

Solar Resource and PV Systems Performance at Selected Test Sites

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PV Systems Performance at Selected Test Sites**

By the

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1. Introduction

Under funding from the US Department of Energy (DOE), the Hawaii Natural Energy Institute (HNEI), at the University of Hawaii Manoa (UH), has been developing and deploying photovoltaic (PV) test beds to evaluate PV systems in various locations in Hawaii. Selection of the sites and the test protocols was described in detail in the Final Technical Report under Award No DE-FC26-06NT42847; “PV Test Sites and Test Protocols”.

PV systems located on three different islands are in operation under real-life conditions using grid-tied inverters, including a maximum power point tracker (MPPT) used to maximize the DC power from the PV modules. Data have been collected for a sufficient period of time to analyze one year of operation.

This report describes the data analysis for the three test sites necessary to characterize the solar resource and the PV system performance. The seasonal variation and main performance parameters of the PV systems are estimated after introducing the PV systems.

To compare performance of the PV modules, the DC Performance Ratio (PR) was selected for the analysis. The PR gives the operational efficiency relative to the efficiency specified by the manufacturer at standard test conditions, and is the measured DC energy output from the PV divided by the theoretical DC energy output from the PV produced at the test location. The analytical approach used in this report is presented in Appendix 1.

2. Pu`u Wa`a Wa`a, Kailua-Kona, Island of Hawaii

Test site at Pu`u Wa`a Wa`a (PWW) was developed for side by side comparison of PV modules from different technologies and manufacturers, tested individually using grid-tied micro-inverters. The PV test bed and associated data acquisition system (DAS) were commissioned in July of 2010. This test site was entirely developed and instrumented under this grant.

2.1. PV test site and protocol

PWW [1], [2], is a sparsely populated location on the North end of the Kona Coast on the Island of Hawaii (Latitude: 19.8°N, Longitude: 155.8°W, Altitude: 686 m). 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 (Figure 1).



Figure 1: PWW, Kona Coast of Hawaii – PV systems ground mounted on open rack structures (left) at the bottom of the Puu Waa Waa hill (right)

Table 1 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). Two PV modules from each manufacturer were purchased and are tested individually using micro-inverters.

Table 1: 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 2 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 flexible modules from Uni-Solar require connecting two modules in series to match the MPPT voltage range and recommended power of the microinverter. The PV modules are ground mounted, with a 20° tilt, facing south, on open rack structures. The flexible modules are installed on a small standing seam roof, with a 20° tilt, facing south.

Table 2: 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

2.1. One year of operation

Figure 2 is a plot of the daily irradiation at PWW for a year from January through December of 2011. Irradiation is the integral over a time period (a day here) of the irradiance collected by the thermopile pyranometer, tilted in the plane of array (POA). The irradiation varies widely by up to 7 kWh/m² throughout the year. The irradiation averages 3.6 kWh/m²/day with a standard deviation estimated at ±1.2 kWh/m²/day representing a very small seasonal variation. The maximum POA irradiation above the atmosphere [3], extraterrestrial daily solar energy (ETDSE), is also plotted on the graph (blue line). Due to the latitude of Hawaii, the ETDSE exhibits a biannual cycle with small variation throughout the year.

The period of analysis was selected to be one year long after completion of the light induced degradation (LID). The degradation of the PV modules was estimated by examining the daily PR. For the HIT modules from SA, we estimated the decrease in PR to be approximately 4% covering a 5 month period between July 2010 and December 2010. The amorphous modules from UN showed a PR degradation estimated to be ~6% in 5 months before stabilization of the performance in 2011. The degradation of PV modules may have started earlier as the modules were purchased in 2009, used for short periods of time while the test beds were being developed, installed at the site in April of 2010, and covered until commissioning of the test bed in July of 2010. Other crystalline PV modules tested at PWW, analyzed during the first year of operation (July 2010 through July 2011), did not exhibit any LID. For both periods of analysis, the irradiation has the same average and the same deviation.

Figure 3 shows the daily PR of the SA HIT modules. The monthly PR is plotted in red. The PR of the HIT modules is the highest in June and December. Low values of PR occur in March and April. The lowest performance is in August and September. The seasonal variation of the PR, calculated using the standard deviation of the daily PR throughout the year is estimated to be ±2.3%. The yearly PR of the HIT is estimated to be 94.5%. Between the two tested HIT modules, the deviation of the yearly PR is approximately 2.9%.

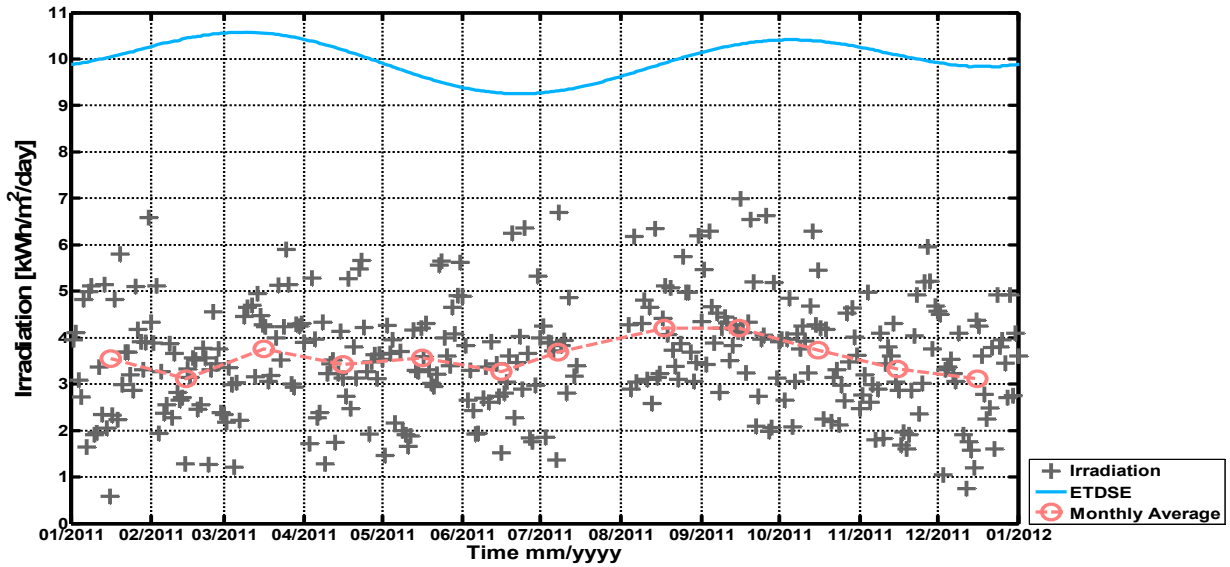


Figure 2: Irradiation for a year of recording at PWW

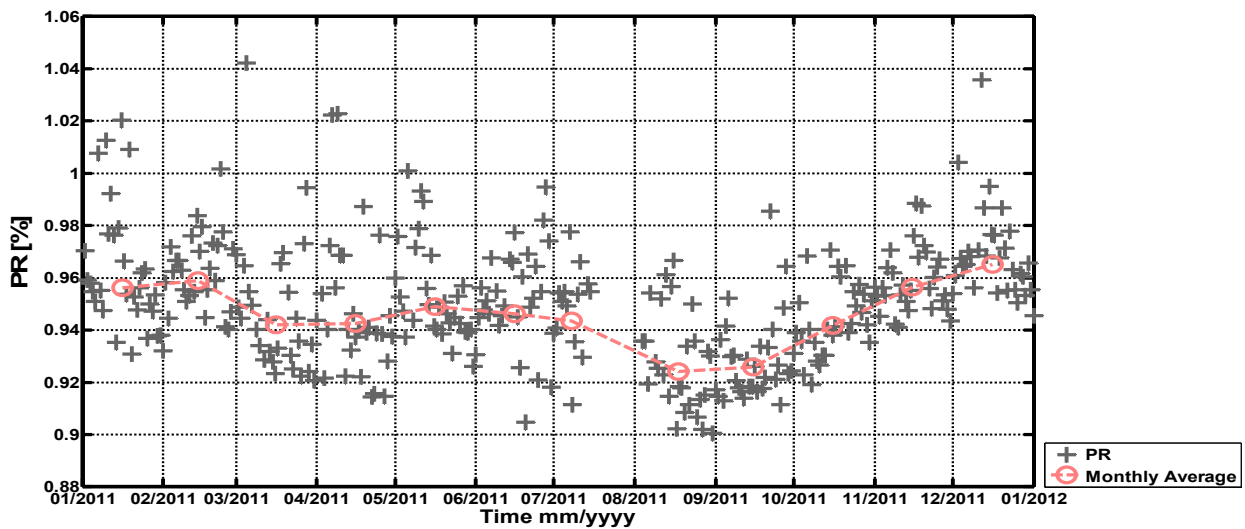


Figure 3: Daily PR of the PV module from SA for a year of recording at PWW

All of the PV modules tested at PWW exhibit the same performance variation with the seasons. High PR occurs in June and December; low PR at the equinoxes and the lowest performance is in August and September.

Table 3 gives the results for all modules operating at PWW. It includes the yearly PR, the seasonal variation of the daily PR throughout the year, and the yearly PR deviation between the two modules from each manufacturer. The period of analysis is indicated in the 2nd column of Table 3.

Table 3: Yearly PR of the PV modules tested at PWW - Standard deviation of the yearly PR between the 2 tested PV modules (StD(PV)). Standard deviation of the daily PR along the year of operation (StD(Year)).

PV	Period of analysis mm/dd/yyyy	PR [%]		
		Yearly	StD(PV)	StD(Year)
SW	07/10/2010-07/09/2011	97.2%	0.2%	2.8%
SA	01/01/2011-12/31/2011	94.5%	2.9%	2.3%
ST	07/10/2010-07/09/2011	91.9%	0.8%	2.6%
UN	01/01/2011-12/31/2011	91.3%	0.2%	2.8%
BP	07/10/2010-07/09/2011	89.5%	0.8%	1.9%

As detailed in Table 3, the yearly PR at PWW varies from 89.5% for the BP poly-crystalline modules to 97.2% for the SW mono-crystalline. The standard deviation of the yearly PR between the two PV modules from the same manufacturer is estimated to be less than 0.8% for most of the PV modules. Only the HIT modules from SA have a high standard deviation between the 2 tested modules, estimated at 2.9%. The seasonal variation of the PV performance throughout the year estimated using the standard deviation of the daily PR is approximately 1.9% for the poly-crystalline (BP), 2.3% for the HIT (SA), and 2.6-2.8% for the mono-crystalline (SW, ST) and for the roof mounted amorphous modules (UN).

