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Multi-objective optimization for reducing the auxiliary electric energy peak in low cost solar domestic hot-water heating systems in Brazil

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ABSTRACT

Domestic water heating in Brazil is commonly done by electric showerheads, characterized by a large installed capacity and a low load factor. In that regard, consumers and utility companies present opposite interests, the first aim to reduce their electricity bill, while companies are interested on shaving on-peak consumption. Solar technologies offer significant potential for domestic applications, but the implementation is commonly hindered by economic issues. The present work shows a methodology for addressing the impact of promotion policies in terms of the benefits for consumers and utility companies. It is proposed a weighting procedure that allows to examine both interests in a single objective function. It enables determining a trade-off curve and optimizing the design parameters of the solar system (collector area, storage volume and set point temperature). Two policy scenarios were analyzed: a rebate program and the implementation of a time-of-use tariff (TOU) scheme. The results derived from the first policy scenario show the existence of a trade-off curve between the initial investment and the yearly electricity consumption, which is useful for addressing the impact of the monetary incentive considered for rebating the initial cost of the solar system. The second policy scenario shows a trade-off curve between the annualized life cycle cost of the system and the yearly on-peak electricity consumption. That curve can be used for assessing the influence of the TOU tariff on the on-peak electricity utilization, allowing to measure the impacts of the tariff scheme, and providing the basic parameters for negotiation strategies between company planners and relevant consumers.

1. Introduction

Brazil has among the largest hydropower potential worldwide (OECD/IEA, 2012), and currently hydraulic resources represent the largest share of country's electricity matrix (EPE, 2016). In fact, due to the contribution of hydropower, the electricity share of renewable sources in Brazil is approximately 75.5% (64% hydropower, 8% Biomass and 3.5% wind) (EPE, 2016). This scenario of strong dependence on hydrological resources looms as a potential threat for the stability of the electricity grid, because it is highly sensitive to seasonal rain cycles. Indeed, long periods of drought depleted water reservoirs in 2013 and 2014, reducing the security of the system, increasing the operational costs of the electricity grid, and, consequently, transferring a significative increment on the price to residential consumers.

Currently, around 73% of the Brazilian dwellings use electric showerheads for bathing; however that average coverage rises to over 90% in the populous and colder southern regions (EPE, 2012). Historically, the widespread utilization of electric showerheads can be traced back to a lack of natural gas availability in the country, to the low costs of hydroelectricity generation and the relatively high efficiency of these devices (Sowmy and Prado, 2008). Because of the high electricity consumption of electric showerheads, this device represents approximately 24% of the total residential electricity consumption. As a result, approximately 5.5% (33.7 TWh/year including losses) of Brazilian electricity consumption is due to the use electric showerheads (EPE, 2012). By analyzing the daily average rate of domestic electricity consumption, is possible to establish that the use of electric showerheads accounts for 92.4 GWh/day. Setting the average daily consumption and considering the statistical load profile of the residential sector described in PROCEL (2007), the average power load profile due to electric showerheads is estimated, as depicted in Fig. 1. According to that figure, electric showerheads are responsible for the two peaks on the residential electric demand profile, between 5–9 AM and 5–9 PM, when the peak load rises to over 11 and 14 GW, respectively. For distribution utilities, the electrical shower represents a serious challenge, due to its high-power demand and the limited period of utilization (low load factor). In recent years, the problem has intensified, because the nominal power of these devices has continuously increased from

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Nomenclature

a_0	intercept collector efficiency [–]
a_1	collector efficiency slope [W/m^2 K]
A_c	solar collector area [m^2]
ALCC	annualized life cycle cost
$ALCC_0$	ALCC for a null time-of-use tariff [€/year]
$ALCC_{0,max}$	maximum ALCC for a null time-of-use tariff in the feasible space [€/year]
b_0	IAM coefficient [–]
C	specific cost [€/m^2], [€/kW], [%]
C_1, C_2	constant penalty value
C_a	specific cost of heating element [€/kW]
C_e	nominal value of the electric tariff [€/kWh]
$C_{e,TOU}^{*}$	intended time-of-use tariff [€/kWh]
$C_{e,TOU}$	added value of time-of-use tariff [€/kWh]
d	diameter [m], discount rate [%]
E	yearly energy [kWh/year]
e_i	thermal storage insulation thickness [m]
E_{peak}	on-peak yearly energy consumption [kWh/year]
$E_{peak,max}$	maximum values of on-peak yearly energy consumption [kWh/year]
F_{test}	collector test flow rate [kg/m^2 h]
H_c	vertical distance of collector inlet and outlet [m]
H_d	heater diameter [m]
H_o	vertical distance of collector inlet and thermal storage outlet [m]
i	inflation [%]
IC	initial cost
IC_{max}	maximum value of the initial cost [€]
L	length [m]
LCC	life cycle cost
N	solar system life cycle [year]
N_b	number of bends in collector pipes [–]
P	power, heating rate [kW]
P_1, P_2	penalty functions
R_{ca}	ratio between utilized and test flow rate [–]
R_d	riser diameter [m]
S	shape factor [–] and feasible space region
T	temperature [°C]
T_{cons}	water load temperature [°C]
T_{ideal}	ideal/desired water temperature [°C]
u	currency conversion factor from Reais to Euros, 3.48 [R$/€]
U	thermal loss coefficient [kJ/m^2 h K]
V_{tes}	thermal storage volume [m^3]
x	independent variable space

Acronyms

ESCO	Energy Service Companies
ESh	electric showerhead
GENOPT	Generic Optimization Program
GPSPSOCCHJ	Generalized Pattern Search implementation of the Hooke-Jeeves algorithm
PV	photovoltaics
PWF	Present Worth Factor
SDHW	Solar Domestic Hot Water
SWERA	Solar and Wind Energy Resource Assessment
TMY	Typical Meteorological Year
TOU	Time of Use
TRNSYS	Transient System Simulation Program
TS	Thermal Storage

Greek

β	collector slope [°]
η	efficiency [–]
κ	thermal conductivity [W/m K]
ϕ	relative weights
ΔT_{on}	upper temperature difference, to turn on the solar pump [°C]
ΔT_{off}	lower temperature difference, to turn off the solar pump [°C]

Subscripts

a, aux	auxiliary
c, col	collector
db	dead band
e	electric
i	inlet
inst	installation
limit	ALCC constrain
m	maintenance
o	outlet
tank	tank
tes	thermal energy storage
w	water

approximately 3 kW on average to a range from 4.4 kW to 6.5 kW and even 8 kW in some models. Using electricity for direct water heating in Brazil is therefore one of the most serious energy issues faced by the electricity sector. Because of that, the electricity grid is designed to supply this peak on the consumption, which implies high transmission and distribution costs for the system operator and utility companies. It is worth noting that the on-peak consumption due to electric showerheads in Brazil is equivalent to the installed capacity of the hydroelectric plant at Itaipu, the second largest worldwide, which illustrates the magnitude of the problem.

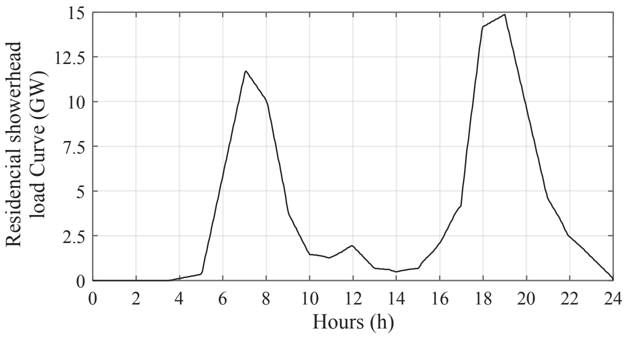

Fig. 1. Estimated showerhead load curve for Brazil.

Heating and cooling applications using solar technologies offer significant potential and can play an important role in energy planning, establishing targets for securing the energy supply and fostering economic development. In particular, solar domestic hot water systems are considered the most mature technology, because they have been used on a large scale since the 1960s (OECD/IEA, 2010). This is not different for Brazil. The large-scale deployment of solar hot water systems could not only reduce the energy consumption that electric showerheads represent, but also reduce approximately 30% of the on-peak power demand over the electricity grid (Almeida et al., 2001; Giglio et al., 2014).

