PERFORMANCE RESULTS OF THE FIRST GRID-CONNECTED, THIN-FILM PV INSTALLATION IN BRAZIL: TEMPERATURE BEHAVIOUR AND PERFORMANCE RATIOS OVER SIX YEARS OF CONTINUOUS OPERATION

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ABSTRACT: To investigate the long-term performance of a building-integrated amorphous silicon thin-film PV installation in a moist maritime climate with warm winters and hot summers, we designed and installed a 2kWp system using frameless BIPV-type, double-junction, same bandgap pin-pin PV modules. The PV system was retrofitted to a University building that houses the Laboratorio de Energia Solar (LABSOLAR) at Universidade Federal de Santa Catarina in Florianopolis (27^{o}S, 48^{o}W), facing true north at latitude tilt. The installation is fully and continuously monitored since start up in 1997, with DC and AC electrical parameters, as well as horizontal and plane-of-array radiation levels and ambient and back-of-module temperatures logged at four-minute intervals. Our results demonstrate that after the first year of outdoor exposure, when the Staebler-Wronski degradation effect leads the output performance to a stabilised level, the effect of operating temperature on system performance is negligible. DC and AC performance ratios over the six years of continuous operation reported in this paper were respectively 91.4% and 81.5%, with back-of-module temperatures reaching over 70^{o}C. We argue that in warm and sunny climates of tropical countries like Brazil, where the building stock in residential suburbs presents large areas suitable for PV integration, the lower conversion efficiency of a-Si PV technology might not be such a drawback (as might be the case in countries like Japan and Germany, where available roof areas are smaller and radiation levels lower), because it is counterbalanced by this technology's good performance under the high operating temperatures prevailing especially in BIPV applications.
Keywords: Thin film, a-Si, Performance

1. INTRODUCTION

The consistent growth of the global PV market over the recent years has been driven mostly by the continuously growing grid-connected market share. Grid-connected PV responds for over 50% of the total PV market [1]. This market share is due mainly to government incentive programs in countries like Japan and Germany. In these countries, average annual radiation levels are around 1000kWh/m^2 or less, and average PV module operating temperatures are considerably lower than in warmer and sunnier sites of tropical countries like Australia, Brazil and some parts of the USA among others. Furthermore, due to a higher population density, the building stock in residential suburbs of Japan, the UK, Germany and other European countries has a considerably smaller roofing area available and suitable for PV integration than buildings in Australia, Brazil or the USA. We have recently shown that even for the region in Brazil with the lowest annual radiation levels, there are no area constraints for roof integration of PV in urban areas for penetration levels[1] below 20%, even if the less efficient amorphous silicon (a-Si) thin film technology is used and only roof areas which receive more than 90% of the maximum annual radiation level at the site are considered [2,3]. One further aspect which contributes to this more favourable relation between available roofing area for PV integration and the respective buildings stock's power demands, is that buildings in tropical countries are in general less energy intensive, and the higher power demands due to air-conditioning loads correlate well with PV power availability.

PV module operating temperatures are also a matter of concern, especially in BIPV applications, were back of module ventilation is often hindered and solar cells can reach over 70^{o}C in warm days at full sun [4]. Under such conditions, the negative temperature coefficient of power that, to different degrees, all PV technologies present [5], will result in power losses of up to 20% for the market-dominant crystalline silicon technology and also for copper indium gallium diselenide (CIGS) thin film PV. The effect will be obviously more prominent at tropical sites, where the choice of a PV technology with a small temperature coefficient of power should always be considered [6].

In the light of all these climate-, building-density- and PV-technology-related considerations, it is argued that while high efficiency, highly-temperature dependent crystalline silicon PV technologies might be the best choice of technology for BIPV applications in countries like Japan and Germany, lower efficiency, but less temperature dependent PV technologies like a-Si and Cadmium Telluride (CdTe) might be a better choice for BIPV installations in places like Australia and Brazil, provided their lower cost per watt can compensate the

[1] The penetration level in a given urban feeder is defined as the ratio of the PV installed power and the feeder's peak load.

increased balance of systems (BOS) costs incurred by the larger areas required.

