OPTIMIZATION OF A COMPACT SOLAR DOMESTIC HOT WATER SYSTEM FOR LOW-INCOME FAMILIES WITH PEAK DEMAND AND TOTAL COST CONSTRAINTS

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Abstract – An optimization method is proposed to size a compact solar domestic hot water system (CSDHWS) for low-income families with multiple hot water load profiles. The Life Cycle Savings (LCS) optimization is carried out using the Transient Simulation Program (TRNSYS) with the Generic Optimization Program (GenOpt) for Florianópolis (27.6S, 48.5W), Brazil. A total of seven variables are simultaneously optimized. Results can be used to locally optimize CSDHWS's based on meteorological data. The proposed optimization method is an effective measure to reduce peak demand as well as total energy consumption.

1. INTRODUCTION

The Brazilian National Electric Energy Agency (ANEEL) requires every electric utility company in Brazil to invest 0.5% of its net profit in energetic efficiency research and development programs. One of the main concerns of the utility companies is the widespread use of electric showerheads and the resulting peak electricity demand between 18h and 21h. Studies have shown that electric showerheads represent approximately 23% of a households energy demand (Prado and Gonçalves, 1998). Electric showerheads are very cheap, usual prices lie under US$30, have a nominal power between 4kW and 8kW and are very efficient (90-95%) in terms of energy conversion. All these aspects guarantee broad use among low-income families.

The Solar Energy Laboratory (LABSOLAR), at the Federal University of Santa Catarina, Brazil, is currently coordinating a project to study the influence of a compact solar domestic hot water system (CSDHWS) on electric energy peak reduction and savings. A total of sixty families will be receiving CSDHWS's and another thirty will have electric showerhead energy consumption measured for comparison. The local government has great interest in implementing housing programs for low-income families with solar energy systems for water heating. One of the main problems is the appropriate system sizing to attend the needs of the greatest number of families, which is the main object of this article. Aspects such as system total cost and peak demand are addressed specifically.

Optimization of solar system design parameters using TMY data and TRNSYS has already been done for a restricted number of parameters using exhaustive simulation. Shariah and Löf (1996) draw important conclusions concerning the tank-volume to collector-area ratio for a thermosyphon solar water heater. In a later study (1997), the same authors investigated the effects of the location of the auxiliary heater on annual performance of thermosyphon solar water heaters under variable operating conditions. One of their findings was that the hot water draw profile, the daily load volume and temperature have a large effect on the performance of the solar heater. Michaelides and Wilson (1997) also studied the effects of the position of the auxiliary heater in thermosyphon solar water heaters. Colle *et al* (2001) proposed a simplified method to optimize the insulation thickness of the thermal storage unit. Borges and Correia (1998) were the first to use TRNSYS coupled with a non-linear optimization routine in order to obtain optimal design solutions of n-dimensional problems, thus avoiding exhaustive simulation.

In the present paper an optimization method and an objective function are proposed, which have the ability to contemplate multiple hot water load profiles. The main goal is to optimize a CSDWHS for a group of different users.

2. SOLAR SYSTEM DESCRIPTION

The CSDHWS consists of a single glazed flat plate collector and a horizontal thermal storage unit equipped with a resistor, located immediately above the collector, as shown in Fig. 1. The system is easily accommodated on the rooftop and integrated with existing piping. An additional electric showerhead with limited nominal power serves as an auxiliary heater. Therefore, auxiliary energy is added at two points. The system is also equipped with a thermostatic mixing valve at the thermal storage unit outlet pipe, which prevents scalding. The CSDHWS is only used for showering purposes.

