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Potential of building integrated photovoltaic solar energy generators in assisting daytime peaking feeders in urban areas in Brazil

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Abstract

Because of the intermittent nature of the solar radiation resource, photovoltaic (PV) solar energy generation is considered a non-dispatchable power source. However, under some conditions, in sunny urban areas with electricity load curves dominated by air conditioning loads, there is a high correlation between PV generation and utility feeder loads. In these situations, a considerable fraction of a given PV generator can be considered dispatchable power. In this work, we assess the potential of grid connected, building integrated photovoltaic (BIPV) generation in the state capital, Florianópolis, in south Brazil (27 °S, 48 °W), which is supplied by the local utility company through 56 feeders. Our interest was to identify which feeder could obtain more benefits with implementation of a PV plant with a specific nominal power. Two factors are important in this analysis: the peak demand reduction value, and the LOLP (loss of load probability, in failures per year), or LOLE (loss of load expectation, in hours per year). We analyzed the hourly demand curves of the 56 feeders and compared them with the PV power generation values obtained from a 2 kW_p BIPV installation that has been operating continuously for nearly 10 years connected to one of these feeders. For our calculations, we defined a PV installation of 1000 kWp_{AC}, which corresponds to penetration level values between 10% and 20%, depending on the specific feeder considered. Our results demonstrate that the use of PV power plants can reduce significantly the summer demand peaks in regions where the load reflects commercial customers demand for midday air conditioning.

Keywords: Grid connected photovoltaics; Building integrated photovoltaics (BIPV); Value of photovoltaic (PV) electricity

1. Introduction

Grid connected photovoltaics (PV) is presently the fastest growing energy technology in the world, which grew in existing capacity by 55% per year from 2000 to 2005 [1]. Second is wind power, which grew by 28% per year [2]. On the other hand, despite constant production cost reductions following a learning curve with a learning rate[1] of 0.2 [3–8], PV conversion of solar energy to electricity is still one of the most costly energy generation alternatives commercially available. For this reason, maximizing the benefits of this decentralized, modular, silent and clean renewable energy technology is of fundamental importance to improve its economic value when compared with more traditional energy technologies. While the off-grid market has been the steady commercial base to support the gradual

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[1] The learning rate (LR) is the relative cost reduction for every doubling of cumulative production due to "learning". A LR = 0.2 results in a 20% production cost reduction for every doubling of cumulative production.

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expansion of the PV industry, grid connected applications have grown to 82% of the terrestrial PV market volume in 2005, with a compound annual growth rate of 55% in the 2000–2005 and 32% in the 1980–2005 periods [1]. This application also uses much larger volumes per individual installation than most of the other PV applications and is forecasted to continue to expand as more countries adopt incentive programs. While, at present, most of this application development is taking place in the developed world, it is expected that, with declining costs, the benefits of the distributed nature of grid connected PV will extend to a more widespread adoption of this application worldwide, with multi-megawatt production plants scattered in many continents [9,10]. Brazil is particularly well suited for the application of grid connected PV due to both a considerable solar resource availability, which results in high energy yields for BIPV installations [11], and to the high value that can be attributed to PV in commercial areas of urban centers [12–14].

PV can contribute to a utility's capacity if the demand peak occurs in the daytime period. Commercial regions with high midday air conditioning loads normally have a demand curve in good synchronism with solar irradiance profiles [15–19]. Another important factor in this analysis is the comparison between peak load values in summer and winter. The greater the demand in the summertime is in comparison with the demand in wintertime, the more closely is the load likely to match the local solar availability profile. This is the typical picture of most capital cities in Brazil. Utility feeders in urban areas all over the country show distinct regions where commercial and office buildings dominate and which present daytime peak demand curves, whereas residential regions have their demand peaks in the evening. To add value to the distributed nature of solar generated electricity, it is important to know the PV capacity of the different regions of a city when installing a PV power plant in order to select the feeder with the greatest capacity credit. In this context, the concept of the effective load carrying capacity (ELCC) of a PV plant was defined to quantify the capacity credit of a strategically sited PV installation [15–20].

