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Solar Domestic Hot-Water Systems for reducing the on-peak consumption considering the time-of-use rate in Brazil

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Abstract

Brazilian demand curve for the residential sector has most of the times a typical shape with a pronounced peak from 18-22 hours. A time-of-use rate was recently introduced to incentive consumers to manage their demand in order to avoid electricity consumption during on-peak hours. Solar Domestic Hot-Water Systems can be a useful tool to reduce the energy consumption and on-peak power demand but represents additional investment costs, so depending on the relation between the different levels of electricity costs, they can be an economically feasible option. The present work shows an optimization procedure to define the sizing of the Solar Domestic Hot Water System for a study case and also presents multi-objective optimization analysis considering the conflicting objectives of the consumers that want a lower monthly expenditure and the utility that wants to smooth the demand curve. Results shows that considering the actual regulation, solar heating systems are economically feasible for both rates with a slightly advantage to the time-of-use rate. Reduction in the on-peak electricity consumption is always achieved, but more precise results needs a more realistic distribution of the heating demand along the year.

Keywords: solar domestic hot water systems, flat rate; time-of-use rate

1. Introduction

Brazilian electricity system is characterized by a large interconnected system with installed capacity of 132 GW and hydrothermal generation basis (64% hydro and 36% thermal/complementary) [1]. Although renewable energies have a big contribution to the energy share, this scenario of hydropower dependence makes the grid very sensitive to drought periods where the reduction of the stored water in the reservoirs increases the electricity costs and risks for the system operation.

Residential consumers are responsible for 45.3% [2] of the total electricity in Brazil and their demand curve is characterized by low variation during daytime and late night hours and a pronounced peak from 18-22 hours. This behavior led to the introduction of a time-of-use rate as a demand-side management initiative in order to shift the on-peak consumption, smoothing the demand curve. Electrical showerheads are devices characterized by their high power and low load factor and are used in 73% of the Brazilian dwellings, representing about 24% of the residential electricity consumption [3]. As a result, roughly 5.5% (33.7 TWh/year including losses) of the electricity consumption is due to the electric showerheads used most of the times during the peak hours.

The regulatory frame of Brazil gives the opportunity to captive residential consumers to choose between a flat rate and a time-of-use rate – TOU that is called “Tarifa Branca” [4]. This regulation

incentive the use of energy outside the peak-hours and energy savings during this time. Solar Domestic Hot Water Systems – SDHWS can at the same time save energy and shift the consumption, but depending on the difference among the time-of-use rate levels, sometimes is more feasible to use electricity to heat the water when it is cheaper than investing money on solar collectors.

Considering the interest of both, consumer and energy supplier, the system needs to be cost-effective in the point of view of the consumer (i.e. reduce the energy consumption) and for the system operator and utility companies (i.e. reduce the peak consumption). Therefore, there is a conflicting interest that can be optimized and for each desired energy quantity that is removed from the peak-hours there is a relation between the TOU rate that minimizes the energy expenditure of the consumer.

The present work discusses this situation showing the tradeoff between the Annualized Life Cicle Costs - $ALCC$ and the quantity of energy that is removed from the on-peak period. The actual regulation is analyzed in terms of the SDHWS use. A multi-objective optimization is applied considering a long-term transient simulation routine for a case study representing a typical thermosiphon SDHWS for Florianopolis – Brazil.

2. System description

The thermal simulations use a SDHWS working on thermosiphon mode because it is the most common configuration in Brazil. The reasons for this are high solar energy availability, absence of low temperatures, operational reliability and lower costs. Fig. 1 shows the basic configuration of the SDHWS used. This kind of system avoids the use of pumps, however, the thermal storage needs to be placed at a higher position than the collector, and therefore is common to place it on the roof or in the attic.

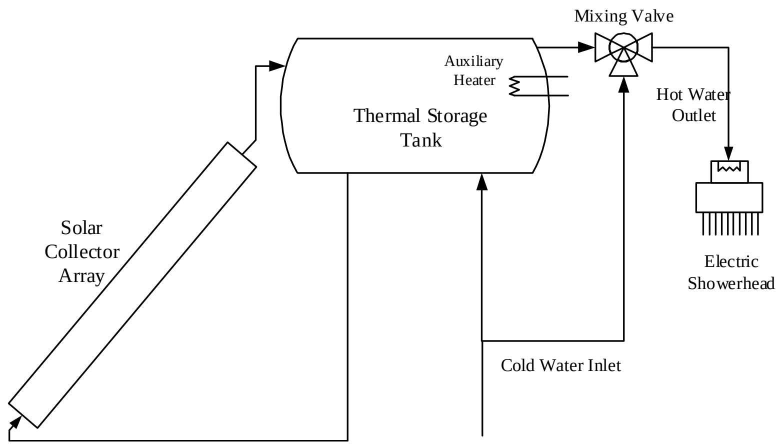

Fig. 1 – Schematic diagram of the thermosiphon solar domestic hot water system.

