GRID-CONNECTED PHOTOVOLTAICS IN BRAZIL

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ABSTRACT

The first grid-connected, building-integrated photovoltaic (BIPV) system in Brazil was installed in 1997 by LABSOLAR, aiming at gaining experience in the design, installation, operation characteristics and maintenance of this type of on-site, distributed generator in the country. The first installation is a 2 kWp, glass-glass, frameless, laminate thin-film amorphous silicon 40m^2 array, which was retrofitted on to LABSOLAR's building at latitude tilt and facing true north. The system is fully monitored, with solar radiation, temperature and electrical parameters being measured and stored continuously, at 4-minutes intervals. Following this first experience, a number of other BIPV systems have been installed in the country, and more experience and performance data has been gathered. More recently, we have started looking at the match between electrical utility's urban feeders load curves and the generation profiles of these grid-connected PV systems, aiming at better exploring the distributed nature of PV generation. This paper reports on the performance of the first grid-connected PV system in Brazil, and on our studies on the potential of BIPV in the country.

1. INTRODUCTION

Brazil is a large and sunny country, with a centralized energy generation model, comprised of a number of large and often remote hydropower plants•, and a complex, extensive and expensive transmission and distribution

• The largest hydropower plant on earth is Itaipu in Brazil, with an installed capacity of 12.6 GW (with expansion to 14 GW currently under construction), flooded area of 1350 km^2, and annual generation in the order of 80 TWh.

(T&D) system, to which considerable T&D losses are always associated. Power demand, on the other hand, is distributed in a large number of dispersed urban centers where 80% of the population lives, with buildings accounting for over 40% of electricity consumption (1). In commercial buildings during summer months, air-conditioning driven loads are responsible for most of the power demand peaks during daytime, and these loads are typically associated with a high solar radiation availability. In this context, grid-connected, building-integrated photovoltaics (BIPV) appears as an ideal power generation source. Due to the intrinsic characteristics of PV generation, BIPV can be sited next to or very close to demand, minimizing T&D losses and infrastructure, and can represent an important avoided-cost tool to utilities if conveniently sited.

Since 1997 LABSOLAR, the solar energy research laboratory at Universidede Federal de Santa Catarina – UFSC, has been involved with grid-connected BIPV systems, having designed and installed the first such type of system in the country. The 2 kWp thin-film PV system is fully monitored, with ambient and module temperatures, horizontal and plane-of-array irradiation, and electrical parameters being continuously monitored and logged at 4-minutes intervals since start up. The latitude-tilted, north-facing 40m^2 surface shown in Fig. 1 was retrofitted to LABSOLAR's building, and more details on system design and characteristics, as well as on operation performance have been reported elsewhere (2 – 6).

Fig.1: View of the first grid-connected BIPV system installed in Brazil. The 2kWp thin-film amorphous silicon installation uses opaque and semi-transparent glass-glass PV laminates, and is oriented towards true north at latitude tilt (27^o).

Following up on the first experience, a number of additional BIPV systems have been installed by LABSOLAR on campus, as shown in Figs. 2 and 3, and also together with the local electricity utility company CELESC (Centrais Eletricas de Santa Catarina - www.celesc.com.br), Figs. 4 – 6. All of these PV installations are continuously monitored by dedicated data acquisition systems, with the aim of accumulating experience in the operation and maintenance of this kind of distributed generators.

Fig.2: View of the University's student guild building and its BIPV system. Disseminating the concept of on-site solar generation to the future generations of decision-makers is part of LABSOLAR's efforts in making PV a more widespread technology.

Fig.3: View of the University's theatre BIPV system. The 10.2kWp installation showcases the PV technology to a widespread audience.

The three identical PV systems designed and installed in a joint-project carried out together with the local utility CELESC, shown in Figs. 4 – 6, were designed also taking into account architectural aspects, making use of flexible thin-film PV laminates. These installations are also fully monitored, and the curved surfaces were introduced to demonstrate to architects and builders the potential of PV laminates as building elements.

More recently, Companhia Energetica de Minas Gerais (CEMIG – www.cemig.com.br) has also demonstrated interest in the topic of grid-connected PV in urban areas, and has also devoted attention and resources from its R&D program to this area.

Fig.4: Lages – SC; one of the three BIPV systems installed in a joint project with the local electricity utility CELESC to monitor the performance and showcase grid-connected PV. The PV system uses flexible PV laminates which are field-applied onto a curved surface.

Fig.5: Tubarao – SC; one of the three BIPV systems installed in a joint project with the local electricity utility CELESC to monitor the performance and showcase grid-connected PV. The curved surface was designed to demonstrate the potential of PV laminates as a building element to architects and builders.