Florianópolis is a capital city located in south Brazil, and it presents one of the lowest solar irradiation levels of all its vast and sunny territory (some 4.5 $kWh/m^2/day$, with the maximum value being around 6.5 $kWh/m^2/day$ in the northeast region [21]). In a country where cooling requirements are considerable and heating requirements are very low, this results in the summer electrical consumption being more than twice the winter consumption. In this context, the central commercial region of the city presents a high midday air conditioning demand, which is expected to result in the load being well matched to the PV's power output. Meyer and Luther [22] have previously studied the correlation between electricity spot market prices and PV generation, which they found to give a good indication of the additional value of PV electricity. In this work, we make the following assumptions: if a PV power plant with a specific power capacity is to be installed in the urban environment, the city of Florianópolis in our case study, which of the utility feeders will benefit most from the peak shaving capability of PV. Two parameters are important in this choice: the demand peak reduction capacity of PV and the number of failures, or demand events not completely supplied by PV generation.

2. Methodology

The methodology described below can be applied to any urban center for which at least hourly electricity demand and solar radiation data are available. For the 56 feeders that supply the city, we identify two parameters: historic demand peak value without PV and historic demand peak value with PV (demand minus PV generation) for a period of 2.5 years using hourly values and calculate the following factor:

$$\text{POPR} = ((\text{historic demand peak without PV-historic demand peak with PV})/\text{PV power}) \times 100\%$$

where POPR is the percent of peak reduction relative to the nominal PV power. Based on the historic demand peak values, for each feeder, we selected a nominal PV power of 1000 kW_{AC} that represents a PV penetration level[2] varying from 10% to 20% depending on the feeder. For a well designed and installed grid connected PV system in Brazil, this corresponds to a nominal PV power of 1250–1300 kW_{CC} [14,23–25].

In a second step, we plotted a graph for each feeder with the following information:

- All demand values greater than the historic peak demand value minus 1000 kW (corresponding to the nominal PV power for a maximum irradiance of 1000 W/m^2).
- All the corresponding demand minus PV generation values.

These values were organized in descending order of the demand minus PV generation values and are shown in the next section for two selected feeders. Two horizontal lines, representing the historic demand peak value and the historic demand peak value minus PV power (1000 kW) are also plotted. If we assume that the PV plant should be considered a dispatchable power source of 1000 kW, the demand with PV values should never exceed the historic demand peak value minus the PV power value (limit value). If this value is exceeded, we can see how much the demand with PV exceeds this value and how often it occurred. An

[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 an 80% performance ratio (*i.e.* ratio of actual AC power and rated DC power of the PV generator), based on the 9 years of monitoring of a BIPV installation operating at LABSOLAR/UFSC [14,23–25].

important parameter is the quantity of hours per year that the demand with PV exceeds the "limit value". We named this parameter PV-LOLE (PV loss of load expectation). The PV-LOLE differs from the conventional definition of LOLE in the fact that the conventional LOLE considers a total loss of load in hours per year and the PV-LOLE is a partial loss of load of the PV generation, which not necessarily means that the feeder failed in supplying the demand.

We have also calculated the PV-LOLP (PV loss of load probability) values for all the feeders with daytime demand peak. Comparing the PV-LOLE and PV-LOLP values, we obtain the mean time, in hours, of failures. For example, a PV-LOLE = 8 h per year and a PV-LOLP = 4 failures per year mean that, on average, a failure in the PV supply had a duration of 2 h.

3. Correlation between PV output and feeder demand

Fig. 1 shows, for one of the typical daytime peaking utility feeders studied (feeder ID # TDE_07), the peak shaving effect of adding a small amount of PV to assist in reducing the load requirements of the feeder. Feeder load profile data were supplied by the local utility CELESC (Centrais Elétricas de Santa Catarina www.celesc.com.br), and the solar radiation, as well as the PV generation data, were obtained from the fully monitored 2 kWp BIPV installation operating at LABSOLAR/UFSC's building since 1997 [23–25].