Currently, Brazil is ranked fourth in terms of the total installed capacity of solar thermal collectors, accounting for 7.7 GW_{th}, approximately, considering glazed (5.2 GW_{th}) and unglazed (2.5 GW_{th}) solar collectors (Mauthner et al., 2016). However, that large installed capacity does not implies a large coverage, because the total installed capacity per 1000 inhabitants is only 38.4 kW_{th}/1000 inhabitants, which is far from European countries and even from China, where the total population is approximately 1.36 billion inhabitants, presenting an installed capacity of 213 kW_{th}/1000 inhabitants. The experience observed in well-developed solar markets shows that a strong increase in the deployment of solar hot water systems could be achieved by introducing long-term subsidy schemes or solar obligations. According to the International Energy Agency (IEA, 2011), Brazil had a target of 15 million m^2 of solar thermal collectors installed in 2015; however, because financial support and public policies are restricted or inexistent, the total surface of installed collectors slightly rises over the 11 million m^2 in 2016 (Mauthner et al., 2016).

Promotion policies for solar domestic hot-water systems (SDHWs) are often divided into five categories: collector area-based subsidies (Germany, Austria, Korea), collector/system performance-based subsidies (Sweden, Netherlands, Australia), tax credits (France, USA), tax deduction (Greece) and mandatory installation (Israel, Spain) Li et al. (2013). Several studies have been carried out focusing on the techno-economic and cultural barriers for SDHW deployments (Sarzynski et al., 2012; Wasi and Carson, 2013; Aste et al., 2015). The key findings include the strong impact on the solar market development by state rebate programs (Sarzynski et al., 2012), and the success in shifting the shock of electric water heaters (Wasi and Carson, 2013). However, from a cost-effective point of view, the evidence shows that capital grants in some cases do not speed up the expected decrease in the market price of the granted technology, increasing the costs paid by the community and inducing market failures (Aste et al., 2015). Thus, there is no consensus on which policy instrument is most cost effective; nevertheless, these studies agree that some government intervention is a requisite for a substantial increase in the deployment of SDHW systems. Nonetheless, the proper size of subsidies should be carefully determined according to a mid-term technical development and cost trends of the technologies. In addition, currently several governments are fostering the implementation of renewable energy. The development of such market encourages establishing agreements with utilities, fostering the deployment of solar systems (commonly PV panels). These agreements shift the financing burden of the subsidy from public institutions to utilities and private entities. Some states are also experimenting with more complex financing arrangements, including third-party contracts, such as ESCO (Energy Service Companies) contracts, facilitating the deployment of solar solutions by shifting the upfront costs from individual private customers to investors willing to assume the risk of the investment. The complexities of these policy tools have not been analyzed in the literature, and presents a particular scenario in Brazil, where the implementation of a subsidy would benefit consumers by reducing their electricity bill and utility companies by reducing the fixed cost related to respond the peak demand associated to electric showerheads.

A different approach for reducing the on-peak use of electricity in households is through behavioral modifications commonly called “demand response”. Through this method, people are encouraged to eliminate on-peak electricity-using activities or shift them to other periods. Aiming to provide an economic incentive for such behavior change, utilities will propose a different scheme for the residential electricity rate structure. This approach is significantly different from the traditional flat-rate structure, moving more closely to the real cost of delivering electricity at the time whe is used. In that context, several authors have studied the effect of utility time-varying pricing on the reduction of electricity consumption (Newsham and Bowker, 2010; Caves and Christensen, 1980; Oconnell et al., 2014). In that regard, the time-of-use-tariff (TOU) has been analyzed by several authors, comparing its benefits to other approaches of demand response. The implementation of TOU schemes does not affect the system’s security, which is the primary concern of the system operator. In addition, in some cases the program induced on-peak reductions of 5% by simply implementing the conventional night-valley filling behavior, and using more complex schemes a 30% reduction can be expected (Newsham and Bowker, 2010). However, the implementation of such a policy can cause substantial hardship for consumers and demands large-scale investments in Smart Grid infrastructure (Starke et al., 2015). The implementation of TOU would induce a major modification on energy planning policies, which should reflect great impact on portfolio planning, as complementary resources could contribute to ensuring system’s balance. Hence, capacity planning applies not only to the infrastructure, but also consumers. In that context, sizing demand response schemes have a significant impact on the economic benefits for companies, but the effect on consumers should also be properly balanced (Caves and Christensen, 1980). The on-peak reduction due to the implementation of TOU depends on the appliances and devices that have an alternative primary use. Such appliances are typically sized according to the maximum demand; however, when considering their use for estimating the impact of TOU may limit the flexibility on its use. This issue is particularly interesting for electric showerheads when the deployment of SDHW system is considered as alternative. Solar thermal systems are able to provide flexibility for users that have economic and operational benefits that have not been properly analyzed in the recent literature.

Considering the technology constraint and the difficulties observed in implementing policies such as TOU, there is no consensus on the impact that it could present in modifying the behavior of domestic users. In this context, this paper aims to assess the feasibility of implementing thermosyphon and forced-circulation SDHWs when two different policies scenarios are applied: a rebate program and a time-based tariff for electricity. For each policy, the systems are analyzed in terms of the technical characteristics, such as the solar collector area, thermal storage volume and set point temperature for the in-tank heater. The optimum configuration is determined for each policy scenario.

The main goal of the policies analyzed herein (i.e., rebate and time of use tariff) is to promote the use of SDHWs, considering the benefits for consumers and the electricity distribution system. Therefore, the system needs to be cost-effective for the consumer (i.e., a reduction in electricity consumption, defined as the consumption from 5 to 9 PM) and for the system operator or utility company (i.e., a reduction on the peak consumption). As aforementioned, the impact of promotion policies is commonly assessed in terms of the benefits that it represents for either the user or the electric system. The analysis proposed considers a multi-objective optimization allowing to analyze the allocation of the benefits perceived by the implementation of solar thermal systems.

The first policy analyzed consists of a rebate program, aiming to assist low-income consumers to cover the capital cost of the SDHWs, by means of rebate or partial financing it through a direct subsidy. The electric utilities can deliver that subsidy, because they have a clear interest in reducing on-peak consumption. Therefore, this case constitutes an optimization problem in terms of the on-peak consumption and the acquisition cost of SDHWs. The coexistence of two objective functions yields a Pareto frontier that is used as a tool for sizing financial incentives to acquire a solar energy system.

The second policy analyzed is the implementation of a time-of-use tariff scheme for electricity consumption, aiming to discourage the consumption in on-peak hours through an increase on the electricity tariff. Thus, the implementation of such a policy also yields a two-objective optimization problem, where the on-peak consumption and Annualized Life Cycle Costs (ALCC) are the objective functions. Hence, a Pareto frontier should show for consumers the trade-off between paying for the electricity during on-peak hours and the increase in the ALCC due a large investment in SDHWs. Using the results of the optimization procedure, an ideal value for the time-of-use tariff can be established based on the distributor's level of commitment on reducing the peak consumption.

The performance evaluation of domestic thermal systems through transient simulations have been extensively analyzed in the literature. The application covers climatization, domestic water heaters, among others. The main differences on the modelling approach is based on the structure, while physical modelling by Computational software's is still broadly used (Liu et al., 2015, 2017a), novel approaches such as Artificial Neural Networks have proven to be highly efficient (Liu et al., 2017b; Cho et al., 2014). The present work considers a physical approach, based on a model developed by our group in a previous study, which was validated with experimental data (Salazar et al., 2005). In this context, the proposed scenarios are assessed by long-term transient simulations routines, considering a case study, configured by thermosyphon and forced-circulation SDHWs, and weather data for a specific location in Brazil: Florianopolis (27.6°S/48.5°W). Two total volumes of daily hot water consumptions were considered, 0.2 m^3 and 0.4 m^3, both at 40 °C. These values were chosen because they represent low-income consumers and standard consumers, respectively, (Borges et al., 2004).

