Development of a PV System as a Way to Promote the Technology

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Abstract — **There is not a government strategy to promote photovoltaic applications in Brazil and an action of the Ministry of Mines and Energy (MME) was to support the development of an industrial silicon solar cell process and the fabrication of twenty PV modules in a pilot scale, using the infrastructure of the NT-Solar/PUCRS. In order to spread the developed technology, a demonstrative grid connected PV system was installed in the façade of the Science and Technology Museum of the PUCRS, Porto Alegre, Brazil. This interactive museum is one of the main museums of Latin America and more than 1000 people visit it per day, many of them are students of elementary and high school levels. The goal of this paper is to present an action of the MME and NT-Solar/PUCRS to promote PV technology and the analysis of the grid connected system. PV system was built with 20 PV modules totalizing 680 W_p. PV modules were fabricated with silicon solar cells developed and processed by the team of NT-Solar/PUCRS. PV system produced an average monthly electric energy of 39.5 kWh. The annual performance ratio was 85.6% and the annual yield of 700 kWh/kW_p was obtained. The measured average monthly energy was 20 % below the simulated value due to low solar irradiation in the south of the Brazil in 2011. On a sunny day in summer, the temperature of the modules was of 41 °C, only 11 °C above the ambient temperature. But in winter the difference between temperatures was of 25 °C, due to a higher solar irradiation. The highest measured daily average temperature of the modules was of 40 °C and occurs near the equinoxes.**

Index Terms — **PV technology, grid connected system.**

I. Introduction and History

Renewable energy is the main resource of the electric energy matrix in Brazil. Hydroelectric power plants produce about 85 % of the energy demanded, with cost closed to US$60/MW. Nowadays, wind power systems present similar cost and this source is abundant in the Brazil's coast. Others renewable energy resources to produce electric energy have been found some difficulties to be competitive and government actions are needed to introduce these energies in the Brazilian electric generation matrix.

Brazil is known due to the beautiful beaches with high solar radiation, but in the country the use of solar energy to produce electricity is not effectively employed. In the last decade, some actions were carried out. In 1995, the Brazilian government implemented a program to promote rural electrification with PV systems, denominated PRODEEM (Program for Energetic Development of States and Municipalities), involving several universities and State Secretariats [1], [2]. Many small stand-alone PV systems were installed. The program Light for All (*Luz para Todos*) was started in 2004 and utilities implemented rural electrification with photovoltaic systems [2].

In 2002, the Brazilian Institute for Metrology, Standardization and Industrial Quality (INMETRO) created a working group for PV systems as part of the Brazilian Program for Labeling (PBE) [3]. The task force was carried out by specialists from universities, Brazilian suppliers, manufacturers and public organizations, and the team established the standards for labeling stand-alone PV systems and their components.

The regulations of Brazilian Electricity Regulatory Agency, (ANEEL) with the normative no. 83 (20/09/2004), specify the conditions requested for using Individual Stand-Alone Systems Based on Intermittent Sources (SIGFI) to supply electric energy to Brazilian consumers in rural areas. Recently, a regulation for grid connected PV systems was implemented by ANEEL.

As a strategy to promote the development of photovoltaic applications, in 2004, the Brazilian Centre for Development of Photovoltaic Solar Energy (CB-Solar) was established at the Solar Energy Technology Nucleus (NT-Solar) of Pontifical Catholic University of Rio Grande do Sul (PUCRS) [4]. An important activity of CB-Solar was to develop a pilot plant, researching cost effective technologies of industrial processes of silicon solar cells and modules, with subvention of three energy companies and a government financing agency [5], [6]. Other action was the development of silicon cell processes and grid connected systems with the subvention of the Ministry of Mines and Energy (MME).

Solar energy research in Brazil dates back to the 1950s [7]. Since 1970 several solar technologies in Brazil were studied and in the 80´s a PV module fabrication was started-up. However, with the progressive reduction of investments, many solar energy research groups closed and only during the 90´s, PV research recovered status in the university. Development of solar energy research in Brazil evolved through the establishment of well-equipped laboratories and spread of post-graduate education.

The Brazilian Association of Solar Energy (ABENS) was created in 1978 with regional offices in some Brazilian states. However the activities ceased after ten years. In 2005, ABENS was re-structured.

