EXPERIMENTAL RESULTS OF A 180 Wp SOLAR HOME SYSTEM TO SUPPLY TYPICAL RIVER DWELLER FAMILIES IN THE AMAZON

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1. Introduction

The application of Solar Home Systems (SHS) in Brazil is extremely interesting because it allows a distributed electricity production next to consumption, essential to supply remote areas. Considering the Brazilian Amazon Region, where there are many isolated communities, there is a great interest in using PV systems to supply small residences.

About three decades have passed since the first SHS was installed in developing countries (Nieuwenhout et al., 2001). In Brazil, experience has been gained in some projects (Trigoso, 2000, Trigoso et al., 2001 and Anhalt, 2002), although this information does not bring sufficient details about some aspects of the SHS's operation. To contribute to the discussion on the importance of SHS application in Brazil, a brief overview of the current legislation, which regulates the use of intermittent sources for the electric service, is made. The paper also presents a performance analyses of a monitored SHS installed in the laboratory of the Grupo de Estudos e Desenvolvimento de Alternativas Energéticas (GEDAE), in Belém-PA, Brazil, and reports the experience acquired with some systems installed in an isolated community under Amazonian climatic conditions.

The experimental performance analyse is accomplished in a 180 Wp solar home system, installed in the laboratory. The system was designed to provide at least 13 kWh per month (or 433,3 Wh daily), according to the Brazilian Electrical Energy Agency (ANEEL) normative resolution number 83/2004, which defines the standards for electric energy supply using Individual Generation Systems with Intermittent Sources. To simulate the real use in a river dweller residence typical for the Amazon region, a system was implemented with timers that allow obtaining the load profile of the households. The efficiency of the system components is determined and presented in this paper. The average daily electricity generation for the PV array in June, July, and August (some of the best months in terms of solar radiation) are between 400 Wh and 900 Wh. It is possible to note the difficulty of the system to provide the 433,3 Wh per day requirement in the worst days of solar radiation, if losses in the rest of process of energy conversion (battery charge and discharge, dc-ac conversion, etc.) are superior to 30 %. Five similar systems were installed and are operating in river dweller residences in the Marajó Island, Pará, Brazil. Some results of these systems are presented, too.

2. Brazilian ANEEL normative resolution number 83/2004

The Brazilian ANEEL normative resolution number 83 (NR83) from September 20th 2004, establishes the procedures and provides conditions for Individual Systems of Electricity Generation Using Intermittent Sources (called SIGFI). On the scope of the governmental project “Luz para Todos”, not only the conventional grid expansion but also the decentralized generation systems (with isolated grids or individual systems) will be contemplated.

The program aims at the universalization of the electricity services, and the individual systems powered by intermittent sources (in which SHS are included) are among the feasible options, and a specific regulation which considers the characteristics and particularities of such systems is necessary.

The obligatory characteristics expected of the SIGFIs installed after the regulation publication are as follows: I – the electricity supply must be ac-sinusoidal, considering the voltage and frequency levels of the municipality where the consumer is located, and according to the values defined by official standards; II – the systems must be classified in one of the cathegories shownd in Table 1.

Tab. 1: Classification and service availability.

Service Class	Reference daily consumption (Wh/day)	Minimum autonomy (days)	Minimum power availability (W)	Guaranteed monthly availability (kWh)
SIGFI13	435	2	250	13
SIGFI30	1,000	2	500	30
SIGFI45	1,500	2	700	45
SIGFI60	2,000	2	1,000	60
SIGFI80	2,650	2	1,250	80

Regarding metering, the utility must install metering equipment in all consumers supplied by SIGFIs which began their operation after the regulation publication and has guaranteed monthly availability greater than 30 kWh, which means that for the systems considered in this work the electronic energy meter is not obligatory.

Regarding the continuity of service, the utility must obey the reference standard of “Interruption Duration for each Consumer” (called DIC). The reference values are 216 hours per month and 648 hours per year. The DIC values can be strongly influenced by the difficulty of access.

3. System description

The SHS basically comprises five elements: The PV generator, composed of two monocrystalline modules of 90 Wp each, and oriented to north with a tilt angle of 10º; the mounting system by means of which the solar modules are attached to a pole; a PWM charge controller of 12 V or 24 V / 20 A; a 12 V battery bank, with two stationary batteries of 150 Ah capacity each; and an inverter of 12 VDC/127 VAC - 350 VA. Figure 1 shows a picture and the line diagram of the system installed in GEDAE’s laboratory.

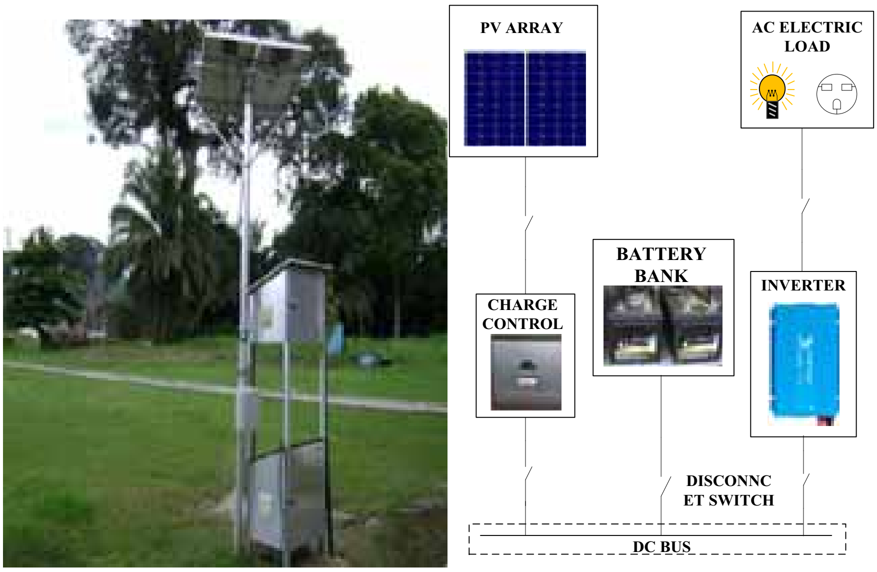


Fig. 1: The 180 Wp SHS installed in GEDAE´s laboratory and its line diagram.

