SOLAR SCULPTURE OF THIN-FILM AMORPHOUS SILICON

A GRID-CONNECTED SYSTEM

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1. Introduction

Grid-connected Photovoltaic Systems have become a more viable option for de-centralised electrical generation, as demonstrated by proven high levels of growth, especially in the last five years: average annual rates of 60% in the five years from 2004 to 2009, and an increase of 53% in 2009 with 21 GW grid-connected PV installations, a six-fold increase in amounts since the end of 2004. This data does not include high-capacity systems (utility scale, capacity ≥200kWp), whose indices are around 102% and 44% for the aforementioned period. The current total of worldwide production is 24 GW of photovoltaic, of which 10.7 GW were produced in 2009, resulting in an annual increase of 55% from 2008 (6.9 GW), REN21, (2010). The binomial cost versus demand was a determining factor in this growth, based on various kinds of incentives. The cost of photovoltaic is somewhere in the US$1–$5/Wp range, depending on the quantity and type of technology of the cell. Crystalline silicon (mono or poly) cells are still the most predominant, however sales of thin-film cells increased by 14% in 2008 and 19% in 2009. In terms of panels, from 16 to 22%, REN21 (2010).

In Brazil, the application of grid-connected PV systems is more present due to the diversity of the systems' installation locations than the still fairly-limited installed capacity. Various factors have been contributing to this scenario, mainly the high cost of photovoltaic (US$12–$15/Wp installed) on the national market, the lack of incentives and guidelines and legislation concerning the generation of solar electricity. On the other hand, countless projects are being developed with grid-connected PV systems, usually with a capacity of under 5kWp, with installation and analysis in almost every state in the country. With the systematic monitoring of these systems, the operational details can be defined, paving the way for the development of simulation models for medium-capacity systems and analysis of the potential for different locations, Barbosa, (2009) and Barbosa et al., (2010), along with aiding in the generation of guidelines, norms and legislation. In 2011, certain changes were announced, such as the publication of the first norms permitting the participation of distributed solar generation in the official energy market[1], and the first commercial solar-power plant beginning operations in Latin America, the Tauá Solar Photovoltaic Power[2], with 1 MW from 4,689 panels over an area of 12,000 m^2 in the state of Ceará, in Northeast Brazil.

This work presents the *Campus Solar Sculpture*, a grid-connected PV system installed in the Campus of the Federal University of Pernambuco (UFPE) and the results of its performance for the first 12 months of operation. The sculpture is presented in the format of trunk of inverted pyramid made from steel and aluminum and its upper base is the PV generator (3 kWp) of thin-film amorphous Silicon cells.

In this paper, two points deserve highlighting: firstly, the use of thin-film (Si-a) cells which, until now, have not been studied under Recife's climactic conditions: humid heat with an air temperature between 23 and 30^{o}C, 60 – 80% relative humidity and average annual solar radiation level of around 5.5 kWh/m^2.d, Tiba et al.,(2000) and with about 30% diffusion radiation; secondly, the innovation of the structural architecture of

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the system which provided a multidisciplinary exchange between engineering and architecture, allowing for the diffusion of the potential for grid-connected PV systems in the area of building designers. Thin-film cells are extremely attractive in the architecture field, especially when there is the need for larger areas, and they work better with diffused light than traditional crystalline cells. The results obtained are expressed as daily, monthly and annual averages for the evaluation parameters: production of useful energy, system and equipment (PV generator and inverter) efficiencies and the global performance.

2. Methodology and installation

The photovoltaic systems installed by FAE Group are products of research, development and technological diffusion projects. In this specific case, the opportunity for the system, aside from producing energy, to also be an artistic object meant that its location needed to be a space open to visitors. The chosen site was the central garden of the Federal University of Pernambuco's Campus, where the solar sculpture was installed. The availability of space and solar cells defined the dimensions of the upper base of the sculpture, which together with its inclination, corresponding with the annual maximization of energy collection, determined the dimensions of the steel structure to support the sculpture. Owing to its location within the city of Recife at 8º 04'03" Latitude South and Longitude West 34º 55'00", the system was aligned towards Geographic North with an inclination (β) of 22^{o} in relation to the horizon, Fig. 1.

