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# Optimizing a mixed water heating system (solar and electric) for rural areas

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**ABSTRACT.** The increasing consumption of electric energy used for heating water especially in peak periods, requires the use of alternative energy sources that meet the same needs being less costly. The use of solar energy for heating water allows reducing the demand and consumption of electric energy by a conventional electric shower. This study aimed at developing a software to simulate, design, and optimize a mixed water heating system (solar and electric), by using the software MATLAB. This software designed independently the area of a solar collector, the volume of the boiler, and the power of the auxiliary electrical resistance, in order to meet the needs of hot water and ensure the least annual cost. The optimized system when compared with the use of a conventional electric shower presented a time for return of the invested capital of around seven months.

**Keywords:** solar energy, solar collector, computer simulation.

## Otimização de um sistema misto de aquecimento de água (solar e elétrico) para áreas rurais

**RESUMO.** O crescente consumo de energia elétrica utilizada para aquecimento de água, principalmente nos horários de ponta, cria a necessidade da utilização de fontes alternativas de energia que atendam às mesmas necessidades e sejam menos onerosas. O uso da energia solar para aquecimento de água permite reduzir a demanda e o consumo da energia elétrica utilizada por um chuveiro elétrico convencional. O presente trabalho objetivou desenvolver um software para simular, dimensionar e otimizar um sistema misto de aquecimento de água (solar e elétrico), utilizando o software MATLAB. O software dimensiona a área do coletor solar, o volume do boiler e potência da resistência elétrica auxiliar de modo independente, de maneira a atender às necessidades de água quente e garantir o custo mínimo anualizado. O sistema otimizado, quando comparado à utilização do chuveiro elétrico convencional, apresentou um tempo de retorno do capital investido de aproximadamente sete meses.

**Palavras-chave:** energia solar, coletor solar, simulação computacional.

## Introduction

The Brazilian residential sector consumed 8220 toe of electricity in 2008, responsible for 22% of electricity consumed in the country (BRASIL, 2009). Ghisi et al. (2007) pointed out that electric showers account for, on average, 20% of electricity consumption in households from 12 Brazilian states, corresponding to more than 60% population. The load curve of the Brazilian electric system reaches a peak between 18:00 and 21:00 hours and this behavior is mainly due to the residential sector and the widespread use of electrical shower for heating water, present in about 73% households. The consequence of this behavior is a high demand for energy associated with a low load factor (NASPOLINI et al., 2010).

Solar water heating may contribute to reduce the demand and cost of energy, and to improve the social welfare (BATIDZIRAI et al., 2009) for its numerous advantages, like facility of construction and installation, low cost of operation and maintenance, easy conversion of existing conventional systems, and absence of local pollution (PUROHIT; MICHAELOWA, 2008).

Brazil has a great potential for a comprehensive utilization of solar energy. The average global solar radiation incident on an area of 8,514,876.599 $km^2$ varies between 4.25 and 6.5 kWh $m^{-2}$ day in the different regions of the country and much of the national territory has values larger than many European countries, where the use of solar energy is quite widespread (MARTINS et al., 2007).

Several authors have investigated simulation models for design and feasibility analysis of water heating systems using solar radiation, highlighting Oliveski et al. (2003), Pillai and Banerjee (2007), Hassan and Beliveau, (2008), Al-Salaymeh et al. (2010) and Dagdougui et al. (2011). The design and feasibility of these systems is highly dependent on climatic conditions, characteristics of energy consumption, employed materials, cost of energy, public policies incentives, and maturity of the local market.

The present study aimed at developing a software to simulate, design, and optimize a mixed water heating system (solar and electric), using the software MATLAB. This software designs the water heating system (solar collector area, boiler volume, and power of the auxiliary electrical resistance), in order to meet the needs of hot water and ensure the least annual cost.

## Material and methods

The study was developed at the Energy Laboratory of the State University of Western Paraná – UNIOESTE, using the software MATLAB 6.0. To simulate the consumption data of hot water for household purposes (water volume and temperature) it was used a thermosyphon solar heating system, with auxiliary electrical resistances. The baths were distributed throughout the day, considering the consumption of 60 liters water for every 10 minutes of bath (the shower has an average flow of 360 liters per hour).

For the design of the water heating system with minimal cost, several values were combined relative to boiler volume, solar collector area, and power of the auxiliary electrical resistance.