Attracting utilities to invest and devote time and human resources to the study of grid-connected PV has been given great emphasis, considering the importance of demonstrating the potential benefits of on-site PV generation to the utilities. In this context, we have started studying the generation potential of grid-connected PV in the whole Brazilian territory in terms of daily energy yields, and have also looked at strategically siting PV systems nearby urban feeders with load profiles that match the PV generation profiles. The next section shows some results from our studies.

Fig.6: Florianopolis – SC; one of the three BIPV systems installed in a joint project with the local electricity utility CELESC to monitor the performance and showcase grid-connected PV. All three installations are fully monitored, to accumulate experience in the operation performance of grid-connected PV systems.

2. THE POTENTIAL OF GRID-CONNECTED PV IN BRAZIL

The potential of PV generation in Brazil is orders of magnitude larger than electricity consumption in the country. Just to draw one example, let us compare the PV potential, in terms of energy availability, with the large hydroelectricity power plants that are the predominant generating source in the country's energy mix. Let us use the beforementioned Itaipu hydropower plant as an example, and imagine we would cover all of the Itaipu lake's surface with a 7% efficient PV plant. Table 1 presents comparative data.

TABLE 1: HYDROPOWER vs. PHOTOVOLTAICS (comparing power production between the Itaipu hydropower plant in Brazil and a 7% efficient PV plant covering the Itaipu lake's surface area)

	ITAIPU	**7% eff. PV**
Area (km^2)	1350	1350
Installed power (GW)	12.6	94.5
Annual generation (TWh)	80	160
% of energy consumed in Brazil annually	25	50

We could go further in this exercise and use the dominant crystalline silicon PV technology; assuming a 14% system efficiency, we could then conclude that covering the Itaipu lake with PV would generate the equivalent to **all** the electricity consumed in Brazil (some 320 TWh/year)! This is just an example, designed to illustrate and quantify the potential of PV in Brazil, and is by no means the most effective way of using PV, since all of the T&D costs and losses inherent of centralized generation would still be there. Furthermore, due to its intermittent nature, PV penetration ratios (the % of PV in a given energy mix) should be kept no larger than 20% (7). Conveniently sited BIPV systems in urban areas can add capacity to the utility grid, and avoid distribution system expansions and the costs involved, adding value to the photogenerated energy.

Detailed performance data analysis of the first grid-connected PV installation previously mentioned, over a seven year period, led to the development of the Brazilian PV Atlas shown in Fig. 7. This figure shows the annual average of the daily energy yield, in kWh/kWp/day, for latitude tilted, thin-film amorphous silicon PV systems for any location in the country. A set of 12 additional maps shows the yields for each of the 12 months of the year (8).

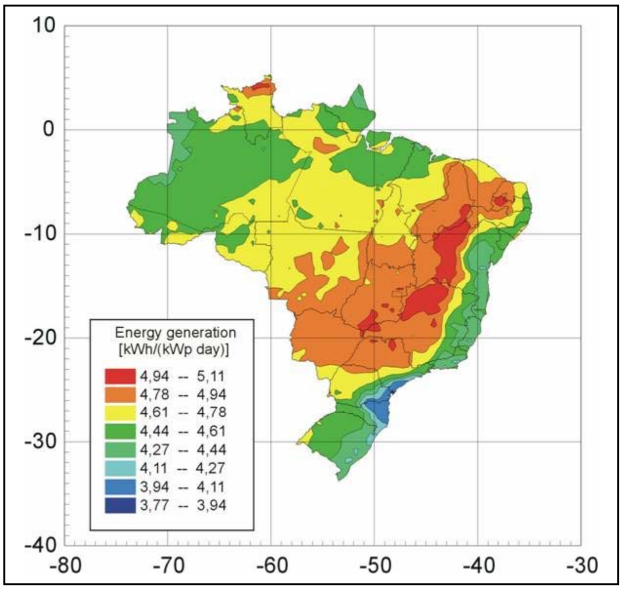

Fig. 7: Brazilian PV Atlas, showing the annual average map in terms of daily energy yield (kWh/kWp/day).

As Fig. 7 shows, even the least sunny place in Brazil will yield over 1350 kWh/kWp/year, with the sunniest sites yielding over 1850 kWh/kWp/year.

The capability that PV power plants have to reduce the demand peak was investigated for the city of Florianopolis. We analyzed the demand curves of the 56 feeders that supply the city for a period of 21 months and found that 24 have a daytime demand peak, and would therefore benefit more from on-site generation from grid-connected PV (9,10). From these 24 feeders we selected 14 that are distanced no more than 10 km from LABSOLAR's solar plant.