Both, the solar collector area and the thermal storage tank volume are sized through an optimization process that will be described later. The efficiency curve of the solar collector was taken from the Brazilian labelling program considering a solar collector that got a class A grade [5]. This efficiency curve is experimentally measured for a specific flat-plate collector, but for optimization purposes it was considered independent of the collector area. The specification parameters used are listed in Table 1.

Table 1. Technical specifications of the solar domestic hot water system

	Parameter	Value
Collector	Collector slope	37.6 °
	Efficiency intercept ($F_R(\tau\alpha)$)	0.728 (-)
	Efficiency slope ($F_R U_L$)	6.18 W/m^{2}K
	Incidence angle modifier coefficient	0.1065 (-)
	Tested flow rate	60 kg/m^{2}h

	Riser diameter	0.0142 m
	Header diameter	0.027 m
Thermal storage	Thermal storage shape factor (Diameter and Height ratio)	0.5 (-)
	Thermal storage insulation thickness	0.05 m
	Thermal storage insulation conductivity	0.126 W/mK
	Thermal storage maximum auxiliary heating rate	3 kW
	Thermal storage auxiliary heating device efficiency	1 (-)
	Thermal storage thermostat temperature dead band	2 °C
	Thermal storage thermostat temperature	45 °
Electric showerhead	Electric showerhead maximum power,	6.6 kW
	Electric showerhead overall loss coefficient	0 W/K
	Electric showerhead efficiency	0.95 (-)
	Electric showerhead set point	40 °C
Installation details	Collector inlet diameter	0.015 m
	Number of bends in the inlet pipeline	4
	Inlet pipeline thermal loss coefficient	1.8 kJ/m^{2}hK
	Collector outlet diameter	0.019 m
	Number of bends in the outlet pipeline	4
	Outlet pipeline thermal loss coefficient	1.8 kJ/m^{2}hK
	Height of the solar collector	1.415 m
	Vertical distance between collector's inlet and outlet	0.864 m
	Vertical distance between collector inlet and thermal storage outlet	1.164 m
	Thermal conductivity of the thermal storage and fluid entirety	2.207 W/mK

Some of the simulation parameters used in the systems are function of the design parameters (i.e. solar collector area and thermal storage volume), and need to be calculated in each iteration of the optimization process. These parameters are, thermal storage overall heat loss coefficient, thermal storage diameter and height, positions of the thermal storage thermostat and heating element, length of the solar collector and inlet piping length, number of parallel solar collector risers and maximum flow rate for the solar pump. The equations used to calculate these parameters were described in detail by [6] and [7].

The proposed SDHWS configuration uses two auxiliary electric heaters, one inside the storage tank and other in line to the load. The second one works as an electric showerhead and was considered in the simulation model just to guarantee the desired temperature for the users.

The thermal performance of the SDHWS depends significantly on the domestic hot water load profile. The chosen profile was previously determined using real measured data of a group of ninety residential consumers during a one-year period ([7], [8]). A statistically representative normalized load profile is then derived as depicted in Fig. 2.

The annual thermal performance and economic analysis were determined using the Transient System Simulation Program (TRNSYS) [9]. All simulations were performed using a Typical Meteorological Year – TMY from the SWERA database [10] for Florianopolis (27.6°S/48.5°W). The performance of the thermosiphon system was calculated through the Morrison and Braun model [11]. In addition, the auxiliary energy supply was simulated as electric heaters with a fixed thermal efficiency and with a maximum power that is modulated to meet the specified set point temperature.

