TIME-OF- USE ELECTRICITY RATE IMPACT IN THE ECONOMIC ANALYSIS ON OF SOLAR DOMESTIC HOT-WATER SYSTEMS

Samuel L. Abreu – abreu@ifsc.edu.br
Instituto Federal de Santa Catarina – IFSC, Câmpus São José
Allan R. Starke – allan.starke@lepten.ufsc.br
Universidade Federal de Santa Catarina - UFSC, LEPTEN/Departamento de Engenharia Mecânica– UFSC
Rubipiara C. Fernandes – piara@ifsc.edu.br
Instituto Federal de Santa Catarina – IFSC, Câmpus Florianópolis
José Miguel Cardemil – jose.cardemil@udp.cl
School of Industrial Engineering, Universidad Diego Portales and Fraunhofer Chile Research Foundation, Center for Solar Energy Technologies, Chile
Sergio Colle – sergio.colle@ufsc.br
Universidade Federal de Santa Catarina - UFSC, LEPTEN/Departamento de Engenharia Mecânica– UFSC

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 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 that considers an average hourly electricity consumption for water heating of 60 dwellings. It presents a multi-objective optimization analysis considering the conflicting objectives of the consumers that want a lower monthly expenditure and the utility company 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.*

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) (EPE, 2014(a)). 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% (EPE, 2014(b)) 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 (EPE, 2012). 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" (Aneel, 2013). This regulation incentive the use of energy outside the peak-hours and energy savings during this time period. 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 an optimum SDHWS sizing that leads to a consumer minimum yearly expenditure in water heating.

The present work discusses this situation showing the trade-off 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. Figure 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 on a upper position in the attic.

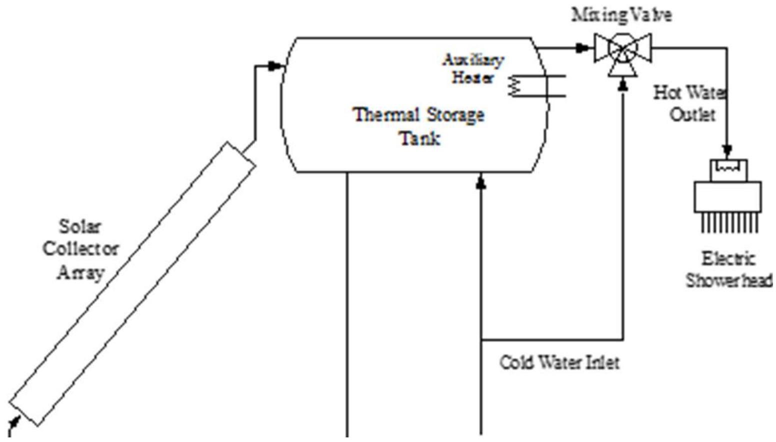

Figure 1- Schematic diagram of the thermosiphon solar domestic hot water system.

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 (Inmetro, 2015). 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 Tab. 1. The cost for the same collector were the reference for the economic analysis.

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

	Parameter	**Value**
Collector	Collector slope	37.6 °
	Efficiency intercept ($F_R(\tau\alpha)$)	0.75 (-)
	Efficiency slope ($F_R U_L$)	7.1 W/m^{2}K
	Incidence angle modifier coefficient	0.1065 (-)
	Tested flow rate	60 kg/m^{2}h
	Riser diameter	0.00953 m
	Header diameter	0.022 m
Thermal storage	Thermal storage shape factor (Diameter and Height ratio)	0.613 m
	Thermal storage insulation thickness	0.05 m
	Thermal storage insulation conductivity	0.126 W/mK
	Thermal storage maximum auxiliary heating rate	3.5 kW
	Thermal storage auxiliary heating device efficiency	1 (-)
	Thermal storage thermostat temperature dead band	2 °C
	Thermal storage thermostat temperature	45 °
Electric showerh	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	0.022 m
	Number of bends in the inlet pipeline	4
	Inlet pipeline thermal loss coefficient	1.8 kJ/m^{2}hK
	Collector outlet diameter	0.022 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	1.0 m
	Vertical distance between collector's inlet and outlet	0.61 m
	Vertical distance between collector inlet and thermal storage outlet	0.91 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 array and inlet piping length, number of parallel solar collector risers and maximum flow rate for the solar pump. The optimization process considers that the total collector area and the storage volume can be continuously varied. After that the most appropriated combination between the individual area and volume available in production can be chosen. The equations used to calculate these parameters were described in detail by Borges (2000) and Salazar (2004).