The boiler volume (V) varies according to the amount of hot water consumed. The initial volume ($V_i$) was set as being the largest amount of water consumed within an hour (this value is corrected for the commercial volume of the thermal reservoir immediately above). The final volume ($V_f$) of the reservoir was defined as being the sum of all volume of water consumed in a day. The increase in boiler volume is 100 liters.

The solar collector area (Ac) varies from 1 to 30 m², with increases of 1 m². The power of the auxiliary resistance (R) ranges from 0 to 12,000 W, with increases of 500 W.

An increase in boiler volume and in solar collector area implies an increased cost for system installation, while an increased power of the auxiliary resistance implies an increased cost of consumed electric energy.

All the costs of the system are calculated and annualized, considering the useful life of equipment and annual interest rate. The consumption costs with conventional electric shower are also calculated and annualized, in order to allow the comparison between the systems. The Figure 1 illustrates the flowchart of the simulation process.

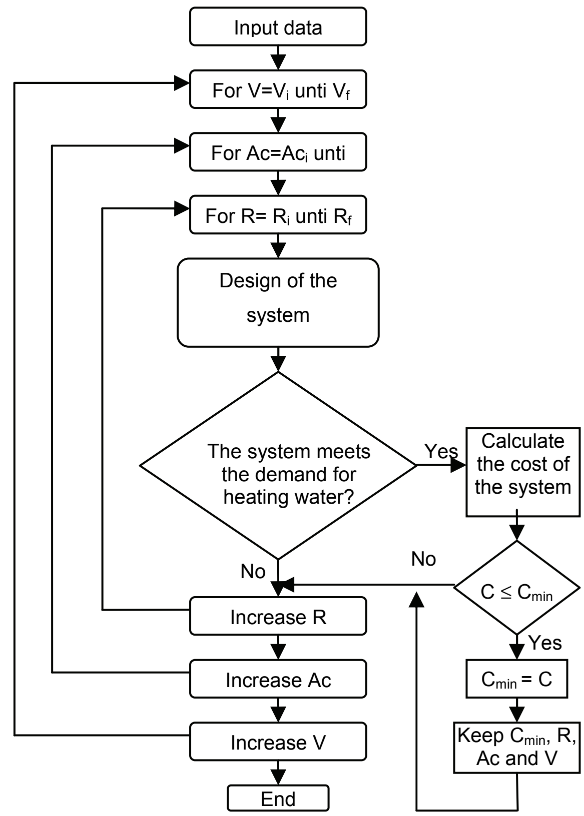


**Figure 1.** Flowchart of the simulation process.

The simulation starts by reading the input data relative to heating system and water consumption. Then, it is evaluated all possible combinations between boiler volume (V), solar collector area (Ac), and power of auxiliary resistance (R), to verify which combination is feasible to meet the requirements for water heating.

If the designed system meets the prescribed requirements, its cost is then calculated. If the cost is lower than the minimal cost initially set, the calculated cost becomes the new minimal cost and the variables R, Ac, and V, are kept.

But if the system does not meet the requirements for water heating, new increases of R, Ac, and V are made, until finding an optimal design of the system (desired heating with minimal cost of the system).

The computer simulation is based on the energy balance equation (DUFFIE; BECKMAN, 2006), where the increase in temperature of the water reservoir (boiler) is assigned to the incidence of solar radiation on the collector, and to the electric energy from the auxiliary resistance, and the decrease in temperature is attributed to the heat loss due to the inlet of cold water into the system.

The equations used in the energy balance are presented below.

$$m_s c_p (T^+_s - T^-_s) = Q_s \Delta t + Q_a \Delta t - (U A) \Delta t (T^-_s - T_a) - - m_c c_p (T_c - T_f); \quad T_s \geq T_c \quad (1)$$

where:

$m_s$: is the mass of water inside the boiler (kg);

$m_c$: is the mass of cold water entering into the system (kg);

$c_p$: is the specific heat of water (Wh $kg^{-1}$ °C);

$T^+_s$: is the temperature at time later (°C);

$T^-_s$: is the temperature at the instant before (°C);

$T_a$: is the ambient temperature (°C);

$T_c$: is the temperature of the water for consumption (°C);

$T_f$: is the temperature of the cold water (°C);

$\Delta t$: is the interval of the simulation analysis (h);

$Q_s$: is the solar power transmitted to the fluid (W);

$Q_a$: is the power of the auxiliary resistance (W);

U: is the overall coefficient of heat transfer (W $m^{-2}$ °C);

A: is the total area of the reservoir ($m^2$).

