from these systems will augment the growing database of PV performance in Hawaiʻi including such projects as Sun Power for Schools. This initial phase includes PV systems installed in different climatic sub regions monitored for performance and response to environmental changes. Thin film PV technologies and micro-inverters are included in this evaluation.

This report includes a short introduction to Hawaiʻi , its electrical grids, and high cost of oil-derived electricity, a description of the PV test protocol and data collection system, and a description of three test sites. Blue Planet Foundation, the University of Hawaiʻi Maui College (UHMC), and the University of Hawaiʻi at Mānoa (UH) assisted in development of the sites.

1.3. Overview

Hawaiʻi is one of the world's most isolated groups of islands. Figure 1 shows Hawaiʻi 's major islands and the service territories of Hawaiʻi 's four utilities. Hawaiian Electric Industries subsidiary, Hawaiian Electric Company (HECO), serves the Island of Oʻahu. HECO has two subsidiaries, Hawaiʻi Electric Light Company (HELCO) serving the Island of Hawaiʻi , and Maui Electric Company (MECO), serving the three islands of Maui, Molokai, and Lanai. (Kauai is served by the Kauai Island Utility Cooperative and is not included in this study).

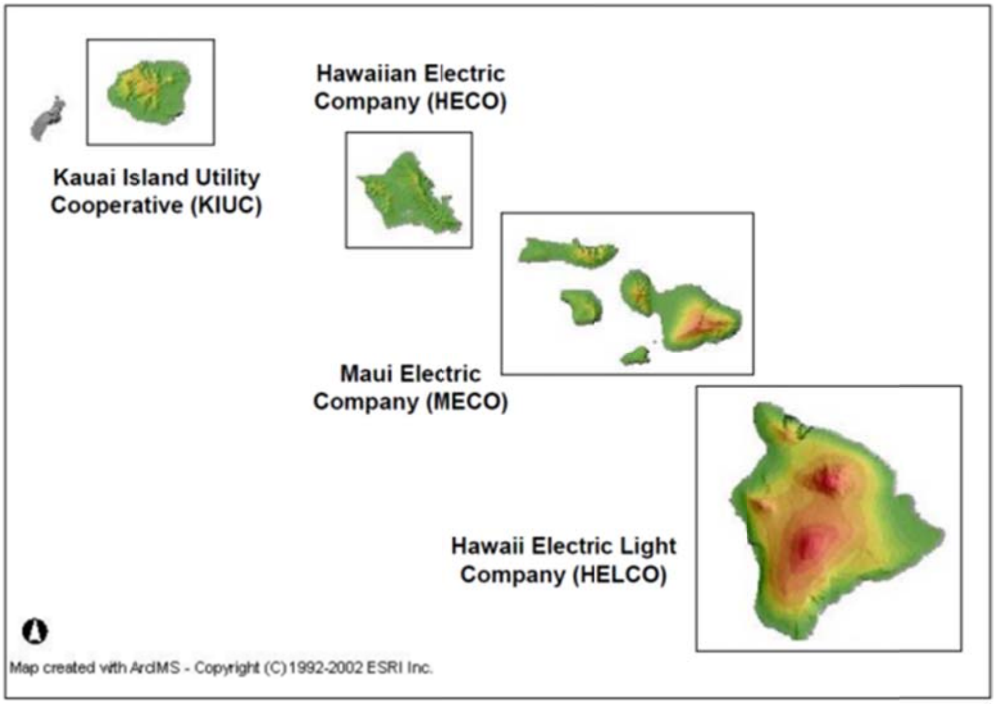

Figure 1: Hawai‘i ’s Major Islands and Utility Service Territories

Hawai‘i is the most petroleum dependent state in the nation, with close to 90 percent of its electricity generated from petroleum. This reliance intensifies the need for alternative, sustainable energy sources to help reduce the high cost and volatility of oil-derived electricity. The Hawai‘i Clean Energy Initiative (HCEI) is focused on improving Hawai‘i ’s energy security and independence, with goals and a roadmap to achieve 70% clean energy by 2030, with 30% coming from efficiency measures, and 40% coming from locally generated renewable sources.

Since the HCEI was initiated in 2008, there has been a rapid increase in the amount of photovoltaic (PV) systems installed across the state. This is the result of the high cost of electricity in Hawai‘i , generous State tax incentives, and supportive programs such as Net Energy Metering, and the Feed-in-Tariff offered by the Hawaiian Electric Companies. With the small size of the island grids and lack of interconnection between islands, the high-penetration of intermittent renewable resources can create significant challenges for grid reliability. Accurate data on PV system performance under different environmental conditions can assist mitigating these challenging issues.

1.4. Climatic Sub Regions

The mountainous topography of the Hawaiian Islands makes the climate one of the most spatially diverse on Earth, and represents a miniature continent [1].

Rainfall, solar radiation, temperature, humidity, and wind vary significantly over relatively short distances. Humid tropical rain forests including the world's wettest spot, arid and semi-arid deserts, temperate, and frozen alpine ecosystems all exist in Hawai‘i . In addition, environmental conditions such as marine, volcanic, urban, and rural areas add to the diversity of the State.

The Western Climate Center [2] has identified seven climatic sub regions in Hawai‘i . These are defined chiefly by the major physiographic features of the State and by location with reference to windward or leeward exposure. Since one region grades into another, it would be misleading to attempt to draw sharp boundaries between adjacent regions. In general, however, the regions and their characteristics are as follows:

1. **Windward lowlands**, generally below 2,000 feet on the north to northeast side of the islands. This region lies more or less perpendicular to the prevailing flow of the trade winds, and is moderately rainy, with frequent trade wind showers. Partly cloudy to cloudy days are common. Temperatures are more uniform and mild than in other regions.

2. **Leeward lowlands**, except for the Kona coast of Hawai‘i which has its own distinctive climate. In these areas daytime temperatures are slightly higher and nighttime temperatures are slightly lower than in windward locations. Dry weather prevails except for occasional light trade wind showers which drift over from the mountains to the windward side. In some leeward areas an afternoon sea breeze is common, especially in summer.

3. **Interior lowlands**, on O‘ahu and Maui. In the northeast these lowlands have the characteristic of the windward lowlands; in the southwest, of leeward lowlands. The central areas are intermediate in character, and – especially on O‘ahu – are sometimes the scenes of intense local afternoon showers from well-developed clouds which form as a result of local heating of the land during the day.

4. **The Kona coast of Hawai‘i** . This is the only region in the islands where summer rainfall exceeds winter rainfall. There is a marked diurnal wind regime, with well-developed and reliable land and sea breezes, especially in the summer. Summer is also the season with a high-frequency of late afternoon or early evening showers. Conditions are somewhat warmer and decidedly drier than in windward locations.

5. **Rainy Mountain slopes on Leeward side.** Rainfall and cloudiness are very high, with considerable rain both winter and summer. Temperatures are equable. Humidity is higher than in any other region.

6. **Lower Mountain slopes on Leeward side.** Rainfall is greater than on the adjacent leeward lowlands, but distinctly less than at the same level on the windward side except that the zone of maximum rainfall usually occurs just to leeward of the crests of the lower mountains. Temperature extremes are greater than on the rainy slopes of the windward sides of the mountains, and cloudiness is almost as great.

7. **High Mountains.** Above 2,000 or 3,000 feet on the high mountains of Mauna Kea, Mauna Loa, and Haleakala rainfall decreases rapidly with elevation. Near the summits of Mauna Loa and Mauna Kea, rainfall is scant and skies are clear a high percentage of the time. Relative humidity may reach values of ten percent or less. The lowest temperatures in the State are experienced in this region, with values below freezing being common.