2. System description

Two types of SDHWs are considered, thermosyphon and active (forced-circulation) according the features depicted in Fig. 2. Thermosyphon systems, which work by natural circulation, are recommended for warm climates due to the low probability of freezing, the operational reliability and lower costs. This system avoids the use of pumps and dedicated control systems; however, the thermal storage needs to be placed at a higher position than the collector, and therefore it is common to place it on the roof, limiting its size because of its weight and drops in piping pressure.

Forced-circulation systems use a pump to circulate the water from the storage through the collector, allowing more flexibility in the installation of thermal storage. For example, it can be installed inside the house. Nevertheless, these systems are more complex, because they require a water pump and a differential temperature controller to ensure the proper operation of the system.

The solar collectors and thermal storage tanks considered are identical for the two systems, with the specifications presented in Table 1. The specifications of the solar collector were taken from INMETRO (2015), considering a class A solar collector, such as the Jelly Fish, model JF20. The main characteristics of the thermosyphon system are also shown in Table 1, as are the features of the forced-circulation system. It is worth mentioning that in both systems, water is used as heat transfer fluid and no heat exchanger is considered.

Several of the simulation parameters used to model the systems are functions of the design specifications (i.e., solar collector area and thermal storage volume) and need to be updated in each iteration of the optimization process. These parameters are the thermal storage overall heat loss coefficient, the thermal storage diameter and height, the positions of the thermal storage thermostat and heating element, the length of the solar collector and inlet piping length, the number of parallel solar collector risers and the maximum flow rate for the solar pump. The equations used to calculate these parameters were described in detail by Morrison and Braun (1985), Duffie and Beckman (2013).

It is worth noting that two auxiliary energy heaters were considered for both systems, one inside the thermal storage and the other in line to the load. The second one works as an electric showerhead and was considered in the simulation model just to ensure that a comfortable water temperature (40 °C) is delivered for the users, in the case that the solar energy and the auxiliary heater located in the tank were not able to supply the thermal load.

The thermal performance of the SDHWs depends significantly on the domestic hot water load profile (Jordan and Vajen, 2000), which varies on a daily basis and depends on consumers' behavior. Thus, the suitable solution is to use a repetitive load profile, which is not completely correct because the consumption patterns vary throughout the year, but the variation is compensated by the temperature differences, which implies total thermal requirements reasonably constant throughout the year (Kalogirou and Tripanagnostopoulos, 2006). Therefore, in this study, a statistically representative load profile was considered, as depicted in Fig. 3 in terms of a normalized consumption. This profile was experimentally determined in a previous studies (Borges et al., 2004, 2005), where a group of ninety families were studied, by monitoring the electrical consumption of showerheads in a one-year period.

3. Methodology

The annual thermal performance and economic assessment of both systems was determined using a transient simulation model, where the effects of meteorological parameters and the hourly consumption profile were considered. For that purpose, the well-known Transient System Simulation Program (TRNSYS) was employed, owing to its modularity and open-source structure. That simulation platform allows a proper evaluation of the optimal sizing of the system i.e., appropriate sizing of the collectors, storage and heat exchanger (Klein and Beckman, 1979). In addition, assessing the performance of solar systems using simulation methods requires weather data input from the location where the system was installed, and a sky model for estimating sola irradiance on inclined surfaces (Loutzenhiser et al., 2007). Therefore, the TMY file available from SWERA database (Martins et al., 2008) for Florianopolis (27.6°S/48.5°W) was considered in this study.

The performance of the thermosyphon system was assessed through an empirical model performed by the TRNSYS Type 45. The thermal performance of the system is analyzed by dividing the thermosyphon loop into several segments normal to the flow direction and applying Bernoulli's equation for incompressible flow to each segment. The flow rate is determined by a numerical procedure and the flow within the loop is assumed to be in steady state. In contrast, the forced circulation

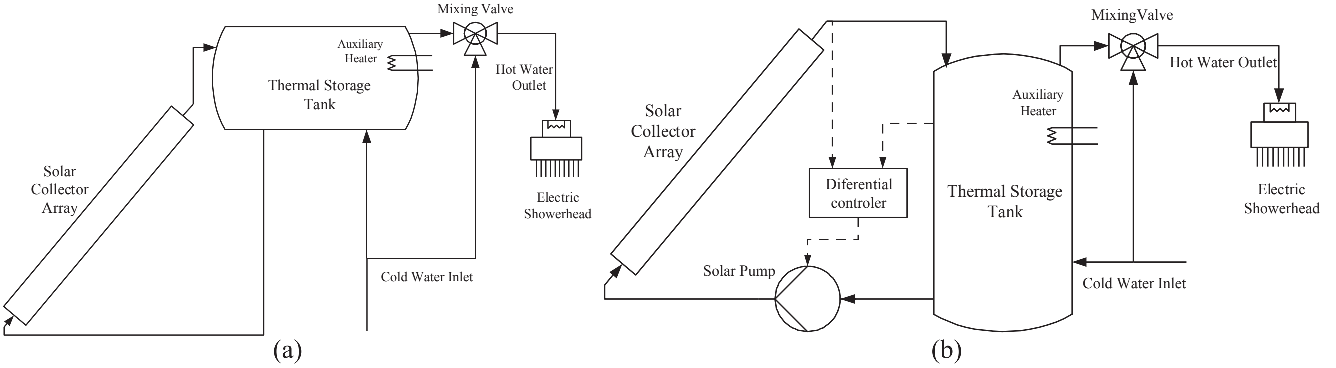

Fig. 2. Schematic diagram of the solar domestic hot water; (a) thermosyphon, and (b) forced-circulation.

Table 1
System specifications.

Parameter	Values	Parameter	Values
		Thermostyphon	
Collector slope, β (°)	37.6	Riser diameter, R_d (m)	0.0142
Intercept collector efficiency, a_o (–)	0.728	Header diameter, H_d (m)	0.027
Collector efficiency slope, a_1 (W/m^2 K)	6.18	Collector inlet diameter, d_i (m)	0.015
Incidence angle modifier coeff., b_0 (-)	0.1065	N° of bends in the inlet pipeline, $N_{b,i}$ (–)	4
Tested flow rate, F_{test} (kg/m^2 h)	60	Inlet pipeline thermal loss coeff., U_i (kJ/m^2 h K)	1.8
TS shape factor, S (–)	0.5	Collector outlet diameter, d_o (m)	0.019
TS insulation thickness, e_i (m)	0.05	Number of bends in the outlet pipeline, $N_{b,o}$ (–)	4
TS insulation conductivity, k_i (W/m K)	0.126	Outlet pipe thermal loss coeff., U_o (kJ/m^2 h K)	1.8
TS max. aux. heating rate, P_{tank} (kW)	3	Height of the solar collector, L_{col} (m)	1.415
TS aux. heating efficiency, η_{tank} (–)	1	Vertical dist. collector's inlet and outlet, H_c (m)	0.864
TS thermostat temp. dead band, T_{db} (°C)	2	Vertical dis. collector inlet – TS outlet, H_o (m)	1.164
ESh maximum power, P_{aux} (kW)	10	Thermal water conductivity, k_w (W/m K)	2.207
ESh overall coefficient, U_{aux} (kJ/m^2 h K)	0	*Forced-circulation*	
ESh efficiency, η_{aux} (–)	0.95	Ratio between utilized and test flow rate, R_{ca} [–]	0.5
ESh set point, T_{ideal} (°C)	40	Upper temp. diff. solar pump, ΔT_{on} (°C)	6
		Lower temp. diff. solar pump, ΔT_{off} (°C)	0.4

system was modeled by integrating different types, such as 1b, 4 and 6, for modelling the transient behavior of the solar collector, thermal storage, and auxiliary heater, respectively. In that context, a stratified thermal storage with a fixed inlet is considered, and the auxiliary heater is assumed to be an electric device with fixed thermal efficiency and maximum power output (Table 1). Therefore, the actual power is modulated to meet the specified set point temperature.

Hence, each system analyzed herein is modeled by combining several components as described in Fig. 4, which shows the flow diagrams that configure the simulation of the thermosyphon (a) and forced circulation (b) systems. The deck files required to run the TRNSYS models for the different configurations analyzed; considered the use of ready-made modules. The list of the modules employed in each configuration is listed in Table 2.