Grid connected PV systems remain mainly as university case study. The first 1 MW was installed in the last year by a Brazilian company and another 1 MW will be installed in this

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year by a Brazilian state utility [8]. There is not a government strategy to promote photovoltaic system applications, but the Ministry of Mines and Energy has been studied programs to achieve this aim mainly to PV grid connected systems. Around the world, the growth of the market is based on grid-connected systems, with an increasing of 36 % in 2011, compared with the sales in 2010 [9].

The MME started an action to promote the use of renewable and alternative energy resources associated with reference research centers. In the photovoltaic solar energy field, an industrial silicon solar cells process was developed and twenty PV modules were fabricated in a pilot scale, using the infrastructure of the NT-Solar implemented in the project "Pilot Plant to Produce Cost Effective Photovoltaic Modules" [5]. In order to spread the developed technology, a small demonstrative grid connected PV system was installed in the façade of the Science and Technology Museum of the PUCRS (MCT). The museum receives more than 1000 visitors per day, mainly elementary and high school students.

The goal of this paper is to present an action financed by MME to promote PV technology and the analysis of the grid connected system during the first year operation.

II. PV Module Fabrication

Using a process developed by the team of NT-Solar, more than 800 silicon solar cells with Al back surface field were fabricated. The I-V characteristics of the solar cells were measured under standard conditions (100 mW/cm^2, AM1.5G and 25°C) in a solar simulator calibrated with a silicon solar cell previously measured at the *Fraunhofer-Institut für Solare Energiesysteme*, Germany. After this step, the devices were classified in order to fabricate the PV modules.

Modules consist of four strings with nine cells of 61.58 cm^2. The cell strings were soldered in an automatic tabber-stringer equipment and the modules were laminated with fast cure EVA. Encapsulation was formed by the following materials: low iron tempered glass, EVA, solar cells and backsheet. The area of the modules was of 0.277 m^2. The electric current as a function of voltage of each module was measured under standard conditions by using a solar simulator Bergerlichtechnik PSS8, class AAA. Solar simulator was calibrated with a PV module previously calibrated in the European Solar Test Installation (ESTI), Joint Research Center - European Community, Italy. Table I presents the average values of the open circuit voltage (V_{OC}), short-circuit current (I_{SC}), fill factor (FF) and maximum power (P_{MPP}) of the twenty fabricated modules. These parameters are compared with those of the best module. The average power was (33 W ± 4%).

III. PV System

The PV system was built with 20 PV modules developed in the NT-Solar, totalizing 680 W_p. Systems with this order of power are worldwide used for experimental analysis [10], [11]. All modules were characterized and classified. The PV system was designed with two PV-arrays in parallel with open circuit voltage of 200 V to be connected to the inverter. Table II presents the average values of the V_{OC}, I_{SC}, FF and P_{MPP} of modules used in PV-array A and B. The inverter was installed near the PV system in order to be visible to the visitors of the museum. Fig. 1 illustrates the PV system.

TABLE I

Average values of the V_{OC}, I_{SC}, FF and maximum power (P_{MMP}) of the twenty fabricated modules and electrical parameters of the best module.

	V_{OC} (V)	I_{SC} (A)	FF (%)	P_{MPP} (W)
Average	21.1±0.2	2.02±0.09	77.7±1.9	33.0±1.3
Best	21.2	2.14	76.2	34.4

TABLE II

Average values of the V_{OC}, I_{SC}, FF and maximum power (P_{MMP}) of the modules used in each PV-array

Array	V_{OC} (V)	I_{SC} (A)	FF (%)	P_{MPP} (W)
A	21.0±0.2	1.96±0.08	78.3±2.3	32.2±1.4
B	21.2±0.1	2.09±0.03	77.1±1.3	33.8±0.7

Fig. 1. PV system installed in the façade of the Science and Technology Museum of the PUCRS, Brazil.

A data acquisition system was also implemented for monitoring the direct current and voltage produced by the PV modules, AC current and voltage, ambient temperature, temperature of the modules, solar irradiance on the PV modules sloped of 90° and wind velocity. The data are being collected each five minutes.