By isolating the variable $T^+_s$ in the Equation 1, it is found the equation of variation of water temperature in the reservoir.

The term $Q_s$ of Equation 1 is the difference between absorbed solar radiation and heat losses through the collector, and can be written as follows:

$$Q_s = A_c F_r [S - U_L (T_{mp} - T_a)] \quad (2)$$

where:

$A_c$: is the solar collector area ($m^2$);

$F_r$: is the heat removal factor of the solar collector (dimensionless);

S: is the solar radiation (W $m^{-2}$);

$U_L$: is the overall coefficient of heat transfer between the collector and the air;

$T_{mp}$: is the temperature of the collector absorber plate

## Results and discussion

For example, the Tables 1 and 2 present the input data of a simulation performed for a 24 hours-period. The Table 1 lists data of water consumption, solar radiation, and temperature throughout 24 hours of simulation.

The Table 2 presents the data of the solar heating system, water temperature, and economic data.

**Table 1.** Hourly data for ambient temperature, solar radiation and hot water consumption (for a 24 hour period).

| Time | Ambient Temperature (°C) | Solar radiation (W $m^{-2}$) | Water consumption (L) |
|---|---|---|---|
| 13:00 | 30 | 830 | 0 |
| 14:00 | 32 | 910 | 360 |
| 15:00 | 27 | 1000 | 180 |
| 16:00 | 25 | 950 | 60 |
| 17:00 | 21 | 500 | 60 |
| 18:00 | 19 | 500 | 120 |
| 19:00 | 17 | 0 | 120 |
| 20:00 | 16 | 0 | 180 |
| 21:00 | 16 | 0 | 0 |
| 22:00 | 16 | 0 | 0 |
| 23:00 | 15 | 0 | 120 |
| 24:00 | 14 | 0 | 240 |
| 01:00 | 13 | 0 | 360 |
| 02:00 | 11 | 0 | 0 |
| 03:00 | 10 | 0 | 0 |
| 04:00 | 10 | 0 | 0 |
| 05:00 | 14 | 0 | 0 |
| 06:00 | 18 | 100 | 0 |
| 07:00 | 19 | 250 | 240 |
| 08:00 | 21 | 300 | 0 |
| 09:00 | 22 | 450 | 360 |
| 10:00 | 26 | 520 | 60 |
| 11:00 | 27 | 680 | 120 |
| 12:00 | 29 | 720 | 0 |

**Table 2.** Input data used in the simulation.

| | |
|---|---|
| Overall coefficient of heat transfer between the boiler and the air | 5 W $m^{-2}$ °C |
| Overall coefficient of heat transfer between the collector plate and the air | 4 W $m^{-2}$ °C |
| Heat removal factor of the solar collector | 0.75 |
| Specific heat of water | 1.16 Wh $kg^{-1}$ °C |
| Temperature desired for the water for consumption | 40°C |
| Average temperature of the cold water | 15°C |
| Average flow of the shower | 360 L $h^{-1}$ |
| Cost of the energy (rural tariff – COPEL) | R$ 0.22 $kWh^{-1}$ |
| Annual interest rate | 8% |
| Useful life of the solar heating system | 25 years |

In the Table 2, the coefficients relative to the solar heating system (overall coefficient of heat transfer between the boiler and the air, overall coefficient transfer between the collector plate and the air, and heat removal factor of the solar collector) are average values quoted by Duffie and Beckman (2006), under similar conditions of utilization of the system.

From the input data presented, the application performs the optimized design of the system, according to the results presented in Table 3.

**Table 3.** Design of the solar heating system.

| | |
|---|---|
| Solar collector area | 30 $m^2$ |
| Boiler volume | 600 L |
| Auxiliary electric resistance | 10 kW |
| Initial cost for installation | R$ 11,951.69 |
| Annual cost of electricity | R$ 19,918.00 |
| Annualized total cost | R$ 21,338.00 |

Besides the design of the entire heating system, the Table 3 presents the initial cost for installation, the annual cost of electricity consumed by the auxiliary resistance, and the annualized total cost (considering an interest rate of 8% a year and all the other costs, including maintenance).

The Figure 2 illustrates the variation on the average temperature of water inside the boiler.