ArcGIS software from ESRI [3], a geographic information system (GIS) package was selected and used to visualize the weather conditions in Hawai‘i with the maps presented below. Complete data sets representing all aspects of the different climatic sub regions were not found. Therefore available solar and precipitation data sets were selected to visualize and assess the climatic sub regions. This allowed an estimate to be made of the solar resource and rainfall at the three test bed sites.

Details covering the GIS data sources are as follow:

1. Irradiation: State Department of Planning and Economic Development, Energy Division "Sunshine Maps," 1985 [4].

The increment and unit of the irradiation data set is 50 cal/cm^2/day which is converted into 0.58 kWh/m^2/day. The Sunshine Maps were selected because of the high spatial resolution on the islands of Hawai‘i .

2. Precipitation: Rainfall isohyets collected for the Rainfall Atlas of Hawai‘i by the Geography Department of the University of Hawai‘i [5].

The precipitation data set is data that was collected over a 30-year period from 1978 to 2007, and is expressed in mm per year.

Figure 2 shows the solar data and precipitation for the Island of Oʻahu. This map visually supports the description of the climatic sub regions presented previously. We observe that the windward side collects most of the precipitation on the island especially on the peaks of the Koolau mountain range, the eastern range. The irradiation is < 4.7 kWh/m^2/day for most of the windward side. The leeward side is the sunniest area reaching up to 5.2 to 5.8 kWh/m^2/day as you move towards the west end of the island and away from the mountain ranges. The interior lowland (central) areas between the Koolau and Waianae (western) Mountain ranges have a wide-range of irradiation levels ranging in value from 4.4 to 5.8 kWh/m^2/day. This type of map will be used to help characterize the anticipated solar environment for each of the test locations and the climatic sub region defining each test site.

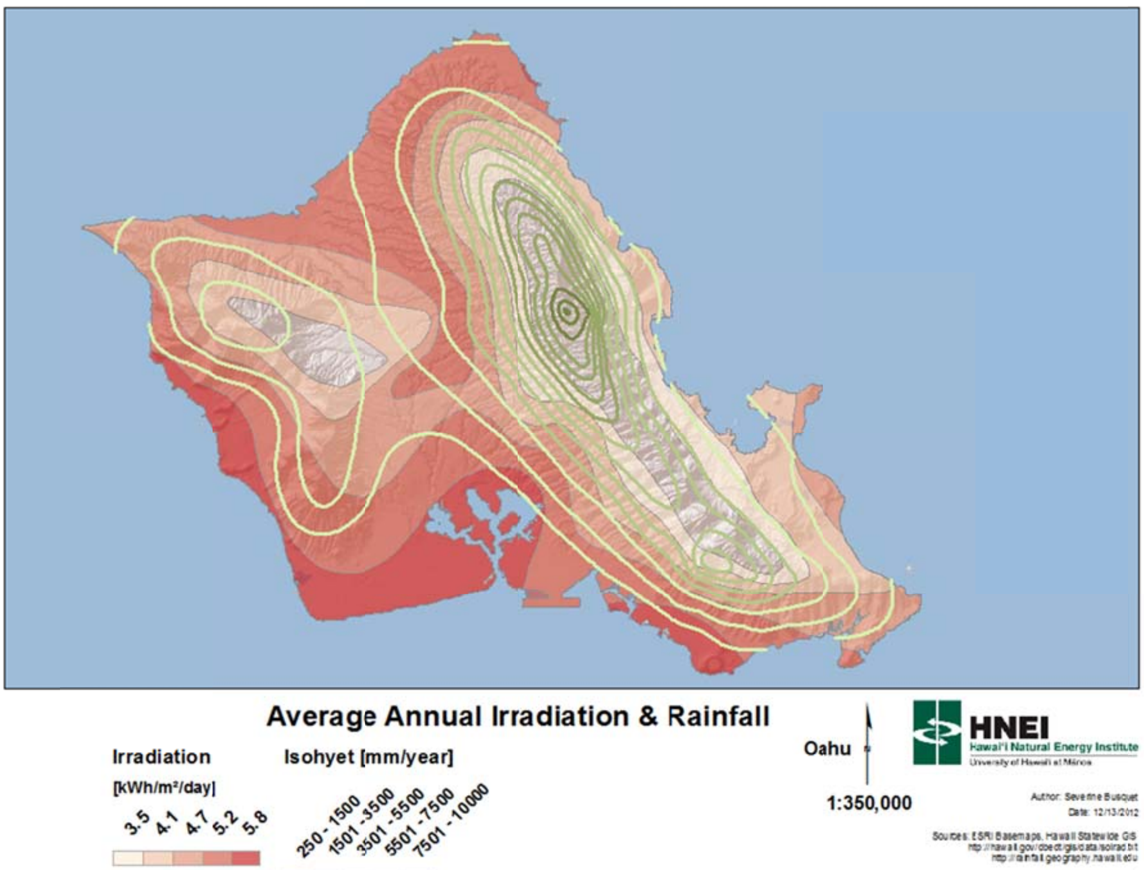

Figure 2: Irradiation and precipitation at the test sites – Oʻahu

In this work HNEI collected high-fidelity PV performance data at three test sites. Section 2 of this report describes the test protocols, including the data collection. Section 3 provides additional information for each of the sites including a description of the location, expected irradiation and climatic sub-region, and detailed information on the PV systems and instrumentation that was deployed at each test site. Data from each of the sites has been collected for more than one year. These results are summarized in a separate report.

2. Test Protocols

PV modules were deployed at three sites. This section describes the hardware, data acquisition process, and data management for the sites. The climate characteristics and the PV deployed at each of the sites are described in Section 3.

Instrumentation packages were developed and deployed at each of the test sites to collect high-resolution collection of weather parameters including the solar resource, and collection of various measures of PV system performance. Data is collected every second, synchronized to the same NIST clock, and transferred to a data server located on the UH Mānoa campus. Here the data sets from the test site are stored, analyzed, and visualized.

All three test sites are equipped with similar instrumentation, and a time-synchronized, high-speed data acquisition system (DAS) hardware and software, to limit variation of the measurements between sites. However, as needed, the DAS monitoring equipment was adapted to each test site for optimum data collection and ease of integration. This includes adapting to the characteristics of the PV system in terms of the number of PV modules or strings for each PV array, their electrical characteristics, and the location of the measurement sensors.

Instrumentation to support analysis at each site includes: (1) weather station system (WSS); (2) PV monitoring units (PVMUs), consisting of sensors, power and signal conditioners, enclosures; data cables and data cable management; (3) high-speed DAS consisting of an embedded controller, input/output (I/O) boards, data and power management unit, and enclosure and ventilation system; and (4) data server and internet connection devices for creating a secure internet based-network between data server and all test site controllers.

Analysis tools were developed using Matlab software for the following: (1) extraction of data files into a Matlab database; (2) graphical visualization of raw data for any recorded day; (3) calculation of daily solar energy and PV performance ratio; (4) calculation of the PV performance as a function of irradiance levels; and (5) characterization and visualization of the solar resource, and PV performance ratio and parameters.

The next sections detail the hardware and software used for data collection and analysis. Additional details of the PV modules and the system layout for each site are discussed in section 3.

2.1. Weather

Each test bed site is equipped with a WSS to collect the following data (see Figure 3):

- Solar radiation using a thermopile pyranometer (PYR) sensor for high precision readings, and solar cell (SR) sensors for high-speed monitoring, located around the PV system;
- Ambient temperature (AT);
- Relative humidity (RH);
- Wind speed (WS) and wind direction (WD); and
- Barometric pressure (BP).

WSS consists of sensors, signal conditioners, supporting structure, data cable management equipment, and an enclosure. A robust WSS that met our requirements was not available on the market as a commercial-off-the-shelf product. They lacked the speed, resolution, flexibility, and ability to be connected to an external DAS. In addition, the WSS for this study required a very adaptable design for ease of integration into the test sites. Therefore we developed a custom design.

