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TÍTULO/TITLE

ACTUAL PERFORMANCE AND ECONOMIC FEASIBILITY OF RESIDENTIAL SOLAR WATER HEATERS

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RESUMO-NOTAS/ABSTRACT-NOTES

Four residential solar water heaters currently available on the Brazilian market have been evaluated to their possible use for substituting the common electric shower head. The tests were carried out with the solar systems mounted side by side on an artificial roof. The hot water demand was simulated following a consumer profile which represents a Brazilian family with an income of seven minimun salaries. The data, which was collected automatically and presented in the form of graphs and tables, shows that an optimized solar water heater could save as much as 65% of the energy demand for residential water heating in the state of São Paulo. An economical study concludes that the installation and maintenance of such a solar system are feasible if long term financing is available.

OBSERVAÇÕES/REMARKS

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Presented at the IV Congress of Energy, 1987, Rio de Janeiro.

RESUMO

Quatro sistemas de aquecimento solar residencial disponíveis no mercado brasileiro foram avaliados considerando seu possível uso na substituição do chuveiro elétrico comum. Os sistemas testados foram instalados lado a lado num telhado artificial. A demanda de água quente foi simulada segundo um perfil de consumo que representa uma família brasileira com renda de sete salários mínimos. Os dados, que foram coletados automaticamente e apresentados em forma de gráficos e tabelas, mostram que um sistema de aquecimento solar atimizado poderia economizar 65% do consumo de energia para aquecimento residencial de água no Estado de São Paulo. Um estudo econômico conclui que a instalação e manutenção deste sistema solar são viáveis se financiamentos a longo prazo forem disponíveis.

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1. INTRODUCTION

The successful application of a new energy source like the solar energy for residential hot water heating has to satisfy three conditions:

- technically feasible,

- economically competitive, and

- socially accepted.

In Brazil the solar energy satisfies the first two conditions and depends on the social acceptance and the consciousness of the population of the deficiency of other energy sources. Hot water in Brazilian households is commonly heated with electricity and represents approximately 45% of the electric consumption. Since the hot water heaters normally are passage heaters with 3 to 4 kw connected load, the electric consumption peaks at certain hours (Figure 1), which makes the installation of an overdimensioned, and therefore expensive, powergrid necessary. In order to verify the viability of the use of solar hot water systems in the state of São Paulo, the Agency for Energy Application (Agência para Aplicação de Energia) contracted the Solar Laboratory of INPE to carry out performance tests on commercially available solar systems. There exists a great number of manufacturers fabricating hundreds of different collectors and storage tanks, but there is a lack of profound knowledge in sizing solar systems to the needs of the user, and the quality of the components and the installation are also often not as good as desired.

This report concerns the realization of the performance test, discussion of the results and the economic feasibility of the implementation of solar hot water systems in the state of São Paulo.

