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HIGH PERFORMANCE RATIOS OF A DOUBLE-JUNCTION a-Si BIPV GRID-CONNECTED INSTALLATION AFTER FIVE YEARS OF CONTINUOUS OPERATION IN BRAZIL

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ABSTRACT

In September 1997 LABSOLAR, at Universidade Federal de Santa Catarina, installed the first grid-connected, thin-film, building-integrated PV system in Brazil. In this fully monitored installation, irradiation levels, temperatures and electrical performance data are measured and logged continuously. The AC and DC performance ratios (PR=ratio of actual to expected output) of this 2kWp double-junction a-Si PV system after over five years of continuous operation have stabilized at an average of 82% and 92% respectively, with annual energy yields of ~1300 kWh/kWp for a ~1500 kWh/m^2 annual *plane-of-array radiation level at the site. Our results show* that in the stabilized state the PR is independent of the cell operating temperature, indicating a negligible temperature coefficient of power and good performance when operated at a warm site. Under the conditions described, undersizing the inverter with respect to the PV array power might lead to considerable power losses.

1. INTRODUCTION

Power and energy rating and performance assessment of photovoltaic (PV) solar modules can be performed using a number of different procedures and standards. PV module rating at Standard Testing Conditions (STC = 1000 W/m^2 radiation level, 25°C cell temperature and AM 1.5 spectral content) is still the industry's preference, but hardly ever translates real operating output in the field [1-7].

With the growing rate of grid-connected PV system installation worldwide, and the use of remote performance monitoring using geostationary satellites [8-10], energy yields and performance indexes become more widespread.

The performance ratio (PR*) translates a measure of the actual vs. the expected power, taking into account the power effectively produced by the device and the manufacturer's power rating (which can be more or less conservative). The PR reveals how close the real power produced by a given PV module (measured outdoors, under real conditions) is to the rated or nominal power (measured in the laboratory indoors, at STC) the consumer has paid for.

Thin-film amorphous silicon (a-Si) is a good choice of PV technology for operation in warm and sunny climates. The small temperature coefficient of power is present only while the material is undergoing stabilization and is cancelled out in the stabilized state. The stabilization of the light-induced degradation (Staebler-Wronski effect – SWE [11]) at a higher performance level when operated at year-round higher temperatures, render a-Si devices good performers in the warm climates prevailing in Brazil, especially for building-integrated photovoltaic (BIPV) systems. Since September 1997, the Solar Energy Laboratory (LABSOLAR) at Universidade Federal de Santa Catarina in Florianopolis – Brazil (27°S, 48°W) is continuously monitoring the performance of the first thin-film, grid-connected, BIPV system in Brazil. We present results for the five years of continuous operation, at the AC and DC levels, showing energy yields and PR figures that demonstrate that new generation, multi-junction a-Si is a good choice of technology for BIPV systems in warm and sunny sites.

2. PV SYSTEM CHARACTERISTICS

The PV installation consists of a 2kWp a-Si array, plus DC/AC inverter, irradiance (horizontal and plane-of-array), and temperature (ambient and back-of-module) measurement instrumentation, and a dedicated data logging system. The generator is comprised of 54 opaque and 14 semitransparent, double-junction (*pin-pin*), glass-glass 60 x 100cm^2 a-Si modules from RWE-Schott, with a total power output rated at 2078Wp at STC, and a total surface area of ~40m^2. The total power is distributed in four ~500Wp sub-systems, and fed to four independent single-phase, line-commutated sinewave inverters (from Würth Elektronik GmbH, model WE 500 NWR, each rated at 650W). The PV array uses unframed modules designed for BIPV applications, that were installed onto a simple steel structure retrofitted as an overhang to the existing building, facing true north with latitude tilt. Electrical parameters as well as irradiance and temperature data are continuously measured and stored at four-minute intervals. Figure 1 shows the BIPV system, and further details on PV system design and configuration have been presented elsewhere [12, 13].

* The Performance Ratio ($PR_{AC,DC}$) is defined as the ratio of the AC or DC energy output (E_{AC} or E_{DC}), and the rated DC efficiency (η_{STC}) times the total solar radiation incident on the module's surface (E_S): $PR_{AC,DC} = 100 \times [E_{AC,DC} / (\eta_{STC} \times E_S)]$ %.

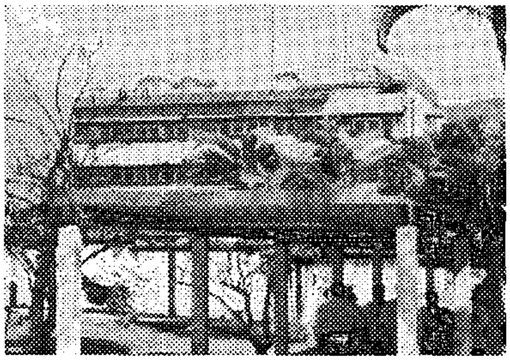

Figure 1: The 2kWp grid-connected, double-junction a-Si thin-film BIPV installation in Florianopolis – Brazil. The latitude-tilted (27°), north-facing array operates continuously since September 1997.