To demonstrate that a-Si is a good choice of PV technology for BIPV applications in Brazil, we have designed and installed in 1997 the first grid-connected, building-integrated a-Si thin film PV system in the country [7,8]. This paper follows up on the continuous and detailed monitoring of this 2kWp PV system, presenting new results on the performance of this installation over six years of operation, and showing energy yields and performance ratios obtained during this period. We also present results on inverter efficiency and on the distribution of the local solar energy resource, in terms of both the fraction of daytime hours and total energy content at each irradiation level, over the same period.

2. PV SYSTEM DESIGN

The PV installation consists of a 2kWp a-Si array, plus DC/AC inverter, irradiance (horizontal and plane-of-array, measured by c-Si-type matrix sensors), 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 [7,8].

Figure 1: View of the 2kWp grid-connected, building-integrated, double-junction a-Si PV system installed at LABSOLAR's building in Florianopolis – Brazil (27^{o}S).

3. RESULTS AND DISCUSSION

After six years of continuous operation the PV system output performance has stabilised at average DC and AC performance ratios of 91.4% and 81.5% respectively, with an annual AC energy yield of 1231kWh/kWp, for a 1507kWh/m^2 radiation level at the site. Figure 2 shows the daily mean AC Performance Ratio over the six-year period. The first 12 months are strongly marked by the light-induced degradation effect, and after that period the system performance shows a seasonal variation typical of a-Si [9], with higher relative output in summer months, due to the higher operating temperatures (partial thermal annealing of the light-induced degradation) and spectral effects (lower Air Mass values in summer, leading to "bluer" spectra which are beneficial to a-Si). The figure also shows how a-Si manufacturers underrate their modules to account for the light-induced degradation.

Figure 3 shows the performance ratio plotted versus module temperature for irradiation levels $\geq$ 200W/m^2 for the years of 1997 and 2003. It clearly shows a distinct behaviour with temperature of a-Si PV modules in the new, as-deposited (1997 data) and stabilised (2003 data) states. Data for the years 1998-2002 lie in between the two clouds of data presented, and were not included to show more clearly the differences between the original and the six-year old material. A linear fit to the data reveals a negative coefficient of power ($T_{coeffPmax}$ = -0.220%/^{o}C) for the 1997 data, consistent with the manufacturer's nameplate $T_{coeffPmax}$, and a negligible, or very small positive effect of temperature ($T_{coeffPmax}$ = + 0.089%/^{o}C) for the 2003 data. Crystalline silicon and CIGS PV modules in contrast typically present a constant negative temperature coefficient of – 0.400%/^{o}C to – 0.450%/^{o}C [5, 10, 11].

Figures 4 and 5 show results on the distribution of the plane-of-array irradiation at the site, distributed at 100W/m^2 bins, averaged for the six years of continuous operation. While most of the daytime hours (~60%) present radiation levels $\leq$ 200W/m^2 (Fig. 4), this corresponds to only less than 10% of the incident energy reaching the PV installation with irradiation levels $\leq$ 200W/m^2 (Fig.5). On the other hand, while only 4% of the daytime hours present irradiation levels $\geq$ 1000W/m^2 (Fig. 4), this represents some 15% of the total solar energy reaching the PV modules at that irradiation level (Fig. 5). Furthermore, while only less than 20% of the daytime hours see light with irradiation levels $\geq$ 700W/m^2 (Fig. 4), the correspondent amount of energy is nearly 60% of the total energy reaching the plane-of-array (Fig. 5). This high irradiation level distribution was measured at one of the regions with the smallest solar energy resources in Brazil, as we have previously shown [8]. From these results it seems that the common practice of inverter undersizing [12,13] with respect to PV array nominal power might lead to substantial output losses, for the a-Si technology in climates like the one prevailing in Brazil, which are probably not likely to occur with the more typical crystalline Si technology, due to the power losses that occur at the high operating temperatures associated with higher radiation levels, and/or in cooler and cloudier sites.

