Renewable Energy 48 (2012) 92–99

Contents lists available at SciVerse ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Assessing the technical and economic viability of low-cost domestic solar hot water systems (DSHWS) in low-income residential dwellings in Brazil

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ARTICLE INFO

Article history:
Received 9 December 2011
Accepted 23 April 2012
Available online 24 May 2012

Keywords:
Solar water heating
Low-income residents
Benefits
Energy
Financial and emissions

ABSTRACT

Domestic solar hot water systems (DSHWS) have been used worldwide for many decades. Activities in this area are usually targeting middle- or upper-class residential dwellings, and solar collector design and sizing is carried out aiming at this market. In developing countries of the sunbelt, however, there is a huge potential for low-cost DSHWS in low-income residential dwellings. We have assessed the technical and economic viability of this technology, both from the electric utility's perspective, and from the standpoint of low-income residential consumers. We have analysed data of 12 months of continuous monitoring of a statistically representative sample of consumers at a low-income residential building in Florianopolis – Brazil (27°S, 1550 kWh/m^2/year solar irradiation average). We have studied the power consumption of 60 residential units equipped with a commercially available, low-cost DSHWS, and a 30 units control group, where hot water was supplied with the electronic showerhead typical of Brazilian dwellings. Annual electricity savings averaged 38%, and peak-time electricity demand was reduced by 42%. For discount rates of up to 9.5%, this technology is attractive from a utility's perspective for large-scale deployment. The financial benefit from avoided CO_2 emissions has limited economic attractiveness, and can only be justified under a large-scale deployment program.

1. Introduction

Solar irradiation resource availability in Brazil is one of the highest in the world, ranging from around 1500 kWh/m^2/year in the south, to over 2100 kWh/m^2/year in the northeast [1,2]. Despite its large surface area (8.5 million km^2), over 80% of the Brazilian population is concentrated in urban areas, mostly in the south-east and south regions of the country, where a more temperate climate results in the need of water heating systems for domestic use all year round. Residential, commercial and public buildings in urban areas correspond to over 45.2% of the electricity demand in the country, with residential buildings being responsible for 22.3% [3]. In this context, like in most of the other countries of the sunbelt, solar water heating is a natural choice of technology for residential buildings [4,5]. However, for a number of reasons which include the low-cost of resistance-heating showerheads, and the lack of information on the lower life-cycle cost of domestic solar hot water systems (DSHWS) when compared with electric showerheads, electrical resistance-heating is still the major source of energy input for water heating in Brazil [6–8]. The majority of households in the south (98.6%), south-east (90.7%) and central-west (85.1%) areas of the country use electrical showerheads [8]. These simple devices operate with an instant heating, 4–8 kW resistive element, in which water temperature is controlled both via water flux and a two-to-four positions manual setting of the electrical resistance. More recently, and in order to allow for a more comfortable water temperature selection at constant water flux, electrical showerheads with electronic control of the power fed to the electrical resistance were introduced and are becoming popular in the country. However, these devices present a number of technical disadvantages, which include a low power factor, and a high harmonic content on the current waveform, degrading the distribution utility's energy supply quality, and increasing the loads of urban distribution networks [9]. Fig. 1 shows a breakdown of residential consumer typical electricity loads in Brazilian residential buildings, where electrical showerheads represent the largest share, contributing to nearly a quarter of a household's consumption [10].

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doi:10.1016/j.renene.2012.04.046

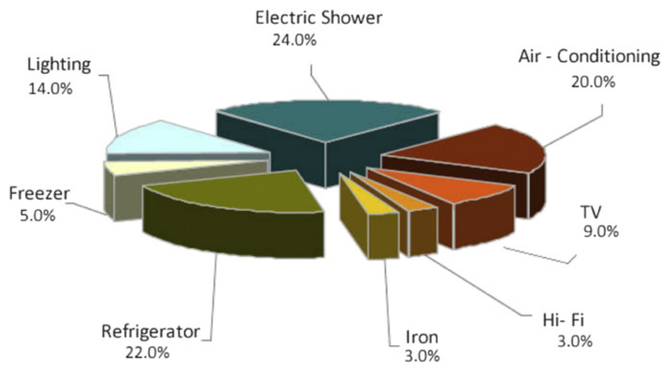

Fig. 1. Breakdown of residential consumer typical electricity loads in Brazilian residential buildings [10].