To simulate the real use in a typical river dweller residence of the Amazon region, a system was implemented with timers that allow obtaining the load profile of the households, as illustrated in Figure 2. An independent programmable data logger was used to monitor all parameters of interest. The device can handle a wide range of sensors including, but not limited to, thermocouples, thermistors, monolithic temperature sensors, 4-20mA current loops, etc. It also includes a wide range of sensor scaling and fitting facilities, including polynomials, expressions e functions. The fundamental inputs measured by the datalogger are voltage, current, resistance, and frequency. All other parameters are derived from these.

Figure 2 presents a detailed diagram of the whole system, and all the devices and monitored parameters.

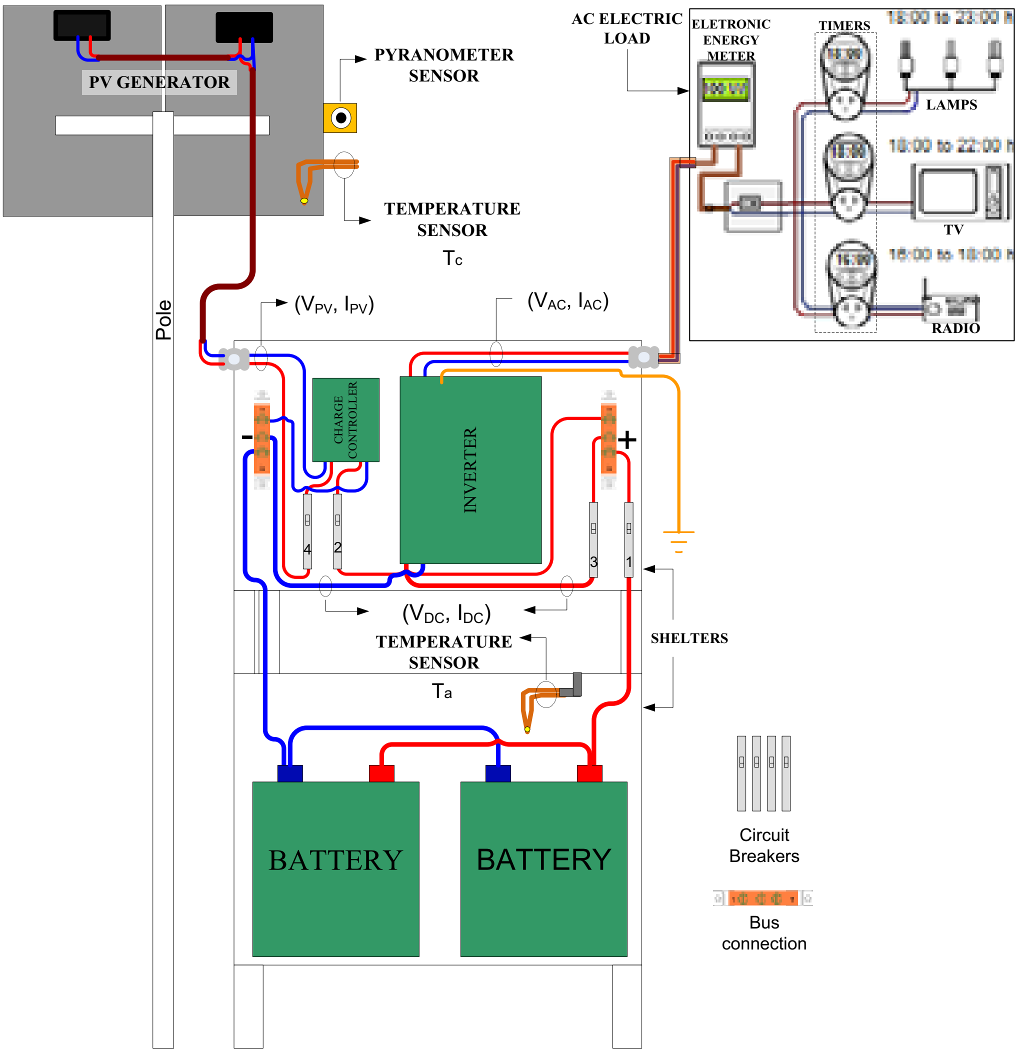


Fig. 2: Schematic diagram of the whole system and monitored parameters.

Although not obligatory, the electronic energy meter located between the electric devices that compose the SHS plays the role of acquiring information about the system´s operation.

4. Experimental results

The experimental results analysis was conducted in two steps. The first consists of the integrated and average values obtained along the two months and eight days of system's evaluation. The second step consists of the analysis of the electric energy balance and temperature. This allows the evaluation of the detailed behavior of the system for different days.