In the indoor area of MCT, a maquette with solar cells installed like to PV modules in a residential PV system was mounted in order to the elementary and high school students learn how a grid connected PV system works. Students can change the relative position of the Sun to the surface of the encapsulated solar cells, simulating different seasons.

IV. Simulated Performance

The system was installed in the façade of the museum due to aesthetical aspects and to be visible to visitors. Porto Alegre is a city located at the south of Brazil, with latitude of –30°. The electric power produced by the PV system with modules sloped 90° to the North is lower than that with the best slope of the PV modules. Fig. 2 compares the monthly electric energy produced by the PV system with modules tilted of 90° and 50°. The simulated average monthly electric power was 50 kWh/month when modules were installed in the façade and 80 kWh/month when modules were tilted 50° from the horizontal. If PV modules are sloped of 50°, the energy production during the year is approximately uniform, as Fig. 2 shows. These data were obtained by a computer program that simulates the hourly production of the PV system during ten years. The reduction of the produced energy is about 40 %, when modules are tilted of 90° from the horizontal. The expected electric energy produced by the modules tilted of 90° is about 60% and 13% lower than the energy obtained when the PV modules are sloped of 50° in summer and winter, respectively.

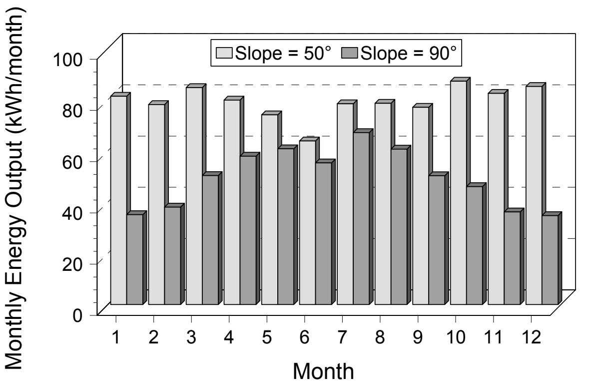

Fig. 2. Comparison of the simulated monthly electric energy produced by the PV system with modules sloped of 90° and 50°.

V. Experimental Analysis

The PV system was connected to the electric grid in November/2010. In the first days of operation, the system did not work as expected. We observed that the solar irradiance was high, but the system did not inject energy to the electric grid. We identify that the voltage of the electric grid was higher than the expected value and, consequently, greater than the AC voltage of inverter. This fact occurred because the AC voltage of the museum presented peaks before the opening of the museum to visitors. The problem was solved increasing of 15 % the maximum output voltage of the inverter. Then, the PV system worked as expected.

Fig. 3 and Fig. 4 compare the ambient temperature to the temperature of the PV modules, in December (summer) and in June (winter), respectively. On a sunny day in December, the ambient temperature near noon was of 30 °C. In this condition, the temperature of the modules reached 41 °C, only 11 °C above ambient temperature. The solar irradiance on the modules was of around 300 W/m^2. The influence of the wind velocity and the free-wall surface on the rear side of the PV-array contributed to maintain the low temperature of the modules. The wind velocity is higher near the noon, in summer, as Fig. 5 shows.

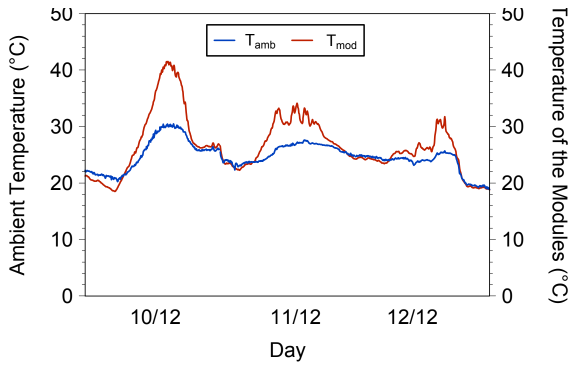

Fig. 3. Ambient temperature and temperature of the PV modules during three days in December/2010 (summer).

