Comparison of PV Module Performance Before and After 11, 20, and 25.5 Years of Field Exposure

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***Abstract* — In 1990, 192 ARCO M75 photovoltaic (PV) modules were installed at the HSU Telonicher Marine Lab in Trinidad, California, 150 m off the Pacific Ocean. Current-voltage (IV) tests were performed on each module prior to the array's construction in 1990 [1] and then again in 2001 [2], 2010 [3], and most recently in 2016 after the array was decommissioned. After 25.5 years, 188 of the original 192 modules remained operational. Over their lifetime, the modules' maximum power at the normal operating cell temperature (NOCT) declined by an average 21.6% with a degradation rate of 0.85% per year. The average degradation rate grew from 0.4%/year in the first 11 years to 0.81%/year after 20 years to 0.85%/year after the total 25.5 years.**

I. Introduction

A. Background

The Schatz Solar Hydrogen Project, directed by the Schatz Energy Research Center, was installed in 1990 at the HSU Telonicher Marine Laboratory in the coastal California town of Trinidad. The project objective was to demonstrate the use of hydrogen to store energy from a renewable energy power system. The system powered the Marine Laboratory aquaria air-compressor either directly from the 9.2 kW-rated solar PV array (with an azimuth of due south and a tilt of 28°) or indirectly using a hydrogen-fueled proton exchange membrane (PEM) fuel cell. The hydrogen for the fuel cell was generated by a Teledyne Energy ALTUS 20 electrolyzer powered by the PV array.

The solar array (see Fig. 1) offered the unique opportunity to measure the performance degradation of the individual modules over 25.5 years of field exposure. Data from this analysis can be used to track the causes of module failures, degradation in power output, and help characterize a timeline of expected performance of such mono-crystalline silicon PV modules. When new, these ARCO M75 modules were rated by the manufacturer at 48 W at standard testing conditions (STC or 1000 W/m^2 at 25°C), which is equivalent to 46.4 W at NOCT (defined here as 1000 W/m^2 at 47°C). Each module is glazed with tempered glass and ethylene vinyl acetate (EVA) encapsulant and contains 33 cells in series with two bypass diodes per module.

Zoellick [1] set the precedent for the three successive testing cycles. He used a capacitive-based curve tracer connected to a computer interactive data acquisition system to test and record IV curves for each module using methods approved by the American Society of Testing and Materials (ASTM).

Fig. 1. A view of the array during decommissioning after two subarrays had already been removed (Photo Credit: Mark Rocheleau)

B. Previous Findings

Zoellick [1] found in his 1990 testing that the average maximum power (P_{max}) was 39.88 W and the average short circuit current (I_{sc}) was 3.29 A, about 10% lower than the manufacturer advertised specifications. Thereafter, Zoellick's results were used as the base case data for the following rounds of testing in 2001, 2010, and 2016. The 2001 cycle of tests [2] found that the average P_{max} and I_{SC} had dropped to 38.13 W and 3.15 A, respectively, representing a 4.40% decline over 10 years of operation.

The 2010 tests, after 20 years of field exposure, reported larger degradation for both parameters. The P_{max} experienced a 12.3% decrease from the 2001 testing to 33.43 W, bringing the total loss to 16.1% from the 1990 tests, and the I_{sc} dropped 6.04%, down to 2.96 A, in the second decade for a total lifetime decline of 10.2%. For the maximum power, the average degradation rate over the 20-year interval came to 0.81%/year, but the degradation rate over the second decade (2001-2010) was 1.4%/year, more than three times the degradation rate over the first decade of 0.4%/year. This suggests that the performance of the modules degraded more rapidly as they aged, instead of following a pattern of linear degradation.

Other IV curve parameters also changed over the first two decades of operation. The series resistance (R_s), parallel resistance (R_p), and the "ekt" variable (which controls the degree of curvature near the maximum power point) all experienced dramatic variations as evidenced by changes in the slopes and curves of the IV curves. After only 10 years, the average R_p had dropped by 33.75%, the average R_s had increased by 10.66%, and the average ekt rose by 26.38%. The inverse of R_p is the slope of the IV curve as the voltage approaches zero, and the negative inverse of R_s is the slope of the IV curve as the current approaches zero. In contrast, the average open circuit voltage (V_{oc}) hardly changed, falling by only 1.0%, or 0.17 V, over 20 years.