2.2. Solar resource characterization

Figure 4 is the histogram of the irradiation at PWW. The distribution is a bell curve, with an average value of 3.6 ± 1.2 kWh/m²/day. The site has variable climatic conditions with approximately the same number of cloudy days and sunny days. To observe the impact of the weather conditions, we selected days based on the irradiation. Sunny days are selected with irradiation above 4.8 kWh/m²/day (average irradiation plus standard deviation). Cloudy days have irradiation below 2.4 kWh/m²/day (average irradiation minus standard deviation).

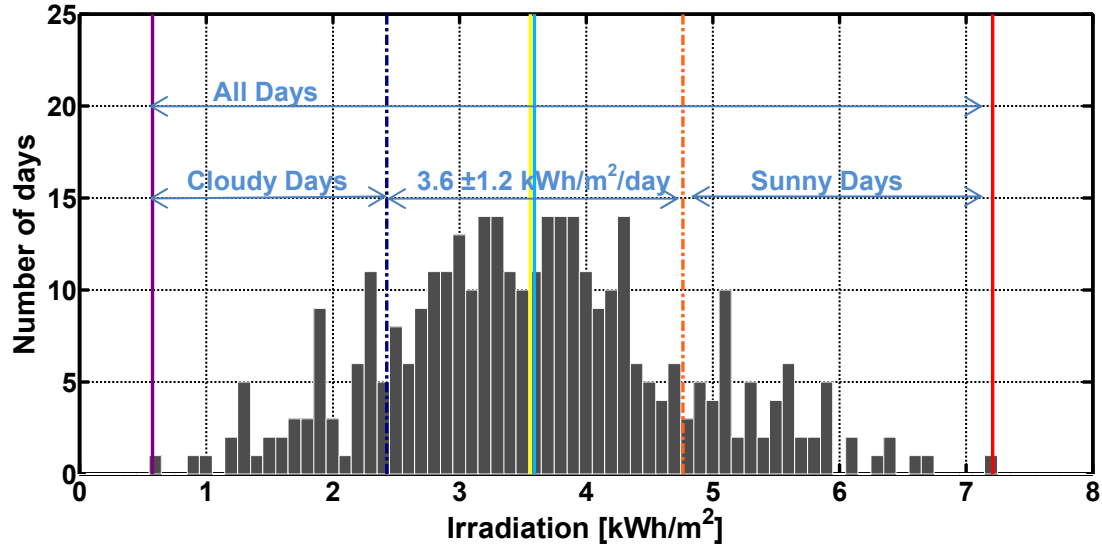


Figure 4: Histogram of the irradiation for a year of recording at PWW. Vertical lines from left to right correspond to: lowest value (purple), high limit for cloudy days (blue), average (yellow), median (light blue), low limit for sunny days (orange), and highest value (red).

Figure 5 shows the solar energy collected per level of irradiance for the different weather conditions (all days, sunny, and cloudy days). This is a bar graph plotted as a line graph for better visualization. Cloudy days collect most of the solar energy at low irradiance levels $< 500 \text{ W/m}^2$. Sunny days shift the solar energy at high irradiance levels with a peak at 950 W/m^2 . All days collect energy at all irradiance levels showing 2 peaks at 300 W/m^2 and 900 W/m^2 .

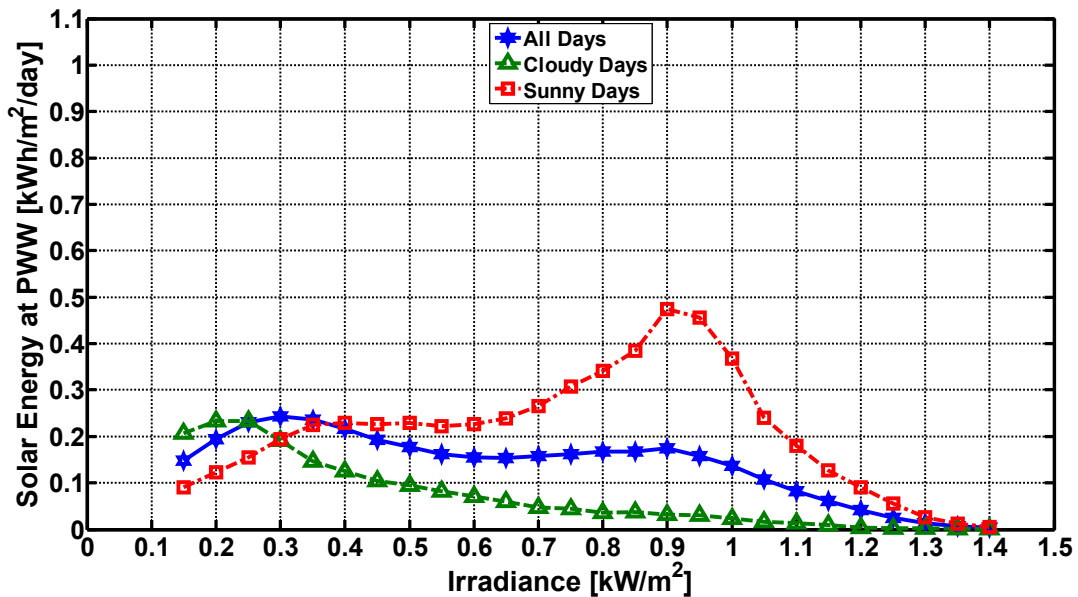


Figure 5: Yearly average of the irradiation collected per levels of irradiance at PWW.

2.3. PV module performance and parameters

Figure 6 is a plot of the yearly average PV power as a function of the irradiance levels. The yearly average PV power increases with increasing irradiance levels until reaching a maximum power at high irradiance levels. The PV power is limited by the inverter at high irradiance levels. Inverter saturation was observed for all modules with the exception of the amorphous UN modules. The irradiance level above which the PV power is limited by the inverter capacity is determined by the dimensioning of the PV system (the rated power of the inverter in comparison to the power of the PV system). The HIT 210 W module is limited to ~230 W by the micro inverter M210 above 1.1 kW/m^2 . All 175 W crystalline modules (BP, ST, and SW) connected to the microinverters M190 are power limited to 205 W above ~1.2 kW/m^2 . Finally, the UN module connected to the inverter model M190 does not show any saturation reaching a maximum power of 165 W or 1.2 times the specified power (136 W).

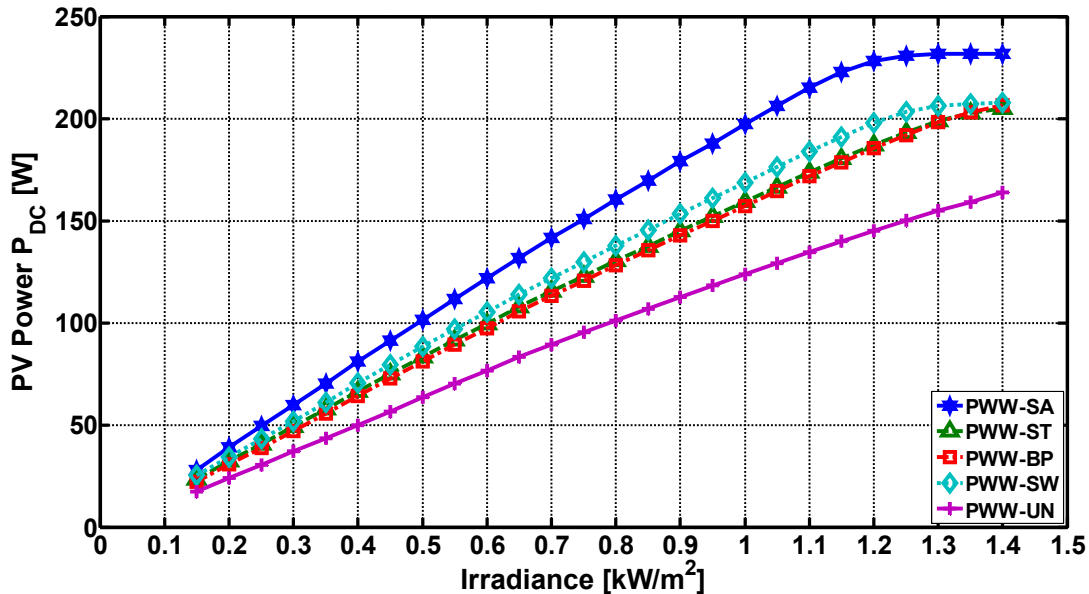


Figure 6: Yearly average PV power as a function of irradiance levels for all PV modules at PWW.

The three crystalline modules (BP, ST and SW) are connected to the same microinverter model (M190) and have the same specified power of 175 W. The SW displays up to 10 W higher power than the ST and BP modules (estimated at 1000 W/m^2), although the experimental set-up is identical for all three PV modules. In addition, the module temperature monitored on the back of the module is similar for the 3 PV modules (between 41°C and 44°C at 1 kW/m^2). This suggests that the SW modules would have an output power 5.7% higher than specified by the supplier. The impact of this underestimated STC power on the PR is calculated to be 5.3%, adjusting the PR from 97.2% down to 91.9% (same as the ST modules).

Figure 7 shows the yearly PR as a function of irradiance levels for all PV modules tested at PWW. At low irradiance levels, the PR of the PV modules increases with increasing irradiance levels reaching a peak between 450 W/m² and 650 W/m² depending upon the PV technology. The PR peaks at 450 W/m² for the mono-crystalline (ST, SW), at 500 W/m² for the HIT (SA), at 550 W/m² for the poly-crystalline (BP) and at 600-650 W/m² for the amorphous (UN) PV modules. After the peak, the PR decreases with increasing irradiance levels. For most PV modules with the exception of the amorphous modules, the PR drops off at high irradiance levels due to saturation of the microinverters.

