Conference Paper

A Measure of Capacity Contribution of Static Mono-Si Photovoltaic Systems

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Photovoltaic (PV) systems generate electricity in the daytime when system demand is generally moderate to high. For Mediterranean countries, there is also seasonal coincidence of high system demand and high PV load factors. The present study quantifies the above statements by calculating the load factor of the PV system when system demand is high (above 90–99% of the maximum demand of the month). The percentage of time the PV load factor is above 90% for these periods of maximum demand is evaluated. The PV load capacity contribution is defined in this study as the minimum PV load factor during these periods of high demand. Actual generation data from a static (without tracking) mono-Si PV system, recorded every half hour for the year 2010 are compared to system demand data. The seasonality analysis indicates that PV contribution to capacity is only significant during the months May–October. For the months November–April, when daily demand peak occurs during the evening, PVs do not contribute towards capacity. The evaluated capacity contribution of PV systems depends on the threshold of maximum demand considered (90%–99%). For the threshold of 95%, the capacity contribution for May–October ranges between 27%–41% of PV installed capacity.

1. Introduction

Photovoltaic systems are becoming an attractive renewable energy source of electricity (RESe). Technological developments, as well as mass production manufacturing, have reduced significantly the cost of PV generated electricity over the last few years. Especially for regions with significant solar potential, such as the Mediterranean region, PVs offer a competitive solution for RESe. A concise review of PV technology and market future prospects is provided in [1].

In addition to energy, PVs provide additional advantages to the electrical system. Weather predictions for cloudiness are, in general, fairly reliable. Therefore, PV generation may be predicted with a high confidence level, and the need to cover their generated power with additional spinning capacity is reduced, thus reducing the cost for additional ancillary reserve services.

Furthermore, peak demand in regions with hot summers and mild winters occurs in the summer, at which time PV generation is at its highest due to minimal overcast. For these reasons, it is expected that PVs can contribute towards the available installed capacity of the system, thus reducing the requirement for the installation of conventional dispatchable generation. For example, based on a recent study of the Cyprus Energy Regulatory Authority [2], concerning the level of RESe feed-in-tariffs and the promotion of RESe in the Cyprus power system [3], the capacity contribution of PV systems is assumed at 50%. However, this needs to be investigated further which is the purpose of this study.

In this work a methodology is developed in order to quantify the capacity contribution of PVs. The approach presented in this analysis considers the daily and yearly variation both in system demand and PV load factor. The methodology is

applied to the Cyprus system to provide a measure of the capacity contribution of PV systems.

In Section 2 the methodology developed is presented, and in Section 3 the results obtained are discussed in detail. The conclusions are summarised in Section 4.

2. Methodology

The methodology to calculate a measure of the capacity contribution of PV systems in Cyprus is outlined as follows

- (1) Calculate the PV load factor in 30-minute intervals for each month of the year. The PV load factor, LF_{PV} , is calculated as the ratio of the actual generation of the PV system to the rated (nominal) capacity of the system.
- (2) Identify the number of high demand periods for each month. High demand periods are periods for which the ratio of demand to the monthly maximum demand is greater than x , where $90\% < x < 99\%$. A lower percentage x covers a wider range of high demand periods. Consider

$$N_{x,m} = \sum_{i=1}^{N_m} i \quad \forall D_i > x * \max(D_m), \quad (1)$$

$$90\% < x < 99\%.$$

- (3) Identify the periods for which high demand coincides with a high PV load factor. The number of periods, $N_{x,m,w}$, for which
 - (a) the PV load factor, LF_{PV} , is greater than w , where w takes values of 0% to 100% in increments of 1%,
 - (b) the demand is greater than $x * \max(D_m)$ is

$$N_{x,m,w} = \sum_{i=1}^{N_m} i, \quad \forall D_i > xD_m, \quad \forall LF_{PV} > w, \quad (2)$$

$$90\% < x < 99\%,$$

$$0 < w < 100\%.$$

- (4) Evaluate y as the fraction of periods for which there is coincidence of high demand and high PV load factor to the total number of high demand periods:

$$y_{m,w} = \frac{N_{x,m,w}}{N_{x,m}}. \quad (3)$$

- (5) Evaluate z , the measure of the capacity contribution, as the value of w for which y is greater than f . A value of 90% is used for f where f is a measure of the reliability of the PV system to provide capacity and is analogous to the availability (100%-forced outage rate) of conventional units. Consider

$$z_{m,x} = \min(y_{m,w}) \quad \text{for } y_{m,w} > f. \quad (4)$$

FIGURE 1: Energy demand and energy generated by a static 7 kW PV system in Cyprus.