Because the analysis considered the assessment of two different policies that can be expressed as objective functions, each system needs to be properly sized according the scenario analyzed. Thus, an optimization routine was performed using the simulation models, considering three design parameters as independent variables: the solar collector area, the thermal storage volume, and the set point temperature for the in-tank heater. The usefulness of combining optimization routines with life-cycle simulations of solar systems was extensively explained in Borges et al. (2005).

Both policies consider conflicting objectives between the benefits perceived by the consumers and the energy supplier. Therefore, considering that the feasible region features a convex domain, the weighted-sum-of-objective-method (Collette and Siarry, 2004) was employed to determine the trade-off surface between the objectives functions in the optimization problems. Through the weighted-sum-of-objective-functions method, it is possible to solve a single objective by assigning relative weights (φ) to the conflicting ones.

The Generic Optimization Program (GENOPT) was employed for the multi-objective and multi-parameter optimization, because 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, which is the case of the thermal simulation routines analyzed. Therefore, the design parameters can be solved only heuristically.

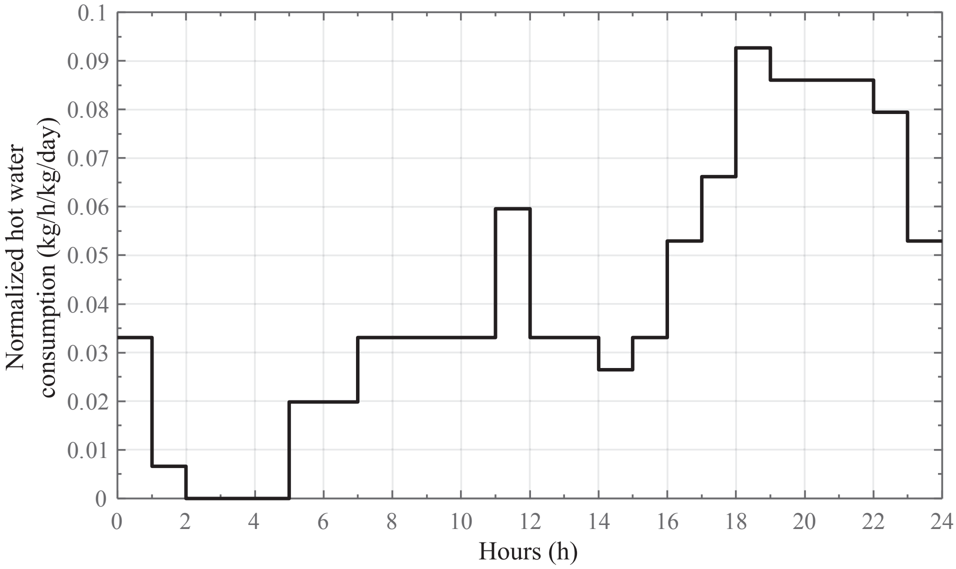

Fig. 3. Hot water daily consumption profile.

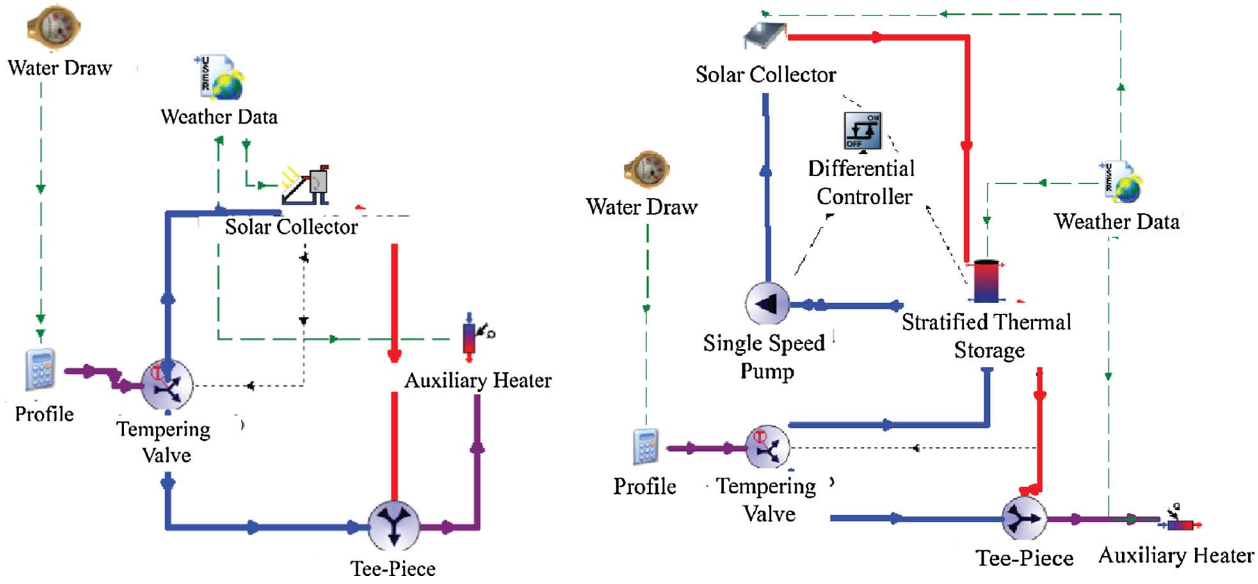

Fig. 4. Simulation flowchart diagram for both systems: (a) Thermosyphon and (b) Forced Circulation.

Table 2
TRNSYS modules employed in each configuration.

Component	TRNSYS module	Component	TRNSYS module
Common		*Thermosyphon system*	
Weather data reader	Type 99	Thermosyphon collector w. integral storage	Type 45a
Water draw	Type 14b	Auxiliary heater	Type 6
Tempering valve	Type 11b	*Forced circulation system*	
Tee piece	Type 11h	Solar collector	Type 1b
Hot water load	User supplied	Differential controller	Type 2b
Auxiliary heater	Type 6	Single speed pump	Type 3d
		Stratified storage – fixed inlets	Type 4a

Table 3
Economic and cost considerations.

Parameter	Value
Solar system life cycle, N (years)	20
Discount rate, d (%)	8
Maintenance inflation rate, i_m (%)	6.4
Solar collector cost, C_c (€/m^2)	119.25
Heating element cost, C_a (€/kW)	6.9
Annual maintenance cost, C_m (% of installed cost)	1
Installation cost, (% of initial cost)	15
Nominal value of the electric tariff, C_e (€/kWh)	0.1385

3.1. Economic figures

The assessment of the economic figures derived from the optimization processes is derived from the life-cycle cost analysis, according to the following equation:

$$LCC(\boldsymbol{x}) = (1 + C_{inst})IC(\boldsymbol{x})[1 + C_m PWF(N,i_m,d)] + PWF(N,0,d)E_{aux}(\boldsymbol{x})C_e, \tag{1}$$

where $\boldsymbol{x}$ the vector variable accounting for the design parameter of the SDHW, namely, the solar collector area (A_c), thermal storage volume (V_{tes}) and set point temperature for the in-tank heater; C_{inst} is the installation cost as a percentage of the initial cost; C_m is the annual maintenance cost as a percentage of the installed cost of the system; C_e is the electricity tariff; E_{aux} is the total auxiliary yearly energy consumption; PWF is the present-worth factor; N is the lifetime of the system; i_m is the maintenance inflation rate; and d is the discount rate. To analyze the system on a yearly basis, the life-cycle cost can be annualized by the following equation:

$$ALCC(\boldsymbol{x}) = \frac{LCC(\boldsymbol{x})}{PWF(N,0,d)}. \tag{2}$$

Finally, the initial cost is defined as follows:

$$IC(\boldsymbol{x}) = (C_c A_c + C_{tes}(V_{tes}) + C_a P_{tank}), \tag{3}$$

where C_c is the solar collector cost per area, A_c is the solar collector area, C_{tes} is the thermal storage cost as a function of the storage tank volume (V_{tes}), C_a is the cost of the heating element per power and P_{tank} is the electric power of the auxiliary heater in the thermal storage.

The economic parameters considered within the analyses described herein are representative of the Brazilian market at the time of the study, as listed in Table 3.