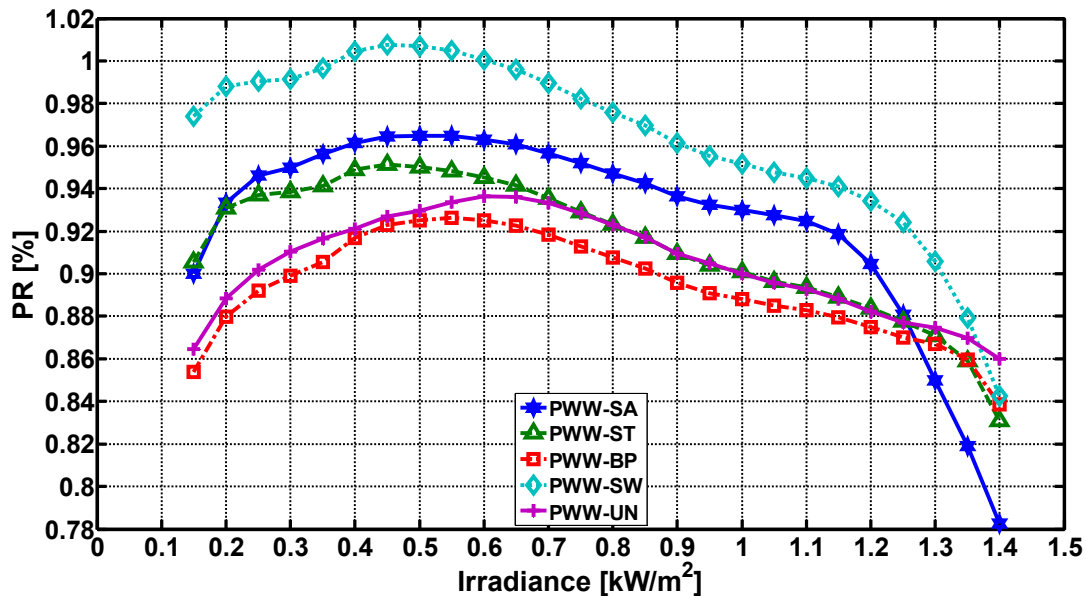


Figure 7: Yearly PR as a function of levels of irradiance – All PV modules tested at PWW.

The PR versus irradiance plots for the two mono-crystalline modules (ST, SW) have a similar shape. The SW plot is estimated to be ~5% higher than the ST plot which would be explained by the 5.3% PR adjustment suggested earlier due to the underestimated STC power of the SW modules. The PR versus irradiance plots for the crystalline and amorphous modules (BP, ST, SW, and UN) are similar above 700 W/m². The mono-crystalline plots show better performance at low irradiance levels than the poly-crystalline and the amorphous. The HIT modules have the most constant PR with the irradiance levels from 200 W/m² to 1.1 kW/m².

Figure 8 shows the performance of the four tested technologies as a function of irradiance levels for the different weather conditions: all days, sunny, and cloudy. The SW mono-crystalline module is not presented in Figure 8 because the observed PR is similar to the other mono-crystalline modules (ST).

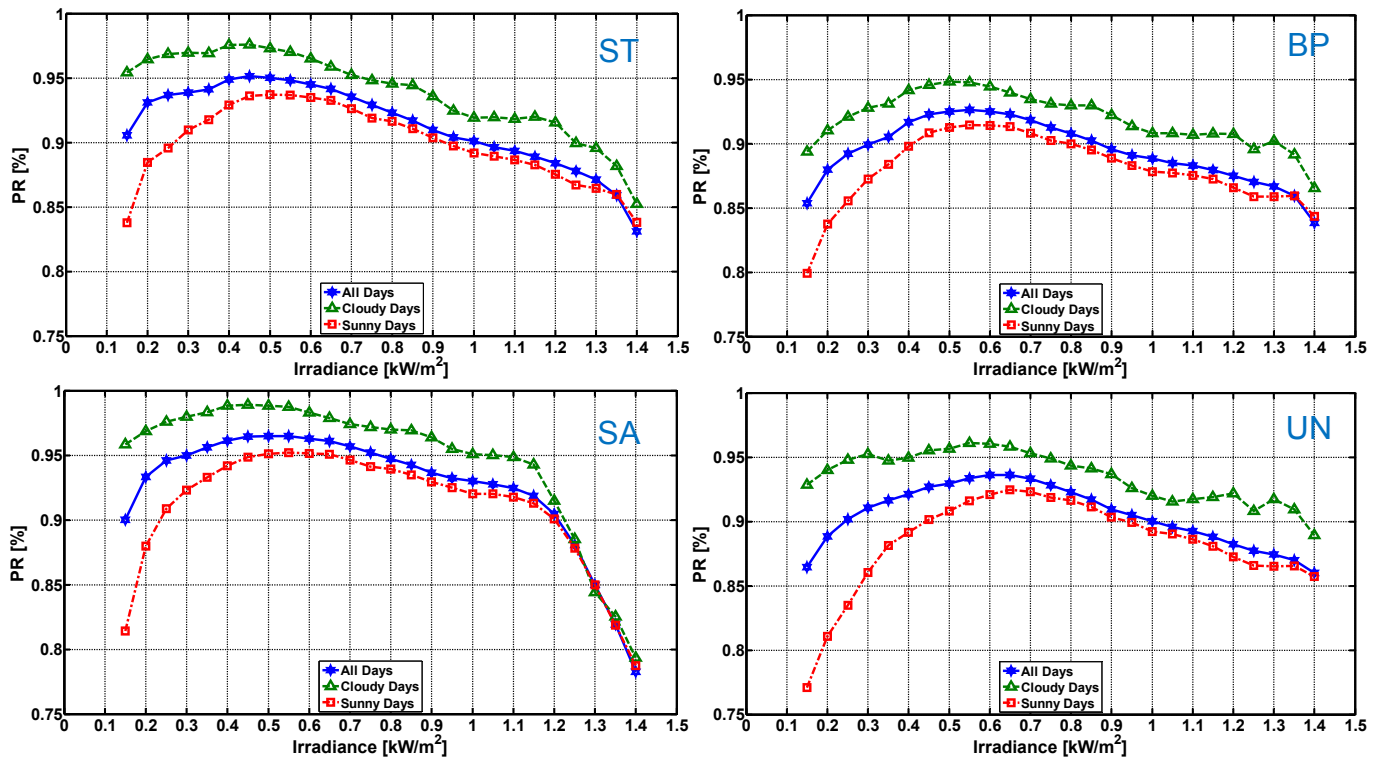


Figure 8: Impact of the weather conditions on the PR of the PV modules operating at PWW.

Impact of the climatic conditions on the PV performance at PWW shows:

- For all technologies and all irradiance levels, PR is higher on cloudy days and lower on sunny days compared to the PR for all days.
- Cloudy days PR shows a bump at high irradiance above 1 kW/m^2 . This is caused by very short periods of high irradiance levels inducing operation of the PV module at a temperature lower than its normal operating temperature.
- Weather conditions affect each module differently at low irradiance levels showing a slight decrease in PR on cloudy days and an increased impact for all days and sunny days. This is due to higher light reflection on sunny days. Sunny days are characterized as clear sky during most of the day. Lower irradiance levels correspond to sunrise and sunset when the sun light has high incidence angle, is highly filtered by the atmosphere, and reflected off the surface of the module. Higher impact of the light reflection is observed on the amorphous technology modules (UN, SA). PR degradation for UN occurs up to 700 W/m^2 .

Table 4 shows the PR values of the PV modules for different weather conditions (All days, sunny and cloudy). These PR values depend on the profile of the irradiation and PR as a function of the irradiance levels.

Table 4: Impact of the weather conditions on the PR values of the PV modules operating at PWW.

PV	PR [%]		
	Cloudy Days < 2.4 kWh/m ² /day	All Days	Sunny Days > 4.8 kWh/m ² /day
SA	97.5%	94.5%	92.9%
SW	101.3%	97.2%	95.2%
ST	95.6%	91.9%	90.1%
UN	94.6%	91.3%	89.6%
BP	92.1%	89.5%	88.3%

As expected, the PR is higher on cloudy days and lower on sunny days. The PR of the SW above 100% on cloudy days confirms the possibility of conservative rating of the PV modules by some manufacturers. The impact of the weather conditions depends on the PV module: 3.7% for the poly-crystalline (BP), 4.5% for the HIT (SA), and 5-6% for the mono-crystalline (SW, ST) and amorphous modules (UN).

Finally, calculations were developed in order to evaluate the impact of the inverter saturation on the yearly PR of the PV modules (Appendix 1). We observed that the most affected modules are the HIT modules from SA (0.08%) having saturation starting as soon as 1.1 kW/m². All other PV modules show an impact of the inverters of less than 0.04%, depending on the irradiance levels when saturation starts. The impact of inverter saturation on PV performance was estimated to be minimal, due to low solar energy collected at irradiance levels above 1.1 kW/m².

3. Green Holmes Hall Initiative, UH Manoa, Honolulu, Oahu

The Green Holmes Hall Initiative (GHHI) test site supports side by side comparison of two residential size, grid-tied PV systems on the UH Manoa campus on Oahu. The PV test bed site was commissioned in December of 2010, and the DAS was commissioned in May of 2011. The site was fully instrumented and the DAS was deployed under funding from this grant.

3.1. PV test site and protocol

GHHI test site is on the UH Manoa campus on Oahu 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 (Figure 9).



Figure 9: GHHI, Honolulu, Oahu – PV systems mounted on open rack structure (middle) located on a flat 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 made of PV modules (Table 5) from two different PV technologies. The PV systems consist of the following arrays (Table 6):

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

PV modules are mounted on open-rack structures, south facing at an angle of 20°.

Table 5: Description of the PV modules tested at GHHI in Oahu.

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

Table 6: Tested PV systems at GHHI in Oahu: 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

3.2. One year of operation

Figure 10 shows the irradiation levels collected at the GHHI test site from October 2011 through September 2012. The maximum irradiation values received at the site throughout the year follow the variation of the ETDSE plot (blue line). The monthly average of the irradiation has higher values for the time period from May through August. The yearly average is measured at 5.8 ± 1.2 kWh/m²/day.

