

MODELLING GRID-CONNECTED PHOTOVOLTAIC SYSTEMS: CASE STUDY OF SOME CITIES IN BRAZIL USING A COMPUTATIONAL TOOL

Gilberto Figueiredo, Wilson Negrão Macêdo and João Tavares Pinho

Grupo de Estudos e Desenvolvimento de Alternativas Energéticas (GEDAE), Universidade Federal do Pará (UFPA), Belém
(Brazil)

1. Introduction

The photovoltaic technology is along the years taking an increasing share on the electric energy production. The grid-connected application became the most used due to easy installation, maintenance, minimum environmental impacts in the energy generation process and also the possibility of its use as distributed and complementary generation. In some countries, where there are incentives for production and consumption of energy generated by this technology, it plays an important role as a feasible and economically viable alternative. Brazil has a great solar resource availability and the grid-connected PV application could be used as a complement of the established hydroelectric plants installed all over the country. However, the difficulty of access and the high prices still remain as obstacles to the beginning of the PV boom in Brazil.

This paper presents a computational tool, developed in the GUIDE (Graphical User Interface Development Environment) environment of *MATLAB*TM, which was used to analyze the potential of photovoltaic generation of four Brazilian cities in different geographical and climatic regions. The program has the main goal of helping with the analysis and design of Grid-Connected Photovoltaic Systems (GCPVS) by modeling their generation and energy conversion equipment. A literature survey shows that this subject has been studied by many engineers and scientists, but with different mathematical concepts (Hamad et al, 2010; Argul, 2003). The calculation methodologies used here are described, and the developed interface of the program explained. Finally some simulations for cities of different climatic characteristics are presented aiming to prove the great potential of GCPVS in Brazil.

2. Mathematical modeling of the system

A GCPVS is basically made of three parts: PV generator, inverter, and grid. The first is the power source, which generates dc power by the direct conversion of the solar radiation. The second has the role of extracting the maximum power of the generator (on a given climatic condition), converting it to ac power, and feeding the energy to the grid. Also, the inverter has to monitor the conditions of the grid and should only connect to it, if the electrical parameters (such as voltage, frequency, harmonic distortion and impedance) are within pre-determined ranges defined by international standards.

Figure 1 shows a schematic representation of a GCPVS, indicating the parameters which are included in the mathematical model used in this paper. The following sub-sections present the mathematical approach for the energy generation and conversion process.

2.1. Photovoltaic Generator

When the solar radiation reaches the surface of the PV module, its power is converted into electric power. Of course, this process depends on the cell technology, since the spectral sensibility varies according to the semiconductor material used, as showed in figure 2 for amorphous and crystalline silicon. As can be seen, the *c-Si* is able to convert the solar radiation into electricity in a wider range of wavelength.

It is possible to estimate the maximum power point of the PV generator using equation 1. This simplified model allows the calculation of the PV generator maximum power for a given level of global irradiance and cell temperature. This model considers the influence of the cell temperature on the generated power with no complex calculation involved, and shows a good relationship between processing time and accurate results, as can be seen in Macêdo (2006) and Figueiredo et al. (2010).

