Three-year PV System Performance in Mexico City

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***Abstract* - In the Research Center (CINVESTAV), located north Mexico City was evaluated a 60 kWp photovoltaic (PV) system. The PV system energy performance ratio (PR) is reported together with the measured solar irradiation, ambient and PV module temperatures for three years. A finally calculated average PR was 86.8% for the 36 months. The average daily energy produced by the PV system during 3 years was 260.45 kWh/day and an average accumulated energy of 95,064.25 kWh per year. If we consider the factor of 1% degradation per year in the generated power, the system will generate about 1,311,887 kWh after 15 years, or equivalent to 87,459 kWh as an average per year.**

***Index Terms* — performance ratio, photovoltaic system, generated energy.**

I. Introduction

In recent years, the solar photovoltaic (PV) systems are becoming one important clean-technology and alternative-energy-sources in several countries. The PV systems are safe, reliable with a low-maintenance cost without on-site pollutant emissions. Nowadays, the utility grid-connected PV systems are increasing in the world, and the underlying deployment scenario assumes 3,155 GW of cumulative installed PV capacity by 2050 [1]. Although the number of grid-tied systems started growing after 2007, the off-grid installed PV capacities in Mexico were 85% in 2010. A net-metering mechanism was created in 2007 for renewable energy based systems under 500 kW capacities. It allows the users to feed into the grid part of their electricity and to receive credits in the form of kWh in return that can be used to offset their electricity bill. Since 2012, net metering is also available to multi-family housing.

Each tenant will pay the difference between its individual consumption and the specific PV-generated-electricity, this difference is allocated to the electric utility company (CFE) to that tenant's utility account, according to a pre-arranged share.

The PV Levelized cost of energy (LCOE) has experienced a significant decrease from 2009 to 2014, which is estimated at -18.4% compound annual growth rate, even though, for the average electricity consumer PV investment is still not competitive with grid electricity prices. The Mexican Government introduced at the end of 2013 an in-depth energy reform for the oil and gas industry, as well as the electricity sector; the reform led to extensive legislative changes in 2014 that will be finished with market rules in 2015. The reform implementation is expected to have a strong impact in the development of the PV market [2].

This study evaluates the electricity generated from a 60kw PV system, taking in consideration the local (Mexico City) weather conditions. The PV module temperature, wind velocity, and the solar irradiations are the main parameters for the PV system performance evaluation. The performance ratio, often called quality factor, is independent of the solar irradiation. Therefore, it is useful to compare different PV system performances.

II. System Description

The 60 kWp PV system is shown partially in Fig. 1 consists of 240 single-crystalline silicon based PV modules with a 250 Watt-peak (Wp) each. The detailed description of PV systems can be found elsewhere [3]. The PV module-arrays were installed on the Institution´s building on the fifth-floor roof and fixed on aluminum framed structures oriented 30° East-faced from the geographical South. The system is located at 19° 30' 38" North-latitude, 99° 07' 50 " West-longitude, and the modules were installed at about the latitude angle of 20°. The PV module arrays are subdivided electrically into five sections. Each section is composed of a string of 48 PV modules that consist of 12-series and 4-parall connections.

Fig. 1. Shows part of 60 kWp PV module array in CINVESTAV, Mexico City.

For each of the five array arrangements is connected to the corresponding inverter; Fronius model IG Plus V11.4-3 DELTA with the capacity of about 11.4 kW/each. The solar irradiance was measured using a reference crystalline-silicon (c-Si) solar cell installed in the same PV module plane of array (POA) with the angle of 20 degrees from the horizontal. Also in a site, a pyranometer Yankee Environmental Systems; Model TSP-1, was installed as a global horizontal solar irradiance measurement.

III. MONITORIN AND PERFORMACE CONCEPTS

A. System monitoring

Data monitoring is one of the important requirements for diverse PV systems. It is used to track performance and comply with regulatory reporting status. Without an accurate data monitoring, the PV system performances cannot reliably be compared to the calculated generation power. Effective data monitoring not only helps to identify system performance troubles, but it also helps to resolve them [4]. The Fronius inverter system integrates all of the monitored and logged data every 5 minutes, included solar irradiance automatically.