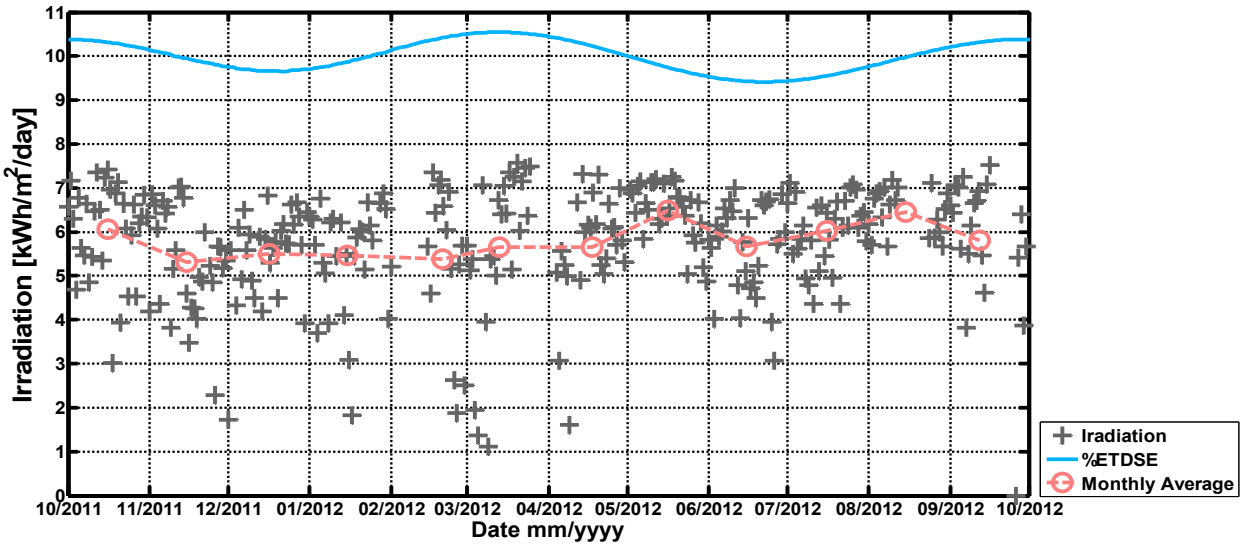


Figure 10: Irradiation for a year of recording at GHHI.

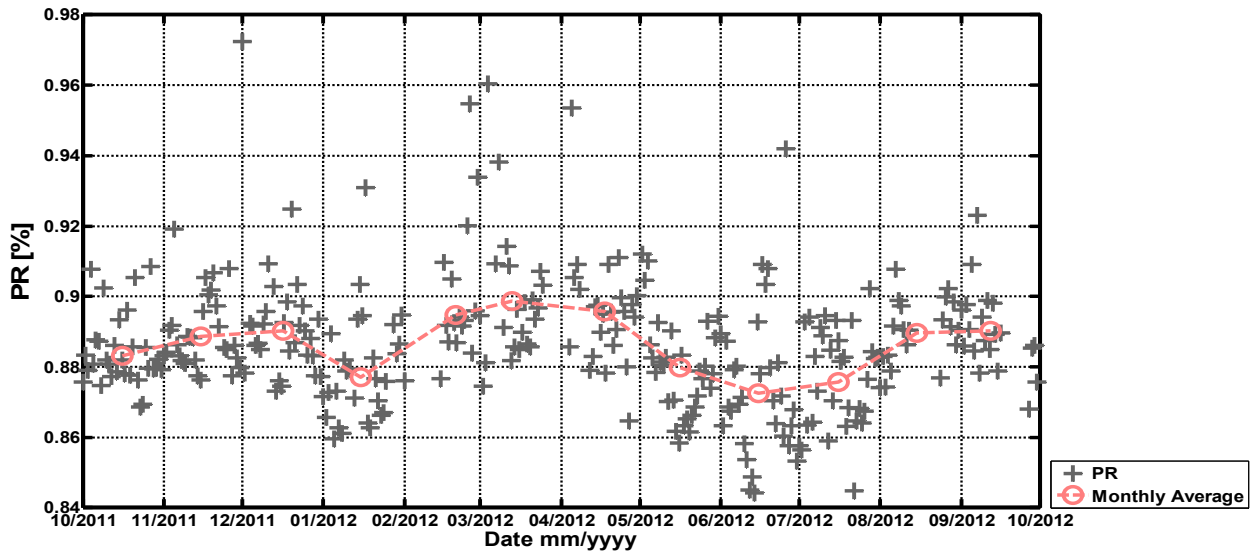


Figure 11: Daily PR for the KYO array operating for a year of recording at GHHI.

Figure 11 describes the daily PR of the KYO poly-crystalline array at the GHHI test site from October 2011 through September 2012. The daily PR of the KYO array at GHHI has high values in March. Low performance happens twice: once in January and then again from May through July. The seasonal variation throughout the year is estimated to be $\pm 2.1\%$. The yearly PR of the KYO array is calculated at 88.5%. There are two strings of 13 PV modules in the array. The yearly PR deviation between the strings is calculated at 1.4% which is a high value for PV array configuration. Indeed, monitoring the performance of strings of PV modules already average the performance of all the PV modules connected in series. The PR deviation between strings is actually observed varying throughout the year showing higher difference in summer. This suggests a

different impact of shading on each string during summer time. The PR monitored from May to July may therefore be lower than expected due to shading of the array.

The second array tested at GHHI is MHI's micro-amorphous array. For these modules, we observed a LID until December 2011. The LID for the micro-amorphous modules is estimated at ~15% from December 2010 through December 2011. Performance of the MHI array at GHHI after the LID period from January 2012 through September 2012 is similar to the KYO array tested at the same site. The daily PR is high in March and low from May through July. As for the KYO array, the PR of the MHI array monitored from May to July may be lower than expected due to potential shading of the array during summertime. The seasonal variation of the daily PR throughout the year is estimated to be $\pm 2.4\%$. The yearly PR of the MHI modules is estimated to be 86.1%. Between the strings of the array, the standard deviation of the yearly PR is $\sim 0.6\%$.

3.3. Solar resource characterization

The histogram of the daily solar energy for a year of recording at GHHI, refer to Figure 12, is skewed to the left indicating that the test site is mostly sunny. The average irradiation is estimated to be $5.8 \pm 1.2 \text{ kWh/m}^2/\text{day}$. At this site, sunny days are selected with irradiation above $7 \text{ kWh/m}^2/\text{day}$. Cloudy days have irradiation below $4.6 \text{ kWh/m}^2/\text{day}$.

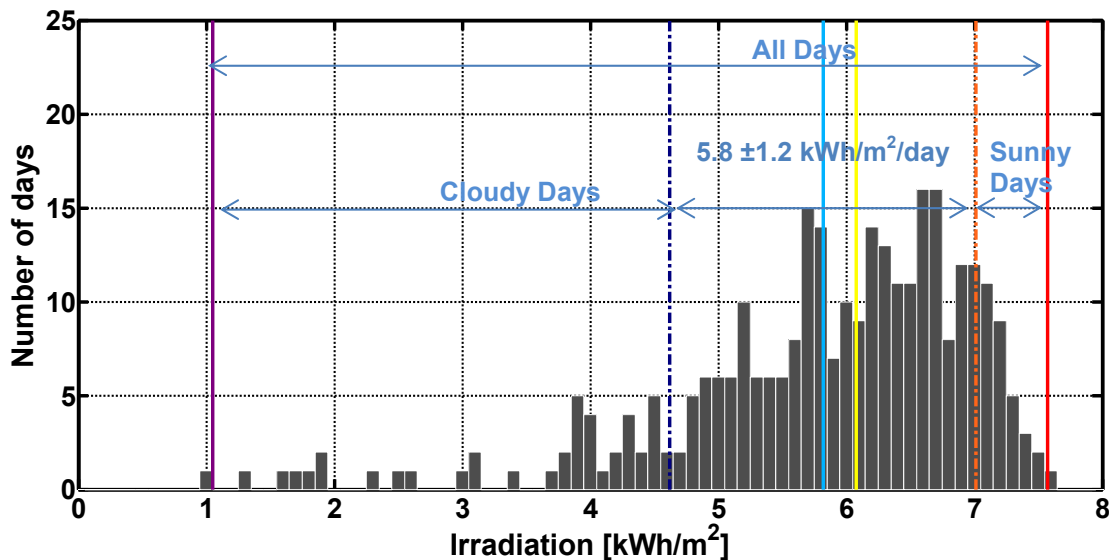


Figure 12: Histogram of the irradiation for a year of recording at GHHI. Vertical lines corresponds to from left to right: lowest value (purple), high limit for cloudy days (blue), average (yellow), median (light blue), low limit for sunny days (orange), and highest value (red).

Figure 13 is a plot of the yearly average solar energy collected versus irradiance levels for different weather conditions (All days, sunny and cloudy). On cloudy days, the

irradiation is collected at all levels of irradiance with a peak at 300 W/m^2 . On sunny days, the irradiation is collected at all levels of irradiance with a peak at 950 W/m^2 . For all days, the irradiation at UH Manoa is collected for all irradiance levels but mostly at high levels. The predominant irradiance level at GHHI is estimated to be 950 W/m^2 . This confirms the mostly sunny weather conditions at GHHI.

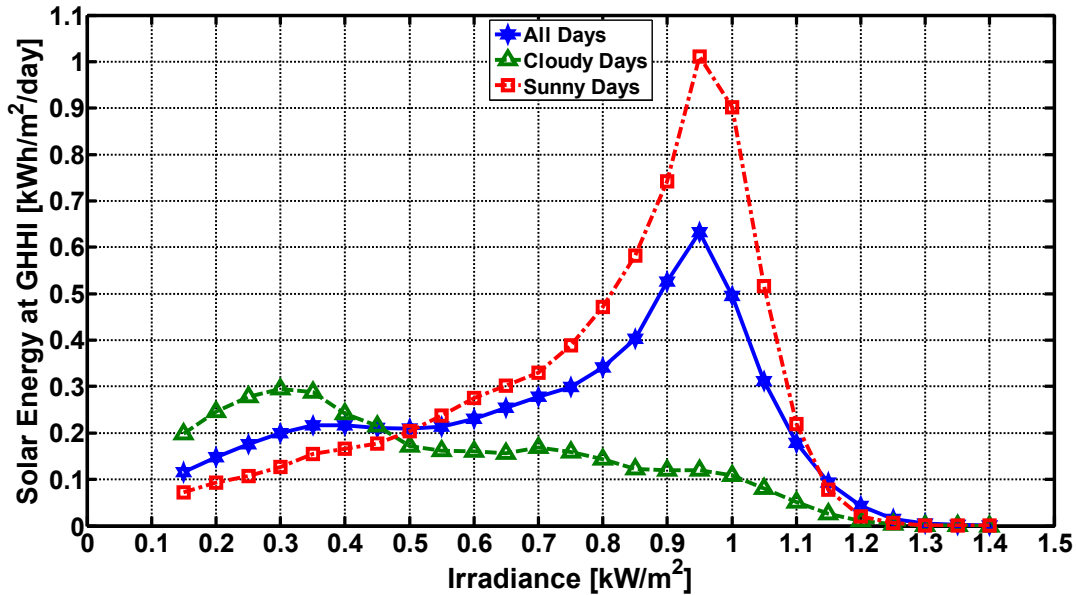


Figure 13: Yearly average of the irradiation collected per levels of irradiance at GHHI.