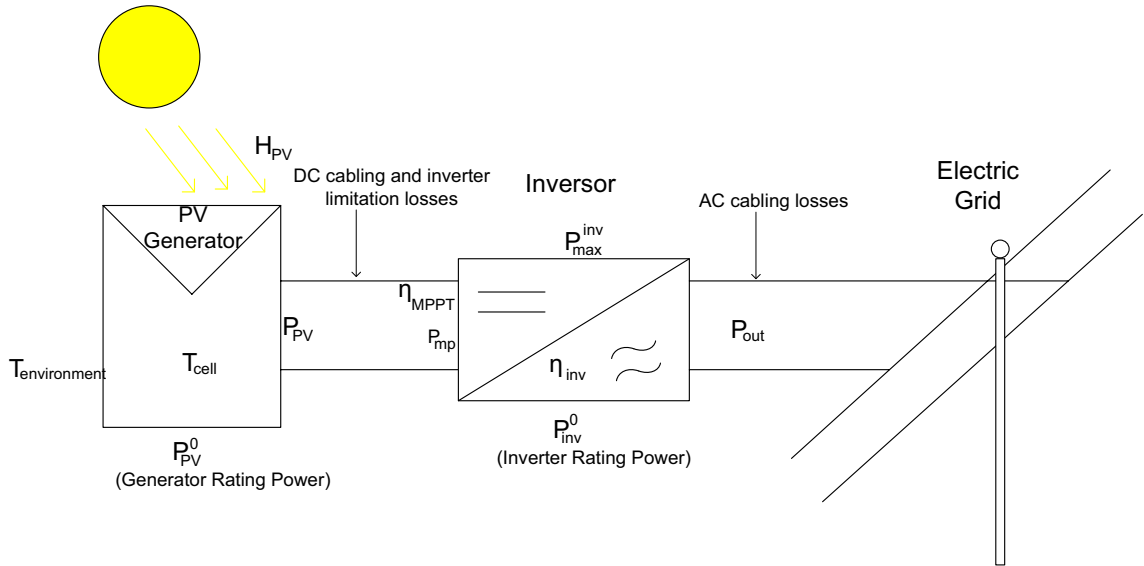


Fig. 1: Schematic representation of the GCPVS.

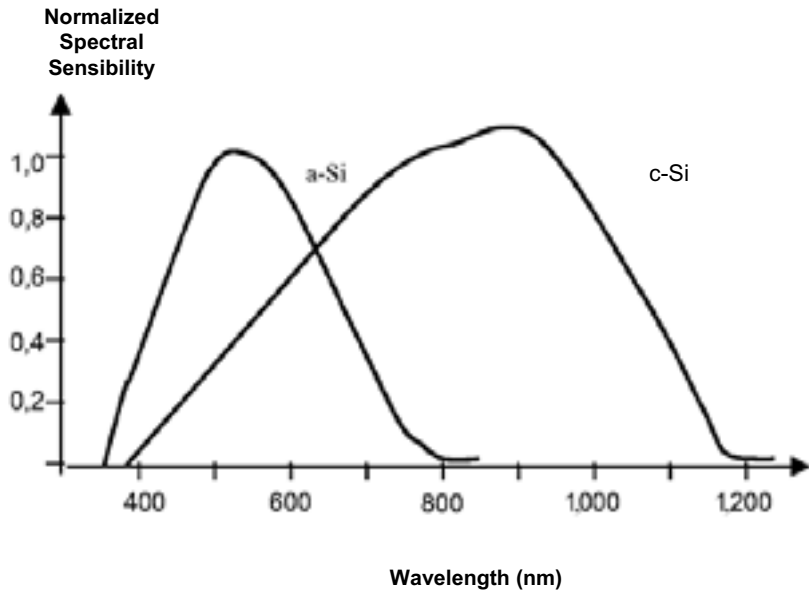


Fig. 2: Spectral sensibility for two silicon technologies.

$$P_{mp} = P_{rated_PV} \frac{G_{PV}}{G_{STC}} [1 - \gamma(T_{cell} - T_{STC})] \quad (\text{eq. 1})$$

In equation 1 P_{mp} is the maximum power, P_{rated_PV} is the total Wp of the PV generator, G_{PV} is the global irradiance on the PV plane, G_{STC} is the reference value (1,000 W/m²), γ is the power temperature coefficient (normally provided by the manufacturer on the data sheet), T_{cell} is the cell temperature and T_{STC} is the reference value (25°C). Equation 1 only evaluates the point in which the maximum power of the PV generator can be extracted, not considering the Maximum Power Point Tracker (MPPT) efficiency, η_{spmp} . Since this process is performed by the inverter, it will be presented in the next sub-section.