B. General performance

Three of the IEC standard 61724 performance parameters have to be used to define the overall system performance with respect to the energy production, the solar resource and overall effect of system losses [5].

The performance ratio (PR) or so-called "quality factor", is the ratio between actual yield (i.e. annual production of electricity delivered at AC) and the ideal yield:

$$\mathrm{PR} = \frac{Real\ Yield\ AC}{Ideal\ Yield\ DC}$$

The *Real Yield* is the total produced electric energy by the PV system, which is monitored and logged directly using system software. The *Ideal Yield* is the total installed system power capacity (as is indicated on the nameplate of the PV module) multiplied by the total solar peak-hour irradiation, i.e. the total energy that should generate an ideal PV system. The PR can be considered by a day, by a week, but mostly on a month basis. In the present job, we consider the values up to 36 consecutive months.

C. Energy losses

Under normal PV system operating conditions, the measured data contains deviations caused by malfunctions such as string defects, shadings, module or inverter malfunctions that influence the measured performance of a PV system.
Sometimes it is intuitive to think in terms of energy losses that occur at every step of the way, rather than component efficiencies. Both concepts are related as:

$$Losses = 1 - Efficiency$$

Here, both terms are expressed in percentage. Commonly, there are three major blocks of energy losses and are indicated in the Table I.

IV. SYSTEM GENERAL PERFORMANCE

The PV system has been monitored for 36 consecutive months from June 2012 to May 2015, and the measured data were logged and recorded every 5 minutes. Figure 2 shows the average month based solar irradiance detected in the plane of array (POA) through c-Si solar cell sensor. The average daily solar irradiance was 4.71kWh/m^2 for three years, with the highest solar irradiances for February to April of each year. In October 2012, as shown in Fig. 2, an outstanding irradiation has been detected. The rainy season in Mexico City normally starts from May-June and up to September-October of every year.

TABLE I. DIFFERENT ENERGY LOSS PARAMETER IN THE PV SYSTEM

Losses	Amount of losses	Loss concepts
Module	**~ 55%**	Solar cell efficiency and temperature dependence of the PV module.
Optical	**~ 6%**	Attenuation of the incoming light through shading, dirt, snow and reflection before it hits the photovoltaic solar cell. In concentrating PV systems, it also includes losses from diverse optical components.
System	**~ 12%**	Losses in the composed electrical devices including DC-AC wiring, connectors, inverters, and transformers.

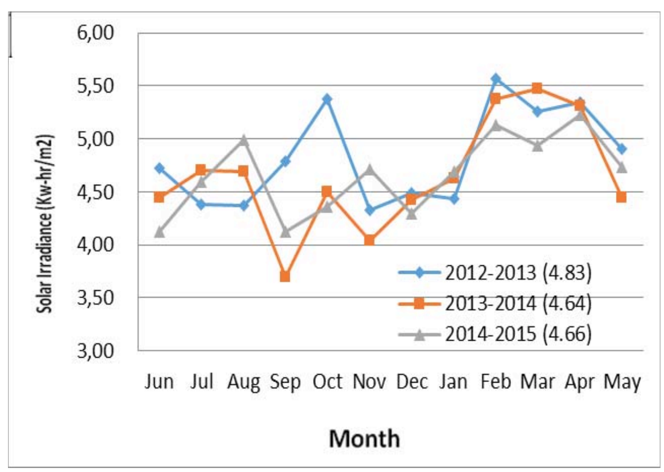

Fig. 2. Monthly average Solar irradiance measured at POA by using c-Si solar cell sensor, which is monitored by Fronius inverter system. The irradiance units were kWh/m^2/day. The number in the parenthesis indicates the average irradiance during the measured period in peak-hours (or kWh/m^2).