From 13 to 14 hours, the average temperature inside the boiler increased, solely due to the solar radiation incident on the system (Figure 2). Likewise, from 14 to 18 hours, the temperature continued to rise, but at lower rates, due to the combined effect of consumption of hot water (and consequent inlet of cold water into the system) and the incidence of solar radiation.

From 18 to 21 hours, and from 23 to 2 hours, the temperature sharply reduced, owing the consumption of hot water and no more incidence of solar radiation. Also it was verified at 1 hour, the auxiliary resistance was switched on to allow the consumption of water at the desired temperature.

From 21 to 23 hours, and from 2 to 6 hours, the temperature decreased at a slight rate, due to the heat losses through the boiler walls (during these intervals there was no incidence of solar radiation, nor consumption of hot water).

At 6 hours in the morning it was started again the incidence of solar radiation on the system, and from 7 to 8 hours, there was the consumption of hot water. At this time, the auxiliary resistance was switched on to keep the temperature at desired levels.

From 8 to 9 hours, the average temperature increased due to the incidence of solar radiation, and from 9 to 10 hours there was a drop in temperature, caused by the significant consumption of hot water during this period.

From the 10 to 12 hours, despite the consumption of hot water, the average temperature remained increasing owed a greater incidence of solar radiation.

The Table 4 shows the design of an electric shower used to supply the same demand for hot water previously presented, as well as the respective annual cost of consumption of electric energy.

For this simulation, the time for return of the capital invested on the solar heating system (discounted payback) when compared to the consumption of a conventional electric shower was 0.59 years (around seven months).

The Figure 3 displays a comparison between the annualized costs of the solar heating system and of the electric shower, as a function of the variation in the electricity tariff.