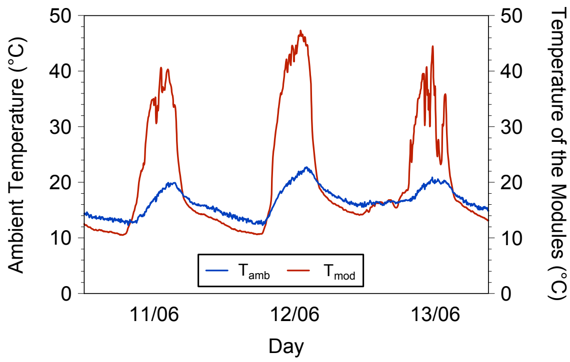

Fig. 4. Ambient temperature and temperature of the PV modules during three days in June/2011 (winter).

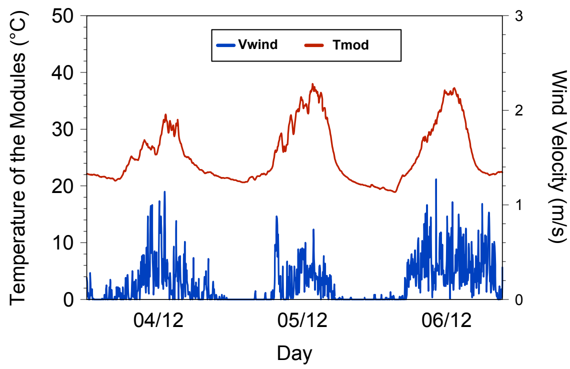

Fig. 5. Temperature of the modules and wind velocity during three days in December/2010.

In winter, the ambient temperature is lower than 20 °C and the modules achieved the temperature of 45 °C. In this case, the temperature of the modules was 25 °C above the ambient temperature. This result was higher than that found in summer, because the solar irradiance on the modules, near the noon on a sunny day, was of 640 W/m^2. In spite of the PV system produced less energy due to the slope of 90°, the low temperature of the modules compensated partially this loss.

Fig. 6 compares the daily average temperature of the modules with the ambient temperature. The average values were calculated taking into account only the data when the PV system was injecting electric energy to the grid. The daily average ambient temperature was lower than 30 °C and higher than 10 °C in summer and winter, respectively. The maximum daily average temperature of the modules was of 40 °C. These values occur near the autumn equinoxes (March - April). The difference between the temperature of the modules and ambient temperature are presented in Fig. 7. The highest difference of temperature ($T_{mod} – T_{amb}$) was of 7 °C and 15 °C in summer and winter, respectively. In any way, the temperature of the modules was low. Two main facts can explain this behavior. First, the daily solar irradiation on the sloped modules was higher in winter, when the ambient temperature is lower, as Fig 6 and Fig. 7 show. The maximum daily solar irradiation was of 2.5 kWh/m^2 and of 4.5 kWh/m^2 in summer and winter, respectively. The second fact is related to the free-wall PV-array and the wind velocity. The highest values of the wind velocity occur near the noon and the heat transfer is better when the temperature of the modules is greater.

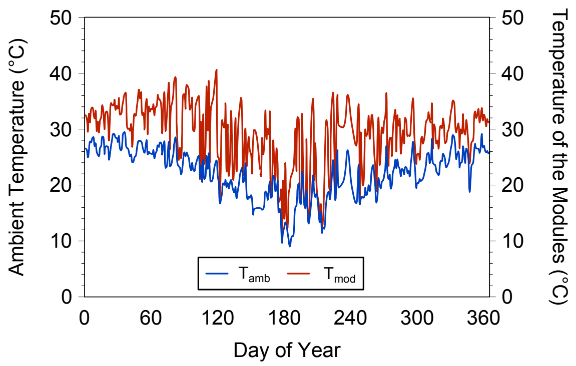

Fig. 6. Daily average ambient temperature and temperature of the modules sloped of 90° from horizontal.

Table III presents the monthly electric energy produced by the PV system and Fig. 8 compares the monthly electric energy to the solar irradiation. The electric energy produced was higher for months near the equinoxes. This result did not agree with the simulated data because in 2011, in winter, the solar irradiation was lower than expected. The measured yearly average monthly electric energy was 39.5 kWh, 20 % below the simulated value. Taking into account results presented in Fig. 2 and Fig. 8, the experimental average monthly solar irradiation on the modules was of 67 kWh/(m^2 month), 16 % lower than the simulated value of 80 kWh/(m^2 month). Another parameter that causes the difference between simulated and measured results was the efficiency of the PV system. In the simulation, the efficiency of the modules and inverter was 12.1 % and 92 %, respectively. From the results presented in Fig. 8, the average efficiency during the year was 10.6 %, 0.5 % (absolute) lower than the data used in the simulation. In winter, the efficiency of the PV system was lower than that in summer of around 1 %.

