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An analysis of the economic viability and greenhouse gas emissions reductions resulting from the use of solar water heaters in a typical Brazilian dwelling

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Abstract: Several countries have reduced their energy consumption and greenhouse gas emissions levels in buildings by promulgating laws, formulating standards and instituting certification programs. In this context, Brazil launched an energy efficiency certification for buildings in 2009. This study aimed to analyze the economic viability and potential greenhouse gas emissions reductions associated with the use of solar water heaters in a typical Brazilian dwelling. Solar thermal systems were simulated at different energy efficiency levels and shower water flow rates. It was found that the use of solar water heater, as compared with electric heater without a hot water storage, presented internal return rate of approximately 26% per year, simple payback around 4.5 years; net present value about US$ 2,194.00 and cost of conserved energy around US$ 0.12 kWh^{-1}. This study also verified that solar water heater use in a typical Brazilian dwelling reduced emissions compared with electric and gas heating by approximately 95 and 256 $kgCO_{2equivalent}year^{-1}$, respectively. The total reduction potential of greenhouse gas emissions by use solar water heaters for the Brazilian residential sector was substantial, around 5.75 million $tCO_{2equivalent}year^{-1}$.
Keywords: solar thermal energy, efficient buildings, economic feasibility, environmental impacts.

1. Introduction

Solar energy is by far the most abundant of all available energy sources - including renewable and non-renewable sources - and can be exploited both directly and indirectly. However, over 80% of the energy currently consumed in world originates from non-renewable sources, mainly from oil and natural gas (Thirugnanasambandam *et al*., 2010). In recent years, many countries have increased their use of renewable energies in seeking to reduce greenhouse gas emissions and reach emissions reductions goals that are defined in international treaties (Kalogirou, 2009).

Commercial and residential buildings consume 20-40% of the energy used in developed countries; in some cases, building usage exceeds the energy consumption of the transportation and industrial sectors (Pérez-Lombard *et al*., 2008). In Brazil, residential, commercial and public buildings account for approximately 14.5% of the total energy demand and 50.8% of the electrical energy demand (EPE, 2016).

An electric water heater with no hot water storage, commonly called an electric shower, accounts for nearly 24% of the electric energy consumed in Brazilian dwellings. The electric shower is the equipment that has the highest electricity consumption in households in Brazil, staying the front of the refrigerator (22%) and air conditioning system (20%) (Eletrobras, 2007).

In Brazil, approximately 73.5% of the residences have electric showers (Eletrobras, 2007). A typical electric shower's power ranges between 4.4 kW and 6.5 kW, which results in high financial costs for users. In addition, the substantial use of electric showers impairs the load management of the national electric system because electric showers significantly contribute to the Brazilian electrical system peak load (Naspolini and Ruther, 2012).

The primary anthropogenic sources of greenhouse gas emissions in the world are the energy supply sector (25.9%), industries (19.4%), deforestation (17.4%), transport (13.1%) and buildings (7.9%) (IPCC, 2008). Several countries have incentivized the use of energy saving measures in buildings by promulgating laws, formulating standards and instituting energy certification programs (Casals, 2006). Brazil launched an energy efficiency certification program for commercial and public buildings in 2009 and added residential buildings to the program in 2010 (INMETRO, 2012).

The mean levels of solar radiation that Brazil receives are superior to those of European countries and exhibit less seasonal variability because most of the country is located in the tropics (Martins and Pereira, 2011). However, the use of thermal and photovoltaic solar energy in Brazil is much lower than in several European countries, including Germany, Spain, Portugal and Greece (Martins *et al*.; 2007).

Studies have confirmed the technical and economic viability of domestic solar water heaters in many countries (Chandrasekar and Kandpal, 2004; Crawford and Treloar, 2004; Oliveira *et al.*, 2008; Kalogirou, 2009; Gillingham, 2009; Naspolini and Ruther, 2012; Hang et al. 2012; Cassard *et al*., 2011; Martinopoulos and Tsalikis, 2014; Ma *et al*., 2014). Besides, researches have also indicated that such water heaters have the potential to reduce greenhouse gas emissions from dwellings (Mirasgedis *et al*., 1996; Tsilingiridis et al., 2004; Kalogirou, 2009; Tsilingiridis and Martinopoulos, 2010; Shimoda *et al*., 2010; Hang *et al*., 2012; Sanders and Webber, 2015; Abd-Ur-Rehmana and Al-Sulaimana, 2016).