Figure 6 shows a plot of the inverter efficiency with respect to plane-of-array radiation levels distributed at 100W/m^2 bins, averaged over the 6 years of measurements at four-minute intervals. The plot correlates well with the manufacturers specifications, with the four inverters displaying a very stable 90% overall average for the six years period. The analysis of both figures 5 and 6 shows the optimum loading of the inverters, which are operating at their maximum efficiency level at the most energy-intensive irradiation levels at the site.

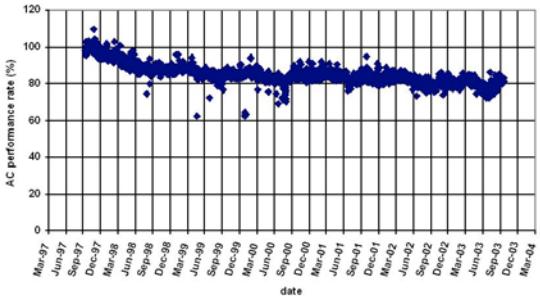


Figure 2: Evolution of the daily mean AC Performance Ratio (ratio of the actual AC and rated DC performance) of the 2kWp BIPV a-Si thin-film system over 6 years of continuous operation in Brazil.

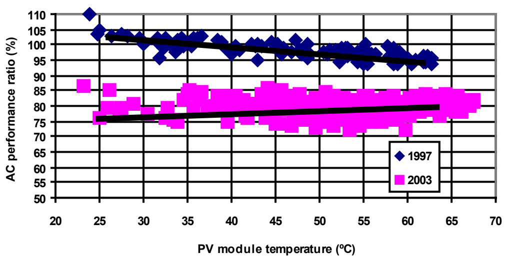
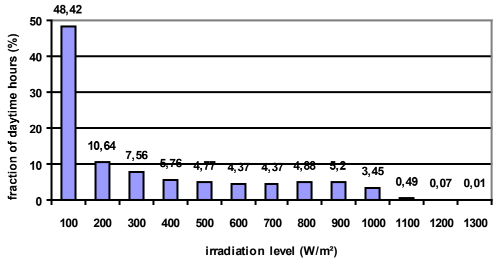
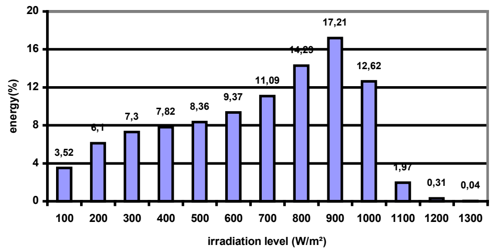


Figure 3: The behaviour of the daily mean AC performance ratio of the 2kWp BIPV installation with back-of-module temperature, showing 1997 and 2003 data, for irradiation levels > 200W/m^2.





Figures 4 and 5: Distribution of the plane-of-array irradiation at the site, with % of daytime hours (top) and % of energy content (bottom) distributed at 100W/m^2 bins, averaged for the 6 years of continuous operation.

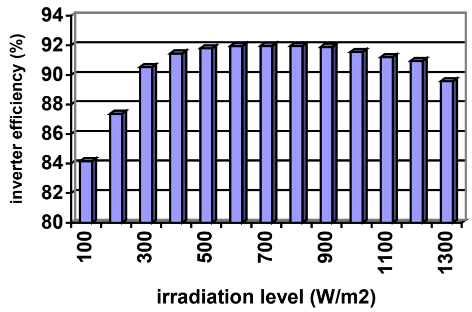


Figure 6: Inverter efficiency vs. plane-of-array irradiation levels distributed at 100W/m^2 bins, averaged over the 6 years of measurements at four minute intervals.

4. CONCLUSIONS

The six years of continuous operation of the 2kWp grid-connected a-Si PV system installed at LABSOLAR have shown that this technology performs well under the prevailing conditions at the site. The PV system displays a high performance ratio and negligible temperature effects at the stabilised state. We have also recently shown that the stabilised performance level of a-Si thin-film is the highest at sites where the minimum operating temperatures are highest [14]. This demonstrates the suitability of a-Si thin film solar modules for high operating temperature BIPV applications, in situations where there are no roofing area constraints, provided the added BOS costs incurred by the larger areas required by this lower efficiency technology can be met by a lower $/Wp price.

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