Fig. 1: Campus system - a)Front view, facing Geographic North, inclination (β=220); b) view looking South (without the box); c) the glass box in the sculpture interior; d) equipments in the box: inverter, data acquisition, and control instruments

The established technical and structural criteria were: type of solar cell technology: thin-film (Si-a); sizing factor of the inverter: $0.8<FDI<1$; support structure: steel and aluminium; the box, to house the equipment and accessories, made from aluminium and tempered glass to allow the equipment to be seen. The main characteristics of the component control and monitoring equipment, responsible for the generation and adequacy of the energy to local network conditions, were:

- PV generator: potential of 2.97 kWp; a useful area of 53 m^2 of amorphous silicon; composed of 66 PV cells. Manufacturing Data: potential (Po-45Wp), efficiency (η=5.6%) in standard conditions (1kW/m^2, 25º C and Air Mass 1.5); characteristic values of current and tension: at the maximum point of potential (I_{max}= 0.6 A; V_{max}= 75V); in short circuit or open circuit (I_{cc}= 0.75 A; V_{oc}= 100 V); 0.8 m^2 area and 15 kg; maximum allowable values for the set-up (20 A; 600 V).
- 3 KVA inverter, with maximum power point tracker, allowing the injection of the produced energy directly into the electricity supply network of UFPE. Manufacturing data: efficiency above 95%; 16 A maximum entry current; 195 to 530 Vcc operating tension.
- Control and monitoring system: control, monitoring and recording of climatologic parameters and the system's operation: electrical command board, data acquisition system and sensors and meters. Radiation monitoring: photovoltaic sensors with a precision of 3 to 10%, type LiCor-200SA. The low cost and the almost instantaneous response made the photovoltaic sensors very useful, as they were calibrated at an interval of six months as recommended by the manufacturer; Cell temperature: Transistor LM-35, linear variation with temperature, 10 mV/^{o}C exit signal, 150^{o}C measuring limit and intrinsic uncertainty of ± 0.25^{o}C; current, tension and potential meters: precision shunts and transducers. Shunt resistors to measure the current from the generator, tension transducer to measure the exit tension from the PV set-up and potential transducer to measure the useful potential exiting the inverter.

To satisfy the operating conditions of the inverter, the PV set-up was configured with 6 parallel interconnected panels with each panel having 11 cells in series. This configuration enables the generator's operating tension to fall within the recommended functioning range of the inverter (195 to 550 volts).

The inverter, all equipment and meters are housed in a glass box located in the inner centre of the sculpture. The radiation sensors are visibly installed on the exterior and secured to the structure itself, horizontally and on the same angle as the generator. The generator's temperature sensors were installed on the underside of the cells. The upper base of the structure, which is the surface of the PV generator, protects the sensors and equipment from weather effects.

The analysis of the performance was carried out through the determination of the global performance ration (PR). One of the most important parameters in the evaluation of the grid-connected PV system, the PR factor gives the relation between the possible production of real and theoretical energy, allowing for different systems to be compared independent of local sunshine hours.