The cost, in euros, of the thermal storage (C_{tes}) was modeled using a regression model based on the prices of tanks of different volumes according the information delivered by the main suppliers in the Brazilian market. The regression model leads to the following correlation:

$$C_{tes}(V_{tes}) = \frac{1}{u}(4798.8V_{tes} - 2889.8V_{tes}^2 + 1196V_{tes}^3 - 216.9V_{tes}^4 + 14.911V_{tes}^5) \tag{4}$$

where u is the currency conversion factor from Reais to Euros (3.48 R$/€ at **July of 2015)** and V_{tes} is the thermal storage volume.

4. Rebate program

The analysis of a rebate program aims to assess the benefits of consumers represented by the initial investment of the solar system (IC), which can be reduced by the rebate program, and the benefits for the electricity companies through the reduction on the on-peak yearly energy consumption (E_{peak}), where the on-peak consumption period is from 5 to 9 PM. Therefore, the optimization problem featuring two conflicting objectives is defined considering the weighted-sum-of-objective functions method, as follows

$$
\begin{aligned}
& min_x\left\{f(\boldsymbol{x}) = (1-\varphi)\frac{\mathrm{E_{peak}}(\boldsymbol{x})}{E_{peak,max}} + \varphi\frac{\mathrm{IC}(\boldsymbol{x})}{\mathrm{IC_{max}}} + \mathrm{C_1P_1}(\boldsymbol{x}) + \mathrm{C_2P_2}(\boldsymbol{x})\right\}\\
& Subject\ to:\\
& x \in S\\
& \mathrm{P_1}(\boldsymbol{x}) = \begin{cases} 0, & if\ ALCC \leqslant ALCC_{limit} \\ (ALCC_{limit} - ALCC(\boldsymbol{x}))^2, & otherwise \end{cases}\\
& \mathrm{P_2}(\boldsymbol{x}) = \sum_t \begin{cases} 1, & if\ T_{cons}(\boldsymbol{x}) < T_{ideal} \\ 0, & otherwise \end{cases}
\end{aligned} \tag{5}
$$

where S is the feasible region mapped by the solar collector area (A_c), the thermal storage volume (V_{tes}) and the set point temperature for the in-tank heater; and $E_{peak,max}$ and IC_{max} are the maximum values of the on-peak yearly energy consumption and initial cost possible on the feasible region, respectively. Those values are used to rewrite the two conflicting objectives in a non-dimensional form. The multi-objective optimization process follows the procedure described in the previous section, but before starting the optimization of the objective function (Eq. (5)), both maximum feasible values should be determined, which is done using the optimization software GENOPT.

Two constraints were considered in this optimization problem. The first is used to guarantee that the annualize life cycle cost of the system ($ALCC$) will be less than a specified value ($ALCC_{limit}$), and the second aims to guarantee that the system supplies water at the desired temperature (T_{ideal}). This constrained optimization problem was solved using a penalty method (i.e., a constant value is added in the objective function when the constrained event is triggered), which are the last terms on the right of Eq. (5) ($\mathrm{C_1P_1}(\boldsymbol{x})$ and $\mathrm{C_2P_2}(\boldsymbol{x})$).

Since the relative importance of each conflicting function is not known, the domain of φ is divided into a series of discrete values and single objective optimizations were run for each value of φ. The results of this analysis can be represented by a curve (Pareto frontier), which shows the initial investment cost versus on-peak yearly energy consumption. This curve is used as a tool for sizing financial incentives to acquire a system, as a solution for decreasing the on-peak power consumption.

4.1. Results

The optimization procedure leads to a trade-off between initial cost and yearly on-peak electricity consumption, as depicted in Fig. 5. The curves represent an $ALCC_{limit}$ of 215 and 430 €/year, for the consumption scenarios of 0.2 m^3 and 0.4 m^3, respectively. Each point of these curves represents the result of the optimization process, using different design values that simultaneously minimize the weighted combination of the yearly on-peak electricity consumption and initial cost.

Three regions are identified in Fig. 5. On the left, with high initial cost and low yearly on-peak electricity consumption, there is the adverse region for the consumer, where a decrease in the on-peak electricity consumption represents a large increase in the initial cost (i.e., low rebate). In contrast, on the right is the adverse region for the utility companies, characterized by low initial cost (i.e., large subsidy) and high yearly on-peak electricity consumption. In this region, a minor decrease on the initial cost represents a significant increase on the on-peak electricity consumption. Between these two regions, a negotiation region is identified, depicted by a small increase on the initial cost, which represents a large reduction on the on-peak electricity consumption.

Within the negotiation region, systems presenting 0.2 m^3 of daily consumption show an increase from 150 to 250 € on the initial cost, providing a reduction from 325 to 125 kWh/year on the yearly on-peak consumption. Thus, rebating 40% of the initial cost (100 € of 250 €) would provide a reduction of 62% of the on-peak electricity consumption, which could be considered a result of high interest to the utility companies. Regarding the systems that present 0.4 m^3 of daily consumption, an increase from 300 to 400 € in initial cost shows a reduction between 500 and 300 kWh/year on the yearly on-peak electricity consumption. Rebating only 25% on the initial cost (100 € of 400 €) would induce a reduction of 40% of the on-peak electricity consumption. It is worth noting that for 0.2 m^3 of daily consumption of hot water, both thermosyphon and forced-circulation systems present similar results. Moreover, for 0.4 m^3 of daily consumption, the forced-circulation system presents lower values of on-peak yearly electricity consumption, for the same initial cost. That result indicates that the forced-circulation systems could be more effective for reducing the on-peak consumption, however, the differences could be highly modified by changes on consumers' behavior.

Fig. 6, shows the effect of $ALCC_{limit}$ on the trade-off curves for both systems (thermosyphon and forced-circulation), considering the scenario of 0.2 m^3 of daily consumption. Four values of the $ALCC_{limit}$ were considered: 130, 185, 200 and 215 €/year. It is noted that the limitation on the $ALCC$, reduces the feasible domain that meet the objective function, reducing the size of the trade-off curves and the negotiation region. That effect is due to the relation between the costs (ALCC) and

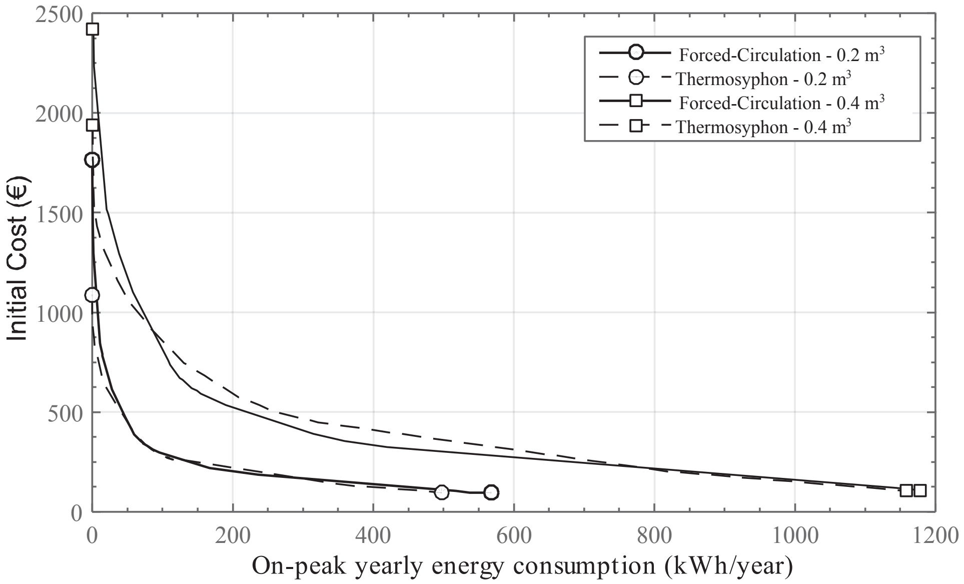

Fig. 5. Trade-off curves between initial cost and yearly on-peak electricity consumption, for an $ALCC_{limit}$ of 215 and 430 €/year and the scenarios of 0.2 m^3 and 0.4 m^3, respectively.