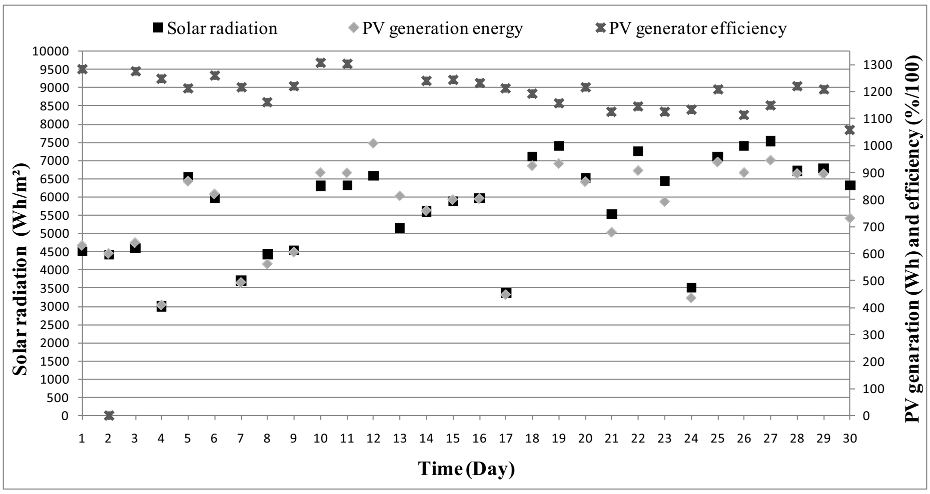
Table 1 presents the energy values of solar irradiation (E_{SOLAR}), PV generator production (E_{PV}), dc input (E_{DC}) and ac output (E_{AC}) of the inverter, inverter efficiency (η_{INV}), and PV generator efficiency (η_{PV}). Based on the information collected, it was possible to note a PV production and energy consumption on the dc and ac sides of the inverter of approximately 54.05 kWh, 57.57 kWh, and 40.77 kWh, respectively. Although the average daily production of the system, during the presented months, is relatively high (780 Wh per day), it is estimated that in the worst months of solar radiation (January, February and March) this value can possibly reach 470 Wh. Such energy is insufficient to supply the 433.3 Wh per day in the ac side, necessary to guarantee the energy availability of 13 kWh per month (in agreement with the Brazilian resolution ANEEL 83), since the average daily efficiency of the inverter is approximately 71 %.

Tab. 1: Energy balance for the PV generator and inverter.

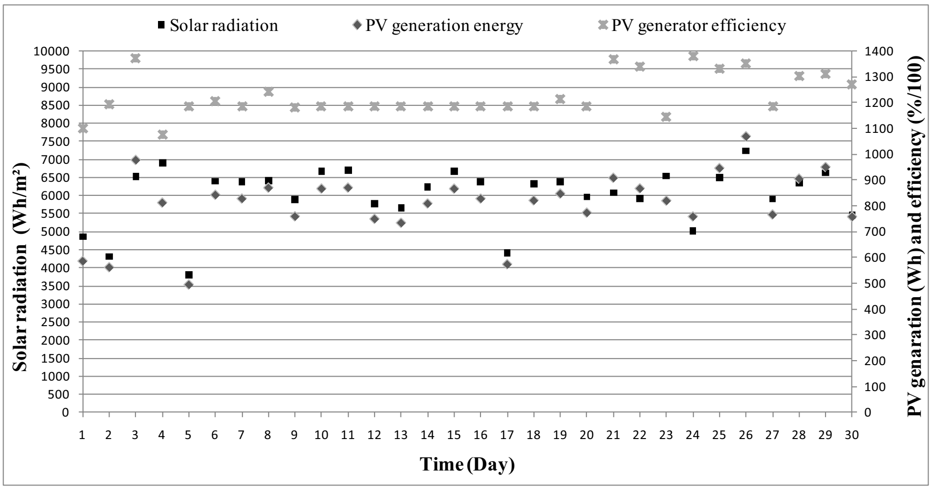
PARAMETER	JUNE	JULY	AUGUST*	TOTAL	DAILY AVERAGE
E_{SOLAR} (kWh/m²)	172.57	186.01	49.16	407.74	5.90
E_{PV} (kWh)	22.91	24.99	6.23	54.04	0.78
E_{DC} (kWh)	25.86	27.20	6.98	60.04	0.87
E_{AC} (kWh)	18.81	19.41	5.03	43.25	0.62
η_{INV} (%)	72.71	71.36	72.06	-	72.04
η_{PV} (%)	12.19	12.30	11.60	-	12.13

*Only first eight days.

Another important aspect is that the average daily PV generation (780 Wh) is inferior to the daily average dc energy demanded by the inverter (870 Wh) to supply the daily average ac energy consumption of the load (590 Wh). It is noticed that the average ac consumption is 36 % greater than the 433 Wh that must be supplied. Figures 3 and 4 show the variation of solar radiation, PV energy production and the consumption on both sides of the inverter, throughout the monitoring days of system operation. The figures also show the measured efficiencies of the PV generator and inverter.