The capacity contribution, z , can be interpreted as follows. The PV system can be expected to have a load factor of at least z with reliability f (a fraction f of the times), when the demand is above x times the maximum demand of the month. It is a measure of the time coincidence of high system demand and high PV generation. It should be noted that this capacity contribution is evaluated on a monthly basis and is based on the monthly maximum and not the yearly maximum demand in order to account for the seasonal variations of demand and PV load factors, both in magnitude and daily profile.

3. Results

3.1. Seasonal and Daily Variation of PV Generation and System Demand. For the present analysis, we assume the operation of a rooftop PV system of 7 kWp capacity. The household is located in an area with available annual solar potential of 1968 kWh/m². The system consists of mono-Si solar PV modules with a capacity of 185 W per module and efficiency of 14.2% [4]. For the computation of the PV system generation, actual 30 minutes solar potential measurements are taken into account.

The results concerning the monthly generated energy of the PV system and the system energy demand are shown in Figure 1. The data presented for system demand are actually the sum of the generated power of all the generating units connected to the transmission system. They include power generation auxiliary units (approximately 5%) and do not include generation on the distribution network (estimated at less than 1%). The term system demand is utilized as it is more commonly used. The weekly peak demand, in MW, of the Cyprus system is shown in Figure 2. As expected, PV generation increases for the summer months and it peaks in August. Summer PV output is approximately twice as high as winter output. Summer system demand is approximately 1.5 higher than winter system demand. Summer is the period when both system demand and PV generation are at their highest. Spring and autumn are the periods of lowest system demand and intermediate PV generation, and winter is the period of intermediate system demand and lowest PV generation.

FIGURE 2: Yearly variation of peak demand in Cyprus.

The maximum recorded PV load factor throughout the year is 88.4%. The recorded load factor is significantly lower than 100% due to the deviation of the actual conditions from the ISO conditions for which the rated output is defined. It is believed that the most notable deviation is high temperature effects which reduce the output of the PV system.

The average system demand and PV load factor profiles for the months of August, January, and May which are typical months for the high, intermediate, and medium system demand periods are presented in Figure 3. It is observed that, while in August peak PV generation is in phase with high system demand, for winter the two profiles are out of phase. Thus, the contribution of PVs to the system capacity is expected to be significant in the summer and insignificant or zero in winter.

There is, therefore, significant time coincidence of high PV generation with high system demand both on a daily and on a yearly basis. The data analysis which follows attempts to quantify the time coincidence of high demand periods and high PV load factors using the methodology defined in the previous section. The results obtained provide a measure of the contribution of PV systems to system capacity for each month of the year.

3.2. Estimate of PV Contribution to System Capacity. The methodology described earlier was applied to the year 2010 data for the 7kW static mono-Si PV system and Cyprus system demand.

Periods for which the demand exceeded 90% of the monthly maximum demand were examined. The data analysis was performed for different cutoff points for high demand. Values of $x = 90\%$ – 99% were used. The value of the required reliability of the PV generation, f , was assumed to be 90%.

The fraction of time, y , for which the PV load factor was above a minimum value, w , was evaluated for each value of x . For the months of November–April, this fraction of time was insignificant or zero in all cases. This result was expected because system demand peak during these months occurs in the evening at which time PV production is zero (Figure 3 for January). One can, therefore, conclude that static PV systems do not contribute to system capacity during these months.

TABLE 1: Number of data points considered for values of $x = 90\%$, 95% , and 99% .

x	Month					
	May	Jun	Jul	Aug	Sep	Oct
90%	42	71	163	97	101	71
95%	12	48	45	34	16	20
99%	1	7	5	9	3	3

TABLE 2: Capacity contribution, z , of static mono-Si systems in Cyprus, defined as the minimum load factor during high demand periods with a reliability of 90%.

x	May	Jun	Jul	Aug	Sep	Oct
90%	11%	17%	23%	21%	37%	0%
91%	10%	17%	23%	27%	37%	0%
92%	26%	20%	28%	27%	37%	0%
93%	26%	20%	28%	29%	47%	5%
94%	34%	26%	28%	27%	38%	15%
95%	41%	29%	28%	30%	27%	38%
96%	48%	31%	35%	30%	38%	38%
97%	56%	29%	35%	30%	27%	51%
98%	63%	31%	42%	30%	38%	41%
99%	76%	24%	47%	36%	64%	60%

For the months May–October, the fraction of time the PV load factor exceeds a minimum value is shown in Figure 4 for values of $x = 90\%$, 95% , and 99% .

