PERFORMANCE ASSESSMENT AND DISTRIBUTED GENERATION BENEFITS OF THE FIRST GRID-CONNECTED, BUILDING-INTEGRATED PV SYSTEM AFTER 10 YEARS OF CONTINUOUS OPERATION IN BRAZIL

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ABSTRACT

Ten years ago, in September 1997, the first grid-connected, building-integrated, photovoltaic (BIPV) system was installed in Florianopolis (48°W, 27°S), Brazil. The fully-monitored, 2kWp installation uses 40m^2 of glass-glass, double-junction, thin-film amorphous silicon (a-Si) PV laminates, which were retrofitted to the existing solar energy research laboratory (LABSOLAR) building, at latitude tilt and facing north. The installation is connected to the low-voltage distribution grid via four line-commutated sinewave inverters, and has been operating and logging operational data continuously since start up. The negligible effect of temperature on the output performance of the a-Si thin-film technology, associated with the large solar energy resource availability in the Brazilian territory, and the consequent large PV module operating temperatures, were decisive in the original selection of this thin-film technology. This has resulted in high performance ratios (over 85% and 80% at the DC and AC levels respectively) and also in a high annual energy yield (1300 kWh/kWp/year for a 1550 kWh/m^2/year irradiation level at the site) reported in this paper. Furthermore, with the operational results from this installation, we have been able to demonstrate the potential of grid-connected PV as a peak shaving tool in an urban area in a developing country. In this paper we show how PV can be strategically and conveniently sited in the metropolitan area of a capital city, in order to optimise the benefits of this distributed energy generating technology.

1. INTRODUCTION

Grid-connected PV is usually perceived as a developed country energy technology, and isolated, stand-alone PV is seen as more suited for applications in developing nations, where so many individuals still lack access to the public grid. The traditional utility concept relies on a relatively small number of considerably large power plants, which are not necessarily close to the urban centres where energy is consumed, and in a large country like Brazil (8.5 million km^2), transmission and distribution (T&D) infrastructure and associated losses are not negligible.

Compared with a share of some 17% of the total world electricity generation, and in spite of the large distances from urban areas, hydropower generation plays a fundamental role in Brazil. The present installed capacity of 73 GW corresponds to over 75% of the national electricity supply. Growing environmental restrictions, and the larger distances from urban centres to the remaining potential, however, are considerably increasing the costs of new hydropower plants. The Brazilian interconnected electricity system is one of the largest and most complex in the world, with an installed capacity of over 96 GW [1]. In 2001, with increasing demand due to favourable economic conditions, and a lack of investments in infrastructure, there was a shortfall and consequent rationing of electricity in some regions in the country, which exposed the fragility of the centralized generation and distribution model in a large country.

In this context, grid-connected, BIPV systems in urban areas can offer an attractive alternative to compose the energy mix in a developing country like Brazil. The large solar radiation resource availability, the complementary nature of solar vs. hydro availability (seasonality), and the distributed nature of BIPV must be taken into account in order to add value to this still costly energy source.

For a decade, the detailed monitoring and the continuous performance of the first grid-connected, building-integrated PV system in Brazil has been intensively assessed. This 2kWp thin-film a-Si PV system generates a set of horizontal and tilted solar radiation, ambient and module temperature, and DC and AC electrical parameter data, which are measured at 3-seconds intervals, and stored as 4-minutes averages. The double-junction pin-pin a-Si system was installed on a BIPV configuration at the LABSOLAR building at Universidade Federal de Santa Catarina (UFSC) in Florianopolis, south Brazil. More details on the system configuration and components were presented elsewhere [2,3]. Making use of the detailed, long-term data of this BIPV installation, and urban feeder[1] demand data for the Florianopolis metropolitan area obtained from the local electrical utility CELESC (Centrais Eletricas de Santa Catarina www.celesc.com.br), we have also studied the match between solar generation and urban load profiles. In this work we use a methodology to strategically site PV systems in the urban environment, in order to optimize the capacity credit of PV, and add value to the photogenerated kilowatthour. It is envisaged that in the near future, as PV costs decline, conventional generation costs increase, and grid parity is eventually reached, the strategic siting of urban-area BIPV systems will become a valuable tool for utilities and energy planners.