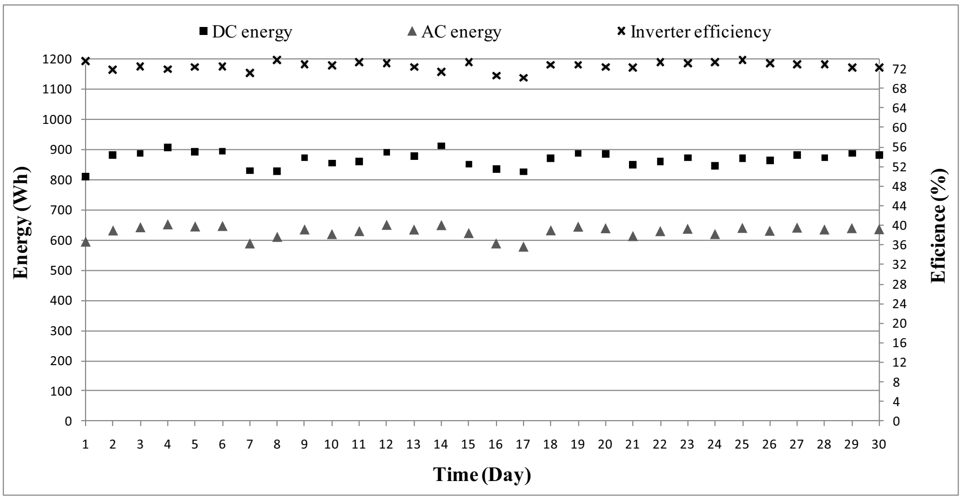


(a) June 2011



(b) July 2011

Fig. 3: Variation of the solar radiation, PV generation, and PV generator efficiency along the days.



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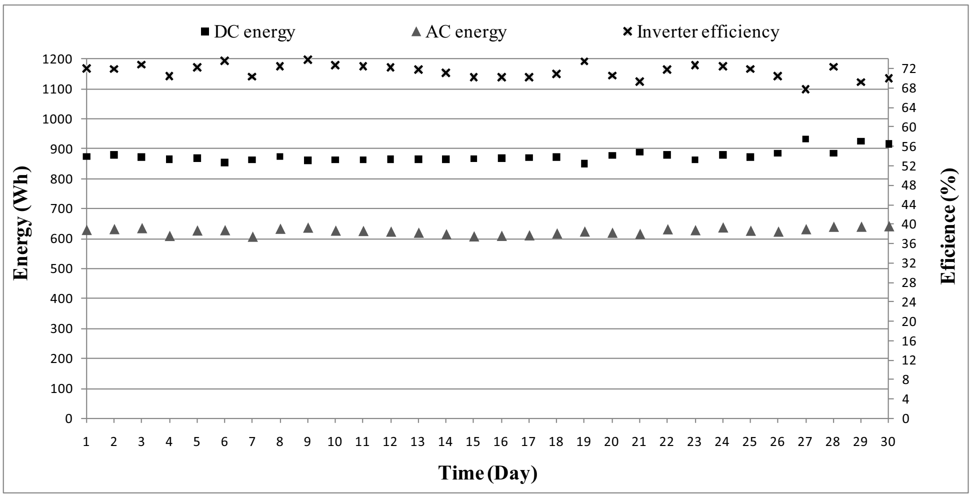


(b) July 2011

Fig. 4: Variation of the dc and ac energy at the inverter.

In figure 3 the variation of the daily average values of solar radiation from 3.000 to 7.500 Wh/m² and daily PV generation between 400 to 950 Wh can be seen. The PV generator efficiency is between 10.5 and 13.5% and has been determined taking into account the total area of each module, that is approximately 0.546 m². Commercial crystalline photovoltaic cell efficiency typically ranges from 18 to 21%. However, the solar cell efficiency is not equal to the module efficiency. The commercial module efficiency is usually 1 to 3% lower than the solar cell efficiency. Practical average values for module efficiency are between 9 % to 14%, due to glass reflection, frame shadowing, higher temperatures, etc. In this work, an average value of approximately 12% was found.

Regarding the energy flow in the inverter, the daily average values obtained for dc and ac energy were found between 810 Wh and 950 Wh, and 590 and 650 Wh, respectively. These ranges must be associated with the inverter´s operational conditions, which depend on dc voltage and current, ac power demanded by the load, temperature, self-consumption, and its efficiency conversion.

The inverter efficiency was determined taking into account the 24 hours in which it is connected. During this time only five hours (18:00 to 23:00 h) of inverter operation occur with significant load demand. Although in certain periods of the day there is no load (lamps, TV or radio) connected to the system, a residual load still remains connected, due to the consumer meter and digital timers used in the experiment. This is an important aspect because it becomes clear that even low demand, when connected for long periods of time, can result in significant consumption of energy for small SHS. Figure 5 shows detailed experimental results of the electric load and PV generation profile for five days of system operation.

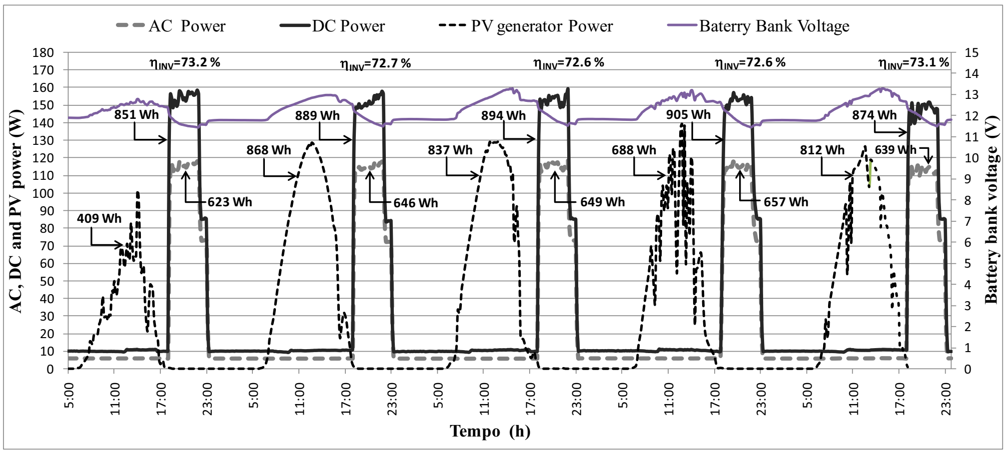


Fig. 5: Balance between PV generation and consumption: ac and dc power of the inverter, PV generation, and battery bank voltage.