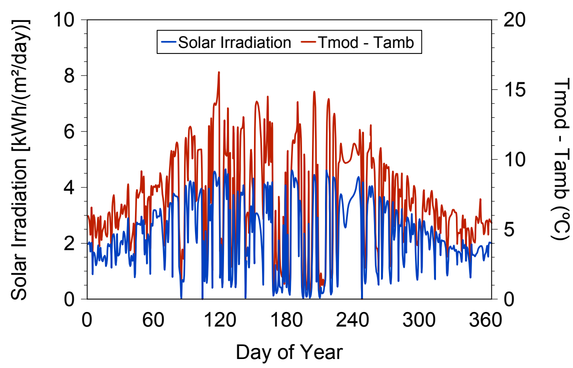

Fig. 7. Daily average irradiation on the sloped modules and difference between the temperature of the modules and ambient temperature.

The measured electric energy produced by the PV system was 474 kWh/year. The annual performance ratio of the system was 85.6%, slightly higher than the value of others PV systems installed in Brazil [11], [12]. The annual yield was of 700 kWh/kW$_p$. This result is lower than the yield of another PV system installed in Brazil with the same inverter [11], that achieved a yield of 1540 kWh/kW$_p$, with the PV-array sloped of the local latitude (São Paulo, Brazil, latitude of – 23°). The main difference is due to the slope of the PV-array. Taking into account the simulated results (Fig. 2) for the PV-array tilted of 50°, the predicted yield should be of 1410 kWh/kW$_p$. However, it is worth to mention that this parameter depends on the solar irradiation in the year.

TABLE III

MONTHLY ELECTRIC ENERGY (E) PRODUCED BY THE PV SYSTEM.

Month	E (kWh)
Jan	32.95
Feb	34.76
Mar	45.85
Apr	46.39
May	41.34
Jun	37.64
Jul	34.89
Aug	38.50
Sep	47.66
Oct	42.73
Nov	36.87
Dec	34.20

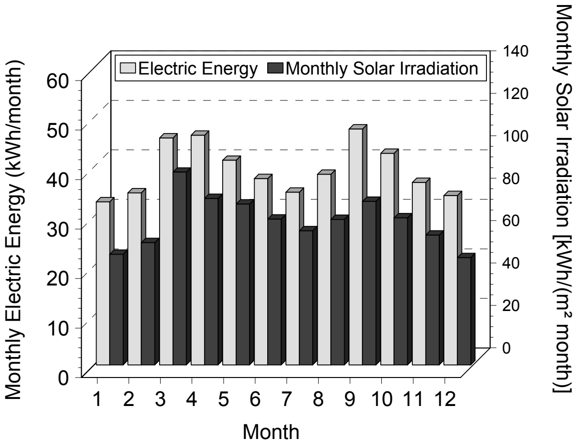

Fig. 8. Monthly electric energy produced by the PV system and monthly solar irradiation on the PV modules.

VI. Conclusions

Silicon solar cells and PV modules were fabricated in pilot scale and a grid connected PV system was installed in the façade of the Science and Technology Museum of the PUCRS as an action of the MME and NT-Solar/PUCRS to promote the PV technology. The PV system of 680 W_p produced the yearly electric energy of 475 kWh. The annual performance ratio was 85.6% and the annual yield of 700 kWh/kW_p was obtained. This result is related to the measured yearly average monthly irradiation, which was of around 20 % lower than the simulated value. The yield obtained with simulated data and the PV-array sloped of 50° was of 1410 kWh/kW_p. The average efficiency of the PV-system was of 10.6 %. On a sunny day, in summer and in winter, the temperature of the modules reached 41 °C and 45 °C, respectively. The highest measured daily average temperature of the modules was of 40 °C and occurs near the equinoxes.

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