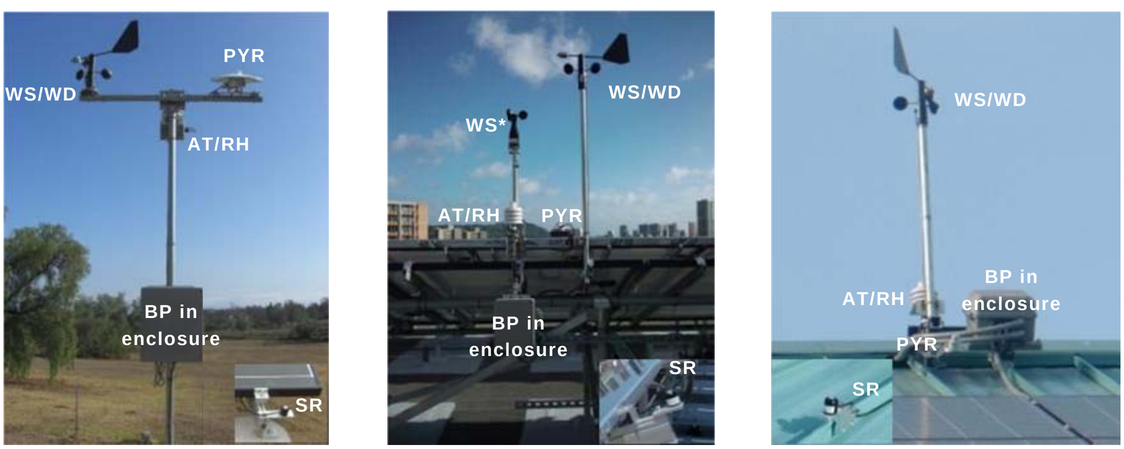

Figure 3: Weather station systems installed at the test sites: Pu`u Wa`a Wa`a (PWW) (left), Green Holmes Hall Initiative (GHHI) (middle), and UHMC (right)

(* GHHI has an additional WS sensor connected to a second monitoring system install with funds from MHI)

Sensors and transducers are mounted on poles and other support structures designed to be easily integrated into the test sites (Figure 3 and Table 1). Although a slightly different architecture, the sensors are the same for each WSS in order to avoid introducing discrepancies in the measurements. Only the PYR installed at Pu'u Wa'a Wa'a (PWW) is different than the other sites because the company Yankee Environmental Systems (YES) was unable to meet our delivery date so a second vendor was selected, Hukseflux, for the test sites on the islands of Maui and Oʻahu.

Table 1: Weather station transducers

Measurement	Technology	Manufacturer	Input and output signal range
Solar Radiation	Thermopile (Secondary standard)	YES # TSP-400 (PWW)	Wavelength: 0.3 to 3 µm 0-1400 W.m^{-2} ~ 0-140 mV
	Thermopile (Second class)	Hukseflux # LP02-10 (GHHI, UHMC)	Wavelength: 0.3 to 2 µm 0-1400 W.m^{-2} ~ 0-21 mV
	Silicon solar-cell	Apogee # SP-110	Wavelength: 0.3- 1.1 µm 0-1100 W.m^{-2} ~ 0-220 mV
Ambient Temperature	PT1000 (Resistance Temperature Detector (RTD))	NovaLynx # 225-HMP50YA with solar shield # 380-280	-40 to +60 ^{o}C ~ 0-1 V
Relative Humidity	Thin film capacitive sensor		10 – 90% ~ 0-1 V
Wind Speed	Magnetic reed switch	NovaLynx # 200-WS-02F + signal conditioner NovaLynx # 135-100	0-99 mph ~ 0-5 V
Wind Direction	20K Ohm potentiometer, single wiper		0-359^{o} ~ 0-5 V
Atmospheric pressure	Piezoelectric ceramic	NovaLynx # 230-600	500-1100 hPa ~ 0-5 V Unit range is programmable: 830-1030 hPa ~ 0-5 V

Table 1 describes the weather station sensors and signal conditioning used at each test site. The table provides the details of each measurement, the technology, the manufacturer and model number, the range of measurement, and the output signal.

The last component of the WSS is the NEMA-4 rated enclosure which protects the electronics, the sensors, the signal conditioners, and the data cable management from the environment.

2.2. PV Monitoring

To assess and characterize the performance of the PV systems, equipment was added to allow electrical measurements to monitor the DC voltage and DC current of the PV systems. We monitor the temperature measurement of the front or back side of the PV module. AC power is monitored at PWW on the AC side of two of the microinverters.

The maximum voltage measured at the sites varies from 40 V to almost 600 V depending upon the number of PV modules or strings of PV modules in series for the particular PV array configuration. The PVMU uses a resistance bridge to scale the voltage to a 0-10 V signal range using metal resistances with low variation over temperature. The 0-10 V signal is connected to the DAS through an isolation unit.

The current monitored at the test sites varies by PV module. The shunt is selected to match the expected maximum current. The voltage signal of the shunt is connected to the DAS through a signal conditioning unit for isolation and amplification to the desired range of 0-10 V.

The module temperature is monitored using a Resistance Temperature Detector (RTD) probe glued onto the back side of the PV module. For the flexible modules the RTD is placed on the top side of the module as close to the PV cells as possible. The 3-wire RTD is connected to a signal conditioning unit providing a 4-20 mA signal. The signal conditioning unit was programmed to limit the range of the temperature measurement from 0 to 100^{o}C in order to have a better accuracy. We note that the temperature measurement acts as a proxy for the cell junction temperature.

AC power is measured at PWW to monitor the performance of a single microinverter, and the string of ten microinverters. The power transducers (ADTEK # CW/CQ) with current transformer (Flex-core # 189) measure the active and reactive power.

The PVMU enclosure protects the shunts, resistance bridge, signal conditioners, power transducers, current transformers, and data and power cable management equipment from the environment (Figure 4). The metallic back plate is grounded for safety.

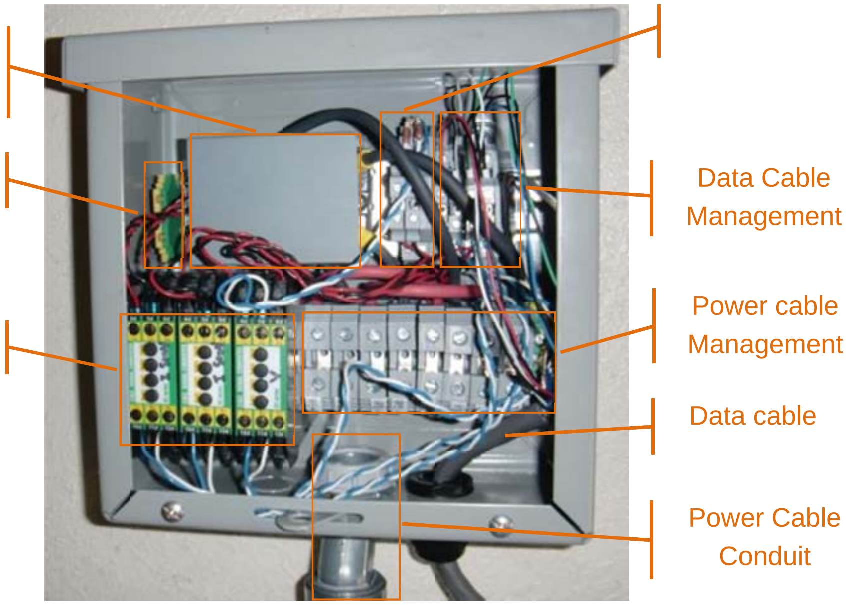

Figure 4: PV monitoring unit (PVMU) at UH Maui College

The WSS and PVMUs monitor and condition the signals collected and recorded by the DAS. The connection between the WSS, each PVMU, and the DAS is made using data cables consisting of nine shielded twisted pairs of 24-AWG conductors protected from the environment in conduits. Once inside the DAS enclosure the data cables are connected to analog input modules.