The dc demand required by the inverter and the ac load demand supplied can be observed in figure 5. It is interesting to note a residual ac demand of approximately 6 W, which reflected to the inverter dc side reaches 10 W. From this value, 2 W to 4 W are associated to the self-consumption of the inverter and depend whether the inverter forced ventilation is working or not. The inverter used in the test does not have the power saving mode, in which the inverter reduces its self-consumption when the load demand is zero. This is an important tool to optimize the useful energy in small SHS, like the one tested in this paper.

Supposing the dc residual demand constant, it is possible to verify that the dc residual consumption, about 240 Wh per day, is an important fraction of the total energy produced by the PV generator and the energy required by the load. The contribution of the electronic energy meter and timers to this value corresponds to approximately 50%, still being a significant quantity of the PV generation. In other words and according to the experiment, the dc residual consumption contributed in a significant way to the deep discharged of the battery bank, as was demonstrated in figure 5, where minimum battery bank voltage values (about 11.6 V) were found.

Figure 6 shows the profile of solar radiation corresponding to the days presented in figure 5, as well as the PV generation. Note that in bad days of solar radiation the PV generation is reduced to less than a half of the generation in good days. In spite of that, the average efficiency of the PV generator remains approximately constant.

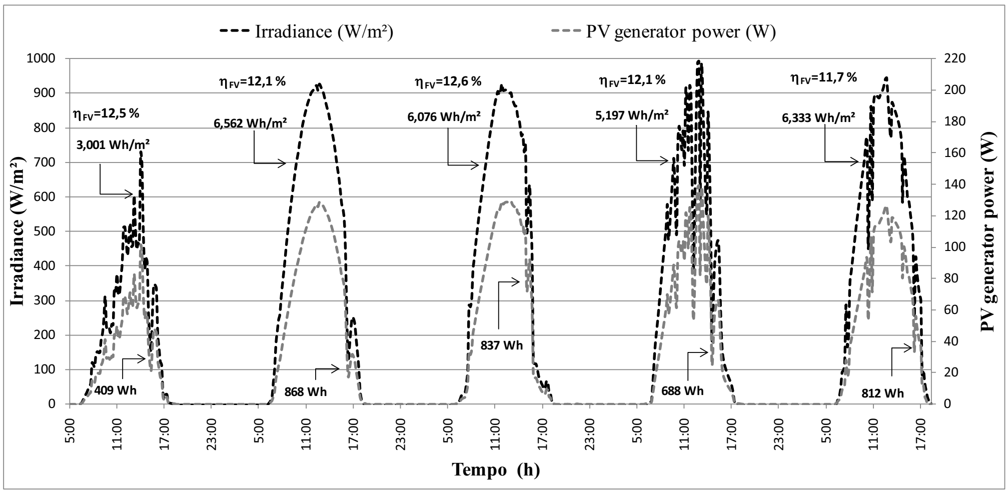


Fig. 6: Profile of the irradiance and PV generator power for five different days.

The average daily production of the PV generator for the five days is between 400 Wh and 900 Wh. The performance of the PV generator is influenced, among other factors, by the cell temperature. All the electrical parameters of PV module and electronic equipment (charge controller and inverter) depend on temperature. Moreover, the capacity of the battery bank is affected by the environment temperature variation. Figure 7 gives a good idea of the PV generator and battery bank’s shelter temperature profile along the five days considered in figures 5 and 6.

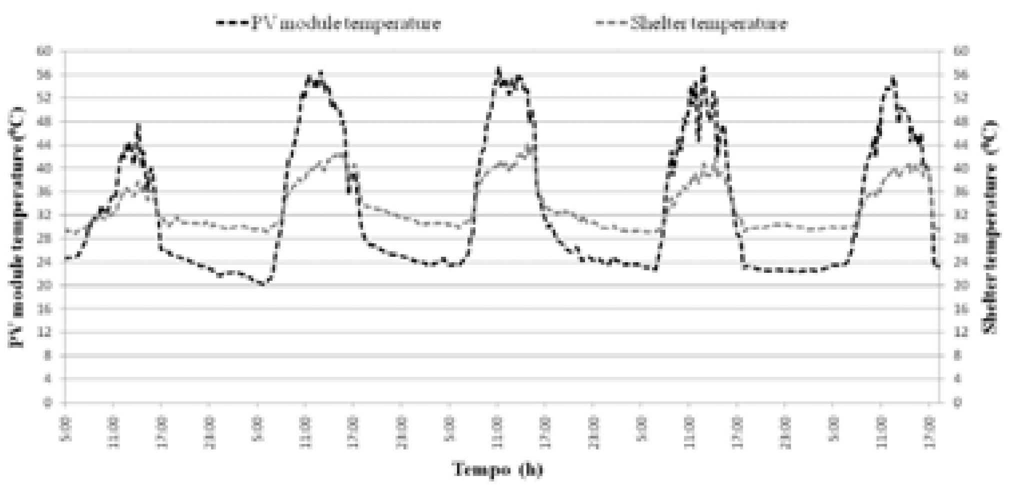


Fig. 7: Profile of the PV module and shelter temperature for the same five different days of figures 5 and 6.

Assuming that the temperature of the battery bank’s shelter is approximately equal to that of the electronic devices’ shelter, the results shown in figure 6 help explain the frequent inverter fan assisted cooling actuation, for temperature control, once the inverter's operating temperature range is between -20ºC and 50ºC. Note that temperature in the inverter ambient can easily exceed 40ºC.