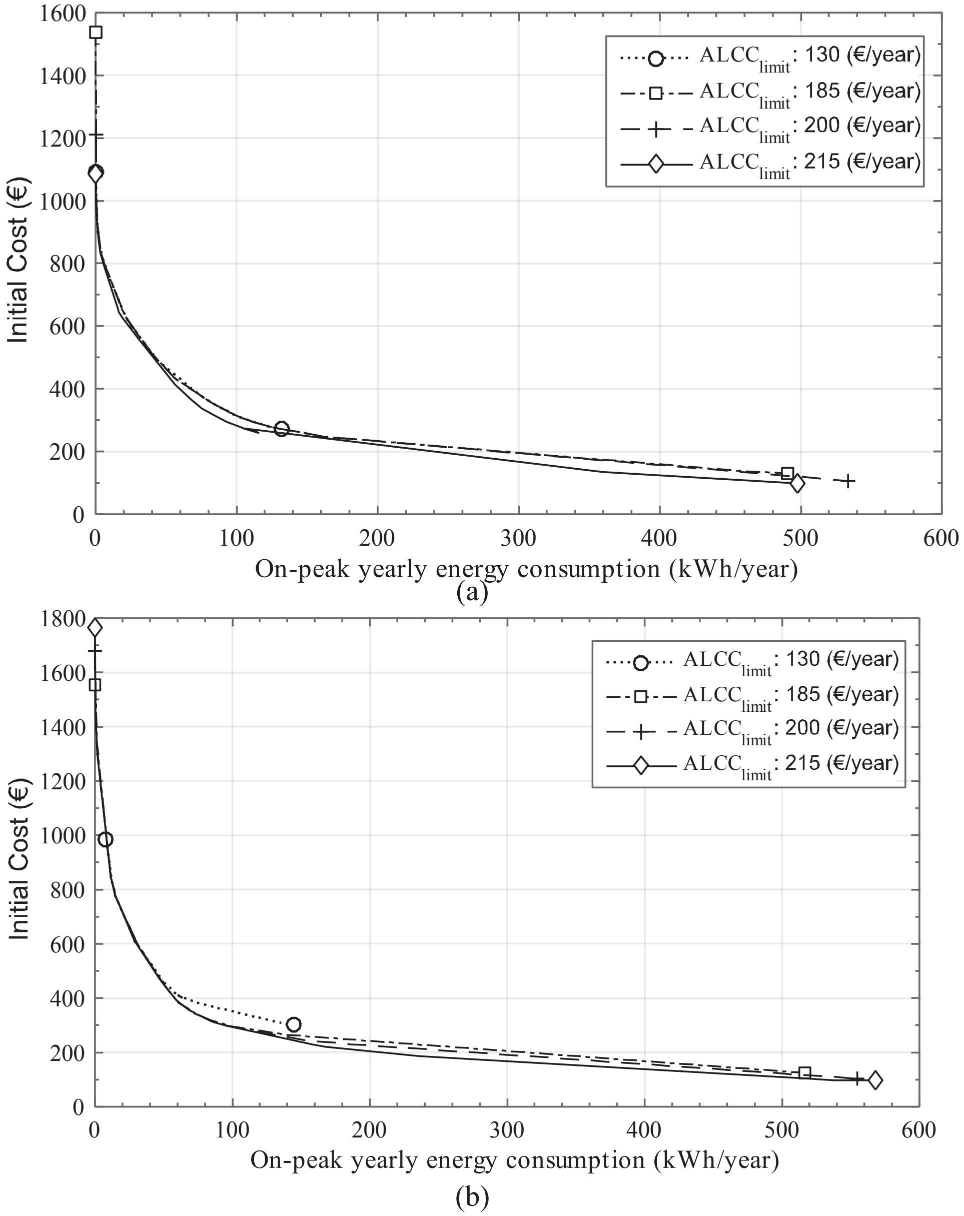

Fig. 6. Effect of the $ALCC_{limit}$ in the trade-off curves of the rebate program for thermosyphon (a), and forced-circulation (b) systems for a $0.2\,\mathrm{m}^3$ of hot water consumption.

the size of the system (collector area and storage volume), since large (expensive) systems implies a lower on-peak consumption. In that cases, the negotiation region reflects that a relatively small subsidy can induce a significant reduction on the on-peak consumption.

The proposed methodology results helpful for estimating the expected effects by defining a specific monetary incentive for rebating the initial cost of the SDHWs. The proper size of this incentive can only be defined by the utility company, depending on its commitment to reducing the on-peak consumption. Nevertheless, is result clear, that large investments (higher that 400 €), could represent a significant reduction on the on-peak consumption, which leads to a lower investment in infrastructure

5. Time-of-use tariff

For this policy scenario, the two conflicting objectives considered are the on-peak yearly energy consumption (utilities benefit) and the annualized life cycle cost (*ALCC*) of the system (consumers benefit). During the on-peak period, same as for the rebate program, a higher electricity tariff was considered. An additional constraint is defined aiming to ensure that the system supplies water at the desired temperature to the consumers (T_{ideal}). Therefore, the optimization problem for this policy scenario is defined as follows:

$$
\begin{aligned}
& min_x\left\{f(\boldsymbol{x}) = (1-\varphi)\frac{\mathrm{E_{peak}}(\boldsymbol{x})}{\mathrm{E_{peak,max}}} + \varphi\frac{\mathrm{ALCC_0}(\boldsymbol{x})}{\mathrm{ALCC0}_{max}} + \mathrm{C_2P_2}(\boldsymbol{x})\right\} \\
& Subject\ to: \\
& x \in S \\
& \mathrm{P_2}(\boldsymbol{x}) = \sum_t \begin{cases} 1, & if\ \ T_{cons}(\boldsymbol{x}) < T_{ideal} \\ 0, & otherwise \end{cases}
\end{aligned} \tag{6}
$$

where $ALCC_0$ is the annualized life cycle cost considering only the nominal value of the electricity tariff (C_e) and $ALCC_{0_{max}}$ is the maximum annualized life cycle cost possible in the feasible region. Eq. (6) considers only the nominal tariff, to minimize the number of optimization runs. Different values of the tariff were considered in a post-processing procedure, in which the following equation was employed:

$$ALCC(\boldsymbol{x}) = ALCC_0(\boldsymbol{x}) + E_{peak}(\boldsymbol{x})C_{e,TOU} \tag{7}$$

where *ALCC* is the total annualized life cycle cost considering the time-of-use tariff – $C_{e,TOU}$, defined as the surcharge value added to the nominal electric tariff (C_e) during the on-peak hours. This approach removes the need for running an optimization routine for each time-of-use tariff scenario. It is worth mentioning that in the case of a null value for the time-of-use tariff, the expression is reduced to $ALCC(\boldsymbol{x}) = ALCC_0(\boldsymbol{x})$. Hence, the results of this analysis are also presented as a trade-off curve between *ALCC* and E_{peak}, for different values of the time-of-use tariff, showing the compromise between paying for electricity at on-peak hours and the increase in the *ALCC* due a large investment in SDHW systems.

5.1. TOU results

Four values of the time-of-use tariff were considered within the analysis of the time-based program: 0, 0.5, 1 and 2 €/kWh. These values are supplementary to the nominal value of the electricity tariff in the period between 5 and 9 PM. The trade-off between the annualized life

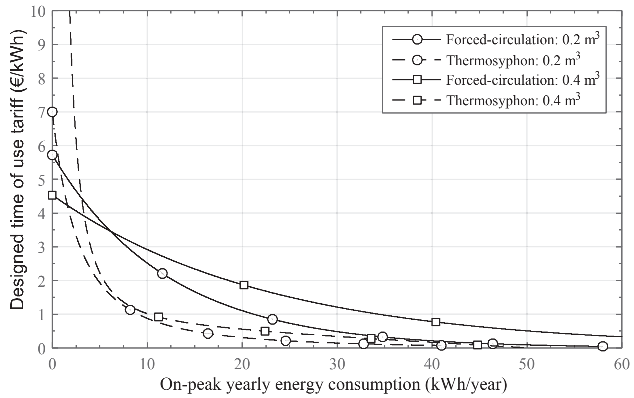

Fig. 8. Designed time-of-use tariff for the forced-circulation and thermosyphon system, considering 0.2 and 0.4 m^3 of hot water consumption scenarios.