Thus, the aim of this study was to evaluate the economic viability and potential greenhouse gas emissions reductions associated with using solar water heaters in typical Brazilian dwellings by examining different shower water flow rates and energy efficiency levels.

2. Methodology

2.1 Typical Brazilian dwelling

A typical Brazilian single-family dwelling has an occupancy of four people and consists of two bedrooms, a living room, a kitchen and a bathroom. These characteristics represent 58% of Brazilian residences (Tavares, 2006) and were employed in this study. This research assumed that residents use hot water only for showering, which is supplied by an electric shower or a solar heater with an electric backup (in the form of an electric heating element inside the storage tank). The solar heater consists of flat-plate solar collectors and a horizontal hot water storage tank through which water is naturally circulated via the thermosyphon effect.

Three shower water flows were considered for different degrees of bathing comfort: i) shower flow of 3 L min^{-1} (5.0 10^{-5} m^3 s^{-1}): less comfortable; ii) shower flow of 5 L min^{-1} (8.3 10^{-5} m^3 s^{-1}): reasonably comfortable; and iii) shower flow of 8 L min^{-1} (1.3 10^{-4} m^3 s^{-1}): very comfortable.

In the Brazilian certification scheme for residential buildings, the energy efficiency levels of the building envelope and the water heating system are evaluated. The buildings are classified of level "A" (more efficient) to level "E" (less effective) (INMETRO, 2012). The energy efficiency of a solar water heating system is defined in terms of the annual solar fraction, as calculated by the F-Chart method (Duffie and Beckman, 2013). The method enables the calculation of the monthly amount of energy delivered by hot water systems with storage, given monthly values of incident solar radiation, ambient temperature and load. In this method, two variables (X and Y) are defined by Eq. (1) and Eq. (2):

$$X = \frac{A_c F'_R U_L (T_{ref} - T_a)}{L}, \tag{1}$$

$$Y = \frac{A_c F'_R (\tau\alpha) H_T N}{L}, \tag{2}$$

where A_c is the collector area; F'_R is the modified collector heat removal factor; U_L is the collector overall loss coefficient; T_{ref} is an empirical reference temperature equal to 100°C; T_a is the monthly average ambient temperature; L is the monthly total heating load; $\tau\alpha$ is the collector's monthly average transmittance-absorptance product; H_T is the monthly average daily radiation incident on the collector surface per unit area; and N is the number of days in the month.

The fraction (f) of the monthly total load supplied by the solar water heating system is given as a function of X and Y by Eq. (3):

$$f = 1.029\,Y - 0.065\,X - 0.245\,Y^2 + 0.0018\,X^2 + 0.0215\,Y^3. \quad (3)$$

For each shower water flow rate (3; 5; and 8 L min^{-1}), solar water heating systems were sized at three energy efficiency levels by to the Brazilian energy efficiency certification for buildings, which are "A", "C" and "D". The solar water heating system was simulated for the meteorological conditions of the municipality of Vicosa (Minas Gerais, Brazil), which is located at 20º45'14" South latitude and 42º52'54'' West longitude. The average annual global solar irradiation in Vicosa is 4.75 kWh m ² day- 1 in the horizontal plane.

The following parameters were used to size the domestic solar water heater: Four residents; One shower daily per resident; Shower time of 10 min; Shower water temperature of 40°C; Flat-plate solar collector with copper ducts and glass covering, optical efficiency factor of 0.779, and global loss coefficient of 6.795 W m^{-2} K^{-1}; Solar collectors oriented to the geographical north and inclined at 10° above the local latitude; and Stainless steel horizontal hot water storage tank with an aluminum cover, polyurethane isolation and a 2,000 W electric resistance as an auxiliary energy source.

