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ASSESSMENT OF THIN-FILM TECHNOLOGIES MOST SUITED FOR BIPV APPLICATIONS IN BRAZIL: THE PETROBRAS 44kWp PROJECT

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ABSTRACT

This paper describes the so far largest PV installation in Brazil. The system was designed to assess the performance of the three commercially available thin-film PV technologies operating in warm climates. The fully-monitored, grid-connected installation comprises six sub-systems using PV modules from four different a-Si (amorphous silicon), one CdTe (cadmium telluride) and one CIGS (copper, indium–gallium, diselenide) thin-film manufacturer. The installation was designed to measure irradiation levels (horizontal and plane-of-array), temperatures (ambient and back-of-the-module) and AC and DC electrical parameters continuously, in order to compare the long-term output performance of these six state-of-the-art module types and two inverter types, looking at annual energy yields and performance ratios. Different inverter/PV array power ratios are also an aspect of investigation, aiming at studying their influence on energy yields in a warm and sunny site.

1. INTRODUCTION

LABSOLAR, at the Universidade Federal de Santa Catarina – UFSC, in Brazil, has been investigating the performance of photovoltaics, especially thin film PV, in warm and sunny climates in a number of applications. PETROBRAS, the Brazilian oil company, is investing in different renewable energy technologies to diversify its energy mix and energy product portfolio. The company, recognizing the present and future role that low-cost PV will play in the world energy scenario, has established links with the University to receive training and build knowledge on PV.

Three thin-film photovoltaic technologies are presently commercially available, each of them with different characteristics when compared with the more traditional and market dominant crystalline silicon (c-Si). Especially for building-integrated (BIPV) applications, some of these peculiarities will lead to different annual energy yields (kWh) for the same PV module STC nameplate rating (kWp). Amorphous silicon (a-Si) presents a low temperature coefficient of power ($T_{coeffPmax}$ = -0.1 to -0.2%/°C), which becomes negligible after the material has undergone stabilization of the Staebler-Wronski effect [1,2], being thus well suited for BIPV applications at warm and sunny sites. However, its lower conversion efficiency leads to higher balance of systems (BOS) costs and twice the area necessary for a c-Si system with the same output. The $T_{coeffPmax}$ is an important parameter for system design in warm climates, as c-Si PV modules for example ($T_{coeffPmax}$ = -0.45%/°C) will produce some 20% less power at 65°C than at the STC temperature of 25°C at which they receive their nameplate rating. In warm and sunny sites, PV modules operate closer to 65°C than to 25°C most of the times. Cadmium telluride (CdTe) thin-film PV modules are also commercially available, with conversion efficiencies slightly better than a-Si's, and a small $T_{coeffPmax}$ (typically –0.2%/°C). Low production costs for large-scale production is one of the advantages of this material; the use of rare and toxic elements (Cd and Te) are often cited as limitations for this technology for widespread use in large-scale (GWp) in the future. Copper indium-gallium diselenide (CIGS) is the third commercially available thin-film PV technology, with the highest conversion efficiency of all thin-films but, like c-Si, a strong negative $T_{coeffPmax}$ (-0.45%/°C).

2. DESIGN CONSIDERATIONS

System design was previously presented elsewhere [3], and the original project has been changed and adapted a number of times in the last 12 months to accommodate changes in PV module and inverter suppliers. This paper presents design details of the final system configuration, which is currently being installed at the Petrobras research centre CENPES in Rio de Janeiro, as well as figures on the expected monthly and annual energy output.

2.1 PV Module and Inverter Types

Table I shows PV module and inverter types and quantities, as well as each of the sub-system's partial and total DC output. The PV system faces true north, at a tilt angle equivalent to the local latitude (23°). Figure 1 shows a schematic one line diagram of the electrical connection. Six different thin-film PV module types (a-Si from UniSolar, RWE-Schott, Dunasolar/EPV and Kaneka; CIGS from Würth Solar; and CdTe from First Solar) and two different inverter types (a low input voltage WE500NWR 650W model from Würth Solar and a higher input voltage SunnyBoy SB1800U 1800W model from SMA) are being deployed. As can be noticed from Figure

1, some high Voc module types (a-Si from Dunasolar/EPV and Kaneka; and CdTe from First Solar) are not compatible with the low input voltage inverter type, and are thus configured only with the higher input voltage SunnyBoy inverter. These are typically BIPV modules, intended for grid-connected applications where high input voltage inverters are more commonly used.

Table I. PV module and inverter type and configuration of the six sub-systems comprising the 44.4kWp grid-connected, thin-film PV installation at the Petrobras research centre CENPES in Rio de Janeiro (23°S). The last column shows the different loading of each inverter, with the SunnyBoy model rated at 1800W and the Würth model rated at 650W. The project aims also at studying the behaviour of different inverter x PV array power ratios at a warm and sunny site.