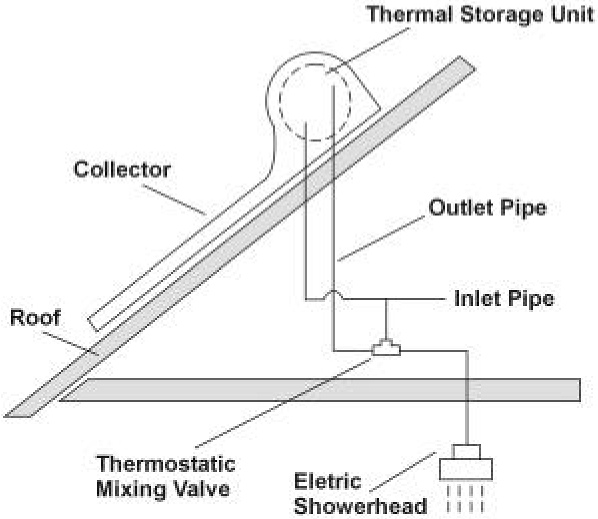

Figure 1 – CSDHWS scheme

3. PROBLEM MODELING

The hot water load profiles are certainly the most important simulation input data. The total lack of information on this subject for Brazilian low-income families is a problem that needs to be overcome. Measured values are rare and expensive. Jónsson and Holtsberg (1994) propose a modelling technique to estimate hot water consumption in district heating systems where only measurements of the total mass flow for both heating and hot water are available. In their study hot tap water consumption was assumed to be in great extent independent of weather. Lowenstein and Hiller (1996) present a methodology that consists in collecting highly resolved hot water draw data (averaged over 15s or less) in order to recognize flow patterns for individual end-uses within a residence. Hot water use is therefore disaggregated using only flow information of hot water from the water-heater. In a later paper (1998), the same authors suggest the temperature monitoring of the hot water lines as a cost-effective measure to increase the range of buildings that can be accurately studied. Abrams and Shedd (1996) collected data in 20 commercial buildings and 16 residential sites form 1983 to 1995. Daily hot water use was found to vary greatly from annual average figures and seasonal variations in cold inlet temperature had substantial effect on energy consumption for service water heating. Jordan and Vajen (2000) simulated a solar combi-system with different hot water load profiles and found that fractional energy savings are 3% lower in the summer period using a more realistic load profile compared to a simplified one. Knudsen (2002) performed numerical simulations with detailed simulation models to investigate the influence of different hot-water consumptions and consumption patterns on the thermal performance of solar domestic hot water systems. In his study, the net utilized solar energy for the systems was higher with the unrealistic domestic hot water load profile than with the realistic profile. Available data on hot water usage is strictly based on measurements performed in developed countries, with few exceptions (Meyer and Tshimankinda, 1998a and 1998b; Papakostas *et al*., 1995). Vine and Szydlowski (1986) investigated domestic hot water consumption in four apartment buildings managed by the San Francisco Public Housing Authority. Their results showed that survey information can de used to estimate hot water use in multifamily buildings without detailed monitoring. This is the only economically viable method available in the present case. A questionnaire was applied on 200 low-income families in Florianópolis, Brazil, in order to obtain a representative hot water load profile for different population segments. Segmentation was done based on the number of family members. The results are at best representative for each family segment living at the public housing plant in question.

The P_1-P_2 method is used to evaluate the Life Cycle Savings (LCS) for each hot water load profile. These values are then averaged based on the percentage of families with a given profile. In this manner, a representative LCS is obtained.

TRNSYS was used to model the CSDHWS and the different hot water load profiles. Optimization was carried out with GenOpt, a java based optimization program developed by the Simulation Research Group at the Lawrence Berkeley National Laboratory.

4. OBJECTIVE FUNCTION

The objective function is divided in two parts, one that contemplates operational costs and the other that evaluates capital costs. Both are calculated over the systems life cycle using modified P_1 and P_2 factors (Brandemuehl and Beckman, 1979).

4.1 Operational Costs

The objective function evaluates the cost of auxiliary electric energy, user comfort and instantaneous power consumption for the CSDHWS.

An hourly based electric energy rate is used, with prices 15% higher between 18.5h and 21.5h. Such a rate has not yet been implemented in Brazil for residential users but is considered by many a matter of time. Therefore, energy consumption during the referred period is discouraged.

User comfort is quantified in terms of the amount of energy required to elevate the water temperature to the desired level (US$/kWh). In doing so, the CSDHWS is penalized every time it is not able to provide water at the specified temperature.

Instantaneous power consumption should not exceed that of stand-alone standard electric showerhead systems. Once again, the positive difference between the actual power consumption and a reference value is integrated over time and multiplied by a cost coefficient.