2.3. Data Acquisition System

After conducting a literature review and market survey (which included equipment available from the National Laboratories including the National Renewable Energy Laboratory and Sandia National Laboratory, and available commercial-off-the-shelf DASs with high-density analog and digital signal conditioners to interface to the PV systems), we selected a DAS from National Instruments (NI) to meet our requirements, (refer to Table 2 for a partial list of the requirements). NI equipment was selected because of its reliability, robustness in a harsh working environment, speed performance, and modularity allowing us to connect many signals of different types (analog, digital, input and output) and use diverse communication protocols. In addition, NI equipment and - LabVIEW software have been used at UH for a long time allowing fast and efficient development.

Table 2: DAS Requirements

Requirements
Design which supports high channel to channel isolation, noise rejection, and surge suppression
Design which supports “front-end” signal conditioning
Design which protects equipment, and installs and expands easily
Design which supports low-cost, high-density I/O, analog and digital modules
Design that is reliable, operates in a harsh environment

The DAS consists of a controller (cRIO-9022 or 9024), and an expansion chassis (NI-9111 or 9114), populated with analog input (AI) modules (NI-9205) to collect the analog signals (32 analog inputs per module) and Digital output (DO) module (NI-9477) for control. There are two chassis available with a capacity of four or eight modules. The controller has two Ethernet ports allowing internet connectivity and communication with the load bank if necessary or with additional chassis if required to collect additional remote signals (Figure 5).
The controller is programmed with LabVIEW software to execute the following: 1) scan the analog inputs every 25 ms; 2) compute an average value of the 40 25-ms values to produce one data sample per second; 3) convert the signals into measurements; and 4) save the data into daily text files. The program includes an application to send commands to turn the ventilation system on and off, reboot the controller, and reset the communication device.

The daily files are transferred over the internet to a database server for storage and analysis at the end of each week. DAS time synchronization and data file transfers require switches and routers connecting the controller to the local network and to the internet. Funding from another grant is being used to increase the level of cyber security and to automate the data transfer procedure using a virtual private network architecture.

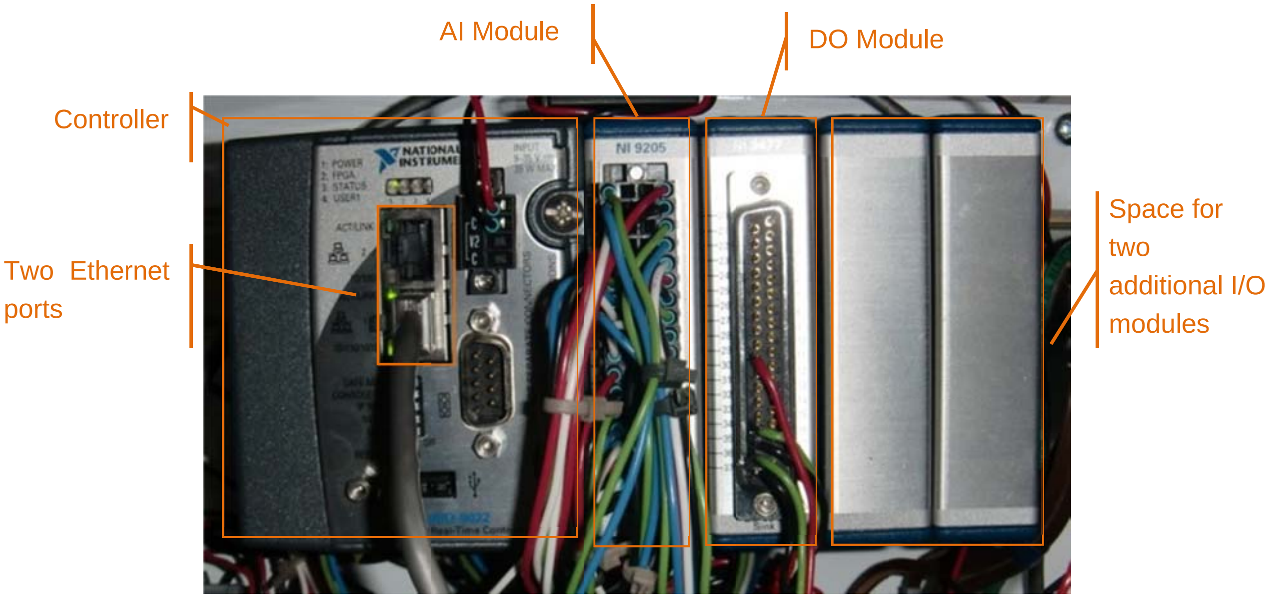

Figure 5: DAS example at University of Hawai‘i Maui College

2.4. Accuracy of Measurements

The accuracy of each measurement in the DAS is presented in Table 3 along with the details covering accuracy of each sensor (WSS and PVMU), the signal conditioners, and the DAS. In most cases, sensor accuracy is available from the datasheet or was specified by the manufacturer’s consultants. The individual sensors range in accuracy from ±0.15% to ±5%. The overall system accuracy calculated by adding all accuracies (worst case scenario) ranges from ±0.5% to ±5.1%.

The PVMUs were calibrated before they were installed at each of the test sites. The calibrations included: (1) current, (2) voltage, and (3) temperature. Current and voltage were calibrated with a power supply, load bank, and digital multi meter (Fluke 177). Temperature was calibrated with a bath thermometer calibrator (Hart Scientific 7102 Micro Bath). For each calibration, different levels of signals were tested to cover the complete range of each PVMU sensor.

Table 3: Accuracies of each measurement monitoring the environment and the performance of modules and auxiliaries at the HNEI test sites on the Island of Hawai‘i , O‘ahu, and Maui

Measurement	Manufacturer & Model #	Accuracy			
		Sensor	Signal conditioner	DAS	Global
Solar Radiation	YES # TSP-400	± 3%	N/A	± 0.1% (the DAS has high accuracy 0.1% for all signals from ± 200 mV to ± 10V)	± 3.1%
	Hukseflux # LP02-10	± 4%	N/A		± 4.1%
	Apogee # SP-110	± 5%	N/A		± 5.1%
Ambient Temperature	Nova Lynx # 225-HMP50YA with solar shield # 380-280	± 0.6%	N/A		± 0.7%
Relative Humidity		± 3%	N/A		± 3.1%
Wind Speed	Nova Lynx # 200-WS-02F	± 3%	± 0.5%		± 3.6%
Wind Direction		± 1%	± 0.5%		± 1.6%
Atmospheric pressure	Novalynx # 230-600	± 0.25%	N/A		±0.35%
Temperature	Omega # SA1-RTD	± 0.15%	± 0.2%		± 0.45%
Voltage	Metal resistance 25ppm/^{o}C	± 0.2%	± 0.2%		± 0.5%
Current	ADTEK # EC-UA-SHT	± 0.25%	± 0.2%		± 0.5%
Power	ADTEK # CW/CQ	± 2%	± 0.6%		± 2.7%

2.5. Data Analysis

The data server with a CentOS 5.5 operating system consists of the following equipment:

- Dual Xeon E5620 2.4-GHz Quad Core
- 6-GB DDR3 1333MHz Ram
- 16 x 2 TB drives in RAID 6 configuration

The server is located behind the firewall maintained by the UH School of Ocean and Earth Science and Technology. Access to the data storage is currently limited to HNEI researchers and technicians.

Different tools were investigated and developed to analyze the data sets and visualize the results of the analysis.

The first application to be implemented was a tool to extract the data as a text file to populate a Matlab database and to be able to visualize the data sets from any test site for any recorded day. The visualization interface consists of sliding lists to select the test site, the date, and the data to plot into four graphs. Figure 6 shows the Matlab interface visualizing the solar radiation, PV power, voltage and current of a PV module (Sanyo) operating at PWW on 2 different days (8/30/2011 and 8/30/2012).