5. The Santo Antônio Systems

This topic presents the experience acquired with the installation of five SHSs, similar to the system introduced in the previous section. Some operational data of two of these systems are shown. The five SHSs were installed in the community of Santo Antonio, municipal district of Breves, state of Pará, Brazil. Figure 8 displays the exact location of the five assisted river dweller residences.

Fig. 8: Geographical coordinates of Santo Antônio's community and their orientation regarding geographical north.

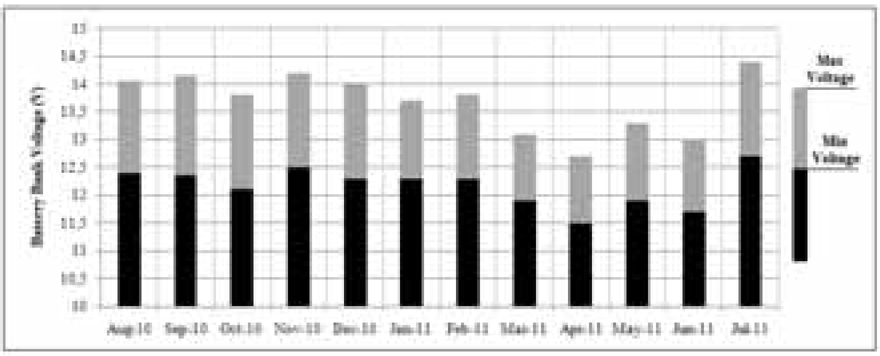
Figure 9 shows pictures of the residences which are surrounded by trees of the native forest. Despite being an appropriate source of energy for loads in the flooded Amazon region, the PV application has to deal with the consequent shading. This disadvantage must be carefully considered during the design and installation of the PV generator.

Fig.9: Two of the five river dweller residences with SHS.

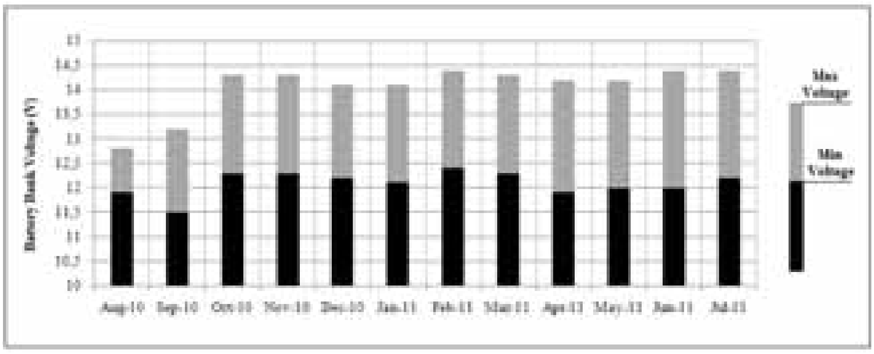
During the first year of accompaniment of the systems several failures of the SHSs were verified, mainly related to the operation of the inverter. Such failures were associated, in most of the situations, to inverter shut off due to overload situations.

Those faults, which usually need human interference to reestablish the system, turned off the load for long time periods. This happens as a consequence of the difficult and expensive access to the community. This fact demonstrates that the choice of appropriate inverters can avoid the human interference, minimizing the number and the duration of the interruptions. This is an important aspect from the point of view of the electric utility.

Figure 10 shows data obtained from the charge controllers installed in two of the five SHS of the community of Santo Antonio. The data displays maximum and minimum average values of battery bank voltage for each month of operation.



(a) SHS1



(b) SHS 2

Fig. 10: Maximum and minimum average monthly voltages of the battery bank.

Analyzing the data from the charge controllers and concerning overcharge and deep discharge protection, it is observed that it is difficult for the battery bank of the SHS 1 to reach full charge. The maximum average voltage remained, in most months, below 14.1 V, which is the voltage limit for the PV array disconnection in PWM controllers (2.35 V / element) (Oliveira, 2005 and Salazar, 2004).

Still from figure 10, it is also possible to identify the months of operation in which an increasing demand results in deep discharge of the battery bank. The high average maximum and minimum voltage in some months, like July 2011, could be associated to the systems failures that caused the shutdown of the inverter for several days.

The battery bank is usually designed for a depth of discharge of 20 % (State of Charge - SOC = 80 %). From Figure 11, it can be inferred that for a 12 V battery bank the corresponding voltage for a depth of discharge of 20 % is 12.2 V.