The number of half-hour periods considered for each month and for each threshold of high demand, x , is presented in Table 1.

As the value of the threshold, x , increases, there are fewer periods ($N_{x,m}$) considered, reducing the number of periods to less than 10 for $x = 99\%$. The data analysis performed suffers from the small number of data points.

On the other hand, as x increases, the data domain is expanded to include periods for which system demand is significantly lower than the monthly peak and therefore less significant for the determination of the capacity contribution of PV systems. Considering that the purpose of capacity in an electrical system is to cover demand peaks, very low values of x would mean that the PV contribution evaluated with this data analysis is underestimated. Although the selection of the value of x is subjective to a certain extent, $x = 95\%$ seems to offer a good compromise between number of values used and demand range close to the monthly peak. The step-wise nature of the plots more predominant for $x = 95\%$ and $x = 99\%$ can be attributed to the relatively small number of periods considered.

For the months of May to October, the values of z calculated are presented in Table 2.

By way of example, the results in Table 2 are interpreted as follows. In the month of June, 90% of the time, static mono-Si PV systems in Cyprus are expected to have a load factor of at least 29% when demand is higher than 95% of the monthly peak. Each value in Table 2, for $x = 90\%$, 95% , and 99% , is

FIGURE 3: Daily average load factor profiles of system demand and static PV system generation for August, January, and May.

the value of w at which a horizontal line $y = 90\%$ intercepts the corresponding plotted line in Figure 4.

The nonmonotonic trends and between different values of x , which are observed on certain instances in the results of Table 2, are due to the small number of periods considered.

Considering the results for $x = 95\%$, it may be stated that the capacity contribution of PV systems, as defined in this methodology, for the months May–October is in the order of 30% of their rated output. For the months of May and October, the capacity contribution is of the order of 40%.

The capacity contribution is higher during the months of May and October compared to the months June–September. The daily demand profile during the summer months is relatively flat between the hours of 11 am and 4 pm, as shown in Figure 3, extending in the early afternoon hours the period of high demand. In the early afternoon, PV load factors begin to decrease earlier than demand. For May and October, peak or near peak demand is around noon, at which time PV load factors are close to their maximum values.

It is also observed that for the months of June–September, both the percent of time, y , as a function of the minimum

load factor, w , and the capacity contribution, z , in general increase at a moderate rate as the threshold for demand becomes stricter. On the other hand, for the months of May and October, evening peak demand nears the mid-day peak demand. Since at the evening PV generation is zero, as the value of x increases, the values of w and z increase steeply as the threshold for demand becomes stricter.

4. Conclusions

A methodology has been proposed to determine the contribution of PV systems to system capacity. The methodology evaluates a measure of the time coincidence of the periods system demand with significant PV load factors. The methodology has been applied to static mono-Si systems in Cyprus. However, the same methodology may be applied to other PV technologies, such as PVs with tracking, and other electrical systems.

For Cyprus, with high solar potential during the summer months, at which time demand for electricity is at its peak, it has been shown that photovoltaic systems

FIGURE 4: Percent of time, y , for which the PV load factor is above the minimum PV load factor, w .

may contribute approximately 30% of their rated capacity towards system installed capacity with a reliability factor of 90%.

The practical implications of capacity contribution of PVs concern both the generation system expansion and annual maintenance plans and the market integration of RESe. The capacity contribution of PVs in the summer months reduces the need for conventional capacity installation to cover the yearly peak demand. Their noncontribution during the winter and part of the autumn and spring months may be resolved by the careful planning of the dispatchable/conventional units' maintenance schedule and is therefore of lesser importance.

Furthermore, the PV contribution of PV systems is an advantageous feature compared to other, less predictable on a yearly basis, technologies of RESe, such as wind turbines. This contribution should be acknowledged in the market integration of RESe and remunerated accordingly for a fair and level comparison of the available RESe technologies.

Nomenclature

- D : System demand
- f : Required reliability of PV systems to provide capacity
- LF_{PV} : PV load factor
- N : Number of demand periods
- x : Percentage threshold of monthly maximum demand
- y : The fraction of time LF_{PV} is greater than the incrementally increasing w ($0\% < w < 100\%$) during high demand periods, divided by the total number of high demand periods in a month
- z : The percentage of time the load factor y exceeds the required reliability, f
- w : An intermediate parameter used to identify periods of coincidence of high demand and high PV load factor. It is a percentage between 0% and 100%.

Subscripts

i: Period
m: Month
PV: Photovoltaic.

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