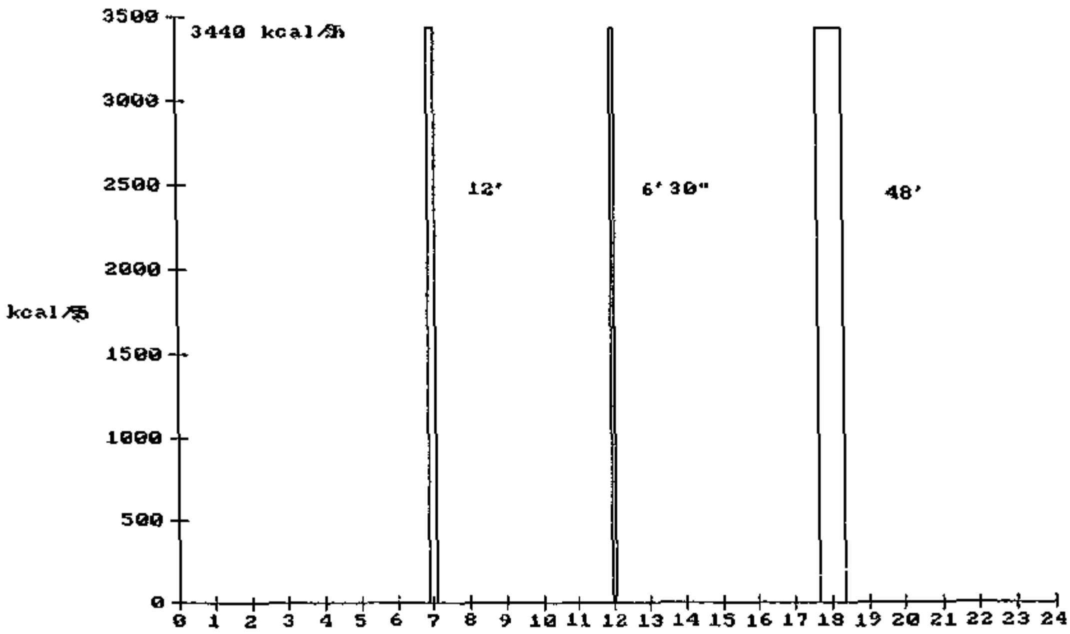

Fig. 1 - Daily domestic hot water load pattern.

2. SOLAR HOT WATER HEATERS UNDER TEST

For the performance test were chosen four different solar systems which could satisfy the preestablished hot water demand of a standard Brazilian family with an income of seven minimum salaries (Figure 1). All systems had been calculated from the manufacturer to provide 150 litre of 40°C hot water per day. An 1.5 kw thermostatically controlled electric heater in each system kept the tank temperature at least at 45°C in the case of the absence of sun.

The characteristics of the four tested systems are summarized in the following table.

TABLE 1

CHARACTERISTICS OF THE SOLAR SYSTEMS

SYSTEM	I	II	III	IV
DATE OF INSTALLATION	22/09/86	04/10/86	17/11/86	08/01/87
NUMBER OF COLLECTORS	2	2 (1)	1	2
TOTAL AREA m^2	3.74	3.72 (1.86)	2.79	3.48
COVER	NONE	CLEAR GLASS 3 mm	DIFFUSE GLASS 3 mm	DIFFUSE GLASS 4 mm
HOUSING	NONE	ALUMINIUM	ALUMINIUM BLACK	ALUMINIUM ANODIZED
INSULATION	NONE	GLASS WOOL 50 mm	POLYURETHANE FOAM 25 mm	POLYURETHANE FOAM
ABSORBER	POLYPROPYLENE PLATE	EPDM FLEXIBLE	COPPER TUBES AND FINS CLAMPED	COPPER TUBES ALUMINIUM FINS PRESSED
ABSORBER SURFACE	PIGMENTATION CARBON BLACK	PIGMENTATION CARBON BLACK	BLACK PAINT	BLACK PAINT
TYPE OF TANK	OPEN VERTICAL CYLINDER	OPEN CUBE	PRESSURIZED HORIZONTAL CYLINDER	PRESSURIZED HORIZONTAL CYLINDER
VOLUME (ℓ)	280	250	150	200
MATERIAL	POLYPROPYLENE	ABESTOS FIBRE	STEEL ENAMEL COATED	STAINLESS STEEL
INSULATION	GLASS WOOL 25mm	POLYURETHANE 100mm	GLASS WOOL 50mm	GLASS WOOL 50 mm
DUCTS	PVC 1 1/2"	POLYPROPYLENE 1 1/2"	COPPER 1"	COPPER 1"
ELECTRIC HEATER	127 VOLTS 8,2 Ω 1,96 KW	220 VOLTS 32,4 Ω 1,49 KW	127 VOLTS 9,3 Ω 1,73 KW	220 VOLTS 26,8 Ω 1,8 KW
THERMOSTAT	YES	YES (NEW 30/01/87)	YES	YES
HEATED VOLUME (% TOTAL VOL.)	50 %	25 %	50%	50%

3. INSTRUMENTATION AND TEST PROCEDURE

In order to obtain comparable data, the four solar hot water heaters were placed side by side on an artificial roof pointing north with an inclination of 35^{o} (Figure 2).