The cell temperature can be calculated from the environment temperature T , as shown in equation 2. $NOCT$ is the Nominal Operation Cell Temperature, normally available in the module data sheet.

$$T_{cell} = T + \frac{G_{PV}}{800} \times (NOCT - 20) \times 0.9 \quad (\text{eq. 2})$$

2.2. Inverter

The tasks accomplished by the inverter are following the MPP, converting the dc power to ac power, feeding this power to the grid, and monitoring the parameters such as voltage, frequency, harmonic distortion, power factor, and impedance of the connection point. Thus, this device interacts with the grid and is responsible for controlling and monitoring the system variables, since it has to disconnect, if one of the parameters is out of the expected range. Also, the device must have an anti-islanding strategy to avoid undue operation.

This paper has the aim of showing an energetic approach for GCPVS by modeling its generation and conversion process. At the inverter, first of all it is necessary to work as close as possible to the MPP. The algorithms used in commercial inverters seldom reach 100% efficiency, although it can be very close to it, depending on the climatic conditions. Using a model proposed by Rampinelli (2010), showed in equation 3, for the static MPPT, the simulation can achieve very accurate results, when compared to measured data.

$$\eta_{MPPT} = \frac{\frac{P_{mp}}{P_{rated_{inv}}}}{\frac{P_{mp}}{P_{rated_{inv}}} + \left(M_0 + M_1 \times \frac{P_{mp}}{P_{rated_{inv}}} \right)} \quad (\text{eq. 3})$$

where η_{MPPT} is the MPPT efficiency, P_{mp} the value calculated using equation 1, $P_{rated_{inv}}$ is the inverter nominal power, and M_0 and M_1 are the power coefficients of the static MPPT efficiency model, as given in (Rampinelli, 2010).

Once the MPPT efficiency is calculated, the next step is to provide the inverter conversion model with the calculated value of PV power. The model used in this paper, showed in equations 4 to 6, has been used in many works, showing interesting results (Figueiredo et al., 2010; Rampinelli, 2010; Macêdo, 2006), mainly when compared to measured data of GCPVS.

$$\eta_{Inv(pout)} = \frac{P_{out}}{P_{PV}} = \frac{P_{out}}{(P_{out} + P_{losses})} = \frac{p_{out}}{p_{out} + k_0 + k_1 \cdot p_{out} + k_2 \cdot p_{out}^2} \quad (\text{eq. 4})$$

$$P_{losses} = P_{PV} - P_{out} \quad (\text{eq. 5})$$

$$p_{out} = p_{PV} - (k_0 + k_1 \cdot p_{out} + k_2 \cdot p_{out}^2) \quad (\text{eq. 6})$$

where η_{Inv} is the inverter conversion efficiency, P_{out} is the output power of the inverter, P_{PV} is the power of the PV generator after considering the MPPT efficiency, and p_{out} is the output power normalized by the inverter nominal power. The coefficients k_0 , k_1 , and k_2 are related to the losses. The first does not depend on the output power, since it represents the self-consumption losses. The parameters k_1 and k_2 refer to the losses due to inverter loading. The first represents the losses which present a linear behavior with the output power (such as diodes voltage drops and sectioning devices), while the second represents those losses with quadratic behavior (mainly due to ohmic losses).

The parameters related to losses can be calculated with just 3 points of the inverter's loading curve. This means that it is only necessary to have the information of the efficiencies for 10%, 50% and 100% loading. Once the parameters are calculated, the task is to solve equation 6, in which p_{out} is the variable of interest.

Before starting the explanation about the user interface, it is necessary to introduce the inverter sizing in relation to the PV generator, called ISF (Inverter Sizing Factor), and showed in equation 7. This variable is used to help choosing the systems optimized size, which allows greater energy generation. Macêdo (2006) studied several systems with different sizes in São Paulo. The results showed that oversizing the PV generator can lead to a greater energy contribution of the systems, without considerable negative impacts on the operation, such as inverter limitation due to power or temperature.

$$ISF = \frac{P_{rated_{inv}}}{P_{PV}} \quad (\text{eq.7})$$

All inverters have a maximum permissible power level at its input. If the PV generator provides a higher level, the inverter starts to limit its peak, and if this condition lasts longer, the temperature limitation acts in the MPPT to lower the power at its input. So, when the oversizing technique is used, care must be taken, since those limitations represent energy losses and occasionally can make the inverter operate in extreme conditions. The optimum sizing must guarantee a good relationship between optimized energy generation and safe operation of the inverter. The choice of the system size can be facilitated when there is a software able to simulate the operational conditions of the system.