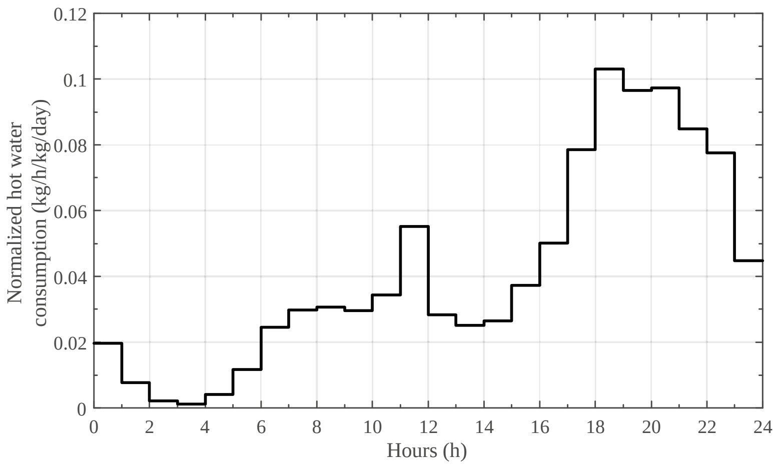

Fig. 2 – Normalized hot water daily consumption profile.

3. Economic Analysis

Starke et al [12] presented a discussion showing the trade-off curves for two incentive policies, a rebate program and a TOU rate with only two different rate levels. The present work focus only in the TOU, but using the regulatory framework that is being implemented in Brazil.

3.1. Time-Of-Use rate

A TOU rate was recently established by the regulatory agency (ANEEL) in Brazil and named "Tarifa Branca" [4]. It is an option for the low voltage consumers to pay different electricity rates depending on the hour of the day and the day of the week. During the business days there are three different rates: off-peak, intermediary and on-peak and during the weekends and holydays the off-peak rate is used. The hours and ratio between the rates are defined by the regulatory agency every four years for each utility company. Fig. 3 show the frame for the TOU rate compared to the flat rate in Santa Catarina [13]. It is worth to note that the flat rate is the weighted average of the TOU rate.

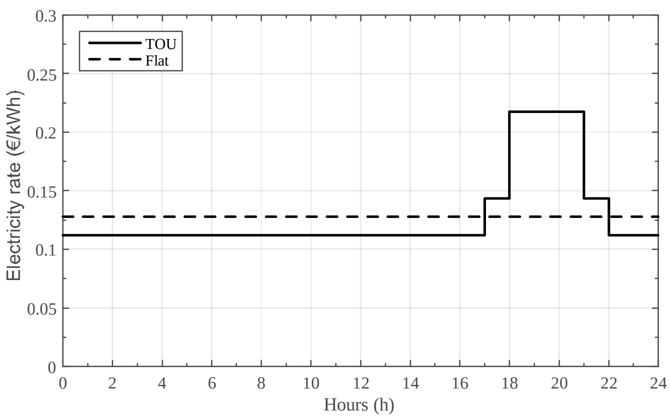

Fig. 3 – Comparative between Time-of-Use and flat rates for Santa Catarina.

The different rate levels are treated in the present work related to a reference value - the flat rate - to enable the construction of different scenarios, thus it is possible to propose a policy to incentive the use of SDHWS. Table 2 shows the actual rates applied in Santa Catarina and their ratio to the flat rate. The Brazilian regulation also has a subsided rate for low income users and also the taxes are lower for the first 150 kWh of monthly electricity consumption, but the TOU is based on the conventional rate, so these aspects are not considered in the present work.

Table 2. Electricity rates of residential consumers in Santa Catarina [13].

Eletricista rate - C_e	**Value (€/kWh)**	**Ratio**
Flat	0.12769	1
On-peak	0.21726	1.7015
Intermediary	0.14332	1.1224
Off-peak	0.11176	0.8752

3.2. Economic figures

The economic analysis considers that the consumer invests on a SDHWS to decrease his yearly expenditures in water heating. Thus, all costs related to the additional investment and expenses of the SDHWS during the lifetime are also taken into consideration. The economic analysis methodology can be seen in details in [14]. First of all it is necessary to define the Life Cycle Cost – LCC for water heating that includes the equipment, its installation and maintenance costs and the auxiliary energy costs during the whole lifetime. It can be calculated bringing all these values to the present as shown in Eq. (1):

$$LCC = (1 + C_i)IC(\vec{x})[1 + C_m PWF(N, i_m, d)] + PWF(N, 0, d)\sum_{year}(E_{aux}C_e) \quad (1)$$

where C_i is the installation cost as a percentage of the initial cost $IC(\vec{x})$ of the SDHWS, C_m is the annual maintenance cost as a percentage of the installed cost of the system, E_{aux} is the hourly auxiliary energy consumption, C_e is the electricity rate that depends on the hour and day of the week; PWF is the present-worth factor of a series of constant values, N is the lifetime of the system, i_m is the maintenance inflation rate and d is the discount rate.