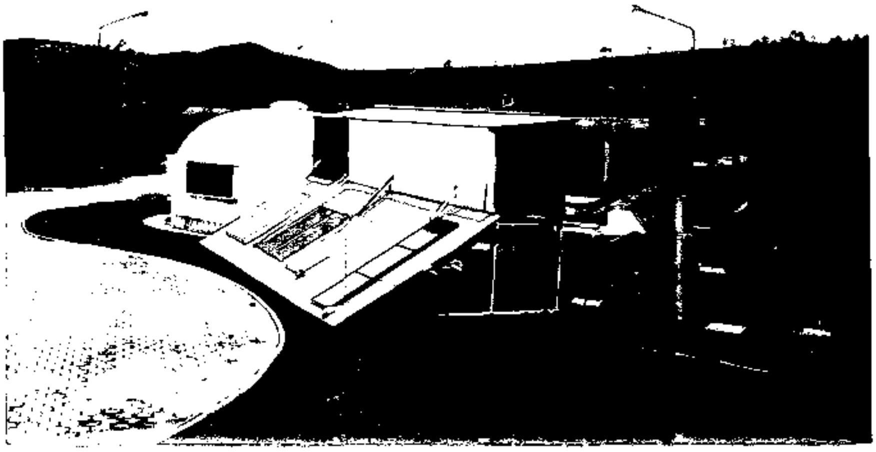

Fig. 2 - Roof with solar collectors.

The environmental conditions, solar radiation in the plane of the collectors, wind velocity at 1,8 m height, ambient and cold water temperature were measured by an Eppley Class I pyranometer, an anemometer and PT 100 resistance thermometers respectively. Three additional PT 100 resistance thermometers were installed throughout every system at the hot water outlet of the tank and the inlet and outlet of the collector array. Furthermore, the electric consumption of the auxiliary heaters was measured by common wattmeters. Auxiliary heating was allowed only two hours in advance of the hot water draw off by means of a timer connected in series with the thermostat. All measurements were taken in 5 seconds intervals and averaged every 6 minutes by a data acquisition system which also controlled the electromagnetic valves for the consumer simulation. The daily data were collected on tape and transferred to a computer for further processing.

A scheme of the measurement concept is shown in Figure 3.

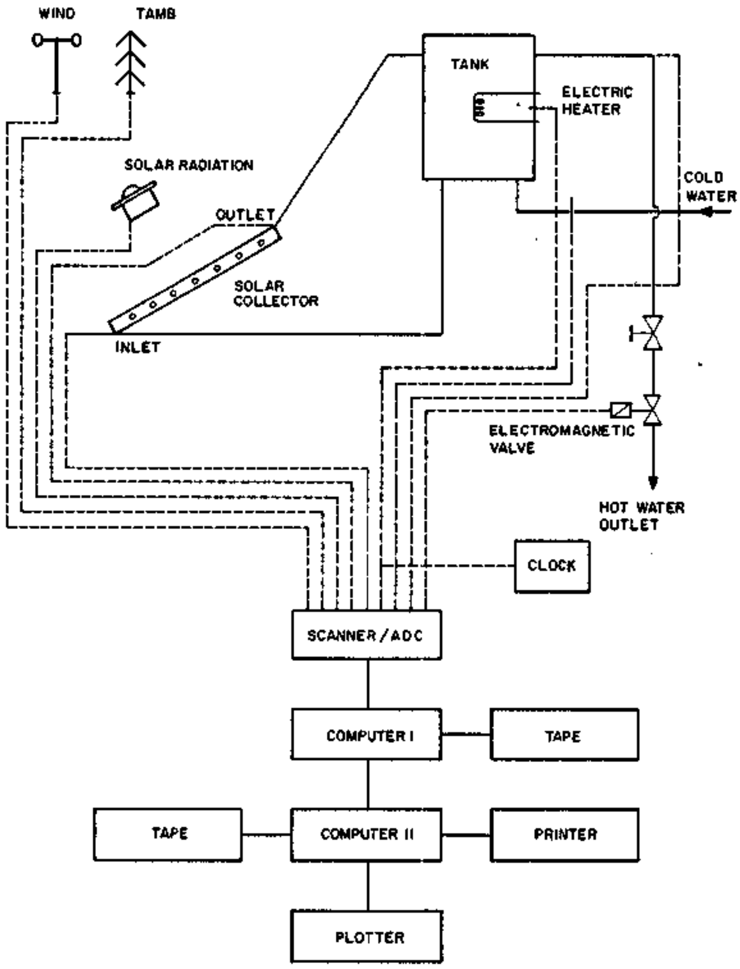

Fig. 3 - Installation of instrumentation.