3. RESULTS AND DISCUSSION

As shown in Figure 2, after five years of continuous operation the PV system output performance has stabilized, at an average AC Performance Ratio of 82%, and an annual energy yield of ~1300 kWh/kWp for a radiation level of ~1500 kWh/m^2 at the site. The average sub-system DC Performance Ratio, at inverter input, was 92% for the same period. The data in Figure 2 also show a seasonal variation in performance, which is typical of a-Si [14], with maxima in summer and minima in winter. These data represent daily average PR values, and include operation at low light levels ($G \leq 100$ W/m^2) occurring in the early morning and late afternoon, as well as in overcast days, where efficiency is lower. Figure 3 shows a plot of DC efficiency vs. irradiation level for the system at the stabilized state, where the low-light level dependency can be seen, as well as the small influence of temperature on device performance. The plane-of-array silicon-cell matrix irradiation sensor used for these measurements presents a small deviation when compared with broadband pyranometer measurements; to compensate for this deviation, the data shown in Figure 3 were corrected according to a procedure presented elsewhere [15].

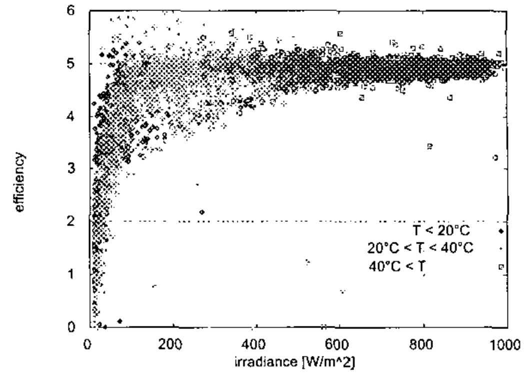

Figure 3: Stabilized hourly DC efficiencies of the a-Si PV system as a function of irradiance, grouped according to back-of-module temperature [15].

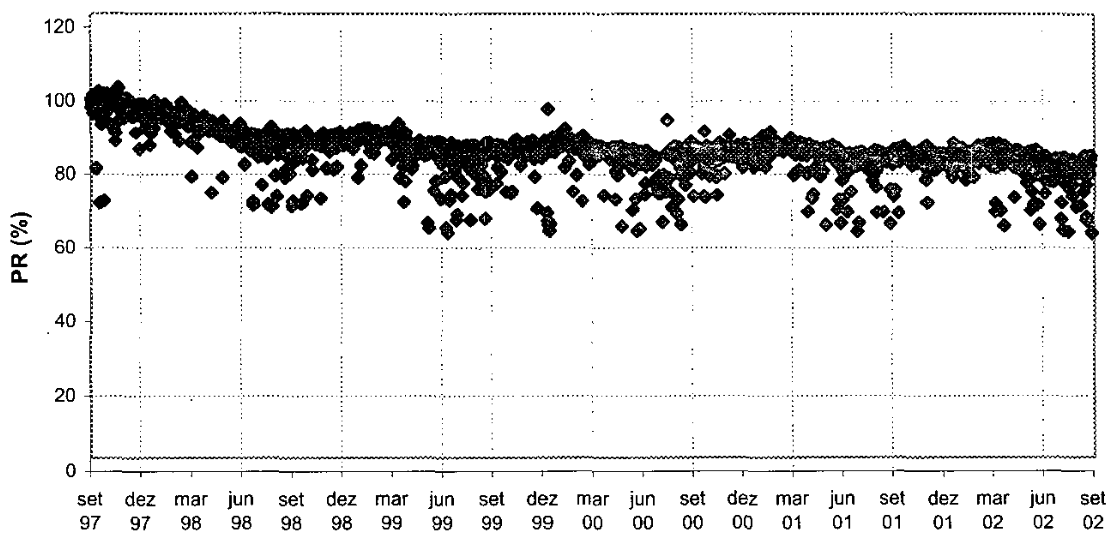

Figure 2: Evolution of the daily mean AC Performance Ratio of the 2kWp BIPV thin-film a-Si installation over five years of continuous operation in Brazil.

Figure 4 shows the behavior of the total system daily mean AC Performance Ratio at the stabilized state (year 2002 data only, with G $\geq$ 200 W/m^2) vs. back-of-module temperature. The plot shows that in the stabilized state, the a-Si PV system's output, translated by the Performance Ratio, is independent of the PV cell operating temperature. The installation displays a negligible temperature coefficient of power (TP_{max}*), a quite important feature for operation at warm and sunny sites. The high operating temperatures over the year, and most importantly, a year-round high minimum PV cell operating temperature at the site, have led to the stabilization of the SWE at this relatively high performance level [16].

Figure 5 shows the distribution of the plane-of-array irradiation incident at the site (distributed at 100 W/m^2 bins), averaged for the five years of operation. It shows that only less than 10% of the solar energy incident on the PV array is in the $\leq$ 200 W/m^2 level; and nearly 60% of the energy reaching the modules is in the $\geq$ 700 W/m^2 range. Furthermore, 15% of the incident insolation is in the $\geq$ 1000 W/m^2 level.