The plots demonstrate the high correlation between power demand and solar availability for three consecutive days with different cloud cover profiles. Monday, 03/04/02; Tuesday, 03/05/02 and Wednesday, 03/06/02. The lower straight line, labeled "Demand limit with PV", represents the demand value that should be guaranteed not to be exceeded due to the contribution of PV. On Monday morning, with an overcast sky, the demand was relatively low. In the afternoon, with higher values of solar irradiation, demand increased but was compensated by the enhanced PV generation. On Tuesday, a clear day with high solar irradiation levels, the demand was high and so was the solar generation profile. On Wednesday, a heavily overcast day with a very small contribution of PV generation, demand was naturally reduced to values below the PV penetration level considered. On that day, not much PV generation was available, but neither was it necessary to guarantee that the maximum demand limit previously defined was not exceeded. These three days show the high correlation between demand and solar availability.

We found that the feeder with the greatest peak reduction potential is also the one that presents the smallest PV-LOLE value. This feeder is located in a commercial region of the city (feeder ID # CQS_11) with a historic peak demand value of 9533 kW, so that the penetration level of our simulated PV system is 10.5%. Fig. 2 shows the plot with the "demand without PV" and the "demand with PV" values for feeder CQS_11, which presents the following information:

(i) Over the 2.5 years analyzed (over 20,000 demand points), only in 51 events were the demand values higher than the historic demand peak minus PV power (9533 − 1000 kW = 8533 kW). For feeder CQS_11, the highest demand peaks occurred in March, one of the hottest periods in the region. This small number of high demand values confirms the high summertime energy consumption in this commercial region.

(ii) Over the same period, only in nine events was the demand with PV value higher than 8533 kW. This corresponds to a PV-LOLE value of 3.6 h per year (0.04%).

(iii) Five failures occurred in these 2.5 years, corresponding to a PV-LOLP value of 2.0 failures per year: two failures with duration of 1 h, two with duration of 2 h and one with duration of 3 h over a 2.5 years period.

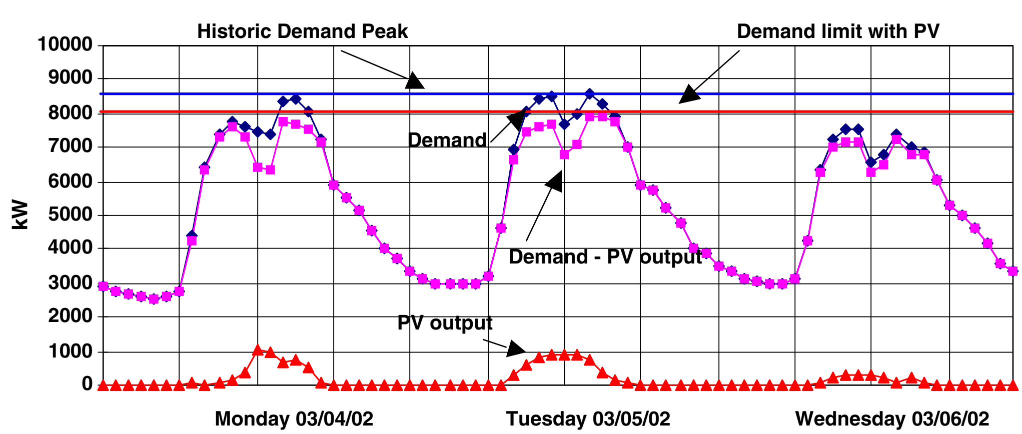

Fig. 1. Demand behavior of feeder TDE_07 for three consecutive days with distinct solar radiation profiles. The upper curve (blue diamonds) is the original load curve profile, the lower curve (red triangles) represents the PV generation for the corresponding clear day and the middle curve (magenta squares) shows the resulting load profile that the feeder has to supply. Even on a cloudy day, the "demand limit with PV" level was not exceeded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