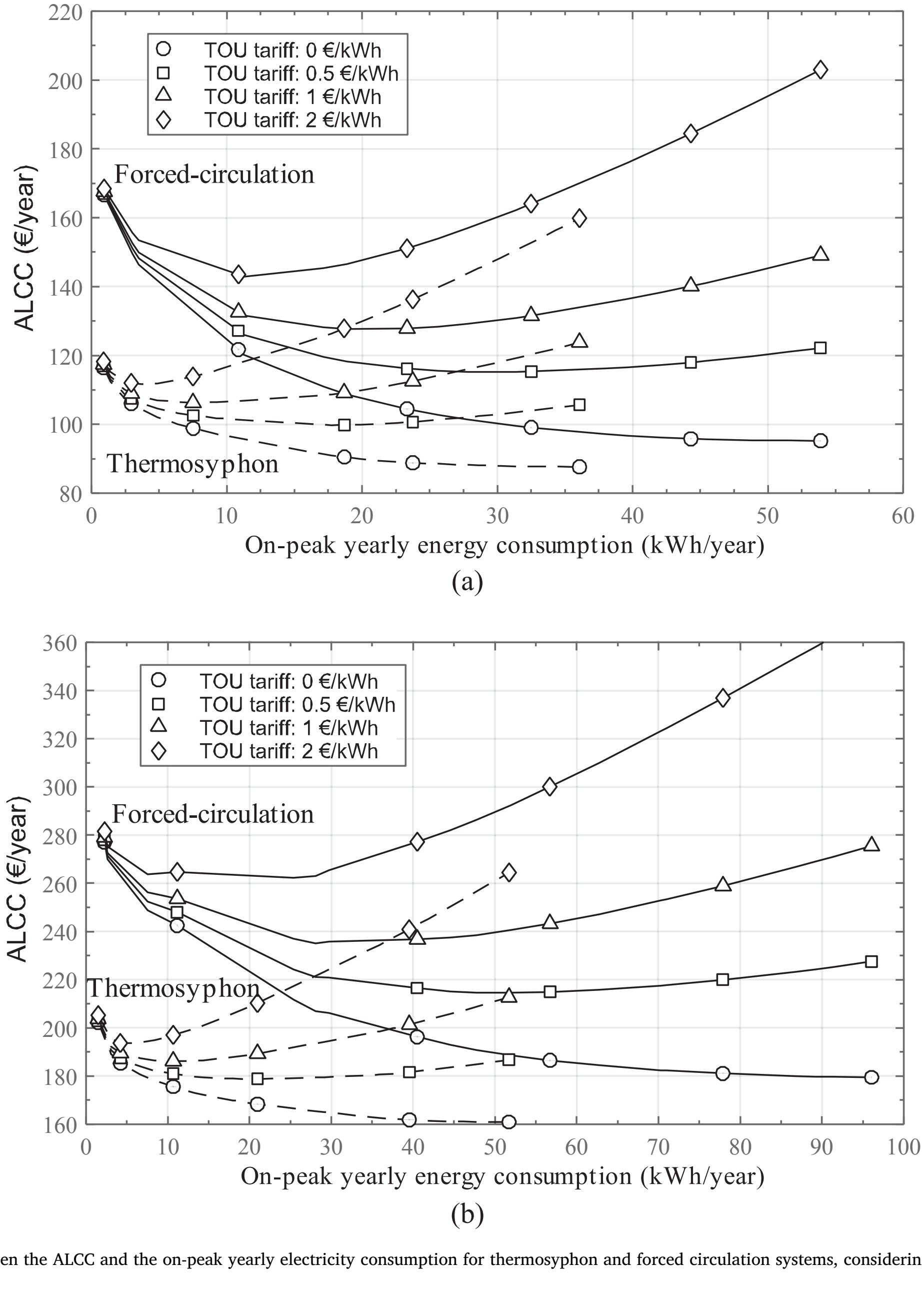

Fig. 7. Trade-off curves between the ALCC and the on-peak yearly electricity consumption for thermosyphon and forced circulation systems, considering 0.2 (a), and 0.4 m^3 (b) of hot water consumption.

cycle cost of the system and the on-peak yearly electricity consumption is shown in Fig. 7, where the Pareto frontiers for the thermosyphon and forced-circulation are illustrated. The curves represented by a null value of time-of-use tariff (TOU tariff) were derived by the optimization process using Eq. (6). In contrast, the other curves were calculated as a post-processing procedure using Eq. (7), which allow us to consider different values for the time-of-use tariff. It is observed that the results are similar for 0.2 m^3 and 0.4 m^3 of hot water consumption, because the difference evidenced is due to a matter of scale. Moreover, under this policy scenario, the thermosyphon system shows better performance than the force circulation, being more effective in reducing the on-peak yearly electricity consumption.

The minimization of the ALCC already induces a substantial reduction on the on-peak consumption. That is evidenced by comparing the values in Figs. 6 and 7. Regarding the values of the TOU tariff, it can be noted that for each tariff illustrated in Fig. 7 there is a minimal value of the ALCC, indicating the existence of an optimal design for the consumer. Therefore, each minimal ALCC, and its respective on-peak yearly electricity consumption, can be determined for each value of the time-of-use tariff. That result is achieved by deriving Eq. (7) with respect of the yearly on-peak consumption and setting it to zero (minimal ALCC), as follows:

$$\frac{dALCC(\boldsymbol{x})}{dE_{peak}} = \frac{dALCC_0(\boldsymbol{x})}{dE_{peak}} + C_{e,TOU} = 0, \tag{8}$$

where $dALCC_0(\vec{x})/dE_{peak}$ can be estimated numerically or analytically if a regression model is applied to the $ALCC_0$ versus E_{peak} curve. Rearranging Eq. (8), the intended time-of-use tariff $C^*_{e,TOU}$ can be calculated as follows:

$$C^*_{e,TOU} = -\frac{dALCC_0(\boldsymbol{x})}{dE_{peak}} \tag{9}$$

This quantity can be plotted as a function of the on-peak yearly electricity consumption, as depicted in Fig. 8. That methodology provides a tool for sizing the values of the time-of-use tariff as a function of the commitment to reducing the on-peak consumption. Moreover, the existence of a negotiation region is clear, where a small value for the TOU tariff can significantly reduce (more than half) the on-peak electricity consumption. Fig. 8 also shows that the designed values of the TOU tariff are similar to the thermosyphon system, regardless the level of hot water consumption. However, this trend is not observed for the forced-circulation systems. When the system faces higher consumption rates, a higher TOU tariff is required to archive the same degree of reduction on the on-peak electricity consumption. In addition, it is observed that since the ALCC minimization, already induces a reduction on the on-peak consumption, the value established for the TOU tariff only affects to those users that do not follow the standard behavior.

6. Conclusions

The present work reported two methodologies for planning financial policies for SDHWs and measured their effectiveness in the reduction of on-peak electricity consumption in Brazil. The approach analyzed in this study considered the interest of both consumers and the energy supplier.

The first policy, a rebate program, delivers a trade-off curve between initial cost and yearly on-peak electricity consumption, where a clear negotiation region is identified. The results show that rebating 100 € of the initial cost can provide a reduction of 62% to 40% on the on-peak electricity consumption, for the system with 0.2 m^3 and 0.4 m^3 of daily consumption, respectively. It is noted that limiting the $ALCC$, reduces the feasible solutions, which is observed as a reduction on the negotiation region. That effect is due to the relationship between the ALCC and the size of the system, since large (expensive) systems implies a lower on-peak consumption. That effect reveals that a relatively small subsidy can reflect a significant reduction on the on-peak consumption. Therefore, that curves can be used as a design tool for defining the monetary incentives for rebating the initial cost of the SDHW system as a function of the commitment, from either the government or utilities companies, on reducing the on-peak consumption. A rebate program as a promotion policy, either from government intervention or from the utility companies, has the potential to encourage the user to acquire an SDHW system and then provide a shift in the scenario of electric water heaters. Because of the high saving potential of this policy, it is likely that it will work with “off the shelf” designs of SDHW.