In a first step we considered that the PV generation was ideal, that is, all days were clear days. The PV power was assumed as 10% of the maximum historical demand value, that is, 10% PV penetration level. For each feeder we calculated the maximum historical value of demand minus PV generation. This value was translated as the Effective Load Carrying Capacity (ELCC) of PV power (11). ELCC can be assumed as the percentage of the installed PV capacity that can be regarded as dispatchable capacity; it will be high for load profiles that match well the PV generation profile, that is, for loads that "follow the sun".

In a second step we recalculated all hourly points of demand minus PV generation with actual values for the 21 months to see how many times the PV generation could not reduce the demand to the expected value. We found that this occurred only in very specific situations, where, in a high demand moment the PV generation was abruptly interrupted by the presence of clouds.

A specific feeder (TDE 07), that supplies the University region where the solar plant is installed, was analyzed in more detail. To see better the high correlation between demand and solar availability, the demand, PV output and demand minus PV output curves for three consecutive days, with different characteristics, are plotted in Fig. 8. We can see that the demand is high if the solar radiation is high. If the day is overcast, the demand reduces to values under the PV penetration level of 10%. The high correlation between demand and solar availability explains why, with actual data of PV generation, so few points are not satisfactory supplied by PV generation.

To determine the maximum capacity of a PV power plant to reduce the peak demand for the 14 feeders, we considered that the PV power generation was ideal, that is, all days, of the 21 months analyzed, were clear days. We selected 12 clear days, one for each month of the year, from the solar plant data. We worked with 10% PV penetration level. The PV output values were normalized for a 1000 W/m^2 solar irradiation level at the greatest historical PV power value. For each feeder, the hourly demand and coincident PV (clear days) output data for the 21 months were compared and the maximum demand minus PV output value was obtained. This value was assumed as the PV peak reduction capability limit. Table 2 shows the ELCC factors, as percentage of the assumed PV power.

TABLE 2: ELCC FACTORS FOR SELECTED URBAN FEEDERS IN FLORIANOPOLIS, WITH 10% PV PENETRATION RATES

Feeder ID #	Historical Demand Peak (kW)	PV Power (kW)	Demand Reduction (kW)	Date of Demand Peak	Hour of Demand Peak	ELCC (%)
CQS_01	5879	587.9	389.93	12/03/2002	16:00	66.32
CQS_10	8078	807.8	645.00	11/03/2002	17:00	79.84
CQS_11	9536	953.6	832.44	13/03/2002	14:00	87.29
CQS_12	8030	803.0	501.18	23/11/2001	15:00	62.41
CQS_TT1	26792	2679.2	2.127.00	12/03/2002	17:00	79.39
ICO_03	6931	693.1	342.07	07/12/2001	16:00	49.35
ICO_07	9536	953.6	812.58	19/03/2002	15:00	85.21
ICO_08	8963	896.3	782.25	12/03/2002	14:00	87.27
ICO_09	5019	501.9	432.11	16/11/2000	10:00	86.09
ICO_10	9273	927.3	604.19	27/10/2000	15:00	65.15
ICO_11	9369	936.9	781.11	11/03/2002	16:00	83.37
ICO_LI	6429	642.9	561.65	14/03/2002	16:00	87.36
ICO_TT2	30759	3075.9	2.500.28	19/03/2002	15:00	81.28
TDE_07	9512	951.2	830.29	12/03/2002	14:00	87.29

With actual PV output values, we recalculate demand minus PV output, to see how many times, in 21 months, the PV generation could not reduce the demand to the expected values. For the specific feeder (TDE 07), that supplies the University region where the solar plant is installed, from approximately 15,000 hourly demand values, only 41 were greater than the expected value and occurred on summer time. This shows the high energy consumption in summer time. From these 41 values, 36 were supplied by the PV generation, remaining only five that exceed the expected value. These five failure events occurred in very specific situations, where, in a high demand moment, the PV generation was abruptly interrupted by the presence of clouds (see Fig. 9).