2. PERFORMANCE ASSESSMENT AND PEAK SHAVING POTENTIAL OF PV

Over the ten years of continuous operation and monitoring, and after undergoing the degradation and stabilisation process typical of thin film a-Si, the 2kWp PV system is now operating with performance ratios of 85% DC and 80% AC respectively, and the total system annual energy yield has consistently ranged between 1250 and 1300 kWh/kWp, for a solar radiation resource in the 1500 to 1550 kWh/m^2 at the site.

The load profile of the Brazilian electricity system as a whole peaks in the early evening, and it is driven partly by lighting, but mostly by the electrical showerheads that can draw up to 8 kW, and are the most common water heating device in Brazilian households. Commercial areas in urban centres, however, present daytime peaking load profiles that are typically driven by air-conditioning, and which are fairly coincident with solar generation profiles and seasonality (usage profiles ranging from 9AM to 5PM, peaking around noon or early afternoon in summer months). In these situations BIPV in urban centres can assist in peak shaving, delivering power when it is most needed and at point of use, minimising T&D losses and increasing grid capacity [4]. In the state capital Florianópolis, nearly 50% of the urban feeders are daytime peaking, and in this work we selected eight of them, representing different areas in the city, to carry out a more detailed study.

For each of the selected feeders we calculated the Effective

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[1] A feeder is defined as a section of the primary or high voltage distribution system derived from a single circuit breaking device in a distribution substation.

Load Carrying Capacity (ELCC) [4-6] for different PV penetration levels[2], aiming at identifying the potential contribution of grid-connected solar generation. Feeder load profile data were supplied by CELESC at 15-minutes intervals, and solar radiation, as well as PV generation data, were obtained from the 2kWp BIPV installation historic. To calculate the ELCC, 12 clear days representing the 12 calendar months were selected, for which both solar radiation and PV generation profiles were available at 4-minutes intervals, and both feeder load data and PV generation data were averaged at hourly intervals for further processing. Clear day data were normalized with respect to the feeders' historic demand peak for each feeder, in order to determine the peak reduction percentage for further comparison. The ELCC was calculated as follows:

$$\text{ELCC} = [(\text{Peak C} - \text{Peak CPV}) / \text{PV}]\ 100\% \qquad (1)$$

Where:
Peak C: maximum historic demand value (kW),
Peak CPV: maximum historic demand value minus the respective PV generation, for a given PV penetration level (kW),
PV: PV nominal installed capacity (kW).

Fig. 1 shows a typical daytime peaking feeder load profile (the TDE_07 feeder, which will be further analysed), and the parameters defined in equation (1) above, which are used to calculate the ELCC parameter. The ELCC was calculated for a series of PV penetration levels, ranging from 1% to 50%, and for eight of the 35 urban feeders in Florianópolis.

Fig. 2 exemplifies the high correlation of a daytime peaking feeder with the solar generation profile.

For the TDE_07 feeder, and simulating a 10% PV penetration level, we show the corresponding load profile (upper curve – blue diamonds) for the three consecutive days with the different climate conditions represented by the lower curves (solar generation – red triangles), and the resulting load minus PV generation profile (middle curve – magenta squares). The upper straight (blue) line represents the historic feeder maximum peak, and the lower (red) straight line can be regarded as a new demand value that we define as the maximum peak with the integration of PV, and which should not be exceeded (Demand limit with PV) to maximize the benefits of PV as a peak shaving tool. On Monday morning (March 4th, 2002), with an overcast sky, demand was low. In the afternoon, with higher values of solar irradiation, the demand increased, but was compensated by the enhanced PV generation. On Tuesday (March 5th, 2002), a clear day with high solar irradiation levels, demand was high, and solar generation was also high. On Wednesday (March 6th, 2002), a heavily overcast day, demand was reduced to values below the PV penetration level of 10%, meaning that there was no (or very little) PV generation available, but the new feeder demand peak limit was nevertheless not achieved, because loads (*e.g.* air-conditioning) were also low and in phase with the overcast conditions.