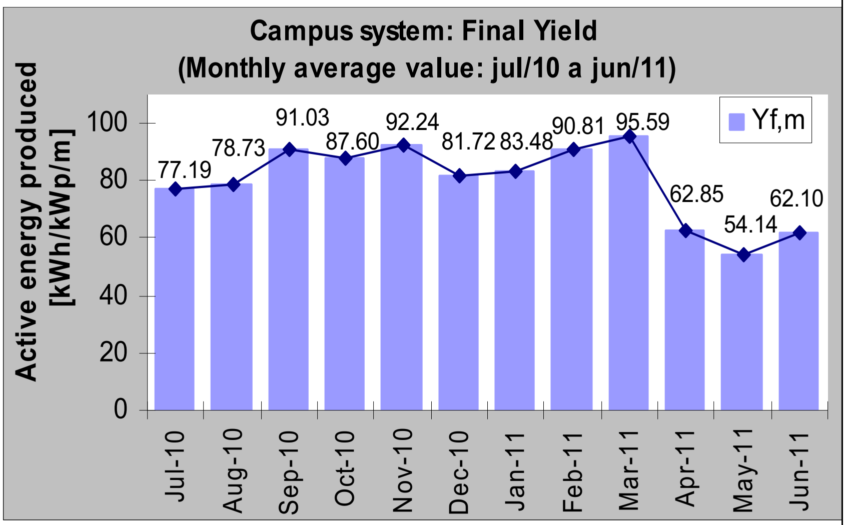
3. Results and evaluations

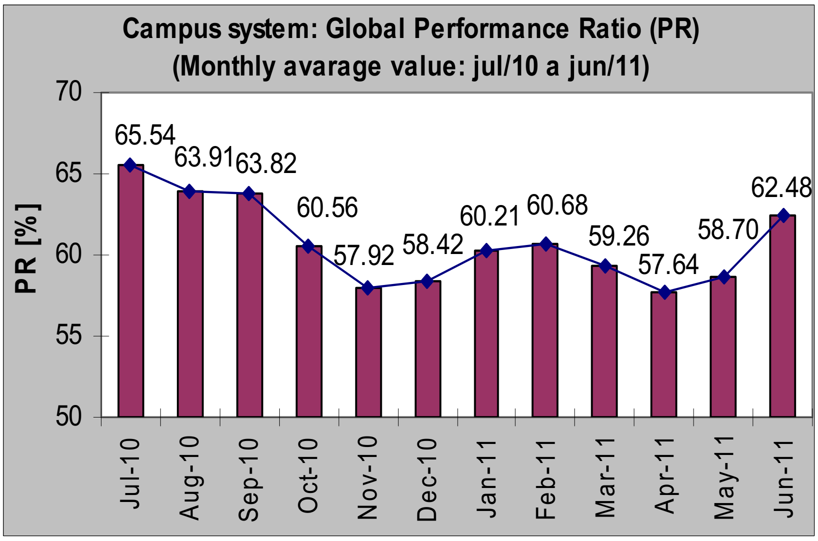
The grid-connected photovoltaic system Campus began operating in mid-June 2010 with monitoring with an acquisition rate of 1 minute. The results obtained from the experimental data are expressed as average daily, monthly and annual values, (FSEC-GP-70-01, 2002, in Mondol et al., 2006). The initial conclusive results in the 12-month operational period from July 2010 to June 2011 can be seen in the graphics and information in Fig.2.

The results for the Final Yield (Y_f), energy produced per kWp, are shown in Figure 2a. The values are between a minimum of 54.14 and a maximum of 95.59 kWh/kWp for month, with a monthly average of 79.80 kWh/kWp.m, or a monthly total production of 237 kWh. Around 931 kWh/kWp for year were produced and 2,844 kWh were injected into the UFPE network during the system' first year of operation.

An annual global performance factor (PR) of 61% is lower than expected, Fig. 2b. In terms of specific energy, around 53 kWh/m^2, a value much lower than that shown by the (Si-p) grid-connected PV system in Recife, of 156 kWh/m^2, Barbosa, (2009).

Fundamentally, these results can be attributed to the low efficiency (3.57%) shown by the (Si-a) PV generator. The efficiency shown by the inverter of around 94% falls within the forecasted range. Therefore, there is some problem in the generation phase (DC) that has not yet been identified, which may have physical origins or be in the measurements or connections.





Average annual value

- Final Yield

Monthly: 79.80 kWh/kWp

Annually: 957.5 kWh/kWp

- Net Injected Energy

Monthly: 237 kWh

Annual Total: 2,844 kWh

- Performance ratio (PR)

Average annual: 61%

- Efficiency

PV generator: 3.57%

Inverter: 94.23%

System: 3.38%

Fig. 2: Campus system – Conclusive final results for the July 2010 to June 2011

3.1. Results analyze

The results for the solar radiation, expressed as average monthly (July 2010 to June 2011) and average annual values of the radiation on the horizontal plane ($\overline{H}_h$) and the PV generator plane ($\overline{H}_{pv}$), in kWh/m^2.d are shown in Table 1. The average annual values obtained are from 4.67 and 4.24 kWh/m^2.d, respectively. It can be seen that the results of ($\overline{H}_h$) are lower than the corresponding records of the historic radiation series for the city of Recife-Brazil, an annual average of around 5.5 kWh/m^2.d, Tiba et al., (2000) However, these results refer to just one year of observations and in a very atypical period with the occurrence of intense rains even during the summer months. Annual measurements of total radiation can to show differences in the 10 to 15% range.

Table 1: Campus system–Solar Radiation on the horizontal and the PV generator plane. (Monthly and annual average value (July 2010 to June 2011).