2.2 Economic viability analysis

Four economic indicators were calculated: net present value (NPV); internal return rate (IRR); simple payback (SP); and cost of conserved energy (CCE). The NPV, IRR and SP indicators were directly calculated by the RETScreen® International program which employs classical financial mathematics (Natural Resources Canada, 2017), and the CCE was calculated using the methodology proposed by Martinaitis *et al.* (2004). The main equations used in the economic viability analysis are presented below.

The net present value is the cash flow for the planning horizon considered, obtained in currency value after deducting the discount rate or interest. The NPV was calculated by Eq. (4).

$$NPV = \sum_{n=0}^{N} \left[\frac{C_n}{(1+r)^n} \right], \quad (4)$$

where NPV denotes the net present value; C_n denotes the cash flow in year n; r denotes the discount rate; n denotes the year; and N denotes the number of years of the planning horizon.

The internal return rate is the discount rate that results in a zero-net present value for the project for the considered planning horizon. The IRR was obtained using Eq. (5).

$$0 = \sum_{n=0}^{N} \left[\frac{C_n}{(1+IRR)^n} \right], \quad (5)$$

where IRR denotes the internal return rate; C_n denotes the cash flow for year n; n denotes the year; and N denotes the number of years of the planning horizon.

The simple payback is the number of years it takes for the net cash flow to equal the initial investment. The SP was calculated using Eq. (6).

$$SP = \frac{C}{C_N}, \quad (6)$$

where SP denotes the simple payback; C denotes the initial cost; C_N denotes the cash flow in year N; and N denotes the number of years of the planning horizon.

The cost of conserved energy is used to compare the implementation costs of a conservation measure per unit of energy saved with the present energy cost. The CCE was obtained using Eq. (7).

$$CCE = \frac{C}{S}\,\frac{r}{1-(1+r)^{-N}}, \quad (7)$$

where CCE denotes the cost of conserved energy, C denotes the total initial cost, S denotes the energy saved by implementing the respective energy conservation measure, N denotes the number of years of the planning horizon, and r denotes the discount rate.

The economic and technical parameters that were used in the viability analysis of the solar water heater are listed below: discount rate of 8% per year; life expectancy and planning horizon of solar water heater of 20 years; electric energy tariff of US$ 0.27 kWh^{-1}; electric energy price adjustment of 2% per year, above inflation; solar collectors for water heating cost of US$ 152.00 m^{-2}; hot water storage tank costs of US$ 370.00 for tank of 200 L and US$ 435.00 for tank of 300 L; hydraulic material cost equal US$ 348.00; and installation labor cost equal US$ 174.00.

2.3 Greenhouse gas emissions analysis

The program RETScreen® International evaluates greenhouse gas emissions (GHG) emissions by employing methodology developed in partnership with the United Nations Organization and the Prototype Carbon Fund of the World Bank (Natural Resources Canada, 2017). The RETScreen® International program calculates the reduction of GHG emissions in equivalent carbon gas units using Eq. (8).

$$\Delta GHG = GHG_{reference} - GHG_{proposed,} \quad (8)$$

where ΔGHG denotes the reduction of GHG emissions; GHG_{base} denotes the GHG emissions produced by the reference case; and $GHG_{proposed}$ denotes the GHG emissions produced by the proposed case.

The GHG emissions reductions associated with using a solar heater instead of an electric shower or a gas heater were calculated for a typical Brazilian dwelling. The version of the program used in this study employs as a reference the GHG emissions factors calculated by the Intergovernmental Panel on Climate Change (IPCC, 1997). In addition, the potential of reducing emissions by solar heaters for the Brazilian residential sector was calculated, based on the following assumptions: number of Brazilian residences equal 67.6 million units (IBGE, 2017); percentage of residences with electric water heating of 73.5% (Eletrobras, 2007); and percentage of residences with gas water heating of 5.9% (Eletrobras, 2007).

3. Results and discussions

3.1 Cost of solar water heater

The Tables 1, 2 and 3 present the dimensions of the solar water heating systems for different shower water flows and efficiency levels by Brazilian energy efficiency certification, for one typical Brazilian dwelling.

Table 1. Dimensions of a solar heater supplying a shower water flow rate of 3 L min^{-1}.