The second policy, the implementation of a time-of-use tariff during the on-peak hours, shows a trade-off curve between the annualized life cycle cost of the system and the yearly on-peak electricity consumption for different time-of-use tariffs. This procedure gives rise to the existence of a minimal value of the ALCC for each TOU tariff, demonstrating the optimal design for the consumer. Consequently, it is possible to determine the value of the on-peak yearly electricity consumption relative to the minimal ALCC for each TOU tariff adopted. This yields a trade-off curve between the designed time-of-use tariff and the on-peak yearly electricity consumption, which helps to size the TOU tariff as a function, again, of the commitment from the utility companies to reducing the on-peak electricity consumption.

The TOU policy enforces a reduction of the on-peak electricity consumption based on a demand control in which the users reduce the energy consumption because of high electricity costs. Based on the reported results, this policy provides a significant reduction in the on-peak electricity consumption. However, when the SDHW system is properly designed, for example using a simulation tool and minimizing the ALCC, the on-peak electricity consumption is already significantly smaller (between 40 and 60 kWh/year) compared to the on-peak electricity consumption presented when the initial cost is the only figure of merit (between 200 and 500 kWh/year – such as the case of the rebate program or “off the shelf” solutions).

The present study provides two methodologies that can be used for policy makers to promote the use of SDHWs to reduce on-peak electricity-using activities. The two policies considered in this study consider the interest of both consumers and the electricity distribution system. Therefore, this study provides the parameters for negotiation strategies between the utility company planners and relevant consumers.

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References

Almeida, M.A., Schaeffer, R., La Rovere, E.L., 2001. The potential for electricity conservation and peak load reduction in the residential sector of Brazil. Energy 26 (4), 413–429.

Aste, N., Del Pero, C., Adhikari, R.S., Marenzi, G., 2015. Effectiveness and weaknesses of supporting policies for solar thermal systems – a case-study. Sustain. Cities Soc. 14 (1), 146–153.

Borges, T.P., Colle, S., Wendel, M., 2004. Impactos Da Adoção De Tarifas Diferenciadas De Energia Elétrica Sobre O Projeto Otimizado De Sistemas De Aquecimento Solar De Água. XII Congr. Ibérico y VII Congr. Íbero Am. Energía Sol., pp. 14–18.

Borges, T.P.F., Colle, S., Wendel, M., 2005. Multiobjective optimization as a decision tool tor financing or rebating domestic solar water heaters. Sol. World Congr. – ISES 2005 1 (4), 2–6.

Caves, D.W., Christensen, L.R., 1980. Econometric analysis of residential time-of-use electricity pricing experiments. J. Econom. 14 (3), 287–306.

Cho, H., Smith, A.D., Mago, P., 2014. Combined cooling, heating and power: a review of performance improvement and optimization. Appl. Energy 136, 168–185.

Collette, Y., Siarry, P., 2004. Multiobjective Optimization: Principles and Case Studies. Springer, Berlin Heidelberg.

Duffie, J.a., Beckman, W.a., 2013. Solar Engineering of Thermal Processes, fourth ed.

New York.

EPE (Empresa de Pesquisa Energética), 2012. Estudos de Demanda. Eficiência energética para os próximos 10 anos (2012–2021). Rio de Janeiro, Brazil (in Portuguese).

EPE (Empresa de Pesquisa Energética), 2016. Brazilian Energy Balance 2016. Rio de Janeiro, Brazil (in Portuguese).

Giglio, T., Lamberts, R., Barbosa, M., Urbano, M., 2014. A procedure for analysing energy savings in multiple small solar water heaters installed in low-income housing in Brazil. Energy Pol. 72, 43–55.

IEA (International Energy Agency), 2011. G-20 Clean Energy, Energy Efficiency Deployment and Policy Progress, Paris, France.

INMETRO, 2015. Sistemas e equipamentos para aquecimento solar de água – Coletores Solares. Brazilia-Brazil.

Jordan, U., Vajen, K., 2000. Influence of the DHW profile on the fractional energy\rSavings: a case study of a solar combi-system. Sol. Energy 69(Suppl.)(1–6), 197–208.

Kalogirou, S.A., Tripanagnostopoulos, Y., 2006. Hybrid PV/T solar systems for domestic hot water and electricity production. Energy Convers. Manag. 47 (18–19), 3368–3382.

Klein, S.A., Beckman, W.A., 1979. A general design method for closed-loop solar energy systems. Sol. Energy 22 (3), 269–282.

Li, W., Rubin, T.H., Onyina, P.A., 2013. Comparing solar water heater popularization policies in China, Israel and Australia: the roles of governments in adopting green innovations. Sustain. Dev. 21 (3), 160–170.

Liu, Z., Xu, W., Qian, C., Chen, X., Jin, G., 2015. Investigation on the feasibility and performance of ground source heat pump (GSHP) in three cities in cold climate zone, China. Renew. Energy 84, 89–96.

Liu, Z., Xu, W., Zhai, X., Qian, C., Chen, X., 2017a. Feasibility and performance study of the hybrid ground-source heat pump system for one office building in Chinese heating dominated areas. Renew. Energy 101, 1131–1140.

Liu, Z., Li, H., Liu, K., Yu, H., Cheng, K., 2017b. Design of high-performance water-in-glass evacuated tube solar water heaters by a high-throughput screening based on machine learning: a combined modeling and experimental study. Sol. Energy 142, 61–67.

Loutzenhiser, P.G., Manz, H., Felsmann, C., Strachan, P.A., Frank, T., Maxwell, G.M., 2007. Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. Sol. Energy 81 (2), 254–267.

Martins, F.R., Pereira, E.B., Silva, SAB., Abreu, SL., Colle, S., 2008. Solar energy scenarios in Brazil, Part one: resource assessment. Energy Pol. 36 (8), 2853–2864.

Mauthner, F., Weiss, W., Spörk-Dür, M., 2016. "Solar Heat Worldwide," SHC – Solar Heating and Cooling Programme. International Energy Agency, Gleisdorf, Austria.

Morrison, G.L., Braun, J.E., 1985. System modeling and operation characteristics of thermosyphon solar water heaters. Sol. Energy 34 (4–5), 389–405.

Newsham, G.R., Bowker, B.G., 2010. The effect of utility time-varying pricing and load control strategies on residential summer peak electricity use: a review. Energy Pol. 38 (7), 3289–3296.

Oconnell, N., Pinson, P., Madsen, H., Omalley, M., 2014. Benefits and challenges of electrical demand response: a critical review. Renew. Sustain. Energy Rev. 39, 686–699.

OECD/IEA, 2010. Technology Roadmap: Solar Heating and Cooling. International Energy Agency. Paris, France.

OECD/IEA, 2012. Technology Roadmap. Hydropower, International Energy Agency. Paris, France.

PROCEL, 2007. Avaliação do Mercado de Eficiência Energética no Brasil – Pesquisa de Posse de Equipamentos e Hábitos de Uso – Ano Base 2005. Rio de Janeiro, Brazil (in Portuguese).

Salazar, J.P. de L.C., Abreu, S.L., Colle, S., Reguse, W., 2005. Energy conservation and electric energy peak reduction potential during peak hours for a group of low-income residential consumers of a Brazilian utility. In: Proc. Sol. World Congr. 2005.

Sarzynski, A., Larrieu, J., Shrimali, G., 2012. The impact of state financial incentives on market deployment of solar technology. Energy Pol. 46, 550–557.

Sowmy, D.S., Prado, R.T.A., 2008. Assessment of energy efficiency in electric storage water heaters. Energy Build. 40 (12), 2128–2132.

Starke, A.R., Ruas, T.D.M., Abreu, S.L., Cardemil, J.M., Colle, S., 2015. Multi-objective and multi-parameter optimization of solar domestic hot-water systems for reducing on-peak power consumption. In: Proceedings of the Solar World Congress 2015, no. November, pp. 8–12.

Wasi, N., Carson, R.T., 2013. The influence of rebate programs on the demand for water heaters: the case of New South Wales. Energy Econ. 40, 645–656.