Month	Jul. 10	Aug. 10	Sep. 10	Oct. 10	Nov. 10	Dec. 10	Jan. 11	Feb. 11	Mar. 11	Abr. 11	May. 11	Jun. 11	Annual Average
($\overline{H}_h$) [kWh/m^2.d]	3,86	4.13	4.93	5.11	5.96	5.28	5.26	5.48	5.60	3.78	3..24	3.45	4.67
($\overline{H}_{pv}$) [kWh/m^2.d]	3.80	3.97	4.60	4.67	5.14	4.51	4.47	4.83	5.20	3.52	2.98	3.21	4.24

Considering the annual average value of 4.67 kWh/m^2.d of incidental radiation on the PV plane, it means that around 247.5 kWh of solar energy was collected daily, generating electrical energy, (E_{pv}).

The generated power (P_{pv}) corresponds to the product of the current and continuous current tension (DC) generated by the PV set-up at every instance of solar irradiation on its surface. These extremely important measurements characterise the PV generator in different operating conditions from the standard, and allow the variation of the currents and tensions generated to be observed with incidental radiation and with the operational temperature of the PV cell. The produced energy (Ea) is the generate energy (E_{pv}) qualified, by inverter, for the local network operation condition. The Fig.3 shows the monthly average value obtained from experimental dates.

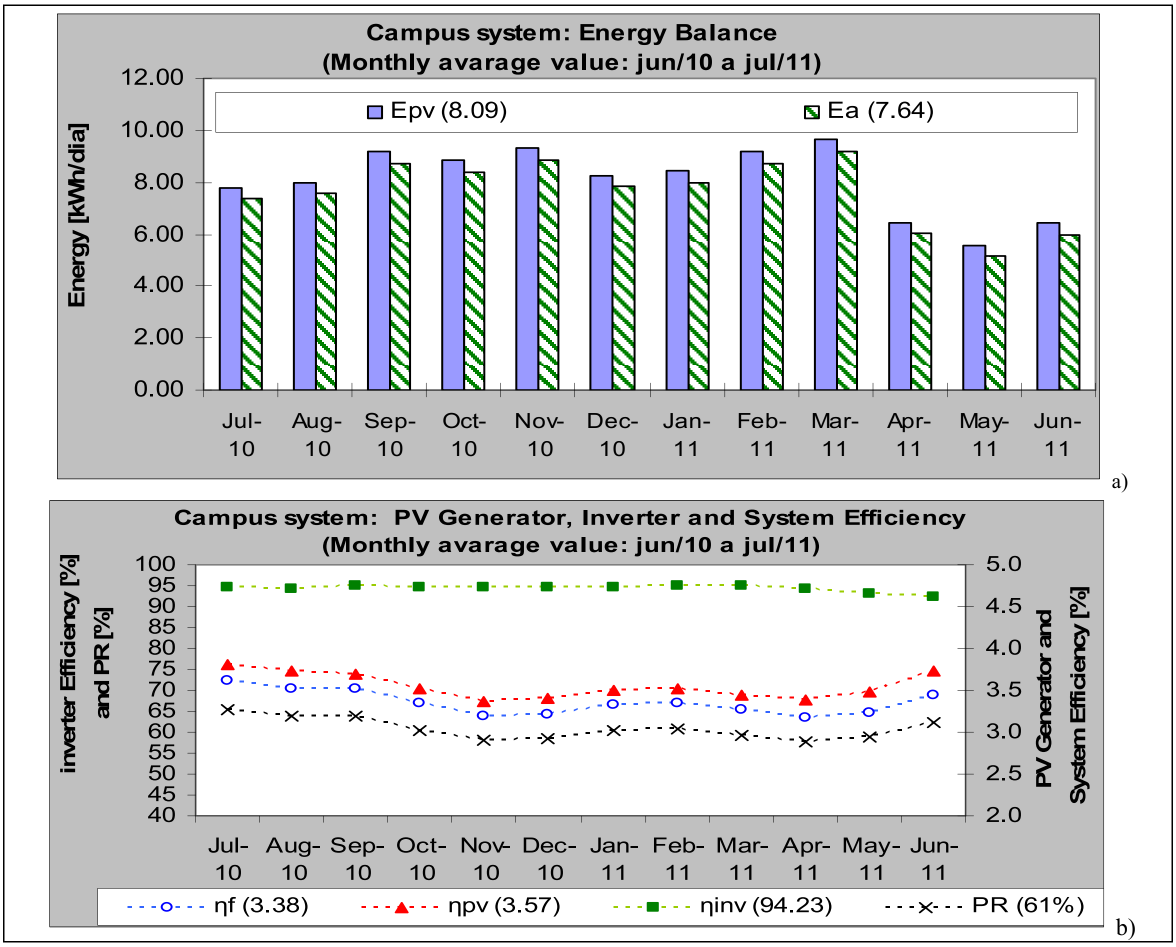


Fig. 3: Campus System: Monthly average results: a) generated and produced energy; b) PV generator, inverter and final system efficiency.