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 60 dwellings during a one-year period (Salazar, 2004; Naspolini, 2012). Statistically representative normalized load profiles are then derived for each month introducing the seasonal energy demand variation on the analysis. The yearly average profile is shown in Fig. 2.

The annual thermal performance and economic analysis were determined using the Transient System Simulation Program (TRNSYS) (Klein, 2010). All simulations were performed using a Typical Meteorological Year – TMY from the SWERA database (SWERA, 2013) for Florianopolis (27.6°S/48.5°W). The performance of the thermosiphon system was calculated through the Morrison and Braun model (Morrison and Braun, 1985). 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.

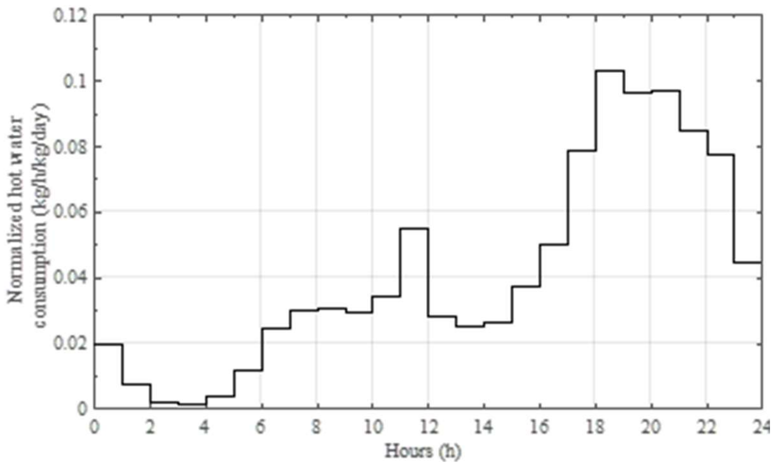

Figure 2 - Normalized hot water daily consumption profile.

3. ECONOMIC ANALISYS

Starke *et al*. (2015) 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" (Aneel, 2013). 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. Figure 3 shows the frame for the TOU rate compared to the flat rate in Santa Catarina (Aneel, 2015). It is worth to note that the flat rate is the weighted average of the TOU rate.

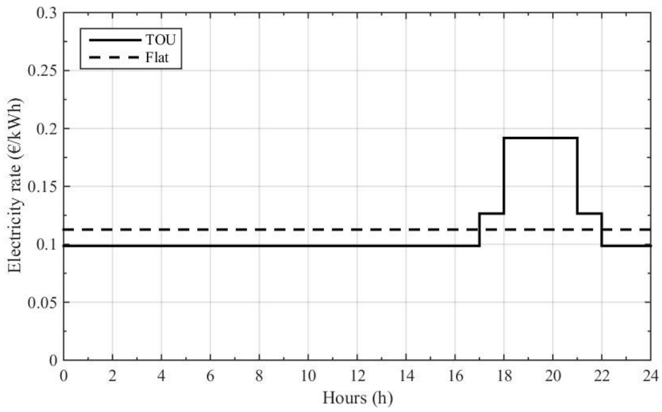

Figure 3 - Comparative between Time-of-Use and flat electricity rates along the day for Santa Catarina.

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 (Aneel, 2015) (exchange rate - 3.943 BR$/€ - november, 2015).

Eletricista rate - C_e	**Value (€/kWh)**	**Ratio**
Flat	0.112688	1
On-peak	0.191734	1.7015
Intermediary	0.126481	1.1224
Off-peak	0.098629	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 taken into consideration. The economic analysis methodology can be seen in details in Duffie and Beckman (2013).

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 using Eq. (2):

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

where C_c is the solar collector cost per area, A_c is the solar collector area, C_s is the storage tank cost 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 $ALCC(\vec{x})$, that can be calculated through Eq. (3):

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

Other commonly used economic figure is the Life Cycle Savings – LCS that representes the difference between the LCC when using the electric showerhead with the LCC using the SDHWS. Life Cycle Savings is a measure of the present value of the savings produced by the use of solar energy.

