MULTIOBJECTIVE OPTIMIZATION AS A DECISION TOOL FOR FINANCING OR REBATING DOMESTIC SOLAR WATER HEATERS

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ABSTRACT

Multiobjective programming coupled to a long-term hourly simulation procedure was used for sizing financial incentives to acquire certain domestic solar water heaters (DSWH) that are effective in reducing on-peak power consumption. A case study was done for Campinas city, southeastern Brazil. The proposed method also specifies the best set of design parameters for the DSWH configuration.

1. INTRODUCTION

Demand (tankless or instantaneous) water heating shares about 9% of the total power of the national power grid on peak hours. The electric showerhead is used in 90% of Brazilian homes. It is a very cheap and easy-to-install equipment (price about US$10.00). In a life-cycle analysis is well known that solar water heating is a better technology. However, low-income families can hardly afford the initial investment for a DSWH.

The cheaper DSWH for the consumer uses an electric showerhead as auxiliary heater. However, a sequence of rainy days can prevent the sun from heating the water, and the electricity consumption on peak hours can be the same of a single electric showerhead. The proper DSWH that prevents on-peak electricity consumption from happening uses a in-tank auxiliary heating element. However, the solar fraction of the DSWH depends on the amount of using in-tank auxiliary heating.

Since electric utilities have interest in reducing on-peak consumption, they could help low-income consumers to acquire proper DSWHs by means of rebating or partial financing. Multiobjective optimization techniques were used as a decision tool for sizing this financial aid. The proposed method uses mathematical programs linked to a long-term hourly simulation routine. The resulting optimal synthesis model was used to correlate rebating or financing loans to optimal design solutions for appliances. A case study was presented, regarding solar water heaters for a Brazilian city.

2. MULTIOBJECTIVE OPTIMIZATION

The coupling of a optimization routine to a simulation procedure in order to build an Optimal Synthesis Program was explained in detail by Borges, Correia et al. (1). In this work, the optimization routine is the software GenOpt (2), and the simulation procedure is TRNSYS (3).

Multiobjective optimization is an excellent tool for dealing with conflicting objectives in engineering design. For the case of two-objective optimization, the Weighted-Objectives Technique is recommended. Using this, it is possible to solve a single-objective problem by assigning relative weights to the conflicting objectives (4).

$$\begin{aligned} &\min\left\{ f(\vec{x}) = f\ f_1(\vec{x}) + (1-f)\ f_2(\vec{x}) = z \right\} \\ &\text{subject to } \vec{x} \in S \qquad (1) \\ &f \in [0;1] \end{aligned}$$

where $f_1(\vec{x})$ e $f_2(\vec{x})$ are the conflicting objective functions and S is the feasible region. Once the relative importance of each objective is not known, a discrete set of values between zero and one is proposed, and single objective optimization runs are performed for each value of f (4).

Borges, Colle et al. (5) have suceeded in using multiobjective optimization for sizing additional prices to the electricity consumed at peak hours by solar water heaters.

3. THE CASE STUDY

The case study chosen was the optimization of solar water heaters for the city of Campinas in the state of São Paulo, Southeastern Brazil (22°48'S; 47°04'W) (Fig 1). The DSWH consists of a thermosyphon solar water heater, a vertical cylindrical thermal tank and an internal electrical backup heating element. Optionally an instantaneous electric water heater with variable power and electronic control can be taken into account. The flat plate collectors work with tap water. Hot water is to be delivered at a minimum temperature of 55°C on the hot tap, and can be mixed with cold water if necessary. The backup heater in the tank is controlled by a thermostat. It should be noted that setting the thermostat to low temperatures would prevent the internal backup heater to turn on. On the other side, a setting to high temperatures will prevent the instantaneous water heater from working

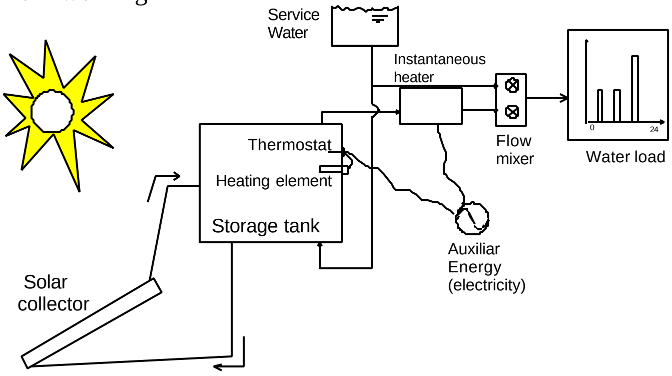

Fig. 1: Equipment Layout

The daily load profile that is applied (400 l of water/day at 40°C), should represent a household load of a family, with 100 liters from 6:00 to 8:00; 100 liters from 11:00 to 13:00 and 200 liters from 18:00 to 20:00 hours. More information on the characteristics of the studied equipment can be obtained from (1).