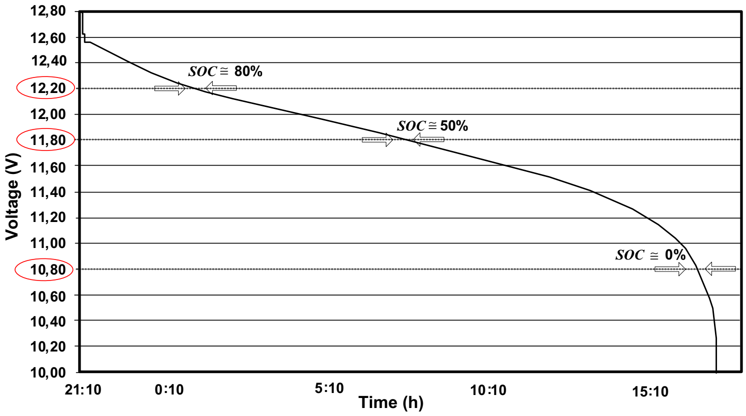
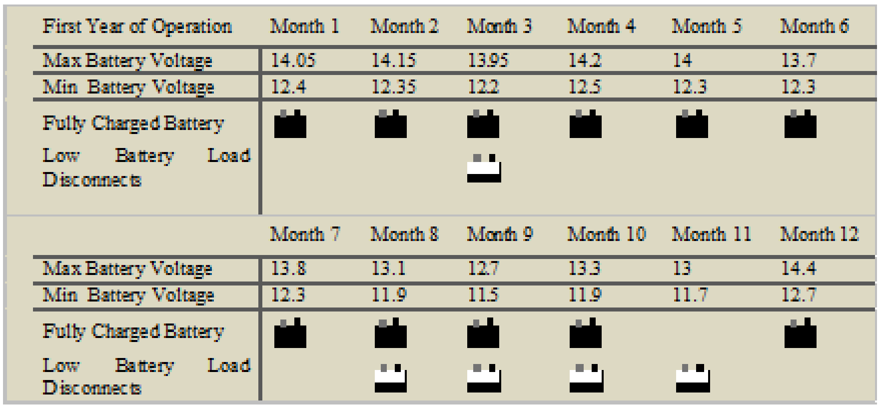


Fig.11: Discharge curve of a battery indicating the voltage for some SOCs (Salazar, 2004).

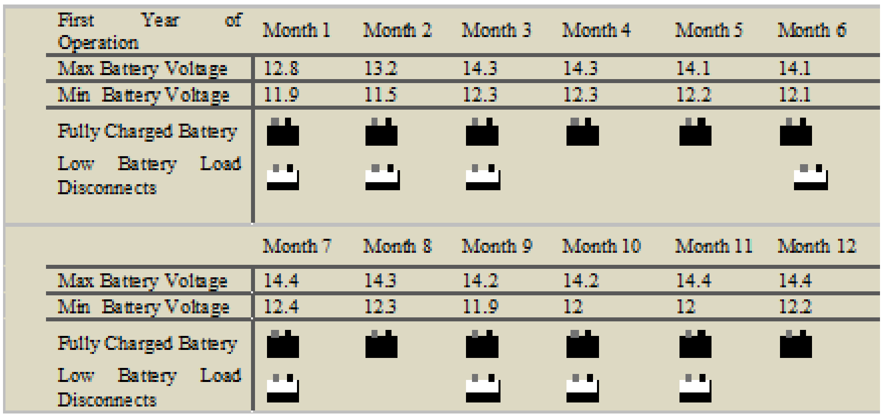
It is noticed, from figures 10 and 11, that in a significant part of the monitoring period both battery banks were submitted to average monthly discharges equal or inferior to 20 % (minimum battery bank voltage equal or superior to 12.2 V). However, in spite of the fact that many monthly averages lead to voltages above 12.2 V, occurrences of deep discharges were registered frequently, as shown in figure 12 and figure 13.



First Year of Operation	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
Max Battery Voltage	14.05	14.15	13.95	14.2	14	13.7
Min Battery Voltage	12.4	12.35	12.2	12.5	12.3	12.3
Fully Charged Battery	■	■	■	■	■	■
Low Battery Load Disconnects			□			

	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Max Battery Voltage	13.8	13.1	12.7	13.3	13	14.4
Min Battery Voltage	12.3	11.9	11.5	11.9	11.7	12.7
Fully Charged Battery	■	■	■	■		■
Low Battery Load Disconnects		□	□	□	□	

Fig. 12: Average annual data given by the charger controller for the first year of operation of SHS 1.



First Year of Operation	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6
Max Battery Voltage	12.8	13.2	14.3	14.3	14.1	14.1
Min Battery Voltage	11.9	11.5	12.3	12.3	12.2	12.1
Fully Charged Battery	■	■	■	■	■	■
Low Battery Load Disconnects	□	□	□			□

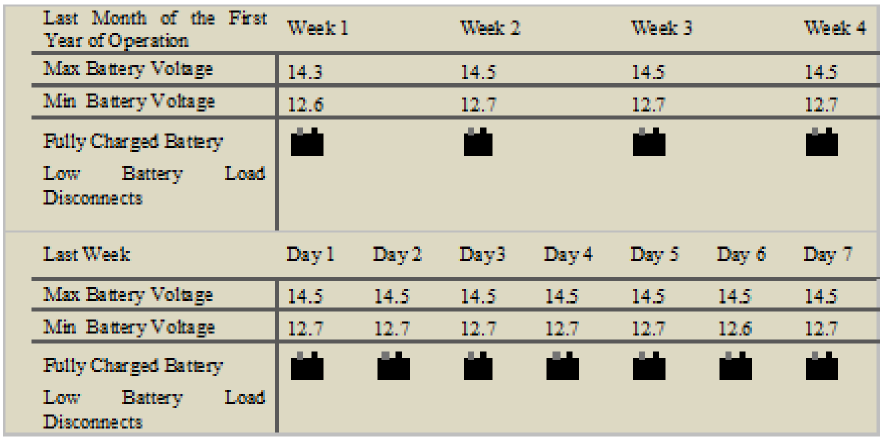
	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Max Battery Voltage	14.4	14.3	14.2	14.2	14.4	14.4
Min Battery Voltage	12.4	12.3	11.9	12	12	12.2
Fully Charged Battery	■	■	■	■	■	■
Low Battery Load Disconnects	□		□	□	□	

Fig. 13: Average annual data given by the charger controller for the first year of operation of SHS 2.