These results, together with the independence of stabilized double-junction a-Si output power on temperature shown, indicate that the issue of inverter vs. PV array power rating should be properly addressed in project design under these conditions [17-18], and that in order to optimize output, inverter undersizing should be avoided in a-Si installations at warm sites.

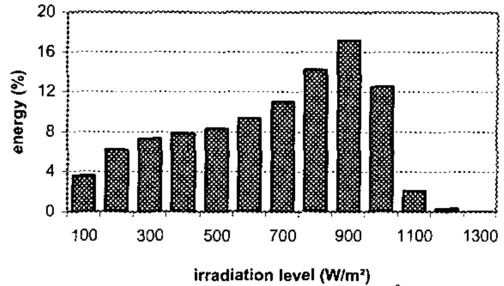

Figure 5: Plane-of-array solar energy, at 100 W/m^2 bins, incident at the Florianopolis site, averaged over five years.

We have previously shown that Florianopolis is one of the sites with the lowest irradiation levels in Brazil [15]. For regions in the country with a higher portion of the incident solar energy due to clear skies, and therefore higher irradiation levels, we expect more than the 15% of the incident radiation measured in Florianopolis to fall in the $\geq$ 1000 W/m^2 level. In these situations, which tend to occur simultaneously with high ambient temperatures which penalize inverter performance, inverter undersizing might also lead to situations where available DC power from the PV array will exceed inverter maximum input power, with the inverter in this case becoming unable to convert all available PV generated electricity.

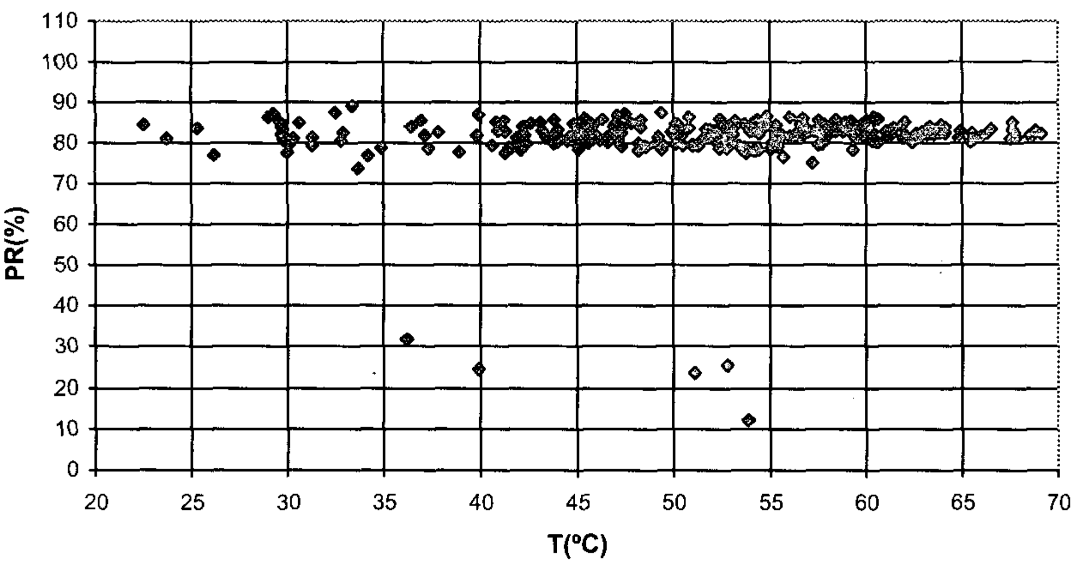

Figure 4: The behavior of the daily mean AC Performance Ratio of the 2kWp BIPV installation with back-of-module temperature at the stabilized state (Year 2002 data, with G $\geq$ 200 W/m^2 measured by a matrix sensor at plane-of-array). The output of the a-Si array is virtually independent of the module temperature at the stabilized state.

*$TP_{max} = dP_{max}/dT \times 1/P_{maxT=25oC}$

4. CONCLUSIONS

We have shown results on the continuous operation over five years of a 2 kWp grid-connected, double-junction a-Si BIPV installation in Brazil. The fully monitored PV array operates satisfactorily at a high performance ratio of 82% AC and 92% DC, averaged over this 60 months period. In the stabilized state our results demonstrate that the a-Si PV module performance is independent of the solar cell operating temperature. We have also shown that a considerable amount of the incident solar energy at the site occurs at high irradiation levels ($\geq$ 1000 W/m^2), which justifies our recommendation of oversizing the inverter with respect to the PV array in warm and sunny climates. In the design of a-Si systems operating under the conditions described here, these aspects will result in different optimum sizing of the system, especially in the inverter vs. PV array power ratio and expected performance, when compared with traditional sizing methods designed for more traditional PV technologies and more temperate climates.

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