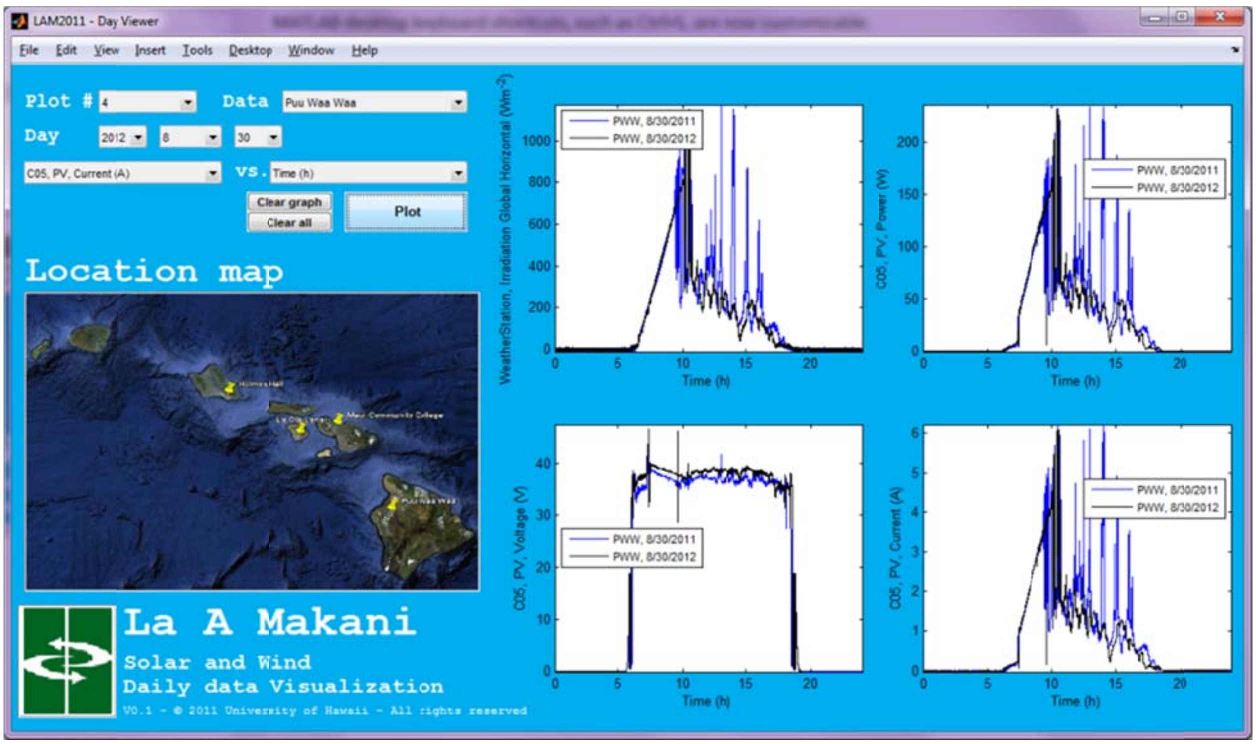

Figure 6: Matlab interface for visualization of the data from the different test sites.

A second set of Matlab applications was developed to support data analysis and visualization of the analysis results. The initial analysis calculates the daily solar energy and PV energy production. The analysis was completed using validated sets of measurements. For each day, the Performance Ratio (PR) of the PV systems is calculated by dividing the PV system energy yield, over the energy yield at Standard Test Conditions (STC: irradiance of 1,000 W/m², solar spectrum of AM 1.5 and module temperature at 25°C). Solar data is analyzed to characterize the solar resource at each test location using selected statistics and averages. The results on the PV performance are presented showing the PR of the PV systems, varying with the seasons over a year of operation, after completion of the light induced degradation period. We also present the annual PV performance per levels of irradiance to visualize the parameters of the PV system operation.

3. Test Site Description

All PV systems studied in this study operate under real-life conditions using grid-tied inverters, which include a maximum power point tracker (MPPT). The MPPT samples the output of the PV modules and selects the most appropriate operating point to obtain maximum power under the prevailing environmental conditions. The PV performance data collected by our test protocol includes the MPPT efficiency. Operational data was recorded for a sufficient period of time to allow the PV modules to complete any initial light induced degradation, and to collect a minimum of one year of operation data in order to visualize the impact of seasonal weather variation on each PV system.

3.1. Pu`u Wa`a Wa`a, Kailua-Kona, Island of Hawai‘i

Pu`u Wa`a Wa`a (PWW) is a sparsely populated location on the North end of the Kona Coast on the Island of Hawai‘i (Latitude: 19.8^{o}N, Longitude: 155.8^{o}W, Altitude: 686 m), (Figure 7). The test bed lies on the western slope of the largest volcanoes, Mauna Kea and Mauna Loa, and on the northern flank of Hualalai Mountain, at the bottom of the cone called “Pu`u Wa`a Wa`a” (right picture in Figure 8). It is on the edge of the Honuaula Forest Reserve [6] and is less than 5 miles from the coast line.

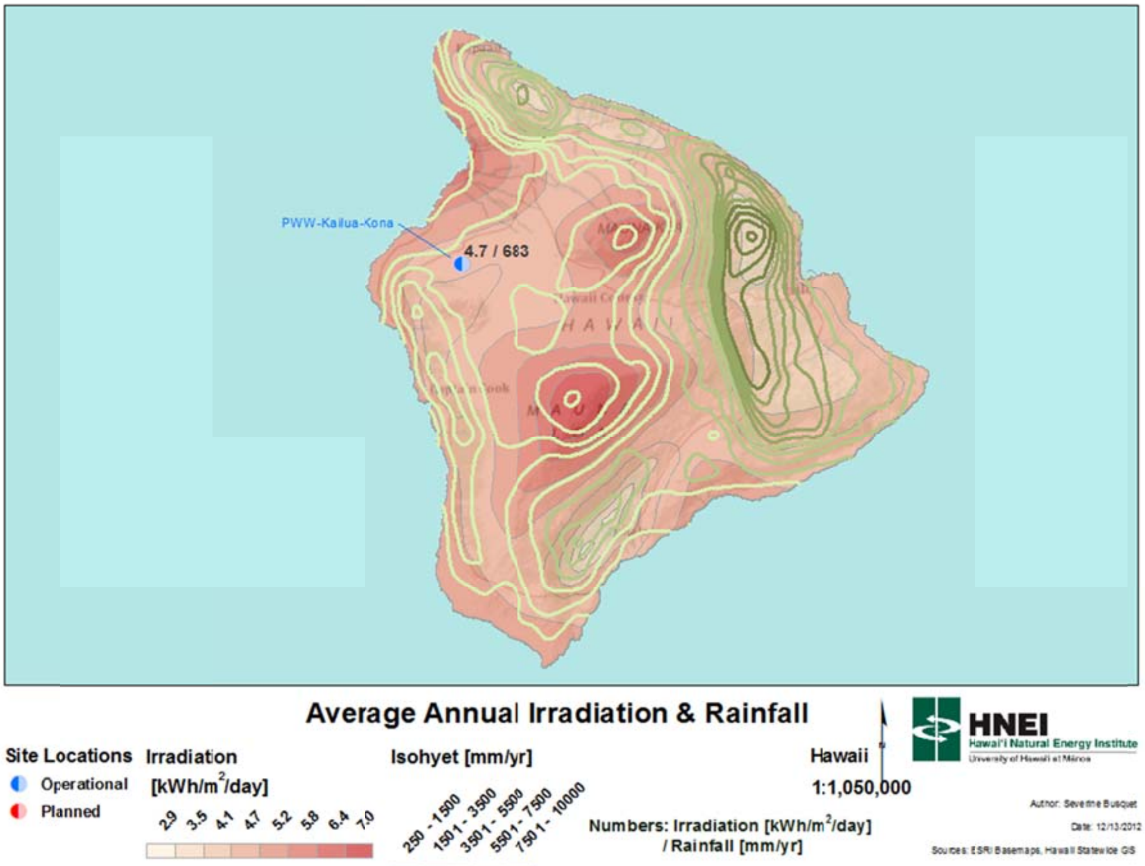

Figure 7: Irradiation and precipitation on the Island of Hawai‘i including values at the PWW test site location.