The results referring to the energies are showed in Fig. 3a: energy generated by the PV, ($\overline{E}_{pv}$) and active energy produced by the system, ($\overline{E}_{a}$). The 8.04 and 7.64 kWh/d results represent the average annual values respectively. The proximity of these results to each other is due to the quality of the inverter.

The average monthly values of the PV generator efficiency (η_{pv}), inverter efficiency (η_{inv}), and final system efficiency (η_{f}), can be seen in Figure 3b. The obtained average annual value of 3.57% for generator efficiency is well below the value specified by the manufacturer of the PV cells (5.6%).

The consequence of the energy generated by the PV and the energy exiting the inverter results from the efficiency of the inverter, which achieved around 94.23% as a average value in the observation period, while the final efficiency of the system reached around 3.38%.

Finally, the Performance ratio (PR) of the Campus System had an annual average of 61%, with a minimum value of 58.03% (March 2011) and a maximum of 65.77 % (July 2010), Fig.3b.

For the PV generator the load is the inverter, which should be capable of operating in a tension range appropriate to the tension of the PV generator's operation. The synchrony between the tensions is guaranteed by the Maximum Power Point tracker of the inverter. The operation tensions were in the 350 to 400 volt range. With the tension controlled by the inverter, the influence of incidental radiation on the PV plane in operation tension is very much reduced, Fig. 4a.

However, the influence of the radiation on the production of energy (Active potential) is greatly accentuated. Evidently, it is related to the dependence of the radiation generated current, Fig. 4b. This fact is confirmed by the ration between the linear coefficients shown in the relations between active potential (AC) and the current generated by the PV (DC), equal to the value corresponding to the average tension of the system operation (368 volts), Fig. 4a. Therefore, the efficiency of the inverter is also influenced by the incidental radiation on the PV, establishing a critical radiation level for the inverter to commence/stabilise its operation. These effects can be observed in Fig. 4c.

The efficiency of the PV generator is a function of the incidental radiation on its surface, its operational temperature and the type of solar cell technology. Compared to the inverter, the influence of radiation and temperature on the PV generator's efficiency is much stronger. The incidental irradiation effect is a strong influence on the generated current and on the temperature of the PV generator, as can be observed in the graphics of Fig. 4b and 4d. The values shown correspond to the instantaneous measurements of incidental radiation, generated current and the temperature of the PV generator. The generator's temperature data corresponds to the average value of the measurements in two points (one in the centre and the other in the lowest point of the PV set-up).

The temperature of the PV generator increases proportionally to the incidental radiation on its surface, as shown by the linear regression in Fig. 4d. Considering this as an indicative result, it can be observed that the resulting relation does not differ from those obtained from mono or policrystalline silicon cells (Si-m; Si-p) in a tropical climate, where the proportionality coefficient is between 0.02 and 0.03 (Barbosa et al, 2009; 2007; 2006;1999).

The results are still too preliminary to allow for a conclusion; however, the verified increase in operational temperature can not be considered responsible for the resulting low values for the (Si-a) PV generator efficiency of 3.58%, annual average value.

The (Si-a) cell stabilizes its exit tension independent of the operational temperature, an interesting choice to simplify the inverter: the fixed operational tension could be sufficient without leading to energy losses that may become very attractive for locations such as Recife with a hot climate and high operational temperatures. Normally, cell efficiency in Standard Conditions is near the lower limit of cell efficiency, which shows in practice as lower yields, between 4 and 5%.