The initial cost IC can be calculated as follows:

$$IC(\vec{x}) = C_c A_c + C_s(V_s) \quad (2)$$

where C_c is the solar collector cost per area, A_c is the solar collector area, C_s is the storage tank as a function of the storage tank volume (V_s). The solution domain $\vec{x}$ represents all possible combinations of A_c and V_s.

Once in the point of view of the consumer the economic figure of interest is the $ALCC(\vec{x})$, it can be calculated as:

$$ALCC(\vec{x}) = LCC(\vec{x})/PWF(N, 0, d) \quad (3)$$

Table 3 lists the actual costs in the Brazilian market and the economic assumptions for the present work.

Table 3. Costs of the SDHWS and economic parameters.

Parameter	**Value**
Solar system life cycle, N	20 years
Discount rate, d	8 %
Maintenance inflation rate, i_m	6.4 %
Solar collector cost, C_c	119.25 €/m^2
Annual maintenance cost, C_m (related to the initial cost)	1 %
Installation cost, C_i (related to the initial cost)	15 %
Exchange rates for Euro at March, 2014 , u ($BR\$/€$)	3.48 BR$/€

The cost, in euros, of the thermal storage (C_s) was considered in the analysis by a regression model based on the prices of tanks with different volumes obtained of the main suppliers in the Brazilian market, as follows,

$$C_s(V_s) = \frac{1}{u}(4798.8V_s - 2889.8V_s^2 + 1196V_s^3 - 216.9V_s^4 + 14.911V_s^5) \quad (4)$$

3.3. Trade-off between the Annualized Life-Cycle Cost and on-peak energy consumption

A trade-off curve is a well known way to help on decision when dealing with conflicting objectives. In the present analysis, the consumer is interested in the lowest $ALCC$, while the utility company is interested in remove consumption from the on-peak and intermediary hours ($E_{aux,peak+int}(\vec{x})$). To create the trade-off curve, the SDHWS needs to be proper sized and to do this an objective function that includes both objectives employing a weighted global criterion method is derived. Then, an optimization routine was applied considering two design parameters as independent variables: the solar collector area and the thermal storage volume. The combination of an optimization routine with a life-cycle simulation of a solar system was extensively explained by [15]. With the weighted global criterion method, it is possible to solve a single objective by assigning relative weights (φ) to the conflicting ones ([16], [15], [17]). The objective function used in the present study includes also a minimum bath temperature as a constraint to guarantee that the system supplies water in the desired temperature to the consumers. Therefore, the optimization problem can be defined as follows:

$$\min_{\vec{x}} \left\{ f(\vec{x}) = (1-\varphi)\frac{E_{aux,peak+int}(\vec{x})}{E_{sh}} + \varphi\frac{ALCC(\vec{x})}{ALCC_{sh}} + \mathrm{P}_1(\vec{x}) \right\}$$

$$\begin{aligned} &Subject\ to: \\ &\vec{x} \in S \\ &\mathrm{P}_1(\vec{x}) = \int_t \begin{cases} 1, & if\ T_{cons}(\vec{x}) < T_{ideal} \\ 0, & otherwise \end{cases} \end{aligned} \quad (5)$$

where S is the feasible region defined by the solar collector area A_c and the storage volume V_s. E_{sh} and $ALCC_{sh}$ are the values of the energy consumption and annualized life cycle costs in the case of an electric showerhead use that were used to rewrite the two conflicting objectives in a non-dimensional form.

To do the multi-objective and multi-parameter optimization, the Generic Optimization Program (GENOPT) was used, since it can be easily coupled with TRNSYS. This software has a large optimization algorithm library from which the hybrid algorithm of the Particle Swarm Optimization algorithm and the Generalized Pattern Search implementation of the Hooke-Jeeves algorithm (GPSPSOCCHJ) were selected. This decision is adequate for specific features of problems in which the objective function is not continuously differentiable, or it must be approximated, that is the case of the thermal simulation routines analysed. Therefore, the design parameters can be only solved heuristically [18].

4. Results

The results of the case study are presented for Florianopolis – Brazil (27.6°S/48.5°W), considering a thermosiphon SDHWS, where the daily hot water consumption was set to 0.3 m^3 at 40 ºC that can represent a common case in Brazil.

Two scenarios were considered, the flat rate and TOU rate so it will be possible to identify what is the best option for the consumer and if the combination between SDHWS and TOU rate can be a good policy to smooth the energy consumption during on-peak hours. Together with these results, also the annualized life cycle cost of the showerhead is plotted, so the proposed alternatives can be compared to the most used solution for water heating in Brazil. The trade-off between the annualized life cycle cost of the system and the on-peak and intermediary yearly electricity consumption is shown in Fig. 4.