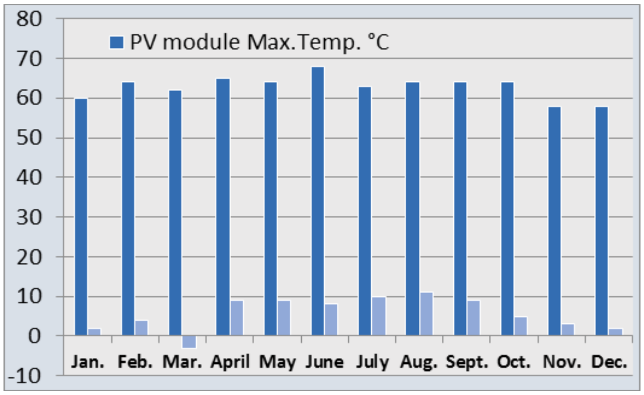

Fig. 3. Maximum and minimum PV module temperatures (in °C) during 2013.

Fig. 3 shows the PV-module day-night temperature cycle, i.e. maximum and minimum temperatures detected during 12 months of 2013. It can be seen that March registered a negative temperature value in the range of -3 °C. The maximum temperature ranges between 58 to 68 °C, with the highest during the sunny days of June. Now, after two years of operation, in some of the PV modules started appearing the so-called "snail trails." However, it seems that this "cosmetic" effect does not perturb directly the electric performance. Recently, twenty of the affected PV modules were renewed by the manufacturer.

Fig. 4 shows the monthly-based average produced energy of PV system. As can be seen, for each of the considered years, February to April was the highest energy generated months. It was produced 310.09 kWh in February 2013. However, September (2013), was the worst with only 176.79 kWh.

These differences were produced by cloudy and rainy days during September (see Fig. 2), but also due to the electric failure in one of the inverter. Also, it must be said that due to the electric grid maintenance performed by CFE, the utility company, there was an interruption on July 24th, on August 17th and on December 1st (all in 2013). Those three days are not considered in our data.

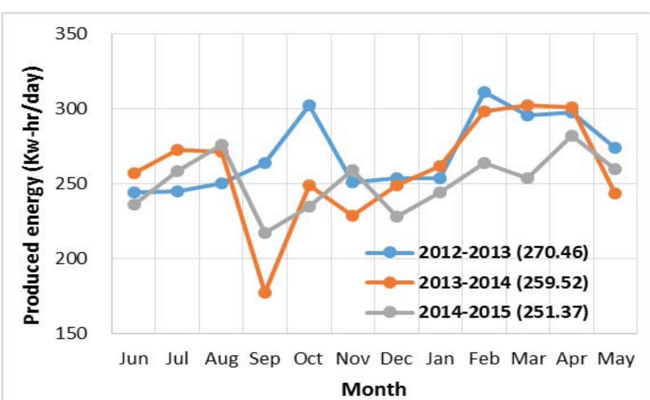

Fig. 4. Monthly-based average produced energy from the PV system. The number in the parenthesis indicates the produced daily average energy during the indicated period in kWh/day.

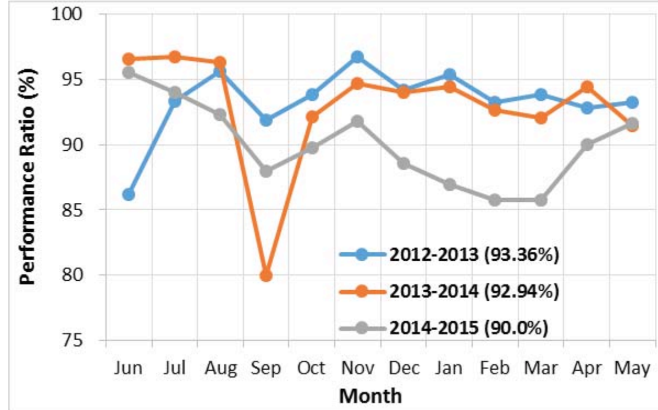

Fig. 5. Measured PR of the PV system during 36 months. The corresponding average PR for the period is indicated in the parenthesis.

Fig. 5 shows the monthly-based performance ratio (PR). It is noted that the worst month was September with 79.98%, and the best was July with 96.74%, both in 2013 (in orange line). On September 2013, the inverter N° 2 had a severe failure in its electronic circuit and did not contribute during 20 days for the energy transformation, which could be calculated as about 30 kWh/day of energy loss. It means, instead of 79.98 %, it might have to be about 93 % of PR. The system average PR for the 36 month-basis performance was 92.1 %, however, the last 12 months of June 2014-May 2015, the system had a lower value of 90 % because of the PV array string outages. The string outages were corrected by replacing the interrupted fuse in the string circuit that is located in the fuse-box under PV array. The daily average energy produced through 3 consecutive years was 260.45 kWh/day, and the total energy during 36 months was 285,192.6 kWh.