Figure 8: PWW test site, Kona Coast of Hawai‘i – PV systems ground mounted on open rack structures (left) at the bottom of the Pu`u Wa`a Wa`a hill (right)

PWW is characterized by frequent overcast afternoons, so the site is expected to have a relatively low to medium solar environment estimated at ~4.7 kWh/m^2/day using the GIS data set. The climatic sub region at PWW is estimated to be a mix between **Kona Coast of Hawai‘i** and **Lower to Rainy Mountain slopes on the Leeward side**. This climatic sub region is expected to have similarities with the more densely populated Kailua Kona's lower slopes.

PWW was designed to conduct side by side testing of PV modules consisting of different technologies from different manufacturers. Each module is tested individually using grid-tied microinverters. Two PV modules from each manufacturer were purchased anonymously and are individually tested.

Table 4 describes the PV modules selected for testing at PWW. The PV technologies are 3-junction amorphous from Uni-Solar (UN), poly crystalline from BP Solar (BP), mono crystalline from SolarWorld (SW), and from Suntech (ST) and heterojunction with intrinsic layer (HIT) module from SANYO (SA).

Table 4: Description of the PV modules tested PWW in the Island of Hawai‘i

PV Module Manufacturers	PV Module Model Number	PV Technology	STC Module Efficiency [%]	STC Peak Power [W]
SANYO (SA)	HIP-210NKA5	HIT (Amorphous and Mono-crystalline)	16.7	210
BP Solar (BP)	BP175B	Poly-crystalline	13.9	175
Suntech Power (ST)	STP 175S-24/Ab-1	Mono-crystalline	13.7	175
SolarWorld (SW)	SW175-P	Mono-crystalline	13.4	175
Uni-Solar (UN)	PVL-68	Amorphous (flexible)	6.1	68

Table 5 provides additional information on the PV systems tested at PWW including information on the inverter, the PV system configuration, and the type of mounting system. Two models of microinverters from Enphase (M190 and M210) are used to connect the PV modules. The PV modules are ground mounted, with a 20^o tilt, facing south, on open rack structures. The flexible modules from Uni-Solar require connecting two modules in series to match the MPPT voltage range and recommended power of the microinverter. The flexible modules are installed on a small standing seam roof, with a 20^o tilt, facing south.

Table 5: Tested PV systems at PWW in the Island of Hawai'i : Inverter, PV system configuration and PV module mount.

PV	Inverter			PV system configuration			PV Module Mounting
	Type	Brand	Power [W]	# of inverters	# of PV modules	PV arrangement per inverter	
BP	Micro	Enphase	190	2	2	PV individually tested	Open rack
SA	Micro	Enphase	210	2	2	PV individually tested	Open rack
SW	Micro	Enphase	190	2	2	PV individually tested	Open rack
ST	Micro	Enphase	190	2	2	PV individually tested	Open rack
UN	Micro	Enphase	190	2	4	2 PV in series	Roof

Each PV module is instrumented with sensors to collect module current, voltage, and temperature. The electrical measurements are collected between the PV module and microinverter (visible on the left picture of Figure 9). The PVMUs are located underneath the PV modules. Data cable conduits are installed on the back of the structure and buried in the ground to carry data cables from the PVMUs and the WSS to the DAS enclosure, refer to Figure 9 and Figure 10 (right photo).

Figure 9: PVMU and data cable management at PWW – PVMU are located underneath each PV module – Conduits protect data cable from each PVMU to the DAS enclosure.

The WSS is located on a tripod secured to the ground (refer to Figure 10).

Figure 10: WSS, data cable management and DAS enclosure at PWW.

Figure 11: Ventilated NEMA-4 enclosure protecting the DAS, test and network equipment - PWW.

The DAS enclosure has a NEMA-4 rating and ventilation system to protect the equipment from the environment. Figure 11 shows the inside of the DAS enclosure including from the top to the bottom, the load bank, the DAS, the Ethernet switch, the battery, and the uninterruptible power supply (UPS). The UPS provides power to the DAS to keep the system on line during short duration utility outages.

The PV test bed and associated DAS at PWW were commissioned in July of 2010. This test site was developed and instrumented under this DOE grant. The installation was presented at an IEEE conference [7].

3.2. Green Holmes Hall Initiative, UH Mānoa, Honolulu, Oʻahu

The Green Holmes Hall Initiative (GHHI) test site is on the UH Mānoa campus on Oʻahu. The UH Mānoa campus (Figure 12) is located on the south side of the mountain slope of the Koolau range (Latitude: 21.3°N, Longitude: 157.8°W, Altitude: 48 m) overlooking Honolulu, 2 miles from the south shore (left photo in Figure 13).

Sunny weather prevails at this site with light trade wind showers which drift over from the Koolau Mountains. GHHI has medium to high irradiation levels estimated to be ~5.2 kWh/m^2/day. Data collected under these environmental conditions will provide data to assess performance of the PV systems operating in a medium to high-solar environment on the south mountain slope of Oʻahu. The climatic sub region is estimated as **Lower Mountain slopes on the Leeward side**. This area is relatively densely populated, and is expected to provide useful data for much of Honolulu's lower mountain slopes.

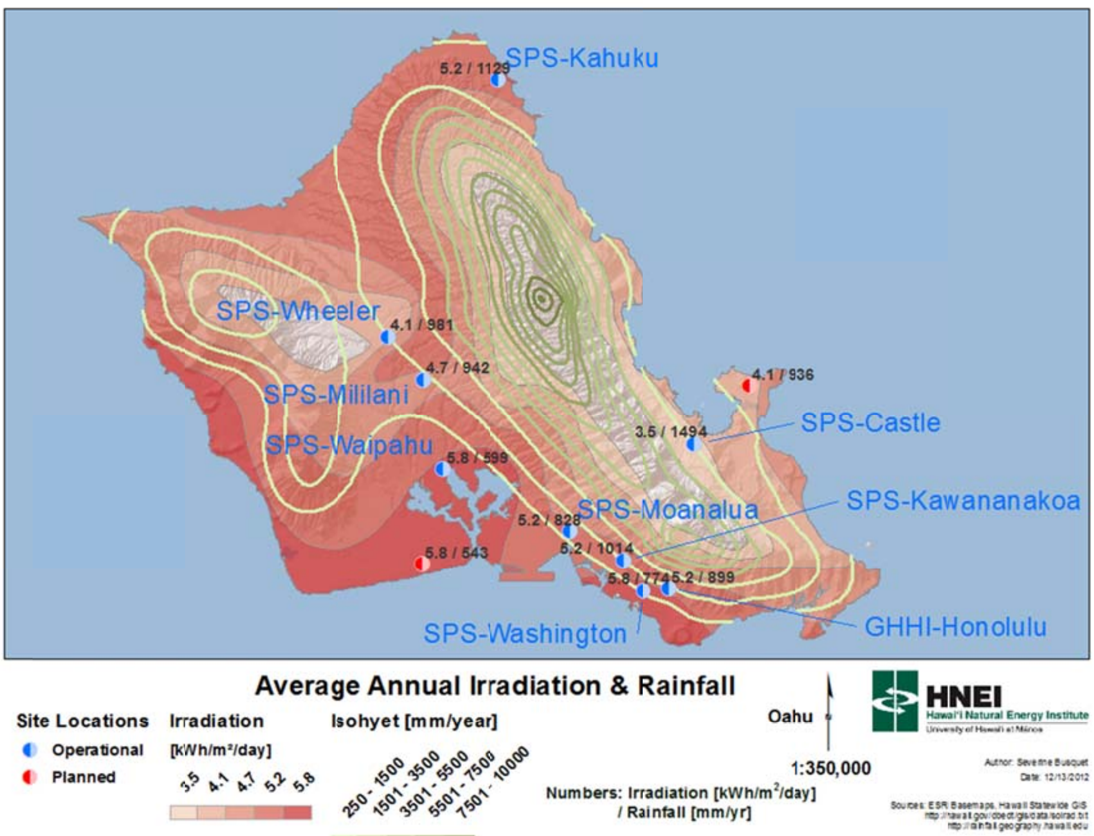

Figure 12: Irradiation and precipitation on Oʻahu including value at GHHI.