II. Procedure

A. Testing

The conditions in which Zoellick [1] performed his tests were replicated as closely as possible in all subsequent rounds of testing in 2001, 2010, and 2016. Each module was tested outside at a module temperatures centered around 47°C with tests ranging from 25-65°C, a solar insolation of at least 800 W/m^2 (but closer to 1000 W/m^2 when achievable), and an air-mass (AM) less than or equal to 1.5. Each module was cleaned prior to testing, eliminating any dust or dirt that would prevent the module from generating at its optimum level for the analysis.

The 1990 and 2016 rounds of testing used a portable and adjustable frame to test each module, but in the 2001 and 2010 testing the array still in operation so each module was tested within the plane of the array. An Eppley PSP pyranometer and a surface mount type-T thermocouple were used to monitor and record the solar insolation in the plane of the module and the module temperature, respectively.

While the different rounds of testing used slightly different methods and technologies to produce IV curves, each one used a capacitive load and was completed in 10 seconds or less. The 2016 testing used a recently acquired Mini-KLA PV IV Curve Tracer [4] and its associated MiniLes (R) program to measure and record the pertinent current and voltage data. This instrument reported the observed P_{max}, V_{oc}, I_{sc}, maximum power voltage (V_{mp}), maximum power current (I_{mp}), the IV curve fill factor (FF), and a plot of the IV curve on its graphical interface. The insolation was measured using an Eppley PSP pyranometer and the module temperature was measured using a type-T surface mount, quick response thermocouple positioned in the center of the back of the module.

B. Data collection and standardization

Zoellick [1] adjusted all observations to 1000 W/m^2 and 47°C based on the observed sensitivity of the module V_{oc}s to insolation and module temperature. His and all subsequent corrections adjusted V_{oc} with respect to the measured module temperature (-0.0603 V/°C) and insolation (0.0009296 $V{*}m^2/W$). Based on a Schottky diode model, Zoellick [1] and all subsequent analyses fit the module IV curve to a parameter model, where:

$$I = I_L - \left[\frac{I_L - \frac{V_{oc}}{R_p}}{\exp\left(ektV_{oc}\right) - 1} \right] \left\{ \exp\left[ekt\left(V + R_s I\right) \right] - 1 \right\} - \frac{\left(V + R_s I\right)}{R_p} \qquad (1)$$

where:

ekt = q/(nkT) [V^{-1}]
I = module current; initial guess [A]
V = module voltage [V]
I_L = light induced module current [A]
V_{oc} = open circuit module voltage [V]
R_s = module series resistance [Ω]
R_p = module parallel resistance [Ω]
q = electronic charge [coulomb]
n = ideality factor per cell [unitless]
k = Boltzmann's constant [Joule/K]
T = temperature [K]

In 2016 testing, the Eppley PSP pyranometer and thermocouple readings were recorded by hand. The MiniLes software takes the data from the Mini-KLA and converts it into a text file. Then software written in Sci-Lab [5], modified from that previously used in the 2010 testing analysis filtered the readings, standardized the data to 1000 W/m^2 and 47°C using the correction factors from Zoellick and used nonlinear regression to estimate the parameters of Equation 1.

III. Results and Discussion

After 25.5 years, every single module from this array is discolored and shows signs of delamination. Signs of hot spots with a range of severity have become common in the modules. Fig. 2 compares the distributions of the P_{max} of the modules from each testing cycle (i.e., 1990, 2001, 2010, and 2016) in a normal probability plot. The initial 1990 curve remains close to linear throughout the curve, and as the modules aged the standard deviation of the P_{max} among the modules increased. This is exemplified by the steeper slopes and wider P_{max} ranges in the later years that include modules that have lost significant power. In the 2016 testing cycle, two modules had their P_{mas} drop below 10 W.

Fig. 3 shows the average P_{max} of all of the modules for each testing cycle and notates the modules' age during testing. There is clearly a lesser linear degradation from 1990-2001 followed by a steeper close-to-linear degradation from 2001 to the end of the project. The degradation rates (i.e. rates of power loss) for the testing windows include 0.4%/year for the first 11 years (1990-2001), 1.4%/year for the next nine years (2001-2010), and 1.3%/year for the last five and a half years of the project (2010-2016). The average lifetime degradation rate of the 25.5-year project came to 0.85%/year. Fig. 3 has a linear trend line whose equation says that roughly 0.35 W were lost each year for the modules, which, based on the original 1990 average of 39.88 W, is just over 0.85%/year of power loss.