V. System Specific Performance

The purpose of monitoring PV system performance ratio (PR) is to determine whether or not the system is working as expected as to the incident solar irradiation. To do this, it requires measurement of the actual system output and its operating conditions. Solar irradiance in a plane of the array (POA) is by far the most important data, and it is the base to calculate PR. Even though, the results obtained and discussed in the previous section (with the reported average PR of more than a 90%) is not reliable as Nils H. Reich et al. [6]. The obtained and used 3-year-based solar irradiance was 4.71 $kWh/m^2/day$ as an average. It was the irradiance detected by c-Si-based solar cell sensor at POA. However, we have previously reported that the average global irradiance (during 14 consecutive years 1999-2012) using global horizontal pyranometer was 18.01 MJ/m^2, or 5.0 $kWh/m^2/day$ as is shown in Fig.6 [7]. Certainly, the differences in spectral and directional response, between pyranometers and c-Si sensors lead to intraday and seasonal fluctuations [8]. For the electricity yield measurements, the inverter-integrated

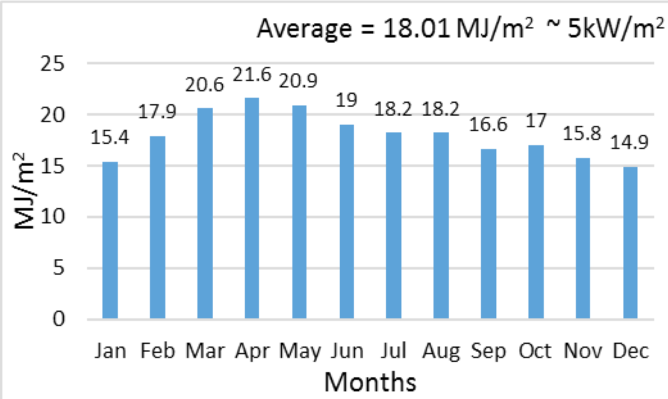

Fig. 6. Monthly averaged solar radiation from January to December during fourteen (1999-2012) consecutive years. The irradiation was measured by using horizontal pyranometer [3].

measurements are usually not sufficiently precise. When selecting irradiation sensor technology, generally two possibilities exist as Pyranometers (thermopile sensors) and solar cell sensors. In solar cells, only crystalline-silicon (c-Si) sensors provide the required stability, with the spectral range from 400 to 1150 nm with a relatively quick response-time to the irradiance changes. However, there are some factors that influence the uncertainty of c-Si sensors as irradiance level; the angular distribution; the shift of transfer function over time; the ambient and sensor´s temperatures. The c-Si reference sensors are calibrated under indoor and outdoor conditions which should comply with IEC 60904-2 and -4, respectively. On the other hand, Pyranometers are based on a thermocouple device with a wider wavelength sensibility in a range from 300 to 3,000 nm [7]. The parameters that influence the uncertainty of pyranometers are irradiance level and spectral distribution of the solar radiation. Furthermore, irradiance change rate during the measurement; cosine effect; its tilt angle; ambient and pyranometer´s dome temperature [9]. The overall uncertainty of the instantaneous irradiance measurement based on secondary standard pyranometers is approximately 3% [10]-[11]. It is reported that in an annual basis, c-Si sensors measure less irradiation than pyranometers. Also, the highest absolute difference between the signal measured by a c-Si sensor and a pyranometer is at clear sky conditions with a low diffuse/direct ratio [12]. The annual difference between the two sensor types depends very much on the sensor and the location, but recent publication [13]-[14] indicate that the deviation between different sensors installed in Germany varies considerably. On the average, the annual irradiation measured by c-Si sensor is 2 to 4% less than the irradiation measured by a pyranometer [15].