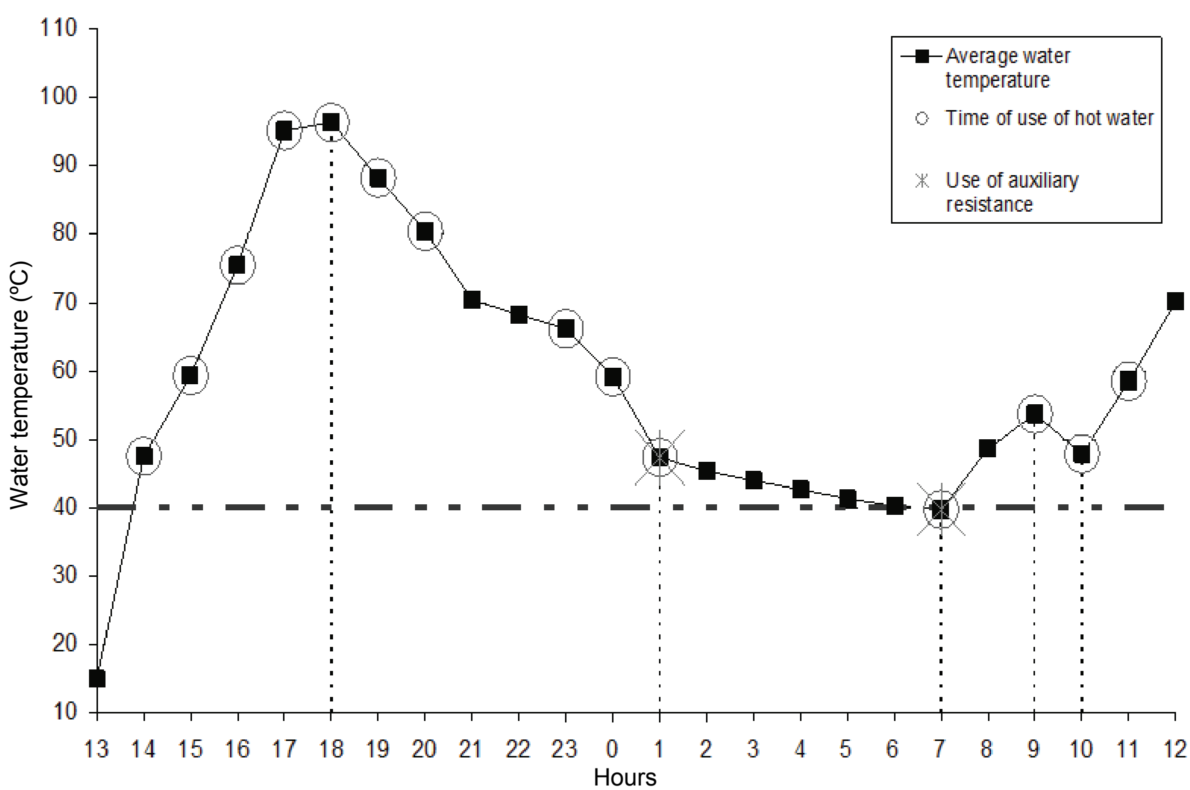


**Figure 2.** Average temperature of water inside the boiler.

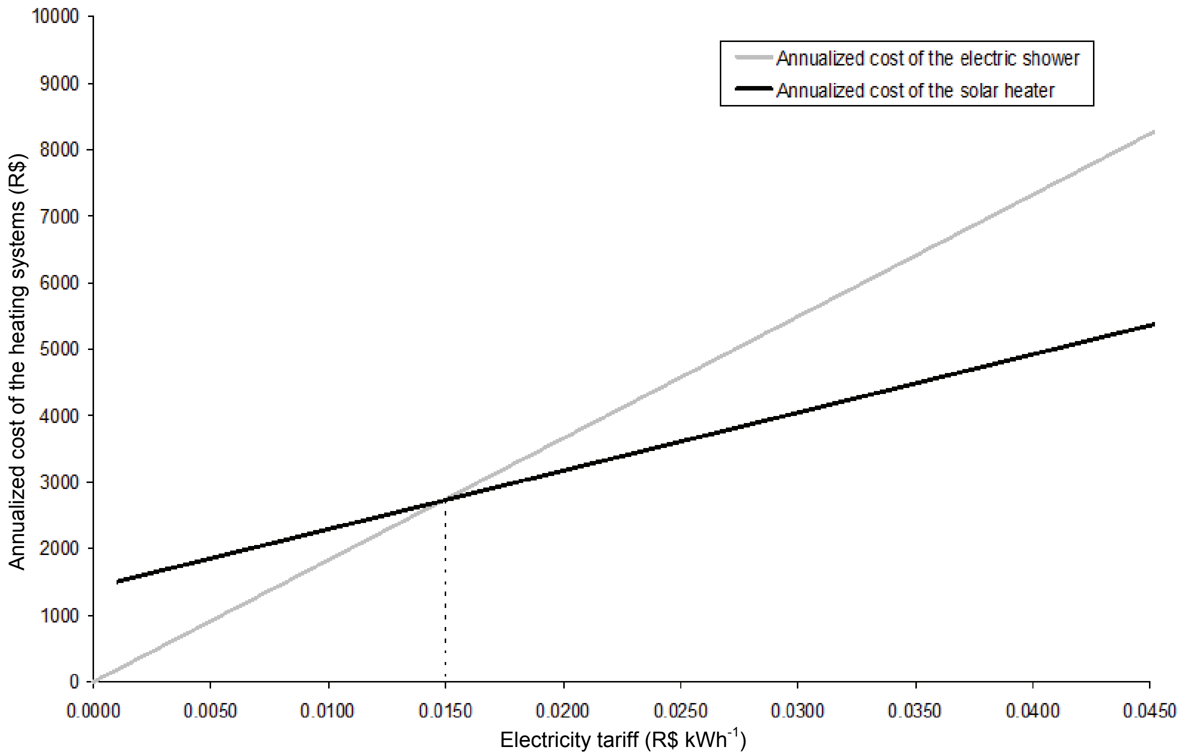


**Figure 3.** Annualized cost of heating systems vs. electricity tariff.

**Table 4.** Design of a conventional electric shower equivalent.

| | |
|---|---|
| Power of the electric shower | 10 kW |
| Annual cost of electric energy consumed by the electric shower | R$ 41,635.00 |

In Figure 3 it is observed that for any electricity tariff above R$ 0.015 $kWh^{-1}$ the cost of the solar heater is economically more feasible than the cost of a conventional electric shower.

## Conclusion

The software developed proved to be a useful tool for design and optimization of a mixed solar heating system allowing to calculate which combination of the system (boiler volume, solar collector area, and power of the elect power of the auxiliary electrical resistance) comply the need for hot water with a minimal cost.

The designed solar heating system spend around seven months to pay off the investment, a quite satisfactory time, when compared to the conventional electric shower, showing that the use of solar energy for heating water is efficient and economically viable.

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