Regarding to the load pattern (Figure 1), the four systems were subjected to a controlled hot water draw off until the precalculated amount of energy was removed:

$$Q_c = \int \dot{m}s \cdot cp \cdot (T_o - T_f). \qquad (1)$$

In order to keep the desired flow rate of 3 ℓ/min constant for all systems, a cold water reservoir with a hopper (overflow) mounted above all tanks provided a constant pressure height. With some valves the flow rate could be regulated precisely and was checked weekly with a graduated bucket and stopwatch.

After the installation of the solar systems and checkout of the measurement equipment, the test program took place, that is every day during 6 months, hot water was drawn off the systems and the performance calculated by measuring cold and hot water temperatures together with the environmental conditions.

4. CALCULATIONS AND RESULTS

The data acquisition system measured all data in five-second intervals and calculated average values every 6 minutes, which are then available for further processing. For every day was provided a data sheet showing graphically the meteorological data, and system behaviour. The solar radiation data; load on the systems; auxiliary heating demand; average, maximum, and minimum ambient temperatures; and wind velocities are summarized in a table. Figure 4 shows the data of a typical day in January 1987. From these data was calculated the performance of each system using the following rating factors:

Solar fraction

$$f = \frac{\text{useful load - auxiliary heating}}{\text{useful load}}$$

Solar efficiency

$$\eta_s = \frac{\text{useful load - auxiliary heating}}{\text{solar radiation on collectors}}$$