Because at high power the inverter could request currents bigger than the charge controller's capacity, the inverter was connected directly to the battery bank and not to the charge controller. For such configuration the load was disconnected only when the battery bank voltage dropped below the inverter minimum operation value, which could reach 10.5 V, depending on the operation condition and system. This configuration also avoids the disconnection of the charge controller at low battery bank voltage and, consequently, guarantees the continuity of the electric power supply.

On the other hand, the occurrence of deep discharges was frequent and the minimum average voltage of the battery bank indicates that it suffered discharges deeper than 50 %, which were due to the lack of discharge control from the charger controller. This leads to a decrease of the bank's useful life. But, due to the long distances and the access difficulties of the dispersed river dweller residences in the Amazon region, the continuity of the electric power supply, for the electric power utility, can be much more interesting than to extend the useful life of the battery banks.

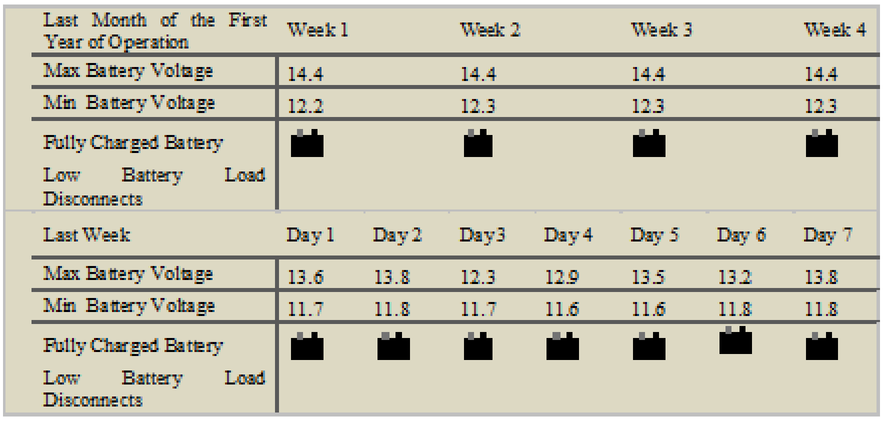
With the data from the first year of operation (figures 10, 12 and 13), it is noticed that there were occurrences of deep discharge in both SHSs, more frequently in SHS 2, in which interruption indication due to low voltage in 8 of 12 months was verified. The average monthly values are a good indication of the average operation of the battery bank. However, these values do not reflect the number of occurrences of deep discharges or full charges, which can be better visualized in figures 14 and 15, where the average daily values of the battery bank voltage and the occurrences of deep discharges or full charges for the last month of operation are presented.



Last Month of the First Year of Operation	Week 1	Week 2	Week 3	Week 4
Max Battery Voltage	14.3	14.5	14.5	14.5
Min Battery Voltage	12.6	12.7	12.7	12.7
Fully Charged Battery	■	■	■	■
Low Battery Load Disconnects				

Last Week	Day 1	Day 2	Day3	Day 4	Day 5	Day 6	Day 7
Max Battery Voltage	14.5	14.5	14.5	14.5	14.5	14.5	14.5
Min Battery Voltage	12.7	12.7	12.7	12.7	12.7	12.6	12.7
Fully Charged Battery	■	■	■	■	■	■	■
Low Battery Load Disconnects							

Fig. 14: Average data of the last month and the last week of the first year of operation given by the charger controller, SHS 1.



Last Month of the First Year of Operation	Week 1	Week 2	Week 3	Week 4
Max Battery Voltage	14.4	14.4	14.4	14.4
Min Battery Voltage	12.2	12.3	12.3	12.3
Fully Charged Battery	🔋	🔋	🔋	🔋
Low Battery Load Disconnects				

Last Week	Day 1	Day 2	Day3	Day 4	Day 5	Day 6	Day 7
Max Battery Voltage	13.6	13.8	12.3	12.9	13.5	13.2	13.8
Min Battery Voltage	11.7	11.8	11.7	11.6	11.6	11.8	11.8
Fully Charged Battery	🔋	🔋	🔋	🔋	🔋	🔋	🔋
Low Battery Load Disconnects							

Fig. 15: Average data of the last month and the last week of the first year of operation given by the charger controller, SHS 2.

According to the data contained in figures 14 and 15 it is observed that there was no occurrence of disconnection for Low Battery Load Disconnects in the last month of operation, but there were occurrences of Fully Charged Battery in all weeks and in all days of the last week of the same month. In SHS 1, this was due to the already mentioned characteristics of the inverter, operating with a configuration that does not allow automatic restart. About the SHS 2, there were no reports of failures during the last month of operation.

6. Conclusion

The experimental data made possible to verify an average inverter efficiency of approximately 72%. This value is very inferior to the 85% generally disseminated in the design process in Brazil. That verification, associated to the residual consumption on the inverter (such as the self-consumption of the inverter), can make the electric PV energy generation insufficient to supply the daily 433,3 Wh in the ac side, necessary to guarantee the energy availability of 13 kWh per month. The energy saving mode is an important function, mainly for low demands like the system presented in the paper.

Practical examples on the importance of inverter quality in the SHS operation were presented in this work. Moreover, some operating results on these systems help understanding the operation in hot and humid regions, such as the Amazon region.

The data also showed occurrences of low voltage disconnection of the battery bank. Since the configuration used does not enable the monitoring of discharging by the charge controller, the batteries suffer deep discharge because the only thing that limits it is the inverter low voltage disconnection protection in the input. Despite decreasing the useful life of the battery bank, this configuration allows the continuity of service and decreases the interruption by overloading the charge controller.

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