Therefore, operational costs can be evaluated according to Eq. (1),

$$\begin{aligned} OC_{CSDHWS} &= \int (\dot{Q}_{AUX1} + \dot{Q}_{AUX2}) c_1 dt \\ &+ \int (\dot{Q}_{AUX1} + \dot{Q}_{AUX2} - \dot{Q}_{AUXR})^+ c_2 dt \\ &+ \int (T_{SET} - T_C)^+ \dot{m} c_p c_3 dt \end{aligned} \quad [1]$$

where + means that only positive values are considered.

The standard stand-alone electric showerhead system (SHS) has its operational costs evaluated by the Eq. (2).

$$\begin{aligned} OC_{SHS} &= \int \dot{Q}_{AUX-SH} c_1 dt \\ &+ \int (\dot{Q}_{AUX-SH} - \dot{Q}_{AUXR})^+ c_2 dt \\ &+ \int (T_{SET} - T_C)^+ \dot{m} c_p c_3 dt \end{aligned} \quad [2]$$

4.2 Life Cycle Savings

Capital costs are expressed as a ratio of the total system costs. In this specific case, the idea is to integrate the solar system in the house mortgage payment, which is paid monthly.

Using modified P_1 and P_2 factors, Eq. (3) is obtained for the LCS of the ith population segment.

$$LCS_i = P_1 (OC_{SHS} - OC_{CSDHWS})_i - P_2 C_S \quad [3]$$

$$P_1 = PWF(N_E, i_F, d) \quad [4]$$

$$P_2 = PWF(N_E, i_{TA}, d) r_{TA} + PWF(N_E, i_M, d) r_M \quad [5]$$

$$PWF(N, i, d) = \sum_{j=1}^{N} \frac{(1+i)^{i-1}}{(1+d)^j} \quad [6]$$

The P_1 and P_2 factors as well as C_S are the same for all hot water load profiles. The difference appears in the $OC_{SHS} - OC_{CSDHWS}$ term. LCS values are averaged through coefficients that represent the percentage of each population segment, obtaining the preliminary objective function value, Eq. (7).

$$OF^* = P_1 \sum_i a_i (OC_{SHS} - OC_{CSDHWS})_i - P_2 C_S \quad [7]$$

$$\sum_i a_i = 1 \quad [8]$$

The total cost constraint is a major concern when treating with solar systems for low-income families, since any additional payment on the monthly mortgage is difficult to meet. Multiplying the preliminary objective function by a normalized exponential factor creates a continuously increasing barrier in the objective function, without introducing discontinuities. This factor is obtained subtracting the total cost constraint from the actual total system cost and dividing this difference by the total cost constraint. We multiply the resulting value by a factor l >1 depending on how strong the total cost constraint is desired. Therefore we have,

$$OF = -OF^{*}{}^{\frac{-(C_S - C_{SR})^+}{C_{SR}} l} \quad [9]$$

where a negative sign has been introduced since GenOpt always seeks for a minimum.

5. OPTIMIZATION PROCEDURE

GenOpt only requires the objective functions value. GenOpt generates the TRNSYS input file, starts TRNSYS with a user defined command line and waits for the simulation to end. Then the value of the objective function is read from the specified TRNSYS output file. Optimization is performed and a new input file is written, with new parameters. This procedure repeats itself until the stopping criterion defined within GenOpt is satisfied.

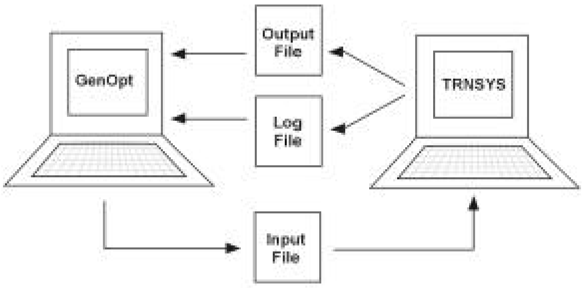

Figure 2 – Optimization procedure

The algorithm used was the simplex method of Nelder and Mead with the extension of O’Neill (O’Neill, 1971).