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	132.78 €/m^2
Annual maintenance cost, C_m (related to the initial cost)	1 %
Installation cost, C_i (related to the initial cost)	15 %
Exchange rate for Euro at November, 2015, u	3.943 BR$/€

The cost, in euros, of the thermal storage C_s was considered in the analysis by a regression model (Eq. (4)) based on the prices of tanks with different volumes obtained of a supplier in the Brazilian market:

$$C_s(V_s) = \frac{1}{u}(12780V_s - 32730V_s^2 + 37030V_s^3 - 8749V_s^4 - 4914V_s^5) \tag{4}$$

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

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 Borges *et al.* (2004). With the weighted global criterion method, it is possible to solve a single objective by assigning relative weights ($0 \leq \varphi \leq 1$) to the conflicting ones (Borges *et al.*, 2004; Borges *et al.*, 2005; Marler and Arora, 2004). 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 using Eq. (5):

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

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

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. Here both values 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 (Wetter, 2008).

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.

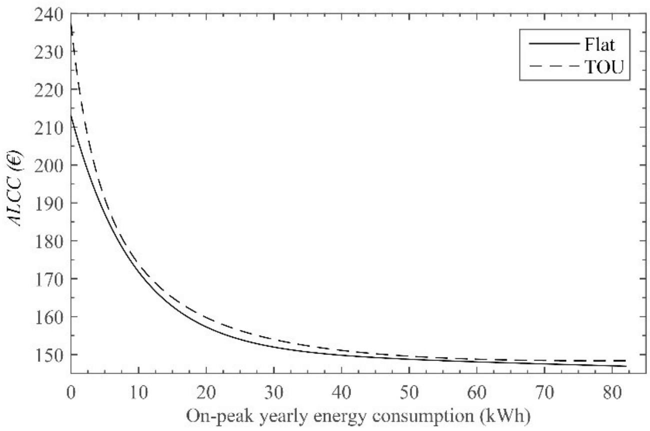

Figure 4 – Trade-off curves of the Annualized Life Cycle Cost versus the on-peak energy consumption for the Time-of-Use and flat rates.

The first observation is that there is not a big difference between the $ALCC$ for both rates, although the flat rate option is slightly better. It happens because the actual economic figures are quite favorable to the use of SDHWS. Figure 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, but when the consumer choose this rate option the difference between the two costs is higher.

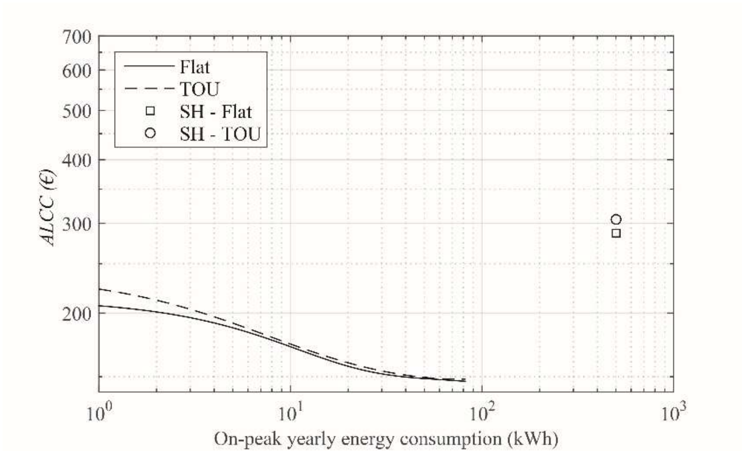

Figure 5 - Trade-off curve of the Annualized Life Cycle Cost versus the on-peak energy consumption together with the Annualized Life Cycle Cost of the electric showerhead (SH) (logarithmic scale) for the Time-of-Use and flat rates.

This can also be verified analyzing the LCS showed in Fig. 6 as a function of the collector area. In this case the storage volume per collector unit area ratio was kept constant in 0.075 m^3/m^2. The observation of figures 4, 5 and 6 leads to the conclusion the LCS is higher for the TOU rate, although the $ALCC$ are also higher for the same case. In other words, the consumer that choose the TOU rate will save more Money with the SDHWS when compared to the electric showerhead, but will have higher annual costs than using the flat rate.