3.4. PV array performance and parameters

Figure 14 is a plot of the yearly average power of the two arrays operating at the GHHI site versus irradiance levels. The PV power increases with the irradiance levels until reaching an irradiance level estimated to be approximately 1.1 kW/m^2 where the inverters limit the PV array power to $\sim 5.4 \text{ kW}$ for the KYO array (connected to the 5 kW SMA inverter) and $\sim 3.3 \text{ kW}$ for the MHI array (connected to the 3 kW SMA inverters).

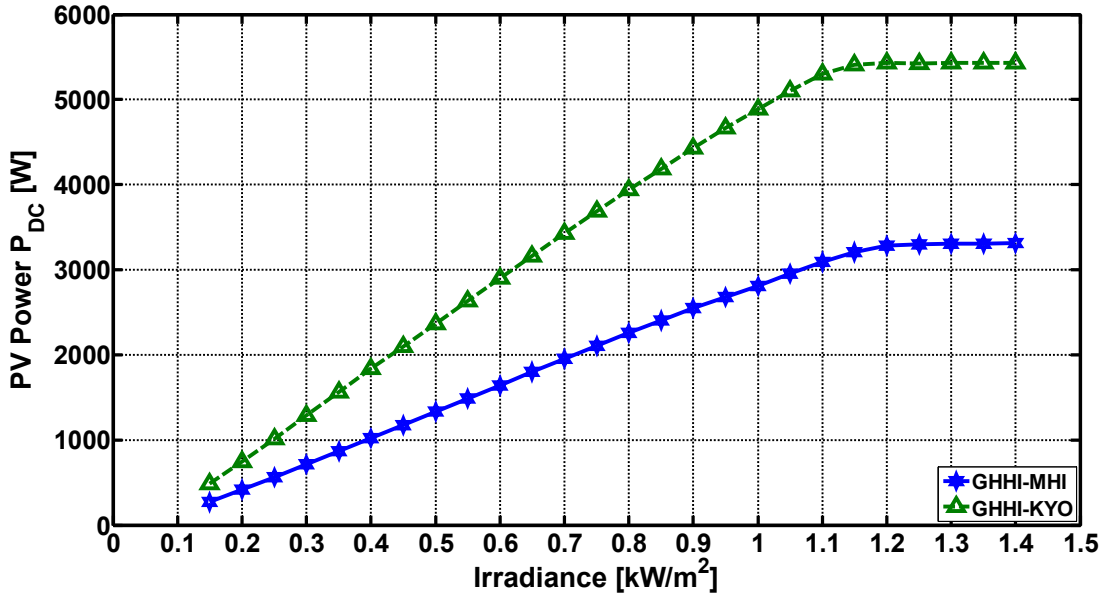


Figure 14: Yearly average PV power as a function of irradiance levels - KYO and MHI arrays at GHHI.

Figure 15 plots the yearly PR of the two PV arrays on the roof top of GHHI as a function of the irradiance levels. Starting with a PR between 60% and 65% at 150 W/m², the PR increases with the irradiance levels up to the irradiance level of 1.1 kW/m². The PR of the KYO array peaks at ~92% for an irradiance level of 800 W/m² and stabilizes until it reaches 1.1 kW/m² before dropping off because of the inverter saturation. The PR of the MHI array reaches a peak value of ~90% at 1.15 kW/m² right before the inverter saturation begins.

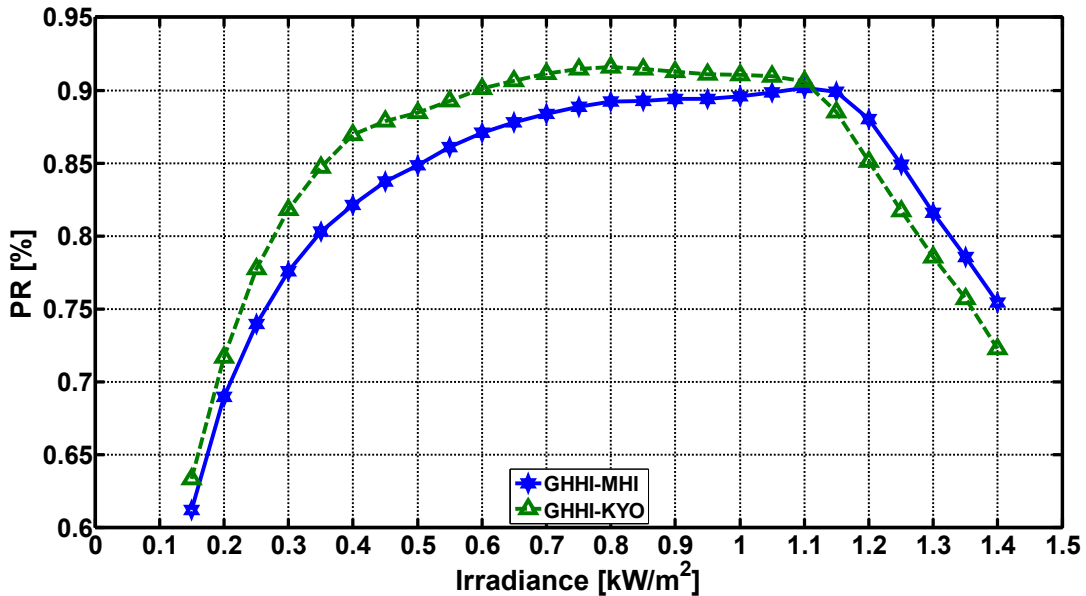


Figure 15: Yearly PR as a function of levels of irradiance - KYO and MHI arrays at GHHI.

Figure 8 shows the impact of the weather conditions on the PR at all levels of irradiance. For both arrays and at all irradiance levels, PR is higher on cloudy days and lower on sunny days compared to the PR for all days. At low irradiance levels, all PV arrays tested at GHHI exhibited a significant amount of PR degradation, estimated to be approximately 20% on cloudy days, and at approximately 30% to 40% on sunny days, compared to the peak performance reached at irradiance levels above 800 W/m².

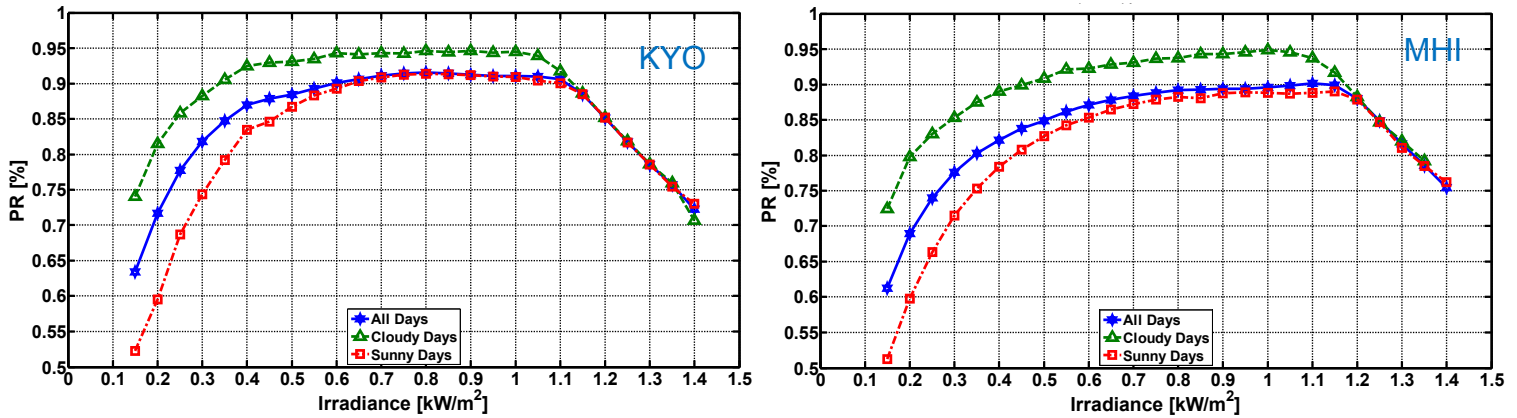


Figure 16: Impact of the weather conditions on the PR of the PV arrays operating at GHHI.

Table 7 shows the PR values monitored for different weather conditions. These PR values combine the profile of irradiation and PR as a function of the irradiance levels. PR is higher on cloudy days and lower on sunny days. Impact of the weather conditions depends on the PV arrays monitored higher for the MHI (2.8%) than for the KYO (1.8%).

Table 7: Impact of the weather conditions on the PR values of the PV arrays operating at GHHI.

PV	PR [%]		
	Cloudy Days < 4.6 kWh/m2/day	All Days	Sunny Days > 7 kWh/m2/day
KYO	90.4%	88.5%	88.6%
MHI	88.7%	86.1%	85.9%

Finally, the impact of the inverter saturation on the yearly PR of the PV arrays was estimated at 0.03% for the MHI and at 0.2% for the KYO array due to an earlier saturation starting as soon as 1.1 kW/m² for the KYO array. The PV system dimensioning is essential to limit the impact of the saturation on the PV system performance.

4. UH Maui College, Kahului, Maui

The PV installation at the University of Hawaii Maui College (UHMC) was an operational site made available to HNEI for data collection and assessment of PV performance. The test site was selected for inclusion in this study because the KYO arrays deployed at UHMC are very similar to the KYO array that is deployed at GHHI in Oahu. UHMC site was fully instrumented and the DAS was deployed in April 2011 under funding this grant.

4.1. Test site and protocol

The UHMC campus is located on the Northern end of the interior lowlands on the Island of Maui (Latitude: 20.9°, Longitude: -156.5°, Altitude: 5 m) a few meters from the north shore and 6 km (4 miles) from the Iao Valley edge of the west Maui mountain range (Figure 17).