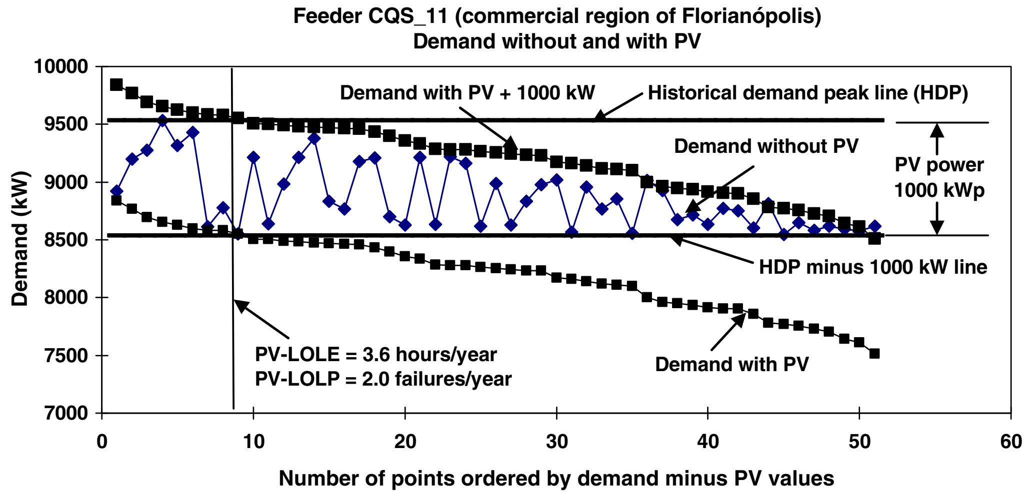

Fig. 2. Highest demand events over the 2.5 years period for feeder CQS_11 and the peak shaving effect of adding 1000 kW of PV generation to limit demand peaks in a commercial region.

(iv) The highest demand with PV value was 8840 kW (worst case). This corresponds to a POPR = 69.3% or, in other words, the PV generation, in the worst case, supplied the equivalent of 693 kW of the 1000 kW PV installed capacity.

(v) Observing the demand and the demand with PV values, we can conclude that there is a high correlation between demand and solar intensity in this commercial area urban region.

(vi) When we add 1000 kW to each of the "demand with PV" points (curve labeled "Demand with PV + 1000 kW" in Fig. 2), we can observe that the PV generation offsets the points of high loading by its nominal power. We can, thus, say that, except for the nine failure events mentioned previously (3.6 h per year), the PV generation reduced the higher demand points by approximately 100% of the nominal installed PV power.

The behavior of all the other analyzed feeders with daytime demand peaks is similar to the behavior of the CQS_11 feeder. Fig. 3 shows the values obtained for feeder TDE_07, which supplies the University region where the BIPV system used to generate the data presented here is installed. The historic demand peak value of the TDE 07 feeder is 9524 kW, and only in 133 events were the demand values higher than 8524 kW (9524 – 1000 kW). Out of these 133 points, 112 could have been entirely supplied by the PV generation, so that the "demand with PV" values would be shifted below the 8524 kW value. The highest demand with PV value was 9017 kW (worst case), corresponding to a POPR = 50.7%.

Table 1 shows the feeders with the best PV-LOLE and PV-LOLP values. For all the seven feeders shown, the quantity of high demand values (values higher than the historic demand peak minus 1000 kW) is very small, varying from 51 (feeder CQS_11) to 181 (feeder TDE_04). The

