Analysis of the generation of a photovoltaic system connected to an internal grid

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Abstract. This paper reports on the generation of a PVS feeding the internal consumption of facility in Georgetown, Guyana. The PVS with a capacity of 8.6 kWp was commissioned in September 2012, and in 2016 its capacity was expanded to 18.6 kWp. From 2013 to 2017, the PV system generated 75319 kWh, of which 75.2% was internally used, and 24.8% was injected to the grid. The annual specific yield ranged between 1404 kWh/kWp and 1626 kWh/kWp, in good agreement with the expected long-term yield of 1551 kWh/kWp for the locality.

1. Introduction
Regular measurements and analysis of the Specific Yield (SY) over the life span of a Photovoltaic System (PVS) allows the detection of malfunctions or degradation of the components, and through prompt operation and maintenance action, facilitates the reliable power generation [1]. Normally large scale PV systems are equipped with sophisticated monitoring systems whereas small scale residential and commercial systems do not always have the same level of monitoring. This could be due to financial constraints. The performance of PV systems mainly depends on the solar irradiation, ambient temperature and local weather conditions as well as on the power conditioning units employed.

Monitoring guidelines are based on the IEC61724 standard. The Standard IEC61724-1:2017 for PVS performance monitoring was revised and released on February 2017, in which “accuracy classes” are defined [2]. In conformity declarations, providers must state the accuracy class of the measurement. The class is not only determined by the hardware that is used, but also by quality checks and measurement procedures. The standard contains detailed specifications at monitoring system component level. For small scale PV systems, Class C, the irradiance and environmental measurements may be derived through other means such as satellite observation. The electrical output measurements are the system output power and energy measurement only.

Performance analysis of 30,000 residential and commercial PVS installed between 2006 and 2014 in 9 different countries in Europe have been reported, with special focus in the capacity and the Mean Specific Yields [3]. The analysis of these systems show that the capacities are between 1 and 6 kWp, with a 45% frequency peak at 3 kWp. The Mean Specific Yields for systems mounted in static structures are between 898 kWh/kWp for the UK and 1450 kWh/kWp in Spain, whereas 2127 kWh/kWp for those mounted on a tracker system.

In many applications where the essential issue is energy generation for self-consumption, most of small scale systems rely primarily in inverter’s energy information and evaluation of the impact of the self-generated energy in the monthly electricity bill. More accurate energy information can be gathered using electricity data loggers in which consumption, energy taken from the grid, PV energy for self-
consumption, and injected to the grid, are recorded at appropriate time intervals. This kind of analysis is seldom published for small scale systems operating in the developing world.

The aim of this paper is to analyze the performance of a PV system located in the premises of the Guyanese Energy Agency in Georgetown, Guyana, calculate the Specific Yield for various years and the energy exchange between the consumer, the grid, and the PV system.

2. System description
The PVS is installed on the roof of the offices of the Guyana Energy Agency (GEA) in Georgetown, Guyana (Coordinates: 6°48'46.81 N; 58° 9'26.96 W). Figure 1 shows the power balance diagram for the GEA offices. The PV generator supply power directly to the internal network of the offices and surplus power is delivered to the grid. The user's power demand ("use") is as much from the grid as from the PVS.

![POWER BALANCE Diagram](image)

**Figure 1.** System power balance of the Guyana Energy Agency (GEA) in Georgetown.

The PVS was developed in two stages. In the first stage, 8.46 kWp of c-Si were installed and entered operation in 2012. In the second stage, the system was expanded during 2015 by 10.0 kWp, for a total of 18.46 kWp. Figure 2 shows the modules of the first stage, installed on the roof of the building with enough distance from neighboring buildings to avoid shade, slight inclination and enough distance from the roof aiding for ventilation.

![Partial View of Photovoltaic Modules](image)

**Figure 2.** Partial view of the photovoltaic modules on GEA’s rooftop.

3. Data acquisition system
The data acquisition system used was the eGauge model EG3000 supplied by eGauge Systems LLC. The data logger reports uninterrupted operation since 12-05-30 18:00. Figure 3 shows the display of eGauge web site showing:

- Demand for power in kW - red line,
- Power generation of the PVS in kW - green line
- Energy taken from the grid - red area
- Energy injected into the grid - white area
Figure 3. Screen-view of the data logging system (Wednesday April 4, 2018).