Figure 17: UHMC, Kahului, Maui – Roof mounted PV systems (left) on the north shore, four miles from the West Maui Mountain (right)

UHMC PV installation consists of three identical grid-tied PV systems. Each PV system consists of two parallel strings of 14 poly-crystalline PV modules from Kyocera (Table 8), connected to a 5 kW SMA string inverter (Table 9). All 84 PV modules are mounted on a south facing standing seam metal roof, with a 20° tilt, as shown in Figure 17.

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

4.2. One year of operation

Figure 18 shows the irradiation at the UHMC site from October 2011 through September 2012. The maximum irradiation values throughout the year follow the variation of the ETDSE plot (blue line). The monthly average of the irradiation has high values in May and low average values in November and December. The yearly average of the irradiation is monitored at 6.1 kWh/m²/day with a seasonal variation of ± 1.2 kWh/m²/day.

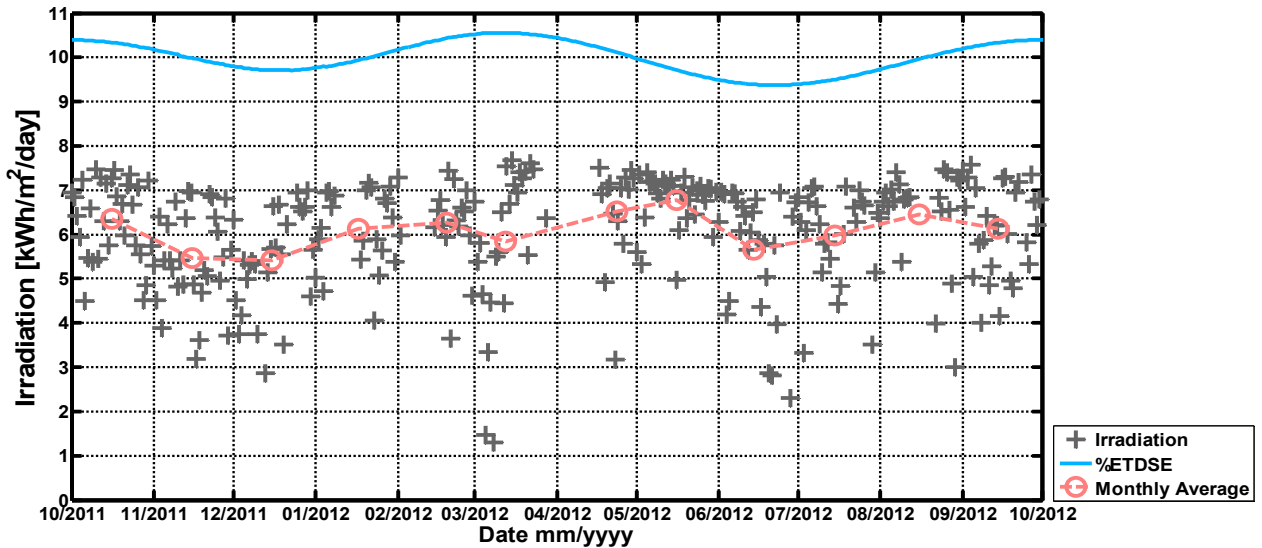


Figure 18: Irradiation for a year of recording at UHMC.

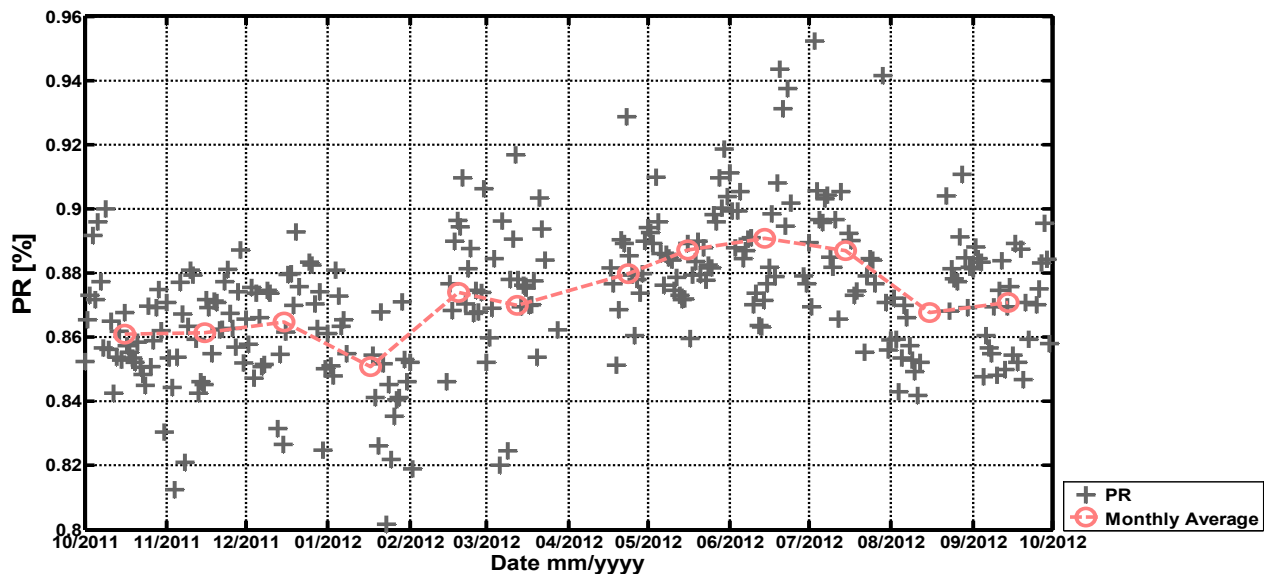


Figure 19: Daily PR for a year of recording at UHMC.

Figure 19 shows the daily PR of the poly-crystalline KYO PV array from October 2011 through September 2012. The daily PR is high from May to July and low from October to January with the lowest PR value occurring in January. The seasonal variation of the daily PR is estimated to be $\pm 2.7\%$. The yearly PR is calculated at 87.2%. The deviation of the yearly PR between strings is estimated to be $\sim 0.3\%$.

4.3. Solar resource characterization

The histogram of the daily irradiation at UHMC, Figure 20, is negatively skewed, representing mostly sunny solar condition, with an average irradiation estimated to be $6.1 \pm 1.2 \text{ kWh/m}^2/\text{day}$. At this site, we selected sunny days with irradiation above $7.3 \text{ kWh/m}^2/\text{day}$ and cloudy days with irradiation below $4.9 \text{ kWh/m}^2/\text{day}$.

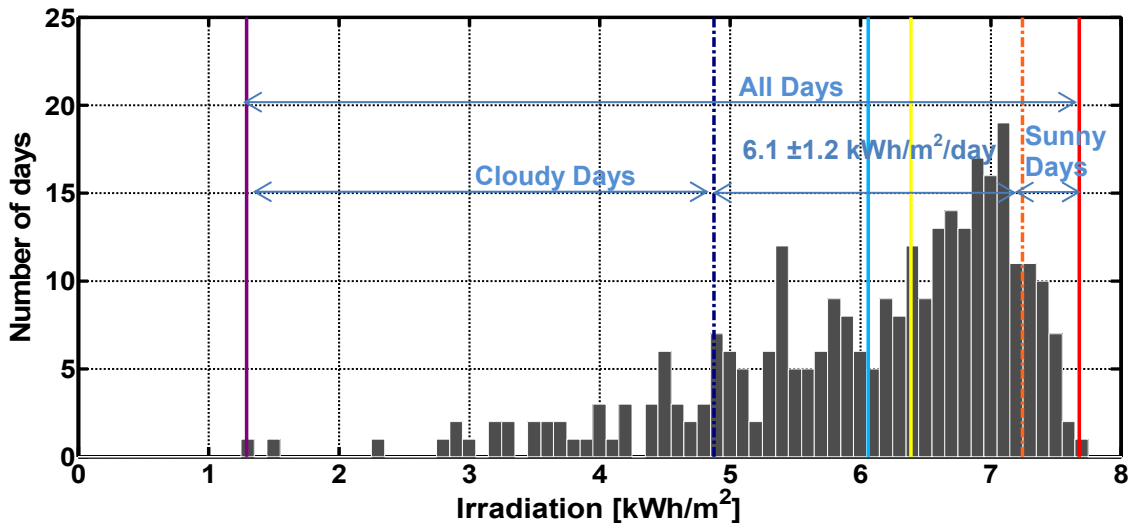


Figure 20: Histogram of the irradiation for a year of recording at UHMC. Vertical lines corresponds to from left to right: lowest value (purple), high limit for cloudy days (blue), average (yellow), median (light blue), low limit for sunny days (orange), and highest value (red).

Figure 21 is a plot of the yearly average solar energy collected versus irradiance levels for different weather conditions (All days, sunny and cloudy). On cloudy days, the irradiation is collected at all levels of irradiance with a peak at 300 W/m^2 . On sunny days, the irradiation is collected at all levels of irradiance with a peak at 950 W/m^2 . For all days, the irradiation at UHMC is collected for all irradiance levels but mostly at high levels. As expected for a mostly sunny location, the predominant irradiance level for all days at UHMC is estimated to be 950 W/m^2 .