Fig. 2 shows the annual average of the daily residential load curve in Brazil, where it can be clearly seen the adverse effect of electric showers on the two demand peaks occurring during the day. The first peak, at around 07:00, is due to the morning shower that a considerable fraction of the Brazilian population (typically the middle-class income population) takes before a typical weekday journey; the second and largest peak, occurring at about 19:00, is due to the evening shower that an even larger fraction of Brazilians take when arriving home in the early evening. This peak is also coincident with the turning on of lights, television sets, and residential air-conditioning units. This leads to the country's largest energy demands taking place from around 18:00 to 22:00. The residential consumer contributes to a significant fraction of these loads, and the electric showerhead imposes a considerable burden on the Utilities, contributing with some 60% of residential loads [10]. Due to their high power demands and low usage rates, which lead to low load factors and high infrastructure investment requirements for utilities, electric showerheads are under a number of governmental energy conservation policy initiatives [10–12]. Despite the considerable cost reduction of DSHWS in recent years, the high initial investment is still one of the major barriers for a more widespread uptake of this technology [13–16].

The economics, technical performance and optimisation [12,17–24], as well as the modelling and sizing [25–36] of a number of different solar water heating technologies deployed in different climates, has been extensively investigated and reported in the literature. However, information on the technical and economic assessment of using low-cost DSHWS in low-income dwellings in developing countries has not been found in the

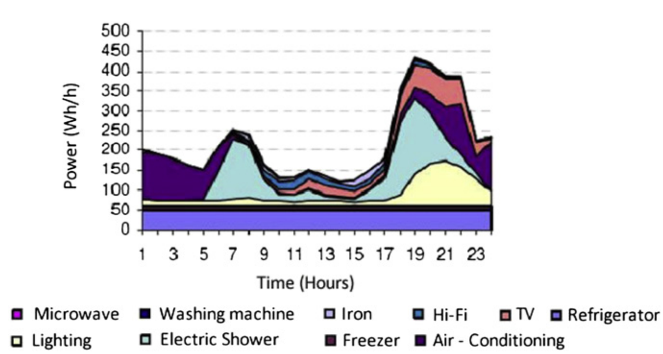

Fig. 2. Annual average of the daily residential load curve in Brazil, showing the strong influence of electric showers (blue regions peaking at around 07:00 and 19:00) [10]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

literature, and is presented in this paper. In this work we have looked into technical and economic aspects of incorporating the solar water heating technology from a societal point of view. We have presented a methodology in which benefits are accounted for from both the individual consumer, as well as from the electric utility's perspectives.

2. Methodology

The methodology presented in this work involves energy demand (kW) and consumption (kWh) measurements carried out in a statistically representative sample of low-income, single-family residential units at "Edifício Residencial Solar Buona Vitta" in Florianópolis – Brazil (latitude: 27°S, solar irradiation average: 1550 kWh/m^2/year), over a one-year period [8]. We have previously shown the average temperature and solar radiation resource distribution in Florianópolis, based on long-term, 1-min resolution data collected at the Baseline Surface Radiation Network/BSRN station that our University hosts under a joint project with the World Meteorological Organisation/WMO [9]. A group of 90 families was selected to participate in this project, based on a questionnaire designed to identify each family's hot water consumption pattern, based on methodologies previously developed and tested [21,37]. In order to be able to assess the benefits of incorporating a DSHWS to single-family, low-income residential apartment units, this group was divided in two sub-groups. Group "SE" consisted of 60 families, for which a low-cost DSHWS, was installed for preheating water for the single shower available at each apartment. The identical DSHWS units were funded with a grant from the local utility under the Energy Efficiency Program regulated by the Brazilian Law No. 9991 dated 24 July 2000, and donated to the 60 families of Group "SE" for this Project. Group "E" was used as a control group, comprised of 30 families, where water heating was supplied entirely with electricity. Each and every one of the 90 families had an identical single shower unit, consisting of an electric showerhead with electronic temperature control, with a maximum power of 6.8 kW at 220 V. For Group "SE", pre-heated water coming from the DSHWS to the electric showerhead had any temperature shortfall compensated by the electric resistance-heating element, in case the incoming water temperature was below the consumer's desired setting. For a consumer from Group "E", all the energy required for the water temperature to reach the desired setting was supplied by the electric resistance-heating element. Group "E" was used as a reference group for measuring both the potential energy savings (kWh), as well as the active power demand reduction potential (kW) resulting from the DSHWS installed in Group "SE" residential units. Each and every one of the 90 residential units was also equipped with an additional and dedicated digital energy meter, connected in series with the electric showerhead's individual circuit. Technical specifications of the DSHWS, electric showerhead with electronic temperature control, and meter used in this project have been published elsewhere [8,9,20,21]. The low-cost, thermosyphon-type solar collector is a commercially available, metal-glass, 1.4 m^2 model, with a close-coupled 100 L water tank, which was also originally developed in our University. The total installed cost was US$ 755, with US$ 655 for the collector + tank, and US$ 100 corresponding to installation costs.

During a 12 months period in 2004, for all 90 households comprising Groups "SE" and "E", individual measurements of the active and reactive power demands, as well as the operating voltage and power factor of all electric showerheads, were carried out at 5-min intervals. Total individual monthly electrical energy consumption data were obtained from the local distribution utility CELESC (Centrais Elétricas de Santa Catarina), and averaged