This map includes the location and weather conditions of other test beds where HNEI has deployed or will deploy PV systems and instrumentation from other grants. SPS refers to the HNEI/HECO SunPower for School project including eight test beds.

Figure 13: GHHI – PV systems mounted on open rack structure (middle) on a roof on the Koolau Range Mountain slope (background, right image) overseeing Honolulu (background, left image).

GHHI supports side by side comparison of two residential size, grid-tied PV systems (Table 7) made made of PV modules (Table 6) from two different PV technologies. The PV systems consist of the following arrays:

- Two parallel strings of 13 poly-crystalline PV modules from Kyocera are connected to a 5 kW SMA string inverter, and
- Six parallel strings of four micro-amorphous PV modules from MHI are connected to a 3 kW SMA string inverter.

Table 6: Description of the PV modules tested at GHHI in O‘ahu.

PV Module Manufacturers	PV Module Model Number	PV Technology	STC Module Efficiency [%]	STC Peak Power [W]
Kyocera (KY)	KD205GX-LPU	Poly-crystalline	13.8	205
Mitsubishi Heavy Industries (MHI)	MT130	Micro-amorphous	8.3	130

Table 7: Tested PV systems at GHHI in O‘ahu: Inverter, PV system configuration and PV module mount.

PV	Inverter				PV system configuration			Mount
	Type	Brand	Model	Power [W]	# of inverters	# of PV modules	PV arrangement per inverter	
KY	String	SMA	SB5000US	5k	1	26	2 parallel strings of 13 PV in series	Open rack
MHI	String	SMA	SB3000US	3k	1	24	6 parallel strings of 4 PV in series	Open rack

The two PV arrays located on the flat roof of Holmes Hall are mounted on three rows of open rack structures, with a 20^{o} tilt, facing south. The grid-tied string inverters are installed on the fourth floor of Holmes Hall (Figure 14).

Figure 14: PV systems at GHHI – PV modules on the roof (left) connected to the grid tied inverters on the fourth floor (right).

There are two PVMUs on the front row of the structure for the MHI array plus one PVMU for the Kyocera array which is located on the third row near the DAS. The enclosures are mounted to the structure supporting the PV arrays. The WSS is also mounted on the structures on the back of the two arrays. Conduits are used to protect the data cables from the environment. A power and communication (P&C) enclosure is located near the DAS which includes power management equipment and ventilation system to power and cool the DAS equipment (Figure 15).

The PV test bed site was commissioned in December of 2010. The site was fully instrumented and the DAS was deployed under funding from this DoE grant, and was commissioned in May of 2011.

Figure 15: On the roof of Holmes Hall: WSS (left); PVMU, data cable management, DAS enclosure and P&C box (right) – GHHI.

3.3. UH Maui College, Kahului, Maui

University of Hawaiʻi Maui College (UHMC) is part of the University of Hawaiʻi system. The campus is located on the Northern end of the interior lowlands (Figure 17) on the Island of Maui (Latitude: 20.9^{o}, Longitude: -156.5^{o}, Altitude: 5 m) a few meters from the north shore and 6 km (4 miles) from the Īao Valley edge of the west Maui mountain range (Figure 16). The location's irradiation is estimated to be approximately 5.2 kWh/m^{2}/day which is similar to the Oʻahu GHHI test site. Information collected under these environmental conditions will provide data to assess performance of the PV systems operating in a medium to high-solar environment on the northshore of Maui. The climatic sub region is estimated to correspond to the windward, north Interior Lowland on Maui.

Figure 16: UHMC, Kahului, Maui – Roof mounted PV systems (left) on the north shore, four miles from the West Maui Mountain (right)

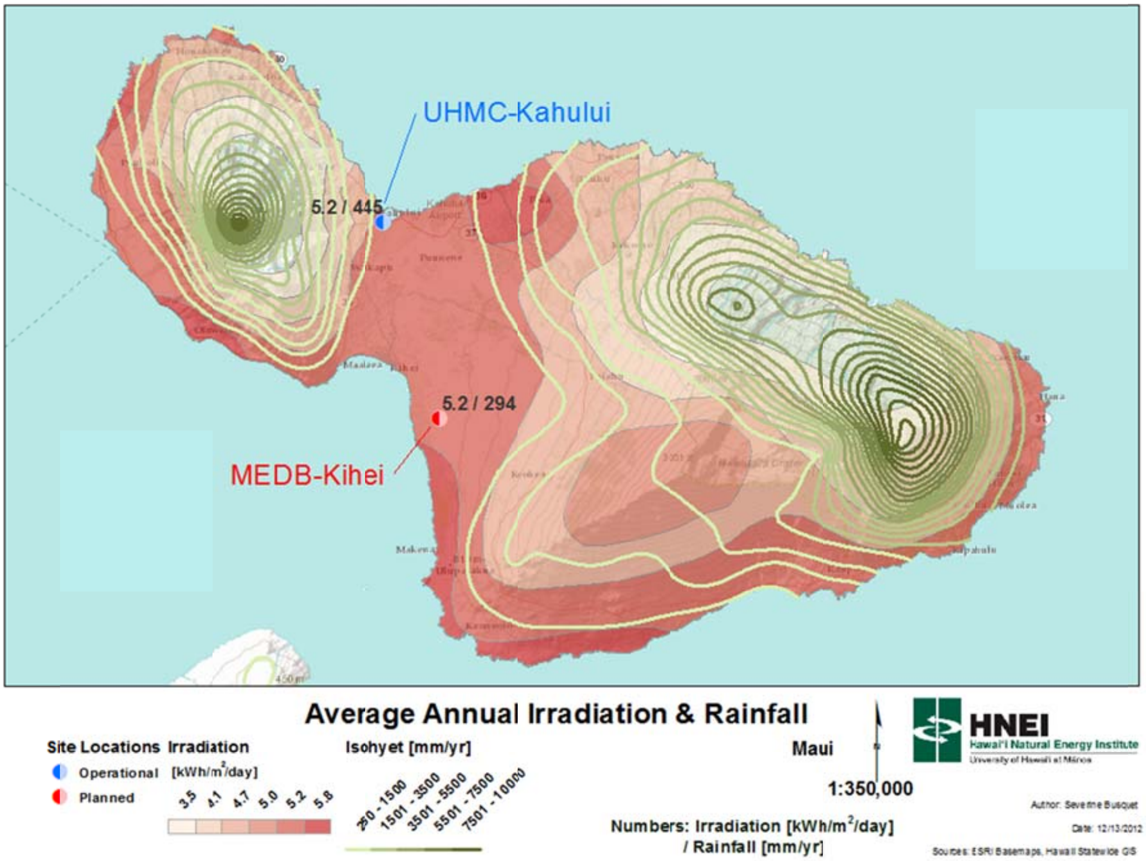

Figure 17: Irradiation and precipitation in Maui including value at the UHMC test site location.