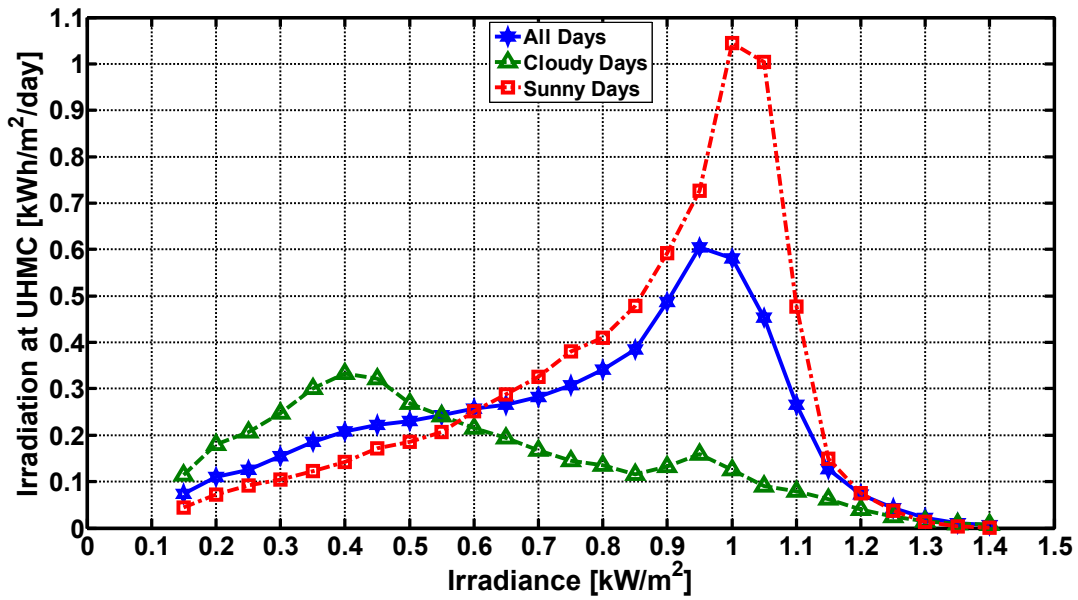


Figure 21: Yearly average of the irradiation collected per levels of irradiance at UHMC.

4.4. PV array performance and parameters

The yearly average power of the KYO arrays is plotted in Figure 22 as a function of irradiance levels. We added the results on the KYO array operating at GHHI for comparison. The power increases with the irradiance until reaching saturation power around 5.4 kW at an irradiance level of 1.2 kW/m².

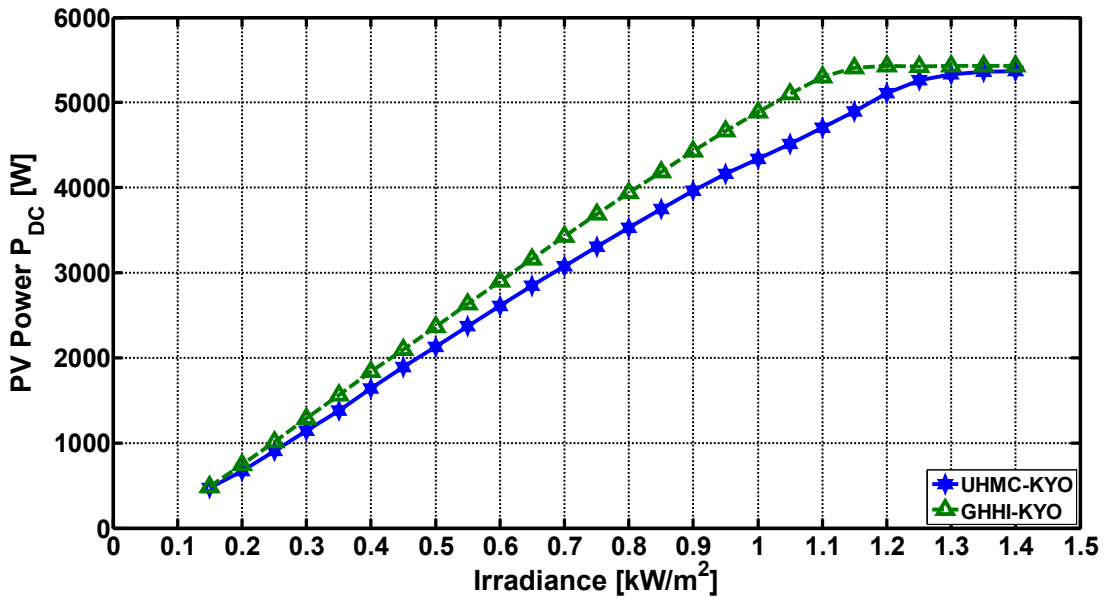


Figure 22: Yearly average power per levels of irradiance - KYO arrays at UHMC and GHHI.

Figure 23 shows the yearly PR as a function of the irradiance levels for the KYO arrays at UHMC and GHHI. The PR of the KYO arrays is slightly different between the two test sites. The PR of the UHMC array increases with the irradiance levels reaching a peak at 90% around 800 W/m². Above that irradiance level, the array at UHMC has a slight drop in performance to 87% from 1 kW/m² before reaching inverter saturation starting at 1.2 kW/m².

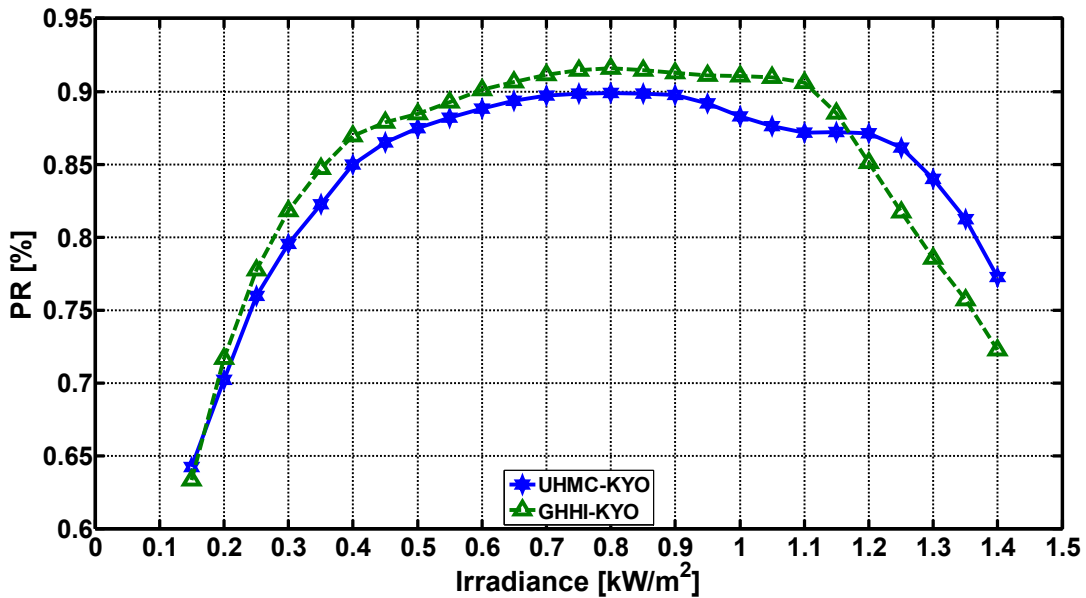


Figure 23: Yearly PR per levels of irradiance - KYO arrays at UHMC and GHHI.

Figure 8 shows the impact of the weather conditions on the PR at all levels of irradiance. At UHMC, the impact of the weather conditions is visible mostly at irradiance levels below 700 W/m². At these low irradiance levels, the PV arrays exhibited a significant amount of PR degradation, estimated to be approximately 18% on cloudy days to 30% on sunny days, compared to the peak performance reached around 800 W/m².

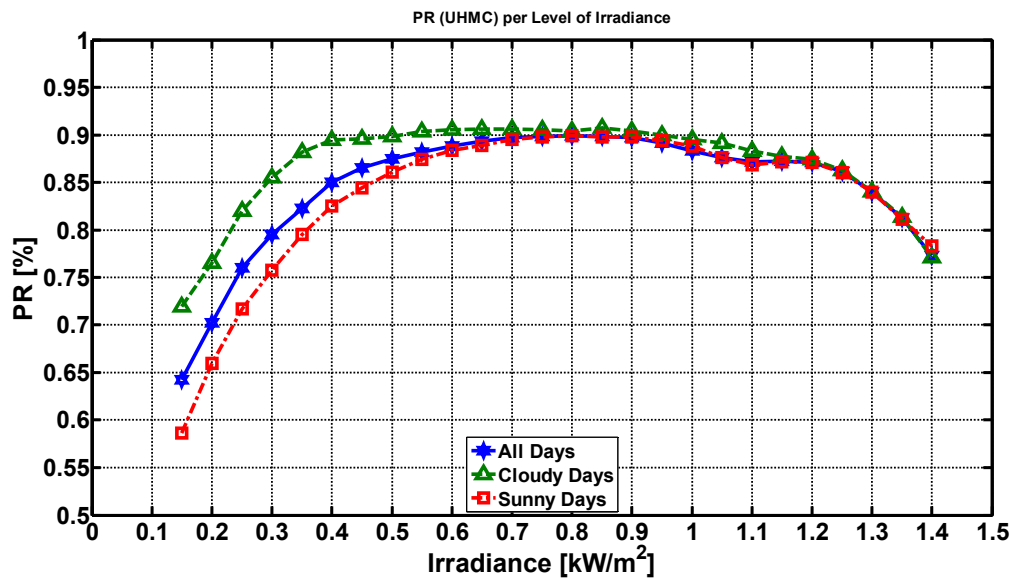


Figure 24: Impact of the weather conditions on the PR of the PV arrays operating at GHHI.

Table 7 presents the PR monitored at UHMC for different weather conditions. The PR of the UHMC arrays is similar for all the weather conditions with the lowest PR observed for all days analysis.

Table 10: Impact of the weather conditions on the PR value of the PV arrays operating at UHMC.

PV	Period of analysis	PR [%]		
		Cloudy Days < 4.9 kWh/m ² /day	All Days	Sunny Days > 7.3 kWh/m ² /day
KYO	10/01/2011-09/30/2012	87.9%	87.2%	87.5%

Finally, the impact of the inverter saturation on the yearly PR of the UHMC PV arrays was estimated negligible evaluated at 0.02% due to the proper sizing of the PV array and the low amount of solar energy collected at high irradiance levels at 1.2 kW/m².

5. Conclusions

Under this grant, HNEI developed and deployed PV test beds on three of the islands in Hawai'i. Test sites include weather stations and high-fidelity, time-synchronized data acquisition systems to collect environmental and performance data of the PV modules and inverters. PV modules representing a variety of technologies including mono and poly-crystalline, amorphous, micro-amorphous, and heterojunction with intrinsic thin layer (HIT) were tested, with data collected over a 12 month period. Analysis of this data has allowed an evaluation of the climatic conditions, the performance of the PV, and a comparison of the main parameters affecting PV system performance.

The solar resource was characterized at each test location, with irradiation levels measured in the PV plane of array. The irradiation levels were found to be approximately 3.6 kWh/m²/day on the Island of Hawaii, 5.8 kWh/m²/day on Oahu, and 6.1 kWh/m²/day on Maui. This shows an irradiation range in Hawaii comparable to much of the mainland US [4].