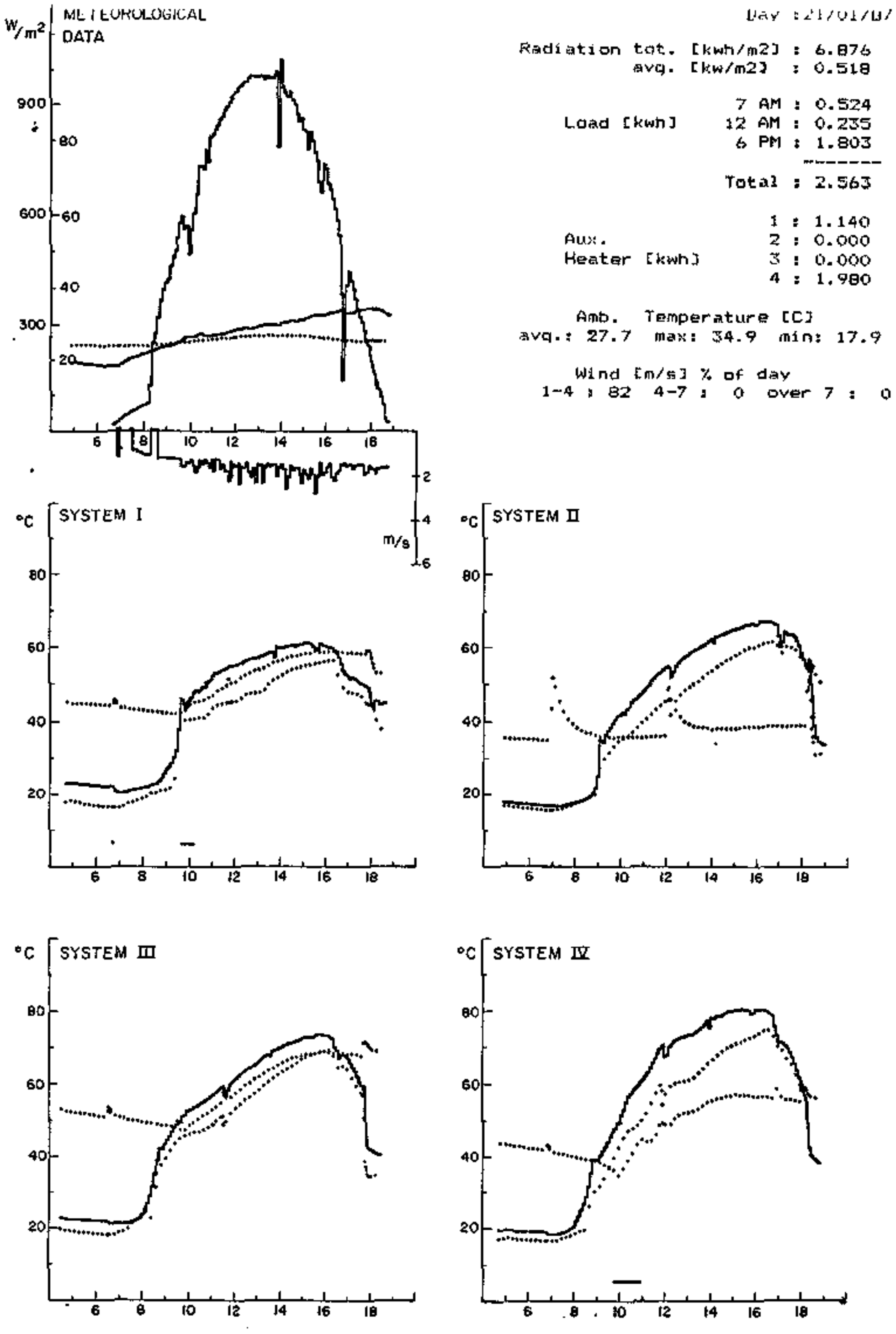

Fig. 4 - Data sheet with meteorological and system data.

a. solar radiation b. ambient temp.
c. cold water temp. d. wind velocity
e. coll. outlet temp. f. coll. inlet. temp.
g. hot water temp. h. aux. heating demand

Since every system has a different time constant and also "remembers" the influences of the past days, performance calculations based on daily data gave no useful data points. In agreement with (1) ten-day averages are the minimum acceptable periods to predict the performance of a particular system. However, a mathematical model (2) shows that five-day averages are already sufficient, if enough data points (3 month) are available. The average data outlined in this report have been correlated using the following formula:

$$f = a \cdot \frac{I \cdot A_c}{Q_c} - b \cdot \frac{T_o - T_a}{Q_c} \quad . \qquad (2)$$

The constants a and b could be expressed as follows:

$$a = F_r \cdot (\tau\alpha), \qquad (3)$$

$$b = (F_r \cdot U_c \cdot A_c + U_t \cdot A_t) \cdot 24. \qquad (4)$$

The data points given in Figure 5 are based on monthly or ten-day averages.

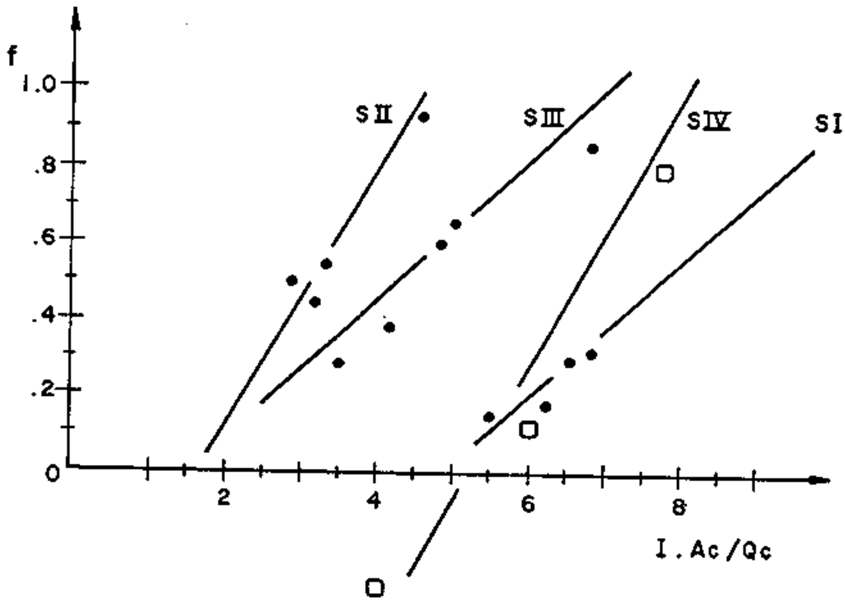

Fig. 5 - Performance data of solar systems.

It could be seen that there exists a great difference between the systems, and the most promising equipment (System IV) did not behave as expected. In order to explain the measurements, the collectors, tanks and other equipment had been inspected during the test. The collector of System I has no thermal insulation and obviously could not compete with the other systems. System II was a surprise with its high solar fraction and apparently simple construction, using rubber hoses as an absorber. Collector III is a conservative construction, but the heat removal factor F_r of the absorber is low due to a bad thermal contact between risers and fins. System IV has an excellent designed collector but its tank, like the ones from System I and III, is badly insulated, which caused the low overall performance of these three systems. The tank of System II is very well insulated and could therefore store all incoming energy without losses.