3. User interface

The models presented so far were inserted in an algorithm implemented in MATLAB to simulate the energy contribution of GCPVS. A user interface was also developed to make the program user friendly. The GUIDE (*Graphical User Interface Enviroment Development*) environment of MATLAB was used to accomplish this task. The software needs climatic data of global irradiance and ambient temperature as input data for the models presented here. Such data can be provided by .txt or .dat files. Figure 3 shows the first part of the interface in which the user can decide the best ISF for the system.

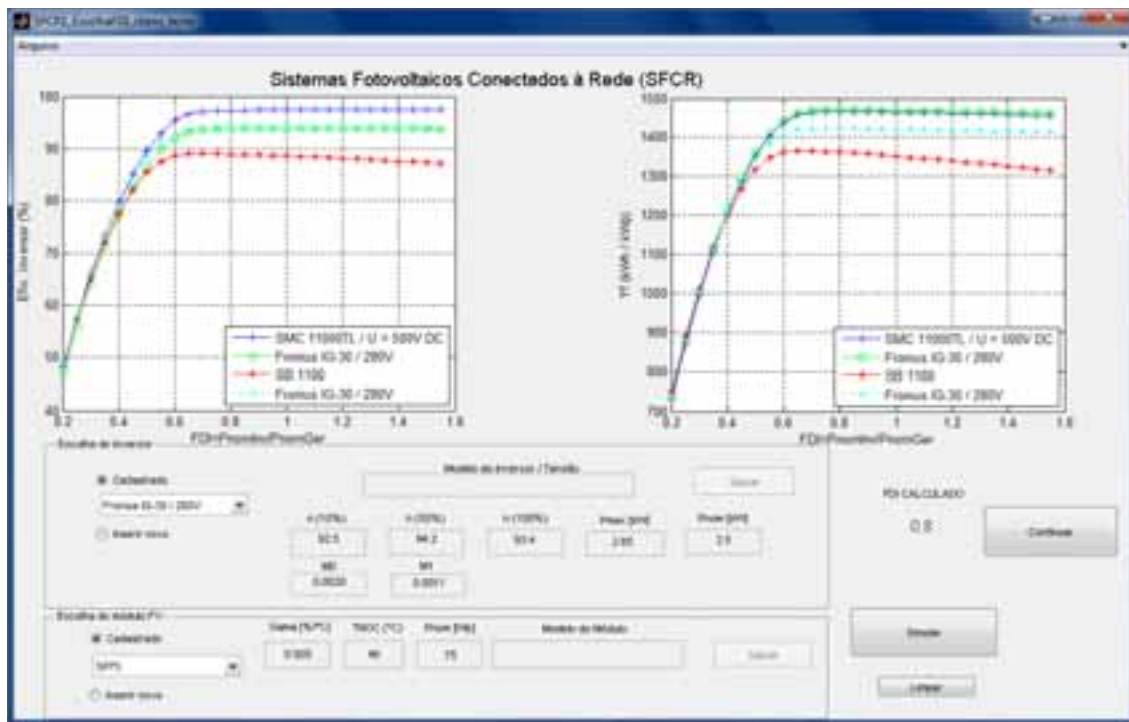


Fig. 3: Initial part of the interface: choosing the sistem's size.

Before running the program, the user needs to choose the PV module and the inverter to be used in the simulation. There is also the possibility to add other devices to the program library. When the “Similar” button is pressed, a pop up window ask for the climatic data files. The program generates two graphics. In the left one there is a plot of ISF *versus* Inverter Conversion Efficiency (%), and in the right ISF *versus* System Yield (kWh/kWp). Both vertical axes are in yearly basis and the ISF varies from 0.2 to 1.6. The program returns a value of the ISF in which the higher yield and conversion efficiency are achieved.