Sub-system #	Module Type	Module Nominal Power	Module Quantity	Sub-group DC Power	Inverter Type	Inverter Quantity	Modules per Inverter	DC Power per Inverter	Inverter/ PV Array Power Ratio
1	US64 Unisolar (a-Si)	64 Wp	48	3.072 kWp	SunnyBoy	2	24	1536 Wp	0.853
			16	1.024 kWp	Würth	2	8	512 Wp	0.788
			20	1.280 kWp		2	10	640 Wp	0.985
			36	2.304 kWp		3	12	768 Wp	1.182
2	ASE-DG-UT RWE-Schott (a-Si)	32 Wp	54	1.728 kWp	SunnyBoy	1	54	1728 Wp	0.960
			66	2.112 kWp		1	66	2112 Wp	1.173
			72	2.304 kWp	Würth	4	18	576 Wp	0.886
			44	1.408 kWp		2	22	704 Wp	1.083
3	DS40 Dunasolar/EPV (a-Si)	40 Wp	80	3.200 kWp	SunnyBoy	2	40	1600 Wp	0.889
			100	4.000 kWp		2	50	2000 Wp	1.111
4	K58 Kaneka (a-Si)	58 Wp	54	3.132 kWp	SunnyBoy	2	27	1566 Wp	0.870
			72	4.176 kWp		2	36	2088 Wp	1.160
5	WS11007 Würth Solar (CIGS)	57 Wp	24	1.368 kWp	SunnyBoy	1	24	1368 Wp	0.760
			36	2.052 kWp		1	36	2052 Wp	1.140
			10	0.570 kWp	Würth	1	10	570 Wp	0.877
			24	1.368 kWp		2	12	684 Wp	1.052
			26	1.482 kWp		2	13	741 Wp	1.140
6	FS45 First Solar (CdTe)	45 Wp	84	3.780 kWp	SunnyBoy	2	42	1890 Wp	1.050
			90	4.050 kWp		2	45	2025 Wp	1.125
		TOTAL	956	44.410 kWp					

2.2 Inverter x PV Array Sizing

We have shown that in the region in Brazil with one of the lowest annual irradiation levels (Florianopolis-SC, where LABSOLAR is sited = 1500kWh/m^2/year), although only some 4% of the annual daytime hours present radiation levels $\geq$ 1000W/m^2, this accounts for nearly 18% of the available solar energy at the site [2,4]. For the site in Rio de Janeiro we expect an even larger amount of energy available at high irradiation levels. Therefore, if a PV system is designed with an inverter / PV array power ratio <1 (and PV module nameplate rating translates real output, which for a-Si in warm climates is closer to being the case), the inverter might not be able to handle a considerable amount of energy over the year. Design practice typically uses ratios of ~0.7 [5,6]. In this context, the issue of inverter sizing must be approached differently from the current practice used at lower irradiation sites. We addressed this by designing some of the sub-systems in this project using the same PV module and inverter types with different power ratios, ranging from 0.76 to 1.18, as can be noticed from Table I. As Figure 2 indicates, inverter efficiency maximum occurs below its nominal maximum power, and PV systems will operate more efficiently if inverters are not at full load. Furthermore, high inverter loading at high irradiation levels at warm sites will also lead to inverters operating at undesirably high temperatures, eventually reaching overtemperature protection levels and reducing inverter life.

Out of the nearly one thousand thin-film PV modules deployed in this project, eight will be left open-circuited in the field, to compare the evolution of output power with time under exposure at the open circuit condition and under load. Additionally, for each module type there are replacement modules that will be kept in the dark for control purposes.

Using LABSOLAR's Brazilian Solar Irradiation Atlas [8] and out previous work on the performance assessment of thin-film a-Si installations in Brazil [4], Table II shows a simulation of the expected annual energy output of the 44.4kWp installation described. Some 70MWh of PV-generated power are expected annually, with an annual yield of over 1500kWh/kWp/year.

Following up on this installation, this project also includes two Petrobras petrol stations to be solar powered.