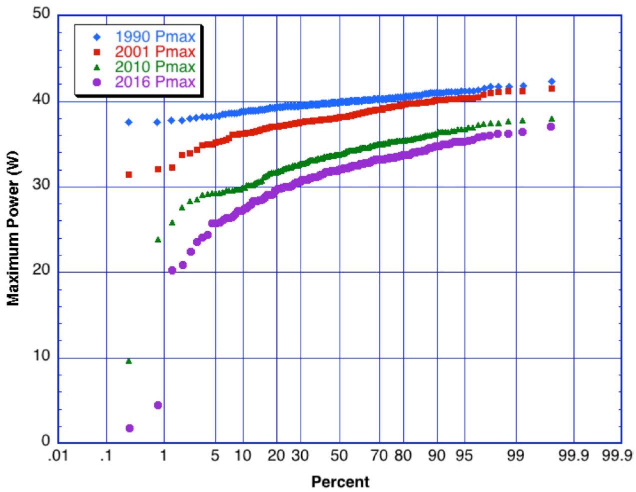

Fig. 2. P_{max} distribution curve for all modules in four test cycles

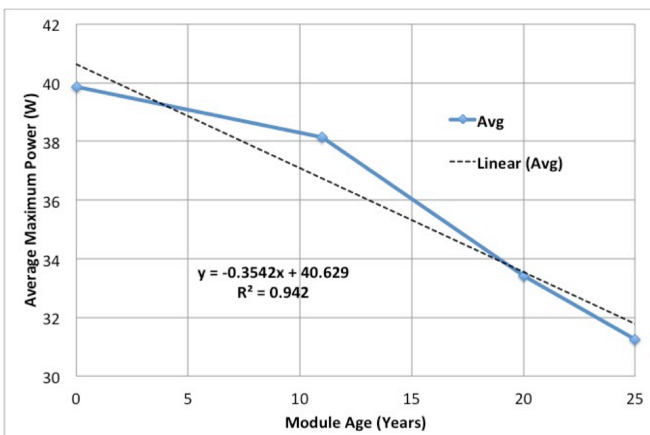

Fig. 3. Average P_{max} based on the age of modules during testing

Each module incorporates two bypass diodes to avoid the creation of localized hot spots, as they direct the current around cells that are either damaged or shaded. The associated effect of the action of the diodes is to reduce the module P_{max}. Fig. 4 shows the IV curves from 1990, 2001, 2010, and 2016 for a single module that lost a small amount of its P_{max} in the first decade of operation but then saw a significant loss in the second decade of field exposure. This second "knee" in the IV curve is a result of the bypass diode directing the current around 22 of the 33 cells in the module. These second knees were uncommon in the 2001 testing, but in the 2016 testing all but 13 of the modules now have significant second knees.

Bypass diodes were removed from several modules in 2016 and then retested. Fig. 4 shows the effect of removing these bypass diodes from a module with a significant second knee. Results show that this action increases the P_{max}, but the potential for exacerbating hot spots may increase.

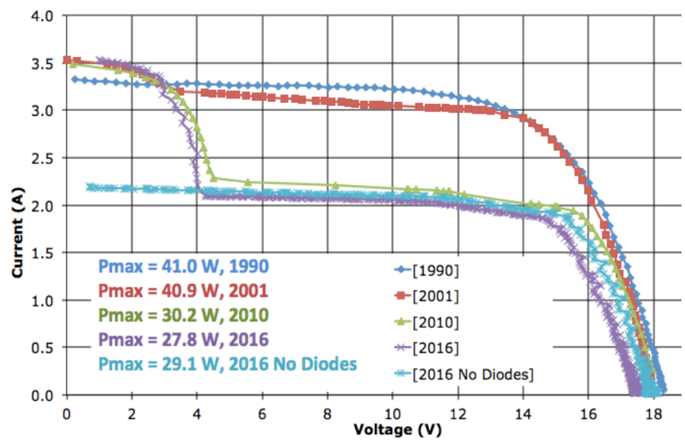

Fig. 4. IV curve for a module that shows the effect of diodes

IV. Conclusion

After 25.5 years, the modules averaged a power loss of 21.8% of their initially tested power outputs for an average degradation rate of 0.85%/year. The 2016 testing supports past analysis conclusions identifying the drop in I_{sc} as the primary source of power loss, which can be attributed to the increased presence of EVA browning, physical delamination, and localized hot spots with the modules. The average standard deviation of the power output also increased from 0.92 W to 4.10 W during this time.

References

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[4] Ingenieurburo, Menncke, & Tegtmeyer GmBH, "Mini-KLA PV I-V curve analyser", Hameln, 2011.

[5] Scilab Enterprises, "Scilab: free and open source for numerical computation [software], 2012.