Energy efficiency level	Area of solar collectors, m²	Hot water storage tank volume, m³	Annual solar fraction of system, %
A	1.0	0.2	72.0
C	0.9	0.2	64.7
D	0.7	0.2	54.6

Table 2. Dimensions of a solar heater for supplying a shower water flow rate of 5 L min^{-1}.

Energy efficiency level	Area of solar collectors, m²	Hot water storage tank volume, m³	Annual solar fraction of system, %
A	1.9	0.2	71.9
C	1.5	0.2	62.7
D	1.1	0.2	50.8

Table 3. Dimensions of solar heater for supplying a shower water flow rate of 8 L min^{-1}.

Energy efficiency level	Area of solar collectors, m²	Hot water storage tank volume, m³	Annual solar fraction of system, %
A	3.0	0.3	71.0
C	2.3	0.3	60.7
D	1.8	0.3	51.5

The initial costs of the solar water systems for a typical Brazilian dwelling is shown in Table 4. It can be seen that greater the level of energy efficiency and shower flow rate intended, bigger the additional investment needs.

Table 4. Total initial cost of the solar water heater for a typical Brazilian dwelling.

Energy efficiency level	3 L min^{-1}, US$	5 L min^{-1}, US$	8 L min^{-1}, US$
A	1,059.00	1,180.00	1,413.00
C	1,028.00	1,120.00	1,307.00
D	998.00	1,059.00	1,230.00

3.2 Economic indicators

The Fig. 1 to Fig. 4 presented the economic viability indicators (IRR, NPV, SP and CCE) for the solar water heater, with different shower water flows and energy efficiency levels, compared to electric shower use.

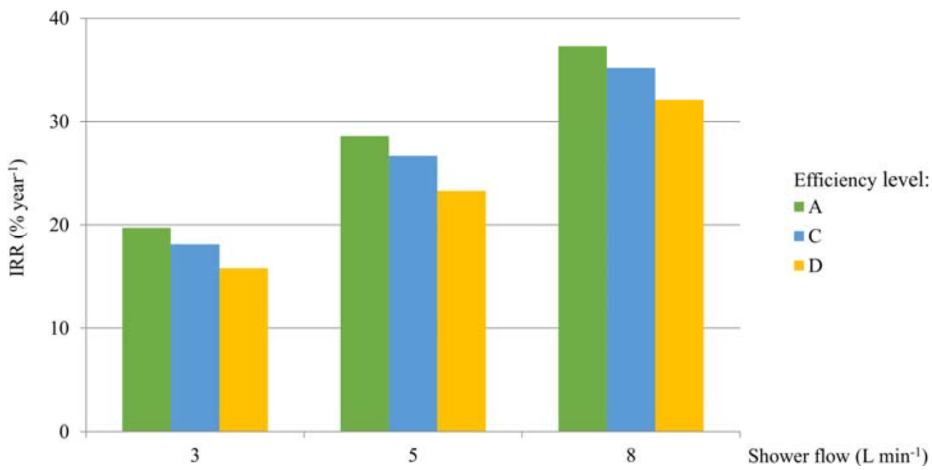

Figure 1. Internal rate of return (IRR) of solar water heater for different shower water flows and energy efficiency levels.

The internal return rate (Fig. 1) was higher than 8% per year for all the cases, this being the minimum attractiveness rate considered in the study; therefore, it was economically viable to replace an electric shower with a solar water heater by this indicator. The highest IRR value was obtained for a shower water flow of 8 L min^{-1} at energy efficiency level “A” (37.3%), and the lowest IRR value was obtained for a shower water flow of 3 L min^{-1} at energy efficiency level “D” (15.8%). The mean IRR for the cases analyzed was 26.3% per year, which represented more than three times the minimum attractiveness rate.

