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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.

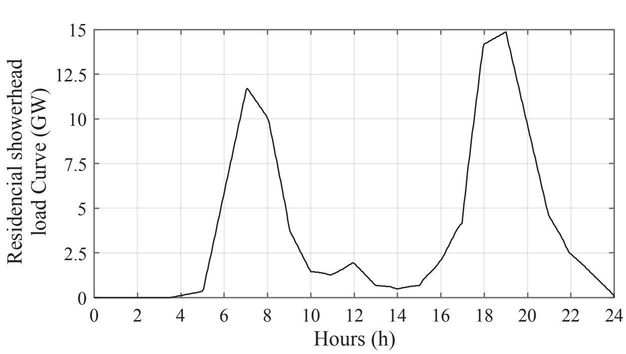

Fig. 1. Estimated showerhead load curve for Brazil.

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