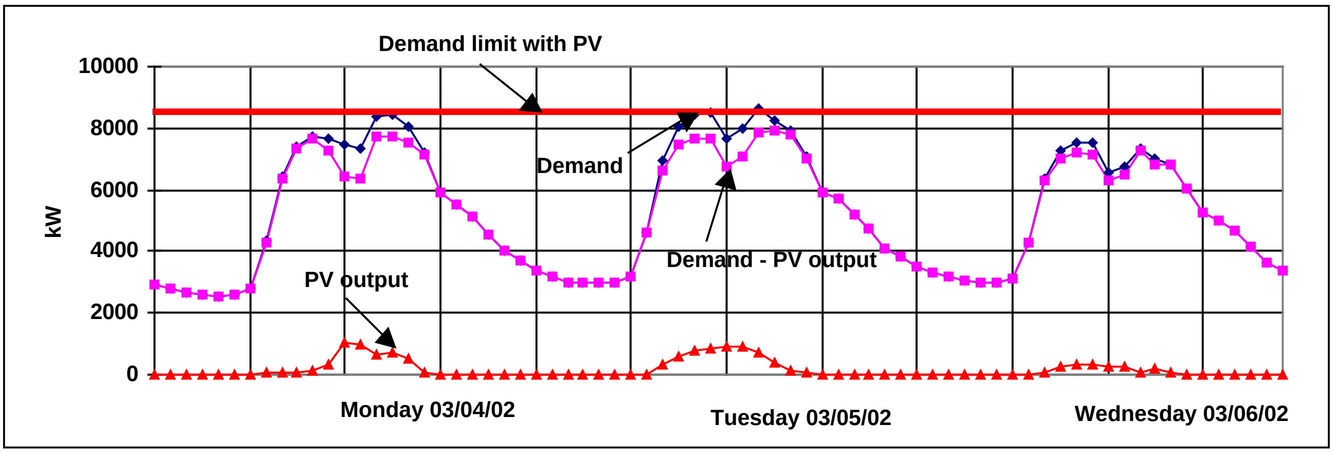

Fig. 8: Demand behavior of three consecutive days with different cloud cover, and the correspondent effect of PV generation on a particular load profile.

The high correlation between demand and solar availability shown in Fig. 8 occurred during a typical sequence of working days as follows: on Monday morning, with an overcast sky, the demand was in a low level. In the afternoon, with higher values of solar irradiation, the demand increased, but was compensated by the PV generation. On Tuesday, with high solar irradiation, near to a clear day, the demand was high and the solar generation was also high. On Wednesday, again with an overcast sky, the demand reduced to values under the PV penetration level of 10%. These three days show the high correlation between demand and solar availability. This can explain why, in 21 months, only 5 times the demand was not supplied by the solar generation as depicted in Fig. 9.

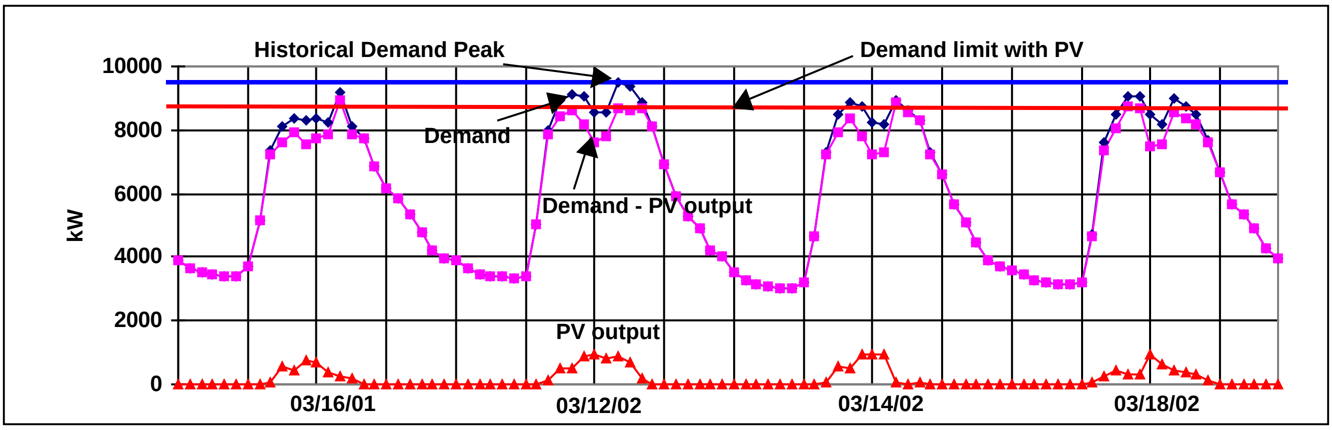

Fig. 9: TDE 07 feeder, 21 months monitoring. Only in five situations the PV generation did not supply the demand with the expected value.

3. CONCLUSIONS

We have shown some of the BIPV installations currently in operation in Brazil, and have presented results on the potential of grid-connected PV in the country, based on the performance of the monitored installations and analysis of a number of urban feeders in the city of Florianopolis. We have also shown that for a considerable number of urban feeders, conveniently sited PV plants can contribute significantly to the reduction of demand peaks, as evidenced by the high values of the ELCC factor associated to these feeders. These feeder loads are typically driven by air-conditioning loads, which present a very good match to solar energy generation. We have performed these calculations for one of the coolest and least sunny regions in the country, and anticipate that for the Brazilian northeast the effect would be much more prominent, and the benefits of on-site generation by grid-connected BIPV installations much more pronounced.

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