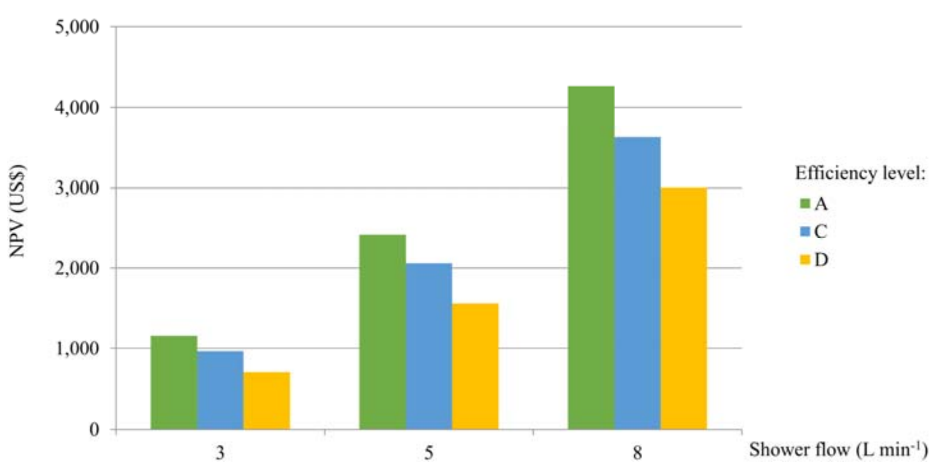

Figure 2. Net present value (NPV) of solar water heater for different shower water flows and energy efficiency levels.

The mean net present value (Fig. 2) for the analyzed cases was US$2,196.00, ranging from US$ 701.00 (for a shower water flow of 3 L min^{-1} at energy efficiency level “D”) to US$ 4,269.00 (for a shower water flow of 8 L min^{-1} at energy efficiency level “A”). Comparing the NPV with the initial cost of the solar water heater (presented in Table 4) showed that the net revenue of the most attractive case was three times the initial cost, and the net revenue of the least attractive case was equal 70% of the initial cost. As the NPV was positive for all the cases studied, the replacement of the electric shower by the solar water heater was also economically viable for this indicator.

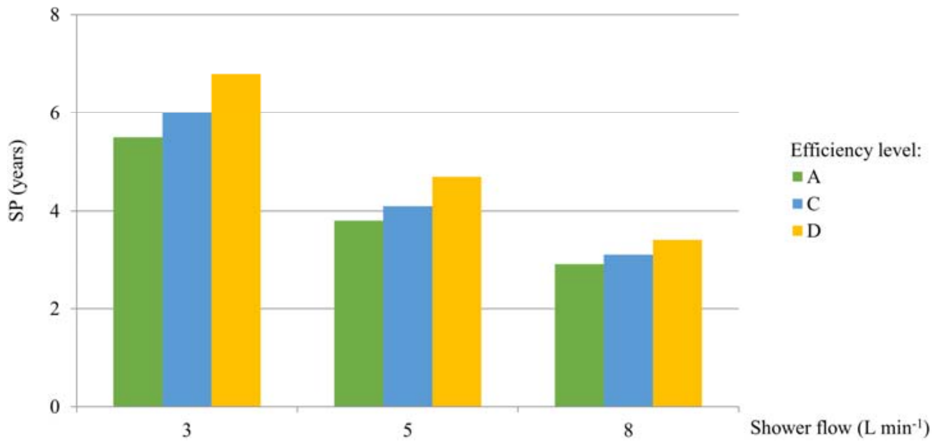

Figure 3. Simple payback (SP) of solar water heater for different shower water flows and energy efficiency levels.

The smaller simple payback (Fig. 3) was obtained for a shower water flow of 8 L min^{-1} at energy efficiency level “A” (2.9 years), while the highest simple payback was obtained for a shower water flow of 3 L min^{-1} at energy efficiency level “D” (6.9 years). The mean SP of the systems considered was 4.5 years. For this indicator, the use of the solar heater was also economically viability, since all the simple paybacks found were less than the planning horizon considered, equal to 20 years.