3.1 Simulation model and life cycle cost analysis

The Morrison and Braun (5) numerical model for the performance of thermosyphon systems, that is available as a standard model in TRNSYS was chosen. It has good accuracy in long-term simulation runs.

Since a TMY file for Campinas city was not compiled yet, one year of weather data taken from august 1996 to September 1997 was used. The data are available with a time step of 10 min.

The annualized life cycle cost of heating water is calculated over the expected equipment lifetime of 20 years. The basic input data for the economic evaluation are given in table 1.

Table 1: Economic conditions for the case-study

Life time	20 years
Interest rate for the consumer	12 % / year
Salvage value	zero
Solar collector cost (average performance)	104.00 US$ / m^2
Solar collector cost (low performance)	52.00 US$ / m^2
Thermal tank with electrical backup heater	291 US$ + 496 US$ / m^3
Accessories and installing costs	15 % of equipment
Annual maintenance costs	1 % of initial investment
Increasing tax of maintenance costs	6 % / year
Electricity price (household)	4.5818 .10^{-5} US$ / kJ (0.1649 US$/ kWh)

The Annual Life Cycle Cost is calculated by:

$$\begin{aligned} ALCC(\vec{x}) &= (291+496V_t+104A_c)\times 1.15\times(U/P,12\%,20)\\ &+(291+496V_t+104A_c)\times 1.15\times 1\%\times(P/G_1,12\%,6\%,20)\times\\ &\times(U/P,12\%,20)\\ &+Q_{tot}\times 4.5818\times 10^{-5}\quad [US\$] \end{aligned} \tag{2}$$

Where:

$$(U/P,i,n)=\frac{i(1+i)^n}{(1+i)^n-1} \tag{3}$$

$$(P/G_1,i,g,n)=\frac{1}{(i-g)}\left[1-\left(\frac{1+g}{1+i}\right)^n\right] \tag{4}$$

Where:

i	interest rate [% annual]
n	number of periods
g	increasing costs tax [% annual]

The resulting Annual Life Cycle Cost is:

$$ALCC=\begin{cases} \overbrace{(291+496V_t+104A_c)\times 1.15}^{\text{acquisition}}\times\\ \times\left(\overbrace{0.1339}^{\text{amortization}}+\overbrace{0.014825}^{\text{maintenance}}\right)\\ +\overbrace{Q_{tot}\times 4.5818\times 10^{-5}}^{\text{auxiliary energy}} \end{cases} \tag{5}$$

Where:

A_c	Collector area [m^2]
V_t	Thermal tank volume [m^3]
Q_{tot}	Auxiliary energy [kJ]

3.2 Implementation of Optimal Synthesis

The search technique selected in GenOpt was the Particle Swarm Optimization. This is an evolutionary algorithm with good performance in problems with multiple local optima.

Table 2: Optimization parameters, and their box constraints.

		Lower bound	base case	upper bound
A_c	Collector plate area	2 m^2	8 m^2	14 m^2
V_t	Thermal tank volume	0.1	0.55 m^3	1 m^3
T_{set}	Heating element thermostat temperature	10 °C	40 °C	70 °C

The chosen decision variables were Solar Collector area, Thermal tank volume and in-tank thermostat temperature setting.

The objectives chosen were the initial investment and on-peak energy consumption. There is also a penalty function that is activated whenever the Annual Life Cycle Cost (ALCC) is greater than a intended goal.

$$\min\begin{Bmatrix} f(\vec{x}) = fP_0(\vec{x}) + (1-f)E_{peak}(\vec{x}) \\ + \text{penalty}(goal, ALCC(\vec{x})) \end{Bmatrix}$$

$$\text{penalty}(a,b) = \begin{cases} 0 & \text{if } a \geq b \\ +100(b-a)^2 & \text{if } a < b \end{cases} \qquad (7)$$

$$\vec{x} = [\mathrm{A_c} \quad V_t \quad T_{th}]^{\mathrm{T}} \qquad f \in [0;1]$$

Where:

E_{peak}	On-peak yearly energy consumption [kWh]
P_0	Initial investment [US$]
$ALCC$	Annual life-cycle cost [US$/year]
A_c	Solar collector area [m^2]
V_T	Thermal tank volume [m^3]
T_{th}	In-tank thermostat temperature setting [°C]
f	Weight to objectives [0..1]
a,b	Real numbers

4. RESULTS AND DISCUSSION

The trade-off between initial investment for the consumer and yearly on-peak electricity consumption was done for several sceneries of maximum Annual Life Cycle Cost for the consumer. These trade-off curves are presented in Fig. 2.