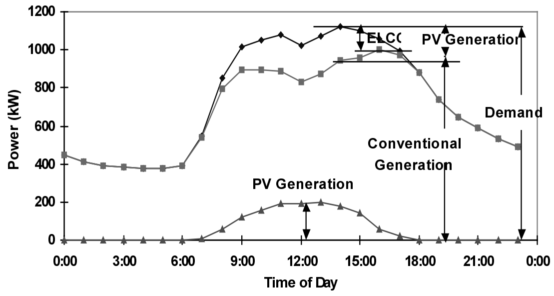

Fig. 1: Example of a typical daytime peaking urban utility feeder (TDE_07). The upper curve (blue diamonds) is the original load curve profile, the lower curve (red triangles) represents the PV generation for the corresponding clear day at a given PV penetration level, and the middle curve (magenta squares) shows the resulting load profile, with a considerably reduced peak, which the feeder has to supply.

We have identified the historic demand peak for each of the eight feeders analysed, and have calculated the ELCC for PV penetration levels ranging from 1% to 50%. Fig. 3 shows the evolution of the ELCC with the increase of the participation of PV (*i.e.* the PV penetration level) in the power supply of the respective feeder. We present this set of curves as a strategic siting tool, which can assist the local utility in assigning peak shaving value (capacity) to

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[2] The PV penetration level is defined as the percentage of the historic peak (AC kW) of a given feeder that is supplied with PV power (DC kW), and in this work we assumed a 80% performance ratio (*i.e.* ratio of actual AC power and rated DC power of the PV generator), based on the performance of the 2kWp PV system reported in this work.

the amount of PV installed. With the results shown in Fig. 3 it is possible to prioritise the installation of PV in the urban environment, selecting first the urban regions served by feeders which lend a higher ELCC to PV, in order to obtain the maximum peak reduction potential for a given PV installed capacity.

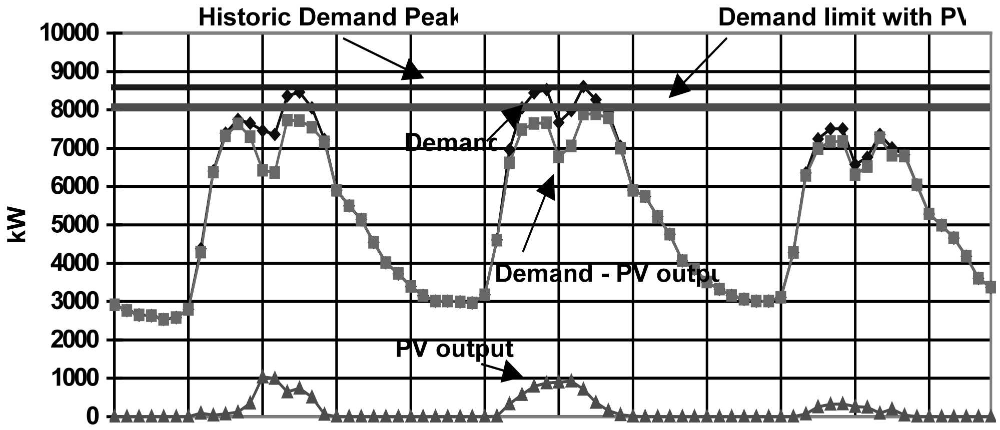

Fig. 2: Demand behavior of feeder TDE_07 for three consecutive days with distinct solar radiation profiles. The upper curve (blue diamonds) is the original load curve profile, the lower curve (red triangles) represents the PV generation for the corresponding clear day, and the middle curve (magenta squares) shows the resulting load profile which the feeder has to supply. Even on a cloudy day the "demand limit with PV" level was not exceeded.