This map also includes the location and weather conditions of a future PV test bed being planned for Maui Economic Development Board. The test bed will focus on thin film technologies and be funded under another grant.

The UHMC test site was selected for inclusion in this study because the Kyocera arrays deployed at UHMC are very similar to the Kyocera array that is deployed on the roof top of Holmes Hall. This comparison should lead to an evaluation of the impact of the location including climate and PV module mounting for a very similar PV System.

UHMC PV installation consists of three identical grid-tied PV systems. Each PV system (Table 9) consists of two parallel strings of 14 poly-crystalline PV modules from Kyocera (Table 8), connected to a 5 kW SMA string inverter. All 84 PV modules are mounted on the south facing standing seam metal roof, with a 20^{o} tilt, on the vocational building as shown in Figure 16.

Table 8: Description of the PV modules tested at UHMC in Maui

PV Module Manufacturers	PV Module Model Number	PV Technology	STC Module Efficiency [%]	STC Peak Power [W]
Kyocera (KY)	KC175	Poly-crystalline	13.7	175

Table 9: Tested PV systems at UHMC in Maui: Inverter, PV system configuration, and PV module mount.

PV	Inverter			PV system configuration			Mount
	Type	Brand	Power [W]	# of inverters	# of PV modules	PV arrangement per inverter	
KY	String	SMA	5k	3	84	2 parallel strings of 14 PV in series	Roof

The data to assess performance is collected from each string of the arrays monitoring current and voltage. The PV data is collected just before the connection of the power cables to the inverters, located above the PV inverters inside the building close to the grid connection breaker box (Figure 18). The DAS and P&C enclosures are located inside.

The P&C enclosure includes power management equipment, ventilation system to power and cool the DAS and its instruments, and an Ethernet switch to connect the controller to the internet through the UHMC network.

Data cables connect the DAS to each PVMU as well as the WSS located on the roof near the PV modules. The WSS (Figure 18) was designed to attach directly to the metal seam roof at a specified angle.

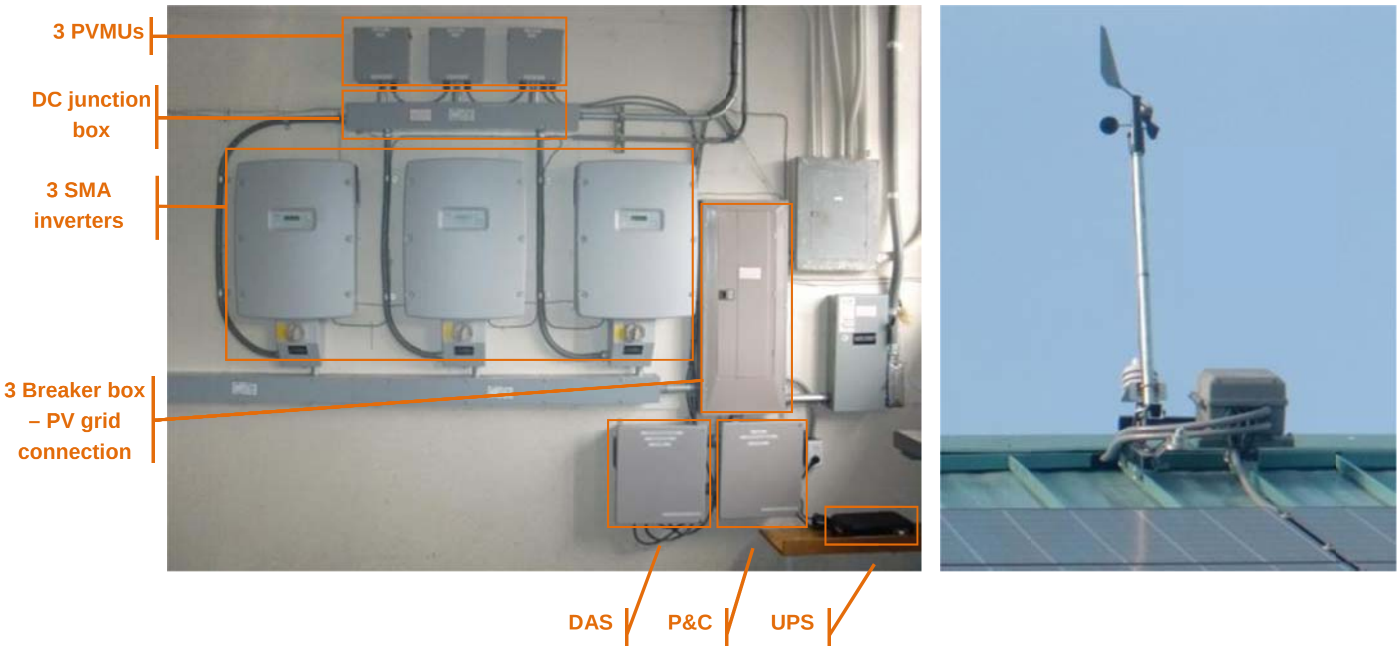

Figure 18: UHMC instrumentation – Roof mounted WSS (right), PVMUs, DAS enclosure and power and communication box (left).

The PV system was funded by a Hawai‘i Rural Development Project of the Department of Labor in a partnership with the UHMC and was commissioned in April of 2010. The development of the DAS and WSS were funded under this DOE grant. The DAS was installed and commissioned in April of 2011.

4. Summary

Under this grant, the Hawai‘i Natural Energy Institute (HNEI), at the University of Hawai‘i Mānoa (UH), developed and deployed PV test beds on three different islands in Hawai‘i . This effort allows collection of high-resolution, time-synchronized data for different PV systems under different climatic conditions. The PV systems at these locations vary in terms of PV module technology, mounting structure, PV system configuration, power, dimensioning, and geographical location. The analysis of the experimental data collected from these PV systems leads to the evaluation of PV performance, determination of the main parameters affecting the PV systems operating in the islands, and an estimate of the impact of weather conditions on system performance.

The anticipated amount of irradiation at the test sites was estimated using GIS data sources to identify climatic conditions at the three tests sites located on three different islands. The selected locations represent three climatic sub regions: 1) a mix between Kona coast of Hawai‘i and

Lower to Rainy Mountain slopes on the Leeward side with a relatively low to medium solar environment on the Island of Hawaiʻi , 2) Lower Mountain slopes on the Leeward side with medium to high solar resource on Oʻahu, and 3) Windward Lowland climate as in the north Interior Lowlands on Maui with medium to high-solar environment.

The PV test bed sites are configured as grid-tied PV systems closely representing residential and small scale commercial grid-tied PV systems. The PV test bed located on the Island of Hawaiʻi was designed to conduct side by side comparisons of individually PV modules selected from different technologies. UHMC and GHHI test sites are PV arrays with string inverters. The GHHI site supports side by side comparison of two PV module technologies. Five PV module technologies from seven different manufacturers were tested including amorphous, micro-amorphous, mono and poly-crystalline, and HIT. Two models of string inverters and two models of micro inverters were selected to connect to the grid and to perform the maximum power point tracking of the PV systems tested at the three sites. The PV modules are south facing, with a 20^{o} tilt, either roof mounted or attached to open rack structures.

The PV systems were carefully instrumented to collect high-speed and time-synchronized data on the PV system and the local environment. Each sensor was selected for the best-value unit with high-accuracy. All test sites are equipped with similar instrumentation and a DAS to minimize the variation in the measurements between sites. All of the DAS are part of an internet based-network including a data server where all data sets are securely transferred into a database for data analysis and visualization.

All of the PV systems, WSSs, and DASs were successfully deployed in 2010 and 2011 and are still in operation collecting essential data to evaluate and understand PV performance in the State of Hawaiʻi . Detailed analysis of this data will be presented in the forthcoming second report under this grant.

5. References

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