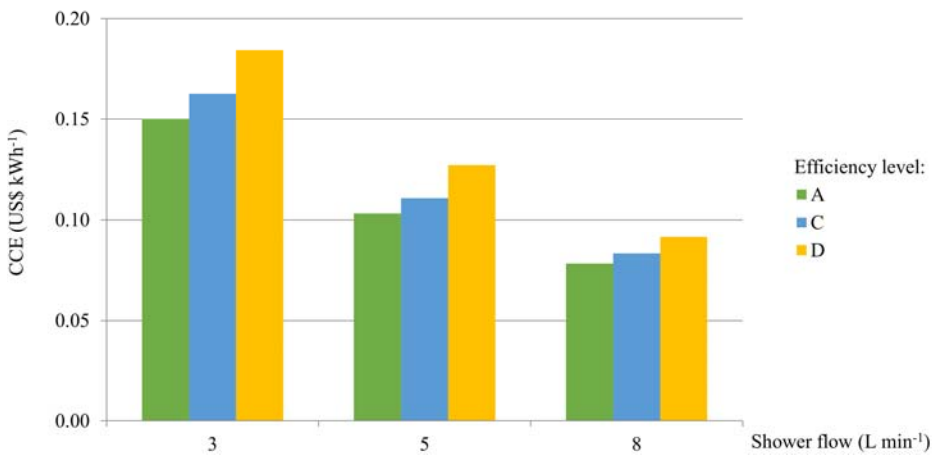

Figure 4. Cost of conserved energy (CCE) of solar water heater for different shower water flows and energy efficiency levels.

The solar water heater also presented economic viability through indicator cost of conserved energy (Fig. 4), because the CCE calculated for all cases was less than the local electricity tariff, equal to US$ 0.27 kWh^{-1}. The CCE oscillated between US$ 0.08 kWh^{-1} (shower water flow of 8 L min^{-1} at energy efficiency level “A”) to US$ 0.18 kWh^{-1} (shower water flow of 3 L min^{-1} at energy efficiency level “D”). The mean CCE for the cases studied was US$ 0.13 kWh^{-1}, approximately half of the electricity tariff paid by residential consumers.

For all economic indicators, the solar heaters dimensioned to supply a flow rate of 8 L min^{-1} were most attractive, while dimensioned to supply a flow rate of 3 L min^{-1} were less attractive. This is because higher the bath flow rate, higher the demand of hot water supplied by solar source and the less consumption of electricity for heating water. When it was analyzed the solar heaters for different levels of energetic efficiency, it was found that the systems classified as level “A” showed greater economic attractiveness, while the systems classified as level “D” showed lower attractiveness. Solar heaters with better energy efficiency levels have higher annual solar fractions, which provides for higher use solar source and less dependence of auxiliary electricity.

This study is consistent with other studies conducted in Brazil, that demonstrate the economic viability of solar water heaters, with capital payback between 1 and 10 years (Oliveira *et al.*, 2008; Naspolini and Ruther, 2012; Martins *et al.*, 2012; Passos *et al.*, 2014). Based on the values presented above, the capital payback time can vary greatly depending on the local parameters, such as incident solar radiation, cost of solar heater and price of electric energy tariff.

3.3 Greenhouse gas emissions

The Fig. 5 shows the potential of reduction of greenhouse emissions gases due to the substitution of electric shower by solar heater for different flow rates and levels of energy efficiency by the Brazilian certification of buildings energy efficiency for a typical dwelling.

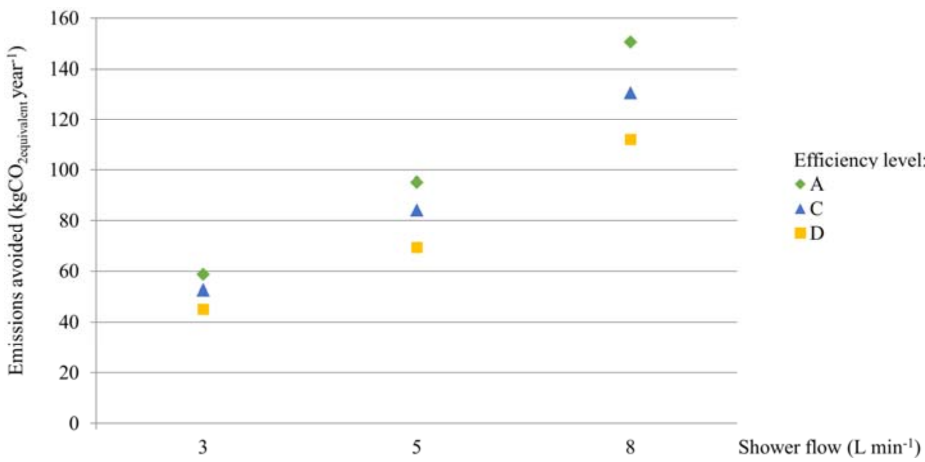

Figure 5. Greenhouse gas emissions avoided in a typical Brazilian dwelling by replacing an electric shower for a solar water heater.