The time setting of the data logger is UTM -5, when Georgetown is UTM -4. For this reason, sunrise and sunset are an hour ahead.

4. Yearly energy

Total energy demand rose from 47455 kWh/year in 2013 to 53194 kWh/year in 2017. The contribution to total use is 77.3% for the grid and 22.7% for the PVS from 2013 to 2017. The PV contribution rose from 17.6% in 2013 to 32.8% in 2017 as consequence of the PV power increase of 10 kWp in 2016 to counterbalance the use increase (see table 1).

Table 1. Grid and PV contributions to energy use.

| Year | Grid (kWh) | PV (kWh) | Use (kWh) |
|------|------------|----------|-----------|
| 2013 | 39,089     | 8,666    | 47,455    |
| 2014 | 39,400     | 8,966    | 48,365    |
| 2015 | 38,998     | 8,603    | 47,601    |
| 2016 | 40,657     | 13,270   | 53,927    |
| 2017 | 35,756     | 17,438   | 53,194    |
| Total| 193,900    | 56,641   | 250,542   |

The injection of solar electricity into the grid increased from 2617 kWh/year in 2013 to 6444 kWh/year in 2017. Therefore, the total generation of the PVS increased from 10982 kWh/year in 2013 to 23881 kWh/year in 2017 because of the 10 kWp increase in generation capacity in 2016 (see table 2).

Table 2. PV generation for use and injection to grid.

| Year | PV Use (kWh) | PV to Grid (kWh) | Total PV (kWh) |
|------|--------------|------------------|----------------|
| 2013 | 8,366        | 2,617            | 10,982         |
| 2014 | 8,966        | 2,778            | 11,743         |
| 2015 | 8,603        | 2,570            | 11,173         |
| 2016 | 13,270       | 4,270            | 17,540         |
| 2017 | 17,438       | 6,444            | 23,881         |
| Total| 56,641       | 18,678           | 75,319         |

| Year | PV Use (%)  | PV to Grid (%)  | PV Total (%)  |
|------|-------------|-----------------|---------------|
| 2013 | 76.2%       | 23.8%           | 100.0%        |
| 2014 | 76.3%       | 23.7%           | 100.0%        |
| 2015 | 77.0%       | 23.0%           | 100.0%        |
| 2016 | 75.7%       | 24.3%           | 100.0%        |
| 2017 | 73.0%       | 27.0%           | 100.0%        |
| Average| 75.2%       | 24.8%           | 100.0%        |
Figure 4 shows the total energy annually used by GEA’s office, the energy from the grid, and the energy generated by the PVS used and injected to the grid. There are significant increases during 2016 in energy use in the facilities and in the PVS capacity (addition of 10 kWp).

The Specific Yield is defined as the total PVS generation in kWh/year divided by the power in kWp-year. This is between 1536 and 1626 kWh/kWh-year for the years 2013 to 2015. For the year 2017, the value is 1403 kWh/kWh-year (during several weeks of 2016, the PV capacity increased by 10 kWp and during the test period the capacity is not clearly defined). Since the Capacity Factor (CF) is the Specific Yield divided by 8760 hours/year, then the CF was between 16.0% and 18.6% (see table 3).

Table 3 also compares these values with the expected long-term specific yield in kWh/kWp-day (also annual) given by SOLARGIS® for the project site. As can be seen, the calculated values for the PVS and those given by the SOLARGIS® are similar and in good agreement.