In figure 3 it is possible to observe that financing US$200 to a consumer that already have US$1000 to aquire a DSWH would decrease the on-peak power consumption from 220 kWh to about 130 kWh.

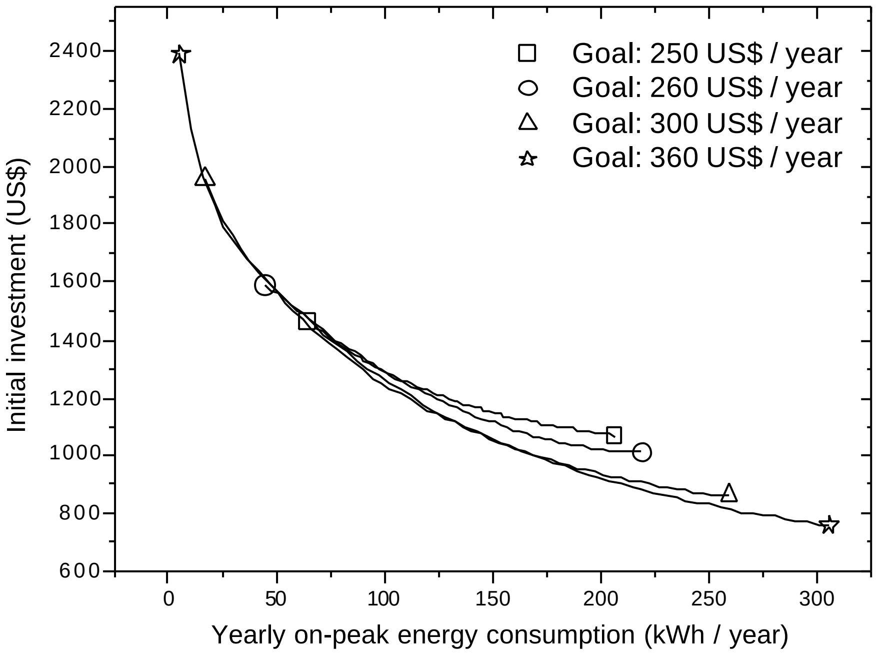

Fig. 2: Trade-off curves for several goals of maximum ALCC limitation

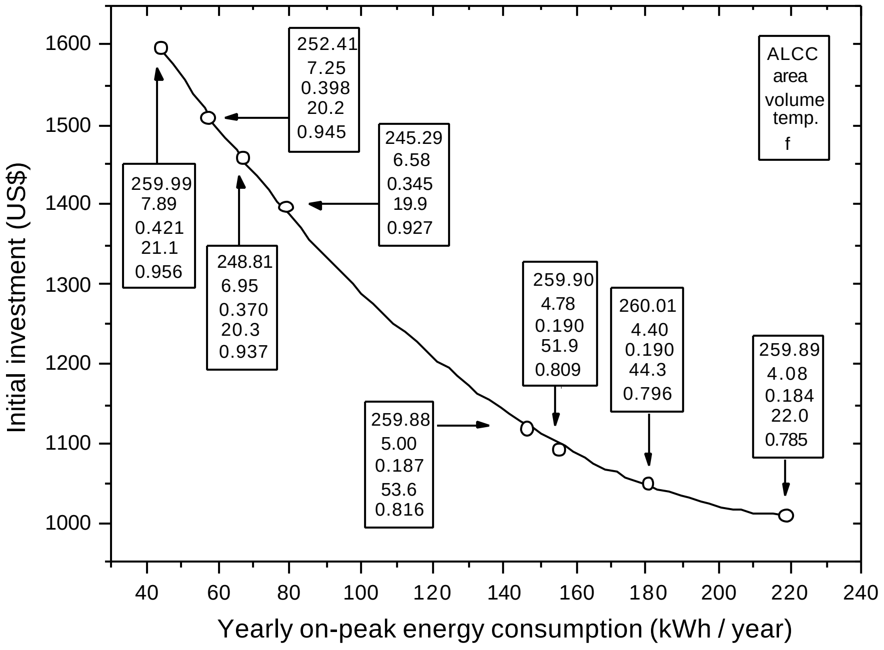

Fig. 3: Trade-off curve and set of configuration parameters for the goal ALCC ≤ 260 US$/year

5. CONCLUSIONS

The proposed method of sizing financial aids to acquisition of DSWH was effective on determining trade-offs between DSWH initial investments and the annual on-peak electricity consumption. For each point of the trade-off curve the optimization procedure determined the best set of design parameters to comply with the objectives. For the case study, the trade-off curve indicates that there is a decreasing utility of the rebate - the greater the rebate is, the less cost effective it gets.

6. ACKNOWLEDGMENTS

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