It is not the correct way to consider the horizontal global irradiance as our PV system reference because the pyranometer is not installed at POA, but taking in consideration the annual average irradiance of 5.0 kWh/m^2, the calculated PR of the PV system reduces from 92.1% to 86.8%. It means around 5 % less PR than that obtained by using c-Si sensor irradiance. However, the newly calculated PR of 86.8% seems more consistent and somehow more reliable than the one calculated using the c-Si sensor´s as was asseverated using different experimental experiences by several authors.

Now, as can be seen in Fig. 5, the obtained PR during 2014 – 2015, had a lower PR compared to previous years (2012 – 2013 and 2013 – 2014). This situation has prevailed because of one of the PV module array string outage that fed the inverter N° 5. The PV array worked only at its 75% capacity for a couple of days in August, all September, some days of October and also December 2014. Furthermore, this string outage was prolonged from January to April 2015. In this sense, the lower PR can be explained during the mentioned period. However, on November 2014 its related PR also was lower than the previous years. To find out the possible cause of the resulted lower PR on November 2014, it has been done some analysis. Table II indicates the average parameters obtained from the acquired and stored data for all of the November period of 2012, 2013 and 2014. Comparing 2014 and 2012, it was possible to determine two factors: a) The obtained average wind velocity during the day-time (during the period that PV modules were operating 6:00 to 18:00 hrs) was 0.590 m/s in 2014, which is less than 0.876 m/s of 2012. b) The average ambient and module temperatures in 2014 were higher than that of 2012. Moreover, these temperature differences were of about 2 to 3 °C for ambient and PV module, respectively. Now, it is difficult to asseverate and confirm whether the analyzed data can explain the obtained PR´s differences, and by using these averaged data-parameters, in any case, the crystalline-silicon based PV module temperature coefficient (- 0.47%/°C) [7], had the influences

TABLE II. DIFFERENT ELECTRIC AND METEOROLOGICAL PARAMETERS FOR CALCULATION OF THE PERFORMANCE RATIO. NOVEMBER OF EACH YEAR; 2012, 2013 AND 2014. THE SOLAR IRRADIATION IS MONITORED BY C-SI SOLAR CELL AT POA

Average in November	**2012**	**2013**	**2014**
Performance Ratio %	**96.72**	**94.65**	**91.81**
Electric Generation kWh	251.39	229.16	259.31
Irradiance kWh/m^2	4.331	4.04	4.707
Irradiance kWh/day	259.92	242.4	282.43
PV module Temp. °C	**30.51**	**33.16**	**33.23**
Ambient Temp. °C	19.16	19.54	20.82
Wind velocity m/s	**0.876**	**0.795**	**0.590**

which lowered the generation power of about 2 to 3%. The obtained average parameters in Table II may indicate the possible reasons to explain the lower PR in 2014.

The predicted total energy produced for the next 15 years was about 1,425,964 kWh without considering PV module degradation and considering 5 kWh/m^2 of average irradiation. However, if we consider the factor of 1% degradation per year in the generated power, after 15 years the system will generate about 1,311,887 kWh, or 87,459 kWh as an average in the year. Being this annual average generation 92% of what we calculated without considering degradation. Furthermore, the predicted system power generation after 15 years, will be only of around 81,755 kWh/year, or 86% of the actual generation power.

VI. Conclusions

The performance of a grid-tied 60 kWp photovoltaic system at the north of Mexico City was evaluated and monitored from June 2012 to May 2015. The seasonal variations of the produced energy were analyzed and interpreted during three years. Despite the failure of the inverter and some of the PV-array string outages, the system worked acceptably with 91.2% of performance ratio. However, the average PR was reduced to 86.8% when the c-Si solar cell sensor was substituted as the irradiance reference with a horizontal pyranometer-data. The obtained lower PR seems to be more consistent for the analyzed system technology.

We believe that one of the major influences of the PV electric generation performance was the PV module operating temperature. The direct solar irradiance increases PV module temperature, but having a higher wind speed reduces it notoriously. Some of the system troubles were briefly discussed including the PV array string outages.

Undoubtedly, the precise solar irradiance detection is one of the most important keys for a reliable PV system´s PR evaluation.

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