Common to all systems was the low quality of the thermostats. They were adjusted equally to 45^oC, but tank temperatures reached 65^oC before the auxiliary heaters switched off. A test on the switching limits carried out in a temperature controlled bath revealed a precision of $\pm 11^o$ which is far too bad. The solar fraction could have been significantly increased if better thermostats had been used.

5. ECONOMIC FEASIBILITY

The economic study is based on the performance data given in Figure 6. In order the compare the four systems, a solar fraction of 0.8 was chosen, that is, every system substitutes 80% of the total demand with solar energy. Since all systems should provide the same amount of energy, it is possible to calculate the necessary collector area for a given solar fraction and estimate the price of an optimal adjusted system. The investments in each system are summarized in Table 2.

TABLE 2

INVESTMENT COSTS OF SOLAR SYSTEMS

System	Tank US$	Collectors US$	Total US$
I	350	($4m^2$) 100	450
II	100	($2m^2$) 100	200
III	250	($3m^2$) 300	550
IV	700	($4m^2$) 500	1.200

Considering an average demand of 3 kwh/day of hot water and a solar fraction of 0.8, the system II needs to collect only 12 kwh/day while system I, III and IV need 30, 18 and 23 kwh/day respectively (Figure 6). Assuming now an average of 4.7 kwh/day of solar radiation, one could calculate the minimum necessary collector area of each system for a given demand. In Table 3 are summarized the real costs of the systems with adjusted collector areas and amortization.

TABLE 3

REAL COSTS OF SOLAR SYSTEMS

System	Adjusted collector area (m^2)	Adjusted system price (US$)	Estimated usability (years)	Yearly amortization *	Cost of kwh (mills)**
I	6.4	510	10	69.25	77
II	2.6	232	10	31.50	35
III	3.8	630	15	64.82	72
IV	4.9	1.310	15	134.79	149

* interest rate = 6%/year

** consumption = 900 kwh/year

The cost of installed kwh permits now a comparison with the cost of electricity for water heating. The price of electricity in Brazil for residential use oscillates between 31 and 62 mills, depending on the monthly consumption. Considering the given cost-price relationship, the investment in a solar system on private basis is only economical if the system II data are meet. Users with a consumption of 200 to 300 kwh/month could assume a pay back time of 8 to 7 years respectively.

However, analysing the financing of a solar system on private basis is not relevant because the electricity tariff is displaced from the real cost. Investments in transmission lines and power stations are high and are paid by foreign loans. The effective cost of 1 kw installed is in the order of US$ 2.500. For each household US$ 750 to US$ 1.500 additional installation cost are necessary to cover the elevated demand of the shower head (Figure 1).

These investments could not be paid by the electricity tariff. A shower head uses 600 to 900 kwh/year, a mere US$ 56 which pay barely the interest of the US$ 750 investment. Moreover, Brazil is a country with little capital and it should not be allowed to provide funds five times more than necessary for residential hot water heating.

6. CONCLUSION

The result of the test shows that the solar fraction of solar water heaters is a function of load, location of operation, and equipment efficiency, and that significant variations of performance exist between different systems. Since load pattern and location were the same for all systems, the variation of performance are caused by construction, adequate sizing, and component failure considerations. It should be remembered that up to now in Brazil there were no reliable test data available on the performance of complete solar water heaters. The obtained data demostrate that an adequate sized solar system could compete with the commonly used shower head. Further, these data here described are invaluable for future decisions on the application of solar energy and may stimulate the production of efficient and cheap solar water heaters. Absolutely necessary are governmental regulations which would permit long term financing of energy saving equipment.

7. NOMENCLATURE

A_c = Area of collector array (m^2)

a = Constant

b = Constant

C_p = Specific heat of water (kj/kg^oC)

f = Solar fraction (%)

F_r = Heat removel factor

I = Integrated solar radiation in the plane of the collector ($kwh/m^2/day$)

I_a = I average ($kwh/m^2/day$)

$\dot{m}_S$ = Mass flow of hot water to consumer (kg)

Q_c = Energy removed from the solar system (hot water) (kwh/day)

T_a = Ambient temperature (^oC)

T_f = Cold water temperature (^oC)

T_o = Hot water temperature (^oC)

U = Heat loss factor ($W/m^{2o}C$)

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