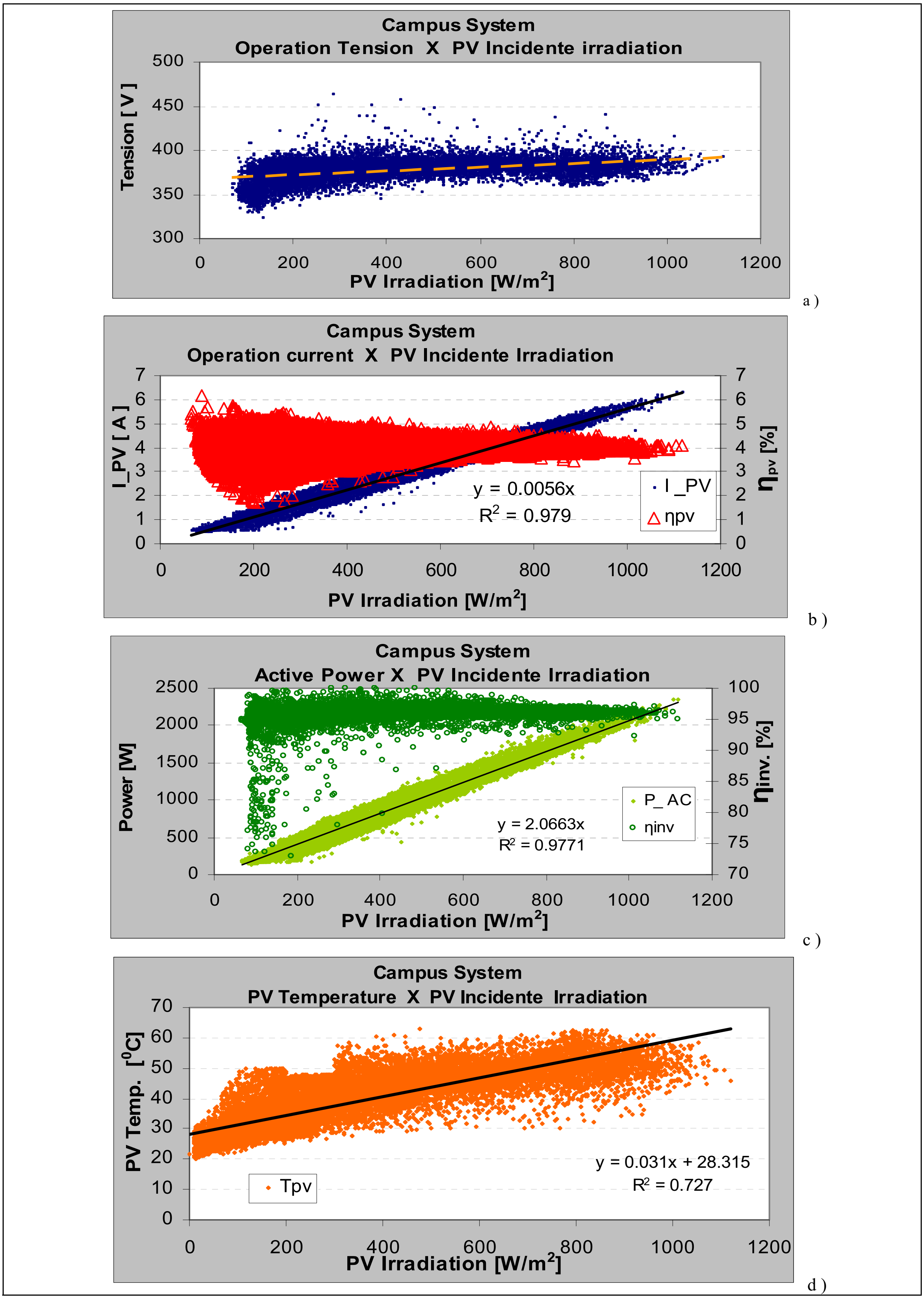


Fig. 4:Campus system: Influence of the incidental radiation on the PV plane on: a) operation tension; b) PV generated current and efficiency; c) active power and inverter efficiency; d) PV operation temperature.

4. Conclusion

The experimental results obtained from the monitoring of the Campus System, in the period from July 2010 to June 2011, expressed as monthly annual averages, show that: The level of incidental radiation was lower than radiation historical indices for the city of Recife-Brazil, whose average annual value is around 5.5 kW/m^2 per day.

- The final productivity of 79.80 kWh/kWp results in around 237 kWh/month. In other words, around 2,844 kWh were injected into the electric network of UFPE in one year.
- The Global Performance Factor (PR) of 61% represents a lower-than-expected yield (>65).
- The Specific Energy, around 53 kWh/m^2, was a much lower result than the value observed in Recife, Brazil, of around 156 kWh/m^2, for the (Si-p) grid-connected PV system.
- Fundamentally, these results can be attributed to the low efficiency (3.57%) shown by the (Si-a) PV generator.

The evaluation methodology used requires a longer monitoring period with the acquisition of data that can lead to a more complete and reliable analysis of the technical performance of the Campus system and its cost/benefit ratio.

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