The algorithm models the power limitation of the inverter, and the cable losses are considered as fixed values. The temperature limitation and the conversion efficiency as a function of the PV voltage are the next steps in the the simulation.. .

The second part of the user interface can be seen in figure 4 (it appears after the user presses the “Continuar” button) and is used to analyze the performance of the system throughout the year (four blue bar graphics on

the left) or during a time interval specified by the user (graphics on the right). Before running the simulation (“Similar” button), the user needs to indicate which ISF will be used, and the analysis time interval at the lower part of the interface.

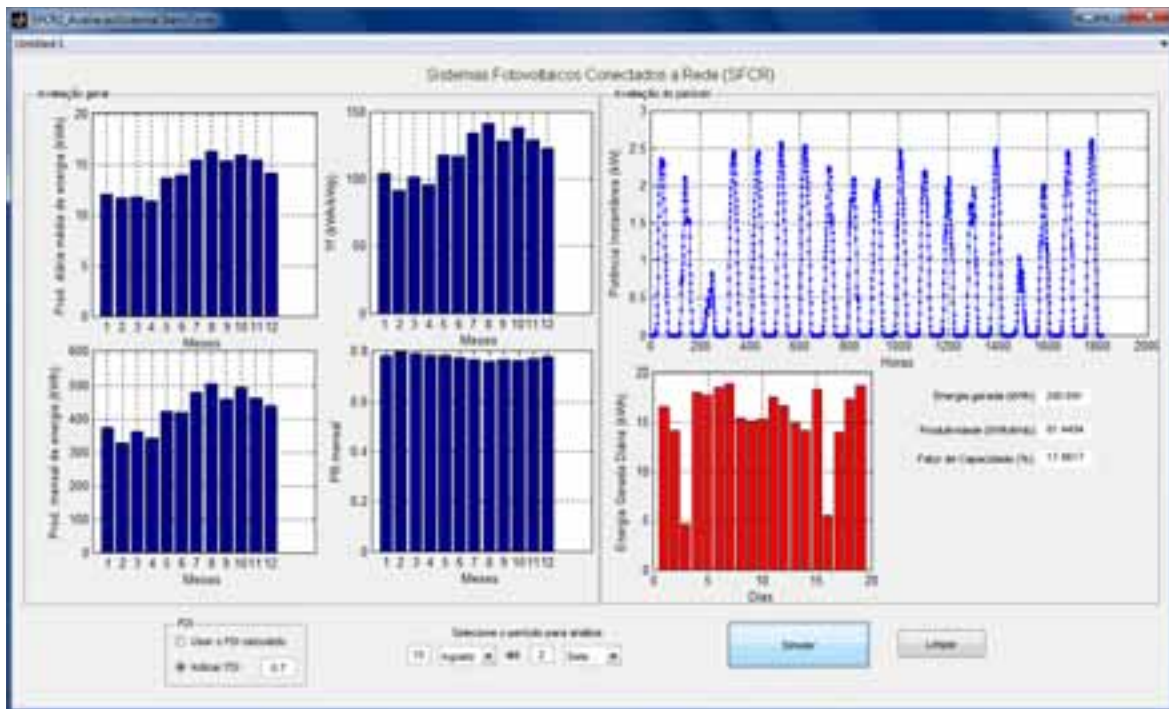


Fig. 4: Second part of the interface: choosing the size of the system.

The first four graphics show: average daily energy generation for each month (kWh), yield for each month (kWh/kWp), monthly energy production (kWh), and the performance ratio for each month (%). On the right there is the energetic analysis of the indicated time interval. The program returns the power profile during the days (blue graphic), the energy generated on each day (red bar graphic), and the information of total energy generated, yield, and capacity’s factor for the period.