Table 3. Specific yield and capacity factor of PVS.

| Characteristic                        | 2013 | 2014 | 2015 | 2017 |
|---------------------------------------|------|------|------|------|
| PVS Capacity (kWp)                   | 8.46 | 8.46 | 8.46 | 18.46|
| Specific Yield (kWh/kWp)             | 1536 | 1626 | 1559 | 1403 |
| Capacity factor                       | 17.80% | 18.60% | 17.80% | 16.00% |
| Expected long-term specific yield (kWh/kWp-day) | 4.25 | 4.25 | 4.25 | 4.25 |
| Expected long-term specific yield (kWh/kWp-year) | 1551 | 1551 | 1551 | 1551 |

5. Monthly generation
Figure 5 shows the monthly generation for the period 2013 to 2017. A similar monthly behavior can be observed for the first three years. In year 2017 there is an increase of the generation due to the increase of 10 kWp in the PVS capacity. Additionally, there is a monthly behavior with maxima generation in April and August 2017 (see figure 5). PV generation during 2016 was affected for the commissioning of the 10 kWp increase.
6. Daily energy average of grid supply, PV generation for use and injection

Figure 6 shows the hourly profile of the average energy supplied by the grid, the energy generated by the PVS for use and injected to the grid for the period 2013-2017. It is important to note that the energy consumption is almost constant around 13 kWh between 7 and 14 hours, the maximum of energy generated by the PV system occurs at 11 hours, one hour before noon (logger time; un-adjusted time). The PV energy hourly profile for use and injection is a typical cosine function with maximum at 11 am.

7. Daily energy average of grid supply, PV generation for use and injection during working days

GEA’s offices operate from Monday to Friday, with exception of festive days. Figure 7 shows for the period 2013-2017 the power taken from the grid, the power supplied by the PVS for use and the power delivered to the grid. Since the average consumption is approximately 13 kW between 7 am (actually 8 am local time) and 14 pm (actually 15 pm local time), most of the energy from the PVS is for self-consumption and a small contribution goes to the grid. The difference with the previous figure is that during workings days almost all PV energy is used in the offices.
8. Daily energy average of grid supply, PV generation for use and injection during non-working days

Non-Working days are all the festive days (only a few during the year) in addition to Saturdays and Sundays. On these days the consumption of this public office decreases noticeably. In figure 8 it can be observed how most of the energy generated by the PVS is injected to the grid. The figure also shows how for the 2013-2017 period the injection to the grid reached at 11 am (corresponds to 12 pm local time) up to 5 kWh while at the same time energy consumption was of 1 kWh.

9. Power ramp behavior

One of the issues of concern has to do with the fluctuations of the power taken / injected to the grid. Figure 9 shows the behavior of the power demand by user and the power supplied by the PVS on April 5, 2018. The variations of power of the use (red line) minus the variations of power of the PVS (green line), give the variation of power for the grid.
Figure 9. Grid and PV power behavior on the 5th April, 2018 (working day).

Figure 10 shows the same power demand for use (blue curve), but also shows the power variations that the grid has to supply to compensate for the rapid variations of power of the PVS (brown curve). The variation of power by the use are significantly lower to those of the grid power due to the PVS. The variation of power by the use is in the order of \( \sim 20 \text{ kW} \pm 2 \text{ kW} \) from 8 am until 3 pm, that is \( \pm 10\% \) if there is no PVS, while the variations of the grid power input due to the PVS variations can be in the order of \( \pm 10 \text{ kW} \) when the demand is of \( \sim 20 \text{ kW} \), that is the grid has to provide very quickly \( \pm 50\% \) for the demand when the PVS is present. The consequences of the high power ramps in a low voltage distribution system are one of the factors that imposes a limit to the total photovoltaic power allowed for injection to a low voltage circuit grid.

Figure 10. Power supply from the grid, under no PV and PV injection the 5th April, 2018 (working day).
10. Conclusions

PVSs decrease the demand of grid power of a facility depending on the installed capacity of the PVS. In this case, in Georgetown, about ¾ of solar energy is for self-consumption and ¼ for injection to the grid. It is important to consider the average and peak power demand by the user, the weekly pattern of power demand, and the capacity of the PVS, for sizing the capacity of the PVS. In this case, the maximum power of the PVS is 18.4 kWp, which compared to the maximum demand of ~22 kW, results in the self-consumption of the power generated by the PVS on working days.

An aspect of concern is the effect that a group of PVSs can have on the quality and reliability of the power supply of a low-voltage distribution grid; this is why there is usually a limit in the total capacity of the PVSs connected to a low voltage circuit.

References

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