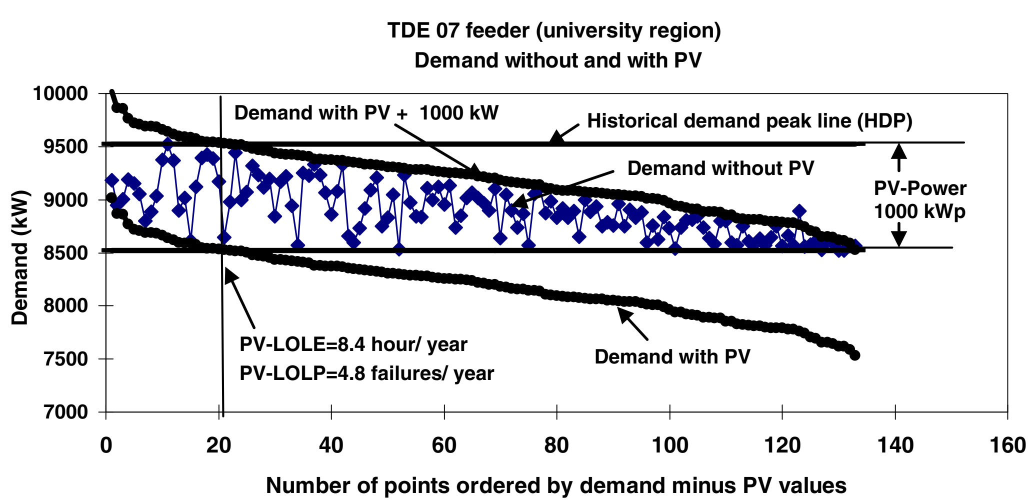

Fig. 3. Highest demand events over the 2.5 years period for feeder TDE_07 and the peak shaving effect of adding 1000 kW of PV generation to limit demand peaks in a mixed commercial/residential region.

Table 1
Seven of the selected urban feeders with daytime peaking demand, and the corresponding PV-LOLE, PV-LOLP, and POPR values

Feeder	Failures	Quantity of demand values greater than demand peak minus 1000 kW	PV-LOLE (h)	PV-LOLP (events)	POPR (%)
CQS_11	9	51	3.6	2.0	69.3
ICO_07	12	54	4.8	2.0	70.9
ICO_08	20	79	8.0	3.2	52.0
ICO_11	28	98	11.2	4.4	50.7
ICO_12	21	111	13.3	6.3	41.6
TDE_04	24	181	9.6	5.6	62.1
TDE_07	21	133	8.4	4.8	50.7

PV-LOLE values, varying from 3.6 to 13.3 h per year and the POPR values varying from 41.6% to 70.9%, indicate that, for these seven regions of the city, the use of a 1000 kW PV power plant could significantly reduce the demand peaks with a very small probability of PV supply failures. Moreover, for the PV penetration levels recommended in this study, this small probability of PV supply failures will not necessarily lead to the feeder failing to supply the grid.

4. Conclusions

In this work, we have studied the behavior of grid connected, building integrated photovoltaic solar energy conversion in the urban environment of a metropolitan area in a Brazilian state capital, aiming at maximizing the benefits of the distributed nature of PV generation. The use of PV power plants strategically sited in urban areas can reduce significantly the summer demand peaks in regions where the load reflects commercial customers demand for midday air conditioning. The small quantities of partial failures, or instants where the PV could not completely satisfy its assigned fraction of the total demand, indicates the additional capacity benefit that a feeder will have from the PV generation plant on top of the energy benefit. We observe that, except for the very few events when PV could not supply its share of a particular feeder load – from 3.6 h (0.04%) to 13.3 h (0.15%) per year for the seven selected feeders presented-PV generation reduced the higher demand points by nearly 100% of the nominal installed PV power. If these PV-LOLE and PV-LOLP values are acceptable for a specific feeder, we can consider the PV plant as a dispatchable power source with nearly 100% of its nominal power.

When planning solar photovoltaic systems in the urban environment, the methodology presented can be used to install these building integrated PV generators in an optimum sequence and maximize the benefits of these clean, quiet, and distributed mini-power plants. With the more widespread use of BIPV systems and the consequent cost reductions resulting from larger production volumes, PV siting optimization tools should play an important role in making the cost of solar electricity more competitive with conventional grid power, evidencing the hidden benefits of solar photovoltaic generation.

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