All test sites exhibit a small seasonal variation ± 1.2 kWh/m²/day as a result of Hawaii's latitude. The site on the Island of Hawaii has variable climatic conditions with approximately the same number of cloudy days and sunny days. Cloudy days collect most of the solar energy at low irradiance levels < 500 W/m². Sunny days collect most of the solar energy at high irradiance levels with a peak at 950 W/m². At this site, two predominant irradiance levels were measured at 300 and 900 W/m². The sites on Maui and Oahu are characterized by mainly sunny conditions with high irradiation, and a predominant irradiance level at 950 W/m².

The PV performance observed in this study can be characterized by a small seasonal variation ranging from $\pm 2\%$ to $\pm 3\%$, and a slightly higher PR, (6% higher), as compared with other published findings with yearly PR estimated from 80% to 91% [5], [6], [7], and [8]. PV modules tested individually at the overcast location on the Island of Hawaii have higher performance (89.5% to 94.5%) than the PV arrays tested at the sunny sites on Maui and Oahu (86.1% to 88.5%), for all days-analysis. Determination of the causes of this relatively high PR value merit additional study, to aid in the selection of optimal PV technologies and possibly system configurations for specific climatic conditions.

The impact of weather conditions on PV performance was investigated by analyzing data from days with different levels of irradiation. It was observed at the overcast site on the Island of Hawaii that for all modules, and irradiance levels the PR is higher on cloudy days and lower on sunny days compared to the PR for all days. Weather conditions affect each module differently at low irradiance levels showing a slight decrease in PR on cloudy days and an increase in PR for all days and sunny days compared to the peak PR value reached at irradiance levels between 450 and 650 W/m² depending on the PV technology. This is due to higher light reflection on sunny days. On sunny days, lower irradiance levels correspond to sunrise and sunset when the sun light has high incidence angle, is highly filtered by the atmosphere, and reflected off the surface of the module. Higher impact of the light reflection is observed on the amorphous technology modules.

At low irradiance levels, all PV arrays tested at the sunny sites exhibited a significant amount of PR degradation, estimated to be approximately 20% on cloudy days, and at approximately 30% to 40% on sunny days, compared to the peak performance reached at irradiance levels above 700 W/m². Of the three PV arrays, the micro-amorphous array was affected the most. And the least affected was the roof-mounted polycrystalline array on Maui, with no impact from weather conditions observed on the performance for irradiance levels above 700 W/m².

The last observed parameter is the dimensioning of the PV system (the rated power of the inverter in comparison to the power of the PV system). It determines the irradiance level above which the PV power is limited by the inverter capacity. This limitation was observed at irradiance levels greater than 1,100 W/m², at all test sites. However, the impact of inverter saturation on PV performance was estimated to be minimal, due to low solar energy collected at irradiance levels above 1,100 W/m². Additional study could be conducted to estimate the potential impact of frequent saturation on inverter durability and long term performance.

Separating the impact of the inverter parameters from PV system configuration, and from climatic conditions, merits additional study to improve future development and deployment of PV systems in Hawaii.

6. Acknowledgements

Blue Planet Foundation, the University of Hawai'i Maui College (UHMC), and the University of Hawai'i at Mānoa (UH) assisted in development of the sites.

7. References

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APPENDIX 1: Analytical Approach

For complete description of the PV test sites and data collection, refer to the Final Technical Report under Award No DE-FC26-06NT42847; “Selected Sites and Test Protocols”.

The DC performance is used to analyze the PV systems.

Daily values, yearly average and seasonal variation

To perform the analysis, we select days with complete data sets, and solar radiation above 125 W/m^2 to maximize the signal to noise ratio.

Irradiance and irradiation

For each day the solar radiation or irradiance expressed in kW/m^2 (power), is integrated over time to obtain the daily solar energy, or irradiation in $\text{kWh/m}^2/\text{day}$ (energy). The daily solar energy is calculated using the solar radiation collected by the highly accurate thermopile pyranometer.

Irradiation and PV energy

For each day, we calculate the irradiation and the PV energy by integrating the irradiance and the DC PV power (DC current x DC voltage) over the time of operation. To evaluate the energy collected for a month or a year, we add the energy collected for the days of the month or year.

Performance Ratio (PR)

Using the solar and PV energy estimates, we calculate the PR per day/month/year. The ratio of the PV energy E_{PV} divided by the power $P_{PV,STC}$ of the PV system specified by the manufacturer at STC, is called the PV yield expressed in kWh/kW or hours. The PV yield, Y_{PV} is an essential performance parameter but it depends heavily upon the solar resource at the test site. To compare results from the different test sites, the PV yield is divided by the solar yield Y_{Sun} (or sun peak hours in hours), to obtain the PR.

The PR is the ratio of the PV yield by the solar yield:

$$PR = \frac{Y_{PV}}{Y_{Sun}} = \frac{\frac{E_{PV}}{P_{PV,STC}}}{\frac{E_{Sun}}{SR_{STC}}} \quad \text{Equation 1}$$

With	PR	Performance ratio [%]
	Y_{Sun}	Solar yield or sun peak hours [h]
	E_{Sun}	Solar energy [Wh/m ²]
	SR_{STC}	Irradiance at the STC [= 1,000 W/m ²]
	Y_{PV}	PV yield [Wh/W or h]
	E_{PV}	PV energy [Wh]
	$P_{PV,STC}$	PV power specified by the manufacturer at STC [W]

Irradiation and PR are estimated per day, per month and per year. For the irradiation, the yearly irradiation and the yearly average of the daily irradiation are the same. For the PR, the yearly (or monthly) PR is different from the yearly (or monthly) average of the daily PR.

We use the yearly PR to compare the performance of the PV systems dividing the yearly PV yield by the yearly solar yield. We visualize the daily irradiation and daily PR thorough a year of operation for each test site and each tested PV system. The seasonal variation of the irradiation and PR are estimated using the standard deviation of the daily irradiation and daily PR thorough a year of operation.

To compare the performance consistency between modules or strings from the same PV model and manufacturer, we evaluate the deviation of the yearly PR between each module (PWW) or string (UHMC, GHHI).

Analysis per level of irradiance

For this analysis, we select operating points per levels of irradiance with increments of 50 W/m². The first level of irradiance is 150 W/m² collecting data points with irradiance from 125 to 175 W/m². The second level is 200 W/m² collecting data points with irradiance from 175 to 225 W/m², etcetera until the highest level noted 1400 W/m² collecting data points with irradiance above 1,375 W/m².

This method of analysis requires using the irradiance monitored at a fast rate, meaning using the solar cell pyranometer signal. For each day, the solar cell pyranometer is calibrated to match the daily solar energy calculated from the thermopile pyranometer data. This analysis method does not include information on the sky conditions and the time of the day as it does not differentiate between a low irradiance of a clear sky in the morning from a low irradiance of an overcast sky during mid-day.

The solar and PV energy (E_{Sun} and E_{PV}) is the sum of the energy collected per level of irradiance “i”.

$$E_{Sun} = \sum_i E_{Sun,i} \quad \text{Equation 2}$$

$$E_{PV} = \sum_i E_{PV,i} \quad \text{Equation 3}$$

Equations 2 & 3 are valid per day, month, or year. The following analysis presents the yearly irradiation and the yearly PR per levels of irradiance. We also estimate yearly average values of the collected data focusing on the DC PV power, and the module temperature visualized per levels of irradiance.

Yearly PR, irradiation and performance per levels of irradiance

Equation 1 is valid per levels of irradiance and described in the following equation with “i” each level of irradiance:

$$PR_i = \frac{\frac{E_{PV,i}}{P_{PV,STC}}}{\frac{E_{Sun,i}}{SR_{STC}}} \quad \text{Equation 4}$$

Equation 5, combining equations 1 to 4, shows how the solar energy and the PR per levels of irradiance both impact the yearly PR value:

$$PR = \frac{\sum_i PR_i \times E_{Sun,i}}{\sum_i E_{Sun,i}} \quad \text{Equation 5}$$

Impact of the weather conditions

To observe the impact of the weather conditions, we selected days based on the irradiation. Sunny days are selected with irradiation above the average irradiation plus its standard deviation. Cloudy days have irradiation below the average irradiation minus its standard deviation. For each sets of days, we calculate the solar energy and the PR per levels of irradiance. We also evaluate the PR of each PV systems per weather conditions.

Solar resource characterization

The solar resource at each site is characterized by analyzing the distribution of the daily solar energy time series and by determining the predominant irradiance levels where most of the solar energy is collected. The second part requires plotting for different weather conditions the yearly irradiation per levels of irradiance selecting the predominant level, the level where most solar energy is collected.

Yearly PV performance per levels of irradiance

The PV performance based upon a year of operational data is presented per levels of irradiance including the yearly average power and the yearly PR for different weather conditions. We observe saturation of the inverters at all test sites for the highest levels of irradiance. We evaluate the impact of the inverter saturation on the yearly PV performance as follow.

Evaluation of inverter saturation impact

In the analysis, the average PV power increases with increasing irradiance levels up to the saturation limit of the inverters. In order to evaluate the impact of the inverter saturation on the annual PR values, we use equation 6 stating that the PR gives the performance of the PV system in operation at the test location relative to the performance specified by the manufacturer at STC.

$$PR = \frac{\rho_{PV}}{\rho_{PV,STC}} = \frac{P_{PV}}{SR} \times \frac{SR_{STC}}{P_{PV,STC}} \quad \text{Equation 6}$$

With ρ_{PV} Operating PV efficiency [%]
 $\rho_{PV,STC}$ PV efficiency specified at STC [%]
 P_{PV} PV power [W]
 SR Solar radiation [W/m^2]

Using equation 6 applied per levels of irradiance, the yearly PR (equation 5) is described dependent on the module power as in equation 7.

$$PR = \frac{\sum_i PR_i \times E_{Sun,i}}{\sum_i E_{Sun,i}} = \frac{\sum_i \frac{P_{PV,i}}{SR_i} \times E_{Sun,i}}{\sum_i E_{Sun,i}} \times \frac{SR_{STC}}{P_{PV,STC}} \quad \text{Equation 7}$$

The calculated PR using equation 7 gives results similar (error below 0.45%) to the yearly PR calculated using equation 5. Using equation 7, we can now modify the power curve versus the irradiance levels to remove the inverter saturation and evaluate the impact of the inverter saturation on the yearly PR value.