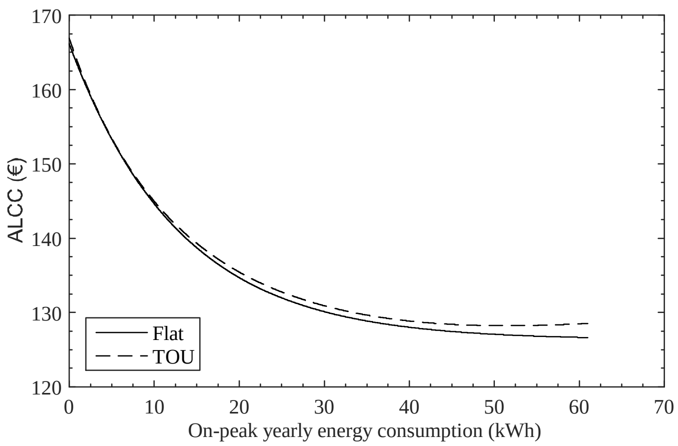

Fig. 4 – Trade-off curve of the on-peak energy consumption versus $ALCC$.

The first observation is that there is not a big difference between the $ALCC$ for both rates. It happens because the actual economic figures are quite favorable to the use of SDHWS. Fig.5 shows the same result, but on a logarithmic scale, together with the $ALCC$ using the electric showerhead for both rates. It shows that the TOU rate increases the annualized costs for the showerhead and decreases for the SDHWS, so, although in both cases there is an economic feasibility, when the consumers choose the TOU rate the difference between the two costs is higher.

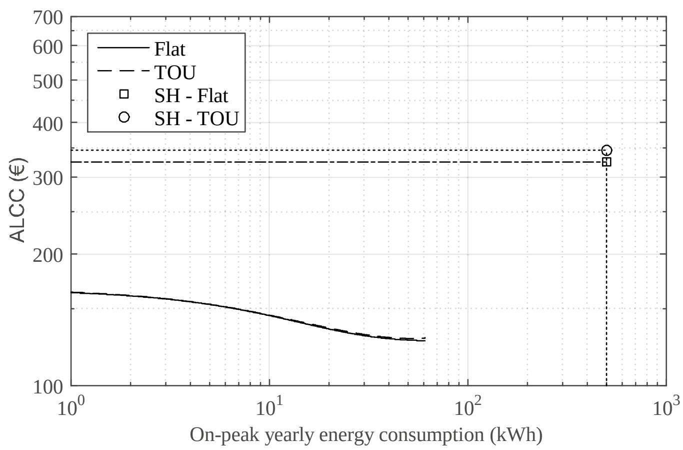

Fig. 5 – Trade-off curve of the on-peak energy consumption versus $ALCC$ together with the $ALCC$ of the electric showerhead (SH).

This can also be verified analyzing the LCS showed in Fig. 6 as a function of the collector area keeping the storage volume on a ratio of 0.075 m^3 per collector unit area (m^2). In this case, the DSHWS was optimized considering only the consumer point of view (φ = 1) that coincides with the higher on-peak consumption in figures 4 and 5.

Figure 7 shows the storage volume per collector area ratio in the optimized size that generates the trade-off curve. The recommended figures for this ratio as a best practice are 0,075 m^3 per square meter given in [14] and around 0,1 m^3 per square meter according to the term of reference for the Brazilian low income housing units program “Minha Casa Minha Vida” [19]. For the present study it was lower, standing around 0,07 m^3 per square meter because the heating energy was considered constant along the year, so the necessity to store more water to attend the demand during the winter months was underestimated. Even so, it is observed that as the objective of on-peak energy savings increase, this value also increases due to the necessity of heating water during the off-peak period. The lower ratio obtained considering only the on-peak energy saving objective (φ = 0) happened because at this point the area increases a lot in order to provide all heating energy from the collectors.