5. CASE STUDY

In order to test the proposed method two hot water load profiles were randomly chosen (Fig. 3) and assigned weight factors (percentages). The daily load volume of each hot water profile is 115.2 litres, corresponding to 4 showers of 7.2 min. This could be a typical situation for a 3 member family, two adults and one child. In the first profile showers are evenly distributed, two in the morning and two at night. In the second profile showers are concentrated at night. A 10 year meteorological data series for Florianópolis, obtained in a BSRN radiometric station, was used (Abreu *et al.*, 2000).

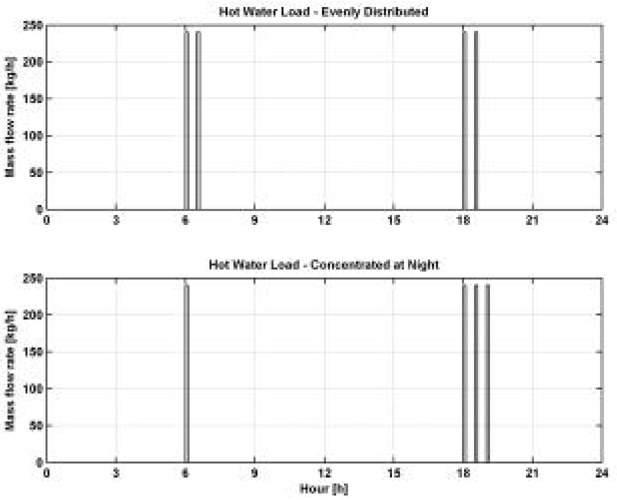

Figure 3 – Simulated hot water load profiles

A total of 7 variables were optimized, as shown in table 1. Table 2 summarizes values of some relevant simulation parameters.

Symbol	Optimized Value	Unit
A_C	1.74	[m^2]
V_T	0.106	[m^3]
$\dot{Q}_{AUX1}$	5.40	[kW]
$\dot{Q}_{AUX2}$	3.89	[kW]
T_{THERMO}	26.9	[°C]
T_{TMV}	38.1	[°C]
b	32.6	[°]

Table 1 – Optimized variables

Symbol	Value	Unit
F_RU_L	5.985	W/m^{2}K
$F_R(ta)_n$	0.699	[-]
b_0	0.163	[-]
$\dot{Q}_{AUXR}$	5.56	[kW]
T_{SET}	38	[°C]
C_A	84.75	[US$/m^2]
C_E	169.50	[US$]
C_V	84.75	[US$/m^3]
C_{SR}	406.78	[US$]
c_1	0.102	[US$/kWh]
c_2	0.254	[US$/kWh]
c_3	0.220	[US$/kWh]
N_E	20	[years]
i_E	0.04	[-]
d	0.06	[-]
i_{TA}	0.03	[-]
i_M	0.06	[-]
r_{TA}	0.0924	[-]
r_M	0.005	[-]
a_1	.40	[-]
a_2	.60	[-]
l	5	[-]

Table 2 – Simulation parameters

All optimization iterations are written in an output file generated by GenOpt and permit some important observations (see Fig. 4).

The reduction of the objective function value noticed between run 300 and 400 was primarily due to three factors. A shift between auxiliary power rates occurred; having $\dot{Q}_{AUX1}$ suppressed $\dot{Q}_{AUX2}$. T_{THERMO} reduced its value significantly, from approximately 39.4°C to the level of its optimal value. This fact indeed helps the overall performance of the collector, since the average collector inlet temperature decreases. The collector inclination also increased from 30.1° to its optimal level. An optimal thermostatic mixing valve set point temperature above the actual desired temperature (38°C) was already expected due to pipe heat losses. The optimal tank-volume to collector-area ratio is 60.92 litres for the simulated CSDHWS.

