

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 significant 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 | | V_{tes} | thermal storage volume [m ³] |
|-----------------------|---|-------------------|---|
| a_0 | intercept collector efficiency [-] | x | independent variable space |
| a_1 | collector efficiency slope [W/m ² K] | <i>Acronyms</i> | |
| A_c | solar collector area [m ²] | ESCO | Energy Service Companies |
| ALCC | annualized life cycle cost | ESh | electric showerhead |
| ALCC ₀ | ALCC for a null time-of-use tariff [€/year] | GENOPT | Generic Optimization Program |
| ALCC _{0,max} | maximum ALCC for a null time-of-use tariff in the feasible space [€/year] | GPSPSOCCHJ | Generalized Pattern Search implementation of the Hooke-Jeeves algorithm |
| b_0 | IAM coefficient [-] | PV | photovoltaics |
| C | specific cost [€/m ²], [€/kW], [%] | PWF | Present Worth Factor |
| C_1, C_2 | constant penalty value | SDHW | Solar Domestic Hot Water |
| C_a | specific cost of heating element [€/kW] | SWERA | Solar and Wind Energy Resource Assessment |
| C_e | nominal value of the electric tariff [€/kWh] | TMY | Typical Meteorological Year |
| $C_{e,TOU}^*$ | intended time-of-use tariff [€/kWh] | TOU | Time of Use |
| $C_{e,TOU}$ | added value of time-of-use tariff [€/kWh] | TRNSYS | Transient System Simulation Program |
| d | diameter [m], discount rate [%] | TS | Thermal Storage |
| E | yearly energy [kWh/year] | <i>Greek</i> | |
| e_i | thermal storage insulation thickness [m] | β | collector slope [°] |
| E_{peak} | on-peak yearly energy consumption [kWh/year] | η | efficiency [-] |
| $E_{peak,max}$ | maximum values of on-peak yearly energy consumption [kWh/year] | κ | thermal conductivity [W/m K] |
| F_{rest} | collector test flow rate [kg/m ² h] | ϕ | relative weights |
| H_c | vertical distance of collector inlet and outlet [m] | ΔT_{on} | upper temperature difference, to turn on the solar pump [°C] |
| H_d | heater diameter [m] | ΔT_{off} | lower temperature difference, to turn off the solar pump [°C] |
| H_o | vertical distance of collector inlet and thermal storage outlet [m] | <i>Subscripts</i> | |
| i | inflation [%] | a, aux | auxiliary |
| IC | initial cost | c, col | collector |
| IC _{max} | maximum value of the initial cost [€] | db | dead band |
| L | length [m] | e | electric |
| LCC | life cycle cost | i | inlet |
| N | solar system life cycle [year] | inst | installation |
| N_b | number of bends in collector pipes [-] | limit | ALCC constrain |
| P | power, heating rate [kW] | m | maintenance |
| P_1, P_2 | penalty functions | o | outlet |
| R_{ca} | ratio between utilized and test flow rate [-] | tank | tank |
| R_d | riser diameter [m] | tes | thermal energy storage |
| S | shape factor [-] and feasible space region | w | water |
| 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] | | |

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 hydro-electric plant at Itaipu, the second largest worldwide, which illustrates the magnitude of the problem.

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

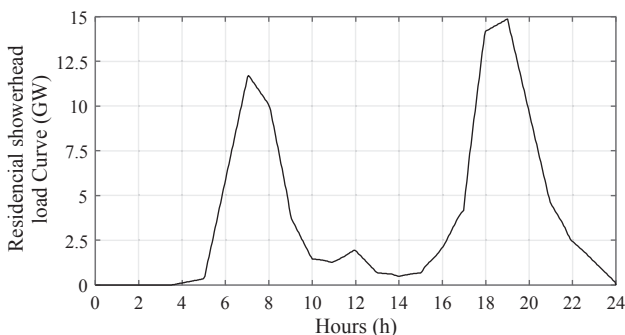


Fig. 1. Estimated showerhead load curve for Brazil.

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