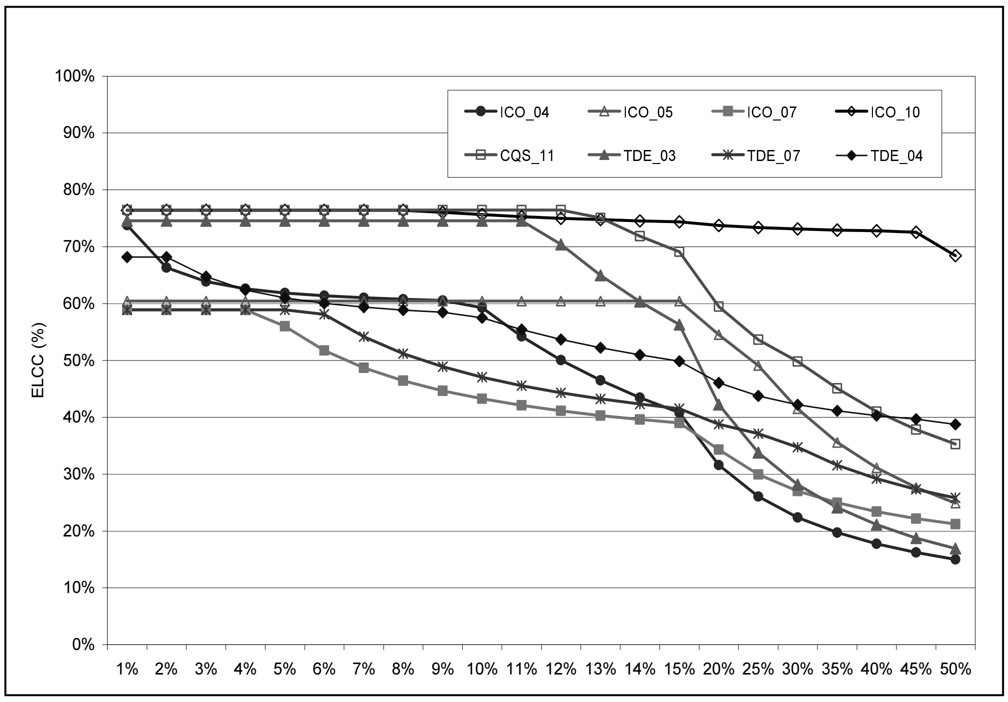

Fig. 3: Evolution of the ELCC parameter for each of the eight urban feeders selected versus PV penetration level. The PV penetration level corresponds to the fraction of the corresponding feeder's historic load peak.

3. CONCLUSIONS

We have assessed the performance of a grid-connected, BIPV installation operating continuously in a metropolitan area in a Brazilian state capital, aiming at maximising the benefits of the distributed nature of PV generation. Using the ELCC parameter to correlate solar energy availability in urban areas with the respective utility feeder power demands, we have shown that for a selection of metropolitan areas there is good coincidence between energy demand and generation. These areas usually present large air-conditioning loads, which result in a good match between power demand and solar availability. For fractions of PV penetration up to 20%, this synchronism was translated by ELCC values starting at more than 75%, which can be interpreted as a metric for PV plant despatchability, and also as a priorization tool for PV siting and integration in the urban environment.

When installing solar photovoltaic systems in the urban environment, the ELCC methodology can be used to strategically site these distributed generators integrated to the building envelope, and maximise the benefits of these clean and quiet mini power plants. With the more widespread use of BIPV systems, and the consequent cost reductions resulting from larger production volumes, PV siting otimisation tools should play an important role in making the cost of solar electricity more competitive with conventional grid power.

4. ACKNOWLEDGMENTS

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