The voltage influence in the conversion efficiency was already implemented in the algorithm, but it only should be considered when the time interval of the climate data is short (maximum 5 minutes). The same can be said for the temperature limitation model. This paper shows simulation results for hourly data, so the efficiencies considered were related to MPPT and dc/ac conversion process. Figure 5 shows an histogram for the PV MPP voltage along the year. This information is useful to choose the best configuration of the generator, considering the voltage MPP range of the inverter. Also, this voltage values can be inserted in the conversion efficiency model.

4. Simulation Results

Brazil has a great area and regions with completely different weather characteristics. The main objective of this paper is to demonstrate the potential for GCPVS in terms of energetic contribution of four cities in different geographical and climatic regions. The climatic data used was provided by METEONORM™ version 6.0, trial license, with hourly values. The cities are: Manaus, in the Northern region, Recife in the Northeast, Rio de Janeiro in the Southeast, and Curitiba in the Southern region. Table 1 shows the modules and inverters used in the simulation for each city.

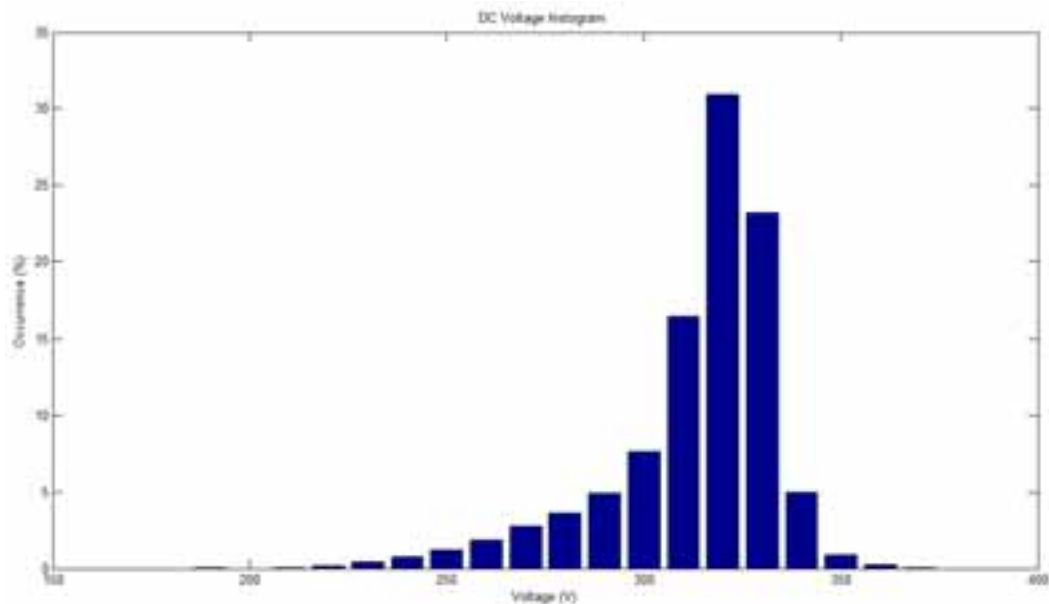


Fig. 5: dc voltage histogram.

Tab. 1: Modules and inverters used in the simulation.

System 1	PV Module	Inverter
	Module 1 (70 W)	Inverter 1 (1 kW)
System 2	PV Module	Inverter
	Module (75 W)	Inverter 2 (2.5 kW)

It was decided to use the ISF calculated by the program to run the energetic contribution. The results can be seen in the following tables, as conversion efficiency (mean value), total yield, energy generated, and capacity factor.

4.1. Manaus

Located in the Amazon region, it has high levels of humidity and temperature. There are mainly two seasons: the rain season in the first semester and the dry season in the second, and PV can be useful in this region since it has a complementary behavior with the hydroelectricity. The results for this city are shown in table 2. The city had good values of yield and capacity factor, even being a location with a lot of rains. The irradiance levels are high almost the whole year, even in the rainy season.

Tab. 2: Simulation results for Manaus.