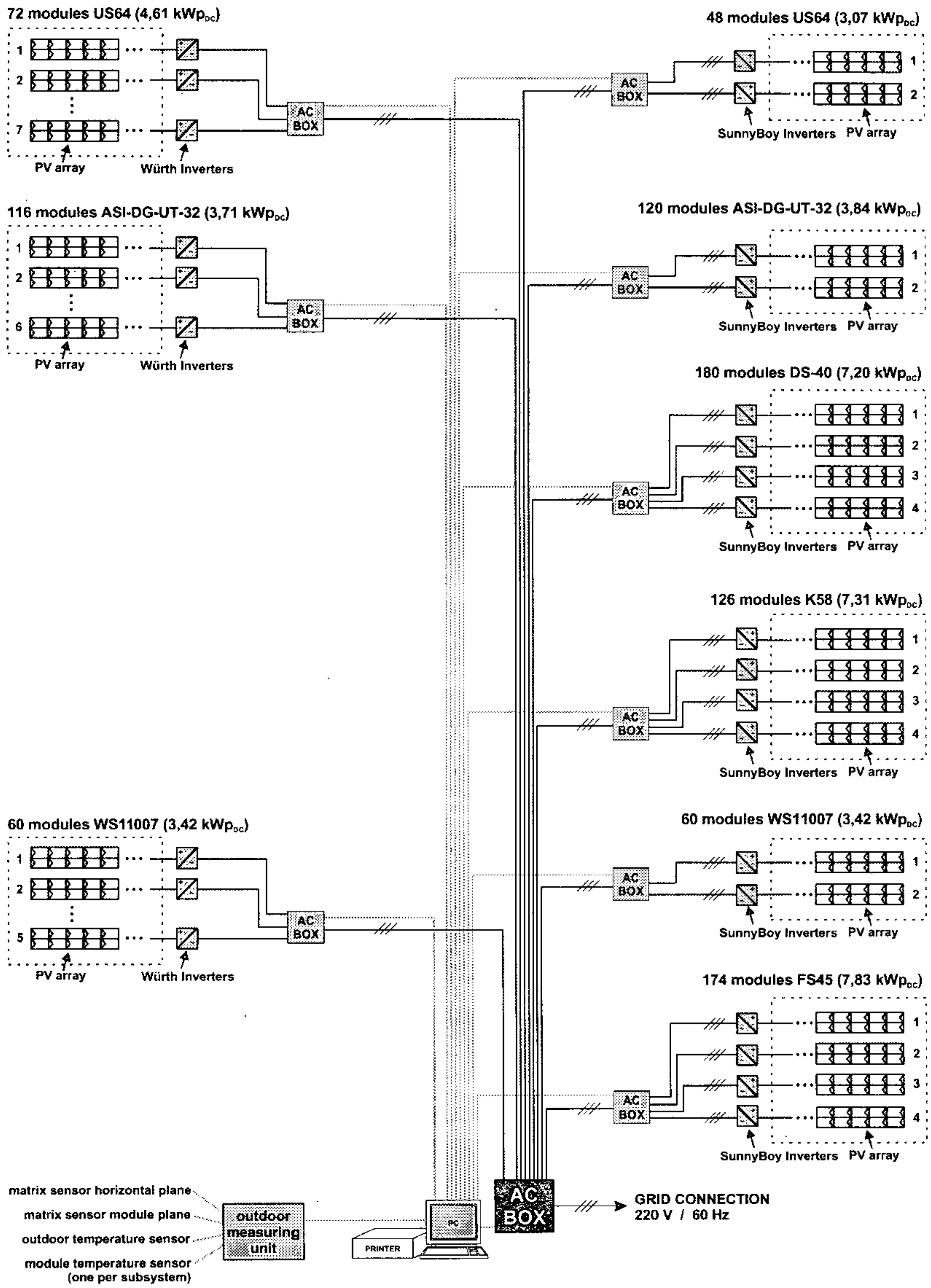

Figure 1: One-line schematic diagram of the 44.4kWp grid-connected PV system at Petrobras research centre CENPES in Rio de Janeiro, showing the nine individual sub-groups using six different commercially available thin-film PV module types and the two different inverter types.

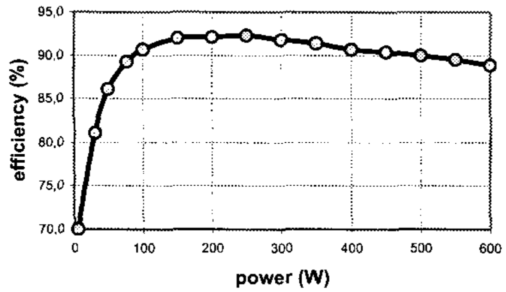

Figure 2: Würth inverter WE500NWR efficiency curve, showing that the maximum efficiency level occurs at partial load [7].

Table II. Monthly plane-of-array solar radiation available at the site, and expected PV-generated electricity for the Petrobras 44.4kWp grid-connected, thin-film PV system in Rio de Janeiro.

Month	Plane-of-array solar radiation (kWh/m²/month)	Expected output (kWh/month)
JANUARY	194,68	7350
FEBRUARY	185,70	7038
MARCH	173,41	6581
APRIL	154,20	5762
MAY	135,28	4992
JUNE	123,72	4508
JULY	119,60	4248
AUGUST	161,08	5788
SEPTEMBER	150,78	5426
OCTOBER	156,49	5883
NOVEMBER	167,52	6347
DECEMBER	183,27	6904
ANNUAL AVG	**158,81**	**5902,17**
ANNUAL TOTAL	**1905,73 kWh/m²/year**	**70826,02 kWh/year**

3. CONCLUSIONS

In this paper we have presented the design concept and main characteristics of the 44.4kWp grid-connected PV installation of the Petrobras research centre CENPES in Rio de Janeiro. The system uses six different thin-film PV module and two inverter types, configured with various inverter/PV array power ratios to assess the performance of different PV technologies and system designs operating at the conditions prevailing at the site. On top of gaining experience on the design, installation and operation of grid-connected PV systems, the project aims at performing a life-cycle cost analysis of the various thin-film technologies available in order to establish the most appropriate for operation in warm and sunny sites.

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