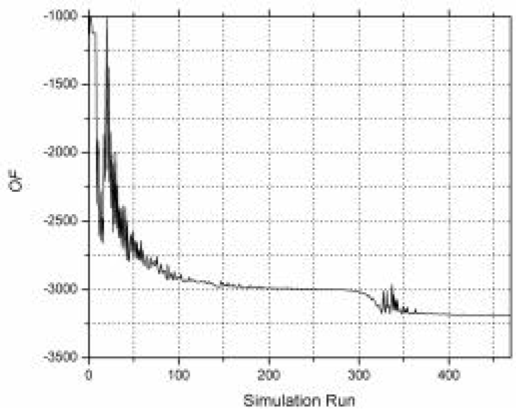

Figure 4 – Objective function value

During the simulation of the optimized system, the systems peak demand was never higher than 5.28kW for the evenly distributed profile and 5.22kW for the night profile. The annual solar fraction reached 79.61% for the evenly distributed profile and 79.65% for the night profile. For the actual system that will be installed (A_C=1.36m^2, V_T=0.100m^3, $\dot{Q}_{AUX1}$=1.5kW, $\dot{Q}_{AUX2}$=6.6kW, T_{THERMO}=40°C, T_{TMV}=39°C), using the optimized inclination angle (b=32.6), the peak demand is reduced to 4.21kW for the evenly distributed profile and 4.00kW for the night profile. This reduction is explained by the higher T_{TMV} value. The c_2 cost coefficient is also very important while interpreting the optimized values. A higher value of c_2 would probably change the relative values between $\dot{Q}_{AUX1}$ and $\dot{Q}_{AUX2}$. A reduction in the solar fraction of 13.92% for the evenly distributed profile and 13.65% for the night profile was observed. System performance improvement is achieved to an expense of only an additional US$37.29 on the system total cost, with optimized parameters.

6. FURTHER DEVELOPMENTS

The project coordinated by LABSOLAR will be measuring power consumption in intervals of 5 min or less of 30 electric showerheads. Based on this acquired data, hot water load profiles will be derived and implemented in the optimization procedure. With meteorological data from other major Brazilian cities as well as hot water load profiles in hands, system sizing will be performed for future housing programs. Other optimization algorithms will also be tested and sensitivity analysis undertaken. A CDHWS with optimized parameters will be constructed and investigated *in situ*.

7. CONCLUSIONS

The proposed optimization procedure has been carried out successfully and is capable of finding an optimum for a group of hot water loads. Coupled with GenOpt, TRNSYS can be used to optimize thermal systems of various types and finalities. Lack of information on hot water usage is still a problem that needs to be overcome in order to size systems adequately.

NOMENCLATURE

OC_{CSDHWS}	Operational Costs of the CSDHWS
OC_{SHS}	Operational Costs of the SHS
OF^*	Preliminary objective function value
OF	Objective function value
$\dot{Q}_{AUX1}$	Auxiliary power in the thermal storage unit
$\dot{Q}_{AUX2}$	Electric showerhead auxiliary power
$\dot{Q}_{AUXR}$	Auxiliary power reference value
$\dot{Q}_{AUX-SH}$	Standard electric showerhead auxiliary power
$F_R U_L$	Slope of the collector efficiency curve
$F_R(ta)_n$	Intercept of the collector efficiency curve
b_0	Incidence angle modifier coeficient
A_C	Collector area
V_T	Thermal storage volume
T_{SET}	Desired hot water temperature
T_C	Actual hot water temperature (end user)
T_{THERMO}	Thermostat set point temperature
T_{TMV}	Thermostatic mixing valve set point
$\dot{m}$	Hot water mass flow rate
c_p	Specific Heat Cofficient
c_1	Electric energy rate
c_2	Instantaneous power consumption penalty
c_3	User comfort penalty
C_S	Total system cost
C_A	Cost of collector area
C_V	Thermal storage volume cost
C_{SR}	Total cost constraint
LCS_i	Lyfe cycle savings of the i-th population segment
PWF	Present worth factor
N_E, N	Period of economical analysis
i_E	Electric energy inflation rate
d	Discount rate
i_{TA}	Mortgage interest rate
i_M	Maintenance inflation rate
r_{TA}	Ratio of yearly mortgage payment to system total cost
r_M	Ratio of first year maintenance costs to system total cost
i	Inflation rate
a_i	Percentage of each population segment
l	Multiplication factor for the cost constraint

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