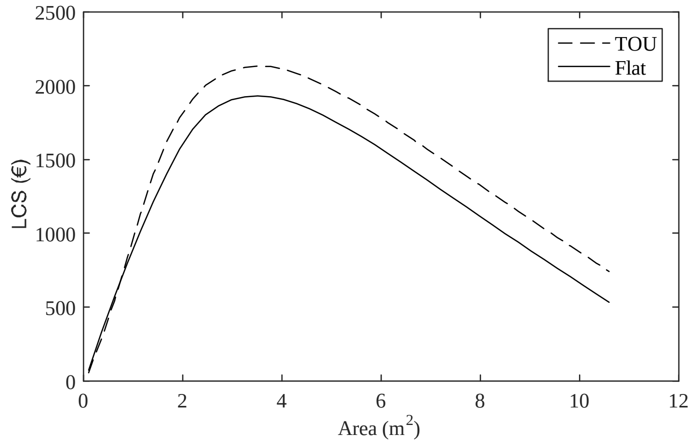

Fig. 6 – Life Cycle Savings - LCS of the DSHWS as a function of the collector area considering a storage volume of 0.075 m3 per unit of area.

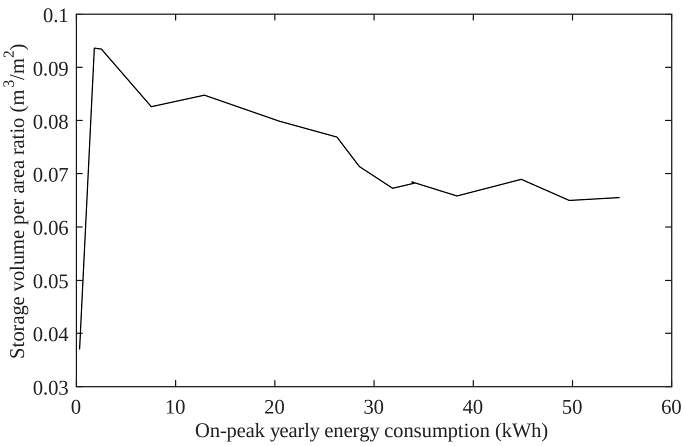

Fig. 7 – Storage volume per collector area ratio as a function of the on-peak energy consumption.

The yearly sum of the electricity demand during a day is shown in Fig 8. As previously discussed, the on-peak energy savings of the SDHWS are not strongly dependent on the used rate. Even considering only the consumer interest, a strong reduction in the on-peak energy consumption is achieved.

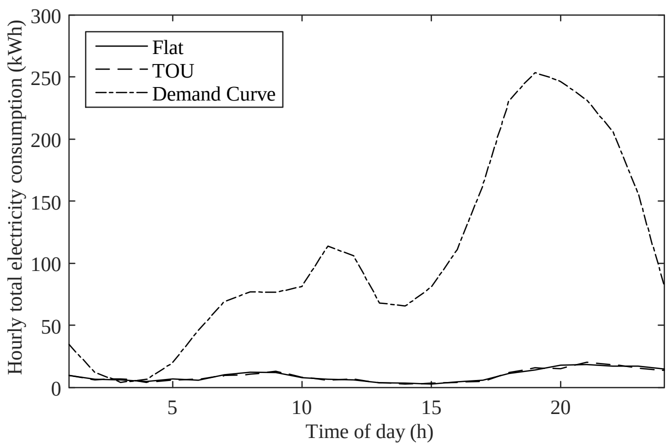

Fig. 8 – Yearly sum of the electricity demand during a day.

5. Conclusions

This work presented an analysis of the trade-off curve between the $ALCC$ and the on-peak plus intermediary electricity consumption. The SDHWS design was optimized in terms of the collector area and storage tank volume from an objective function that minimizes the two conflicting interests employing a weighted global criterion method. A TOU rate was also considered according to the actual Brazilian regulatory frame.

The results shows that independent on the option for the TOU rate, in both cases the SDHWS system is economically feasible, being interesting not only for the reduction of the $ALCC$ but also reducing the on-peak electricity consumption. It is worth to note that the TOU rate increases the $ALCC$ in the case of using an electric showerhead, that turns the SDHWS more attractive when comparison to it.

As the main limitations of the present work, the use of a constant water heating demand led to an overestimation of the energy savings and undersized the area and volume of the SDHWS. Even so, the trade-off curve behavior and the comparative results presented here are valid.

As additional work, an introduction of the solar irradiation forecast to control the storage tank temperature can also decrease the use of electricity during on-peak hours. Another possibility is the use of the ratio between the TOU rates to the flat rate to achieve a specific objective of on-peak electricity savings. A study considering different demand profiles for each month is being conduct using the same database used here for the annual average of hourly consumption profile. Another interesting work, is to do the same analysis considering individual typical consumers, so depending on the type of consumer, the TOU rate can be or not a good option.

Acknowledgement

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