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” (CEF – Caixa Econômica Federal, 2011). For the present study, it is observed that all obtained values are similar to the recommended ratio, but higher ratios attend better the utility interest of reducing on-peak consumption, due to the necessity of store more heatead water during the off-peak period.

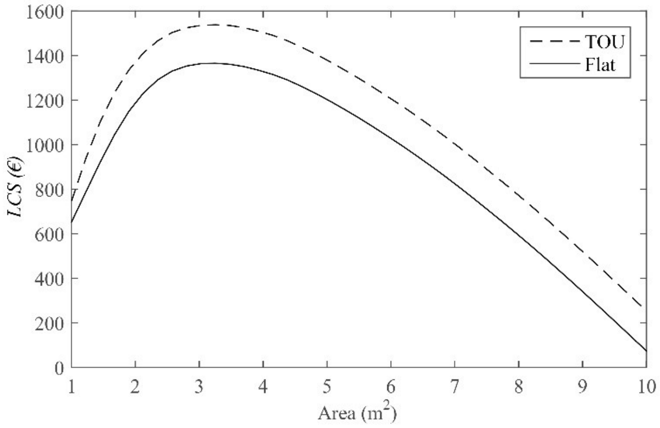

Figure 6 - Life Cycle Savings - $\boldsymbol{LCS}$ of the DSHWS versus the collector area considering a storage volume of 0.075 m^3 per unit of area for the Time-of-Use and flat rates.

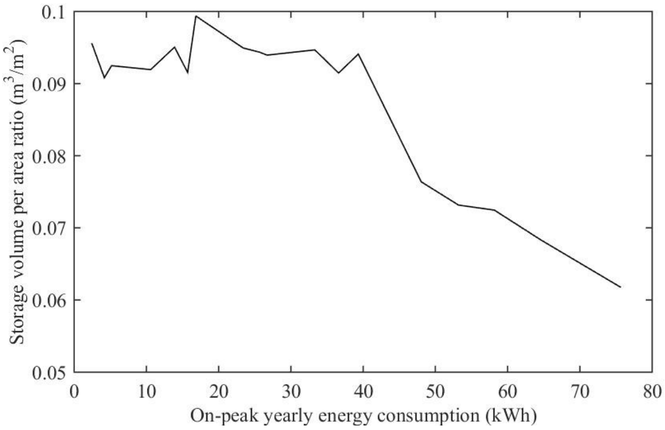

Figure 7 - Storage volume per collector area ratio versus the on-peak energy consumption.

The yearly sum of the electricity hourly demand during a day is shown in Fig. 8 for the case where only the consumer interest (to reduce the $ALCC$). As previously discussed, the on-peak energy savings of the SDHWS are not strongly dependent on the used rate. For both rates there is a great reduction in the on-peak energy consumption that leads to the economic feasibility of the system. Comparing the flat and TOU rates it can be seen that the behaviors are similar, but the part of the consumption is shifted to outside the on-peak period when using the TOU rate.

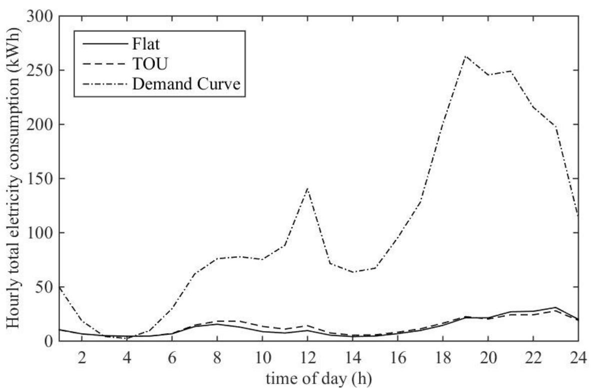

Figure 8 - Yearly sum of the hourly electricity consumption during a day considering only the consumer interest (to reduce the $ALCC$).

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 energy demand varies along the year and is based real average consumption profiles measured during one year for 60 dwellings in the city of Florianópolis.

The results shows that independent on the option for the TOU or flat 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 significantly the $ALCC$ in the case of using only an electric showerhead, that turns the SDHWS more attractive when comparison to it.

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. 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.

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