	ISF	Conversion Efficiency (%)	Yield (kWh/kWp)	Energy Generated (kWh)	Capacity Factor (%)
System 1	0.65	88.9	1,317	2,026	15
System 2	0.75	93.8	1,369	4,564	15.6

4.2. Recife

Located on the Northeastern coast of Brazil, it has a good solar resource. The simulation resulted in the highest yield values among all simulated cities, as can be seen in table 3. The calculated capacity factors are impressive, since those are static systems (without any tracking strategies).

Tab. 3: Simulation results for Recife.

	ISF	Conversion Efficiency (%)	Yield (kWh/kWp)	Energy Generated (kWh)	Capacity Factor (%)
System 1	0.7	89	1,470	2,100	16.7
System 2	0.85	93.9	1,525	4,487	17.4

4.1. Rio de Janeiro

One of the most important cities in the country is most known for its beautiful beaches. Although being located in the Southeastern region, it has a good potential for GCPVS application, as can be seen by the good values of capacity factor and yield shown in table 4, which are very similar to those found for Manaus.

Tab. 4: Simulation results for Rio de Janeiro.

	ISF	Conversion Efficiency (%)	Yield (kWh/kWp)	Energy Generated (kWh)	Capacity Factor (%)
System 1	0.65	88.8	1,339	2,059	15.3
System 2	0.8	93.8	1,400	4,376	15.9

4.2. Curitiba

The results returned by the program show the worst behavior.

Tab. 5: Simulation results for Curitiba.

	ISF	Conversion Efficiency (%)	Yield (kWh/kWp)	Energy Generated (kWh)	Capacity Factor (%)
System 1	0.65	88.7	1,196	1,839	13.6
System 2	0.75	93.8	1,268	4,227	14.5

The ISF is calculated according to the higher values of yield and conversion efficiency and it depends on the characteristic of the inverter efficiency curve. All tables show lower ISF for system 1 than the system 2. This fact means that system 1 is always more oversized than system 2, both related to inverter nominal power, to achieve maximum productivity and energy generation. The future step of this work will be to consider the temperature limitation, to indicate a ISF which does not impact in too many limitation losses.

5. Conclusions

The user interface presented in this paper was developed to help design and analyze GCPVS. It can also easy the use and understanding of the mathematical modeling.

All cities chosen for the simulation presented good values of yield, energy generated, and capacity factor. This shows the great potential for GCPVS application in the country, even in the regions with lower irradiance levels.

Although the software already presents good results, some improvements can still be made, such as considering the temperature limitation and the conversion efficiency as a function of PV voltage, using measured data with shot time interval.

6. References

Argul, J.F., Castro, M., Delgado, A., Carpio, J., Peire, J., 2003, Software modeling of grid-connected photovoltaic buildings, *Progress in Photovoltaics*, 11, 255-273.

Figueiredo, G., Vasconcelos, M. F., Macêdo, W., Manito, A.R.A, Galhardo, B.A.M, Pinho, T.J, 2010, Ferramenta computacional para análise e projeto de sistemas fotovoltaicos conectados à rede elétrica, III Congresso Brasileiro de Energia Solar (Brazilian Solar Congress).

Hamad, A.A., Mohammad, A.A, 2010, A software application for energy flow simulation of a grid connected photovoltaic system, *Energy Conversion and Management*, 51, 1684-1689.

Macêdo, N. W., 2006, Análise do fator de dimensionamento do inversor aplicado a sistemas fotovoltaicos conectados à rede, University of Sao Paulo - USP, PhD Thesis.

Rampinelli, A. G., 2010, Estudo das características elétricas e térmicas de inversores para sistemas fotovoltaicos conectados à rede, Federal University of Rio Grande do Sul - UFRGS, PhD Thesis.

7. Acknowledgements

This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq - Brazil (through the Instituto Nacional de Ciência e Tecnologia de Energias Renováveis e Eficiência Energética da Amazônia: INCT-EREEA), Universidade Federal do Pará (UFPA), and Fundação de Amparo ao Desenvolvimento da Pesquisa do Estado do Pará (FAPESPA).