The mean values of the reduction in GHG emissions achieved by replacing an electric shower with a solar heater were 52; 83; and 131 $kgCO_{2equivalent}year^{-1}$ for water flow rates of 3, 5, and 8 L min^{-1}, respectively. The reductions in emissions were directly proportional to increases in the shower water flow rate because higher the flow rate, greater volume of water will not be heated by the energy source of reference, which is electricity. The mean values of 103, 89, and 76 $kgCO_{2equivalent}year^{-1}$ were obtained at energy efficiency levels of “A”, “C” and “D”, respectively. Higher reductions in emissions were achieved at higher energy efficiency levels because a higher solar fraction of the system, i.e., less electric energy was employed as an auxiliary energy source.

It was found mean values of GHG emission reduction of 52; 83; and 131 $kgCO_{2equivalent}year^{-1}$ for bath flow rates of 3, 5 and 8 L min-^{1}, respectively, due to the replacement of electric shower by solar water heater. The higher the flow rate, the greater the volume of water no warmed by the reference power source (electricity) and, consequently, the greater the reduction of emissions. In contrast, it was obtained mean values of GHG emission reduction of 103, 89 and 76 kg of $CO_{2equivalent}year^{-1}$ for energy efficiency levels of “A”, “C” and “D”, respectively. In this case, the higher the level of energy efficiency, the lower the volume of water no warmed by the reference energy source and, consequently, the lower the emission reduction.

The solar water heater sized to supply a shower water flow rate of 5 L min^{-1} at energy efficiency level “A” presented a reduction of emissions by 95.2 $kgCO_{2equivalent}year^{-1}$, compared with the use of an electric shower. The same solar water heating system reduced emissions by 256.2 $kgCO_{2\ equivalent}year^{-1}$, when compared with using a gas water heater. Thus, the gas heating system produced about three times the amount of emissions produced by the electric heating system. It is emphasized that natural gas has higher GHG emission factor (0.179 $tCO_{2equivalent}MWh^{-1}$) than electric energy generation under the Brazilian electric system (0.082 $tCO_{2equivalent}MWh^{-1}$), which produces 64.0% of its energy from hydroelectric source (EPE, 2016).

The reduction of greenhouse gas emissions by use solar water heater to the typical Brazilian dwelling, of the case with flow rate of 5 L min^{-1} and energy efficiency level "A", was considered to estimate the GHG emission reduction potential for the Brazilian residential sector. The results are presented in Table 5.

Table 5. Current reduction and reduction potential of greenhouse gas emissions by solar water heater for the Brazilian residential sector.

Scenario	GHG ($tCO_{2equivalent}year^{-1}$)
Current reduction by use of solar water heaters	96,511
Reduction potential by replacing electric shower for with solar heater	4,729,046
Reduction potential by replacing gas heater for with solar heater	1,021,093

It is estimated that the emissions of greenhouse gases currently avoided by the use of solar heaters in Brazilian residences are around 96,511 $tCO_{2equivalent}year^{-1}$. This value represents only 1.7% of the total reduction potential by solar water heaters (5,750,139 $tCO_{2equivalent}year^{-1}$). Despite the reduction potential of GHG emissions per unit of energy be greater by replacement of the gas heaters by solar heaters, the final reduction potential of GHG emissions is higher by replacement of the electric heaters by solar heaters, since the use of electric heaters is much greater than of gas heaters in Brazil.

Currently, the Brazilian certification program for energy efficiency of buildings only considers energy consumption and not its greenhouse gas emissions. However, the inclusion of the quantification of emissions in Brazilian labeling is under discussion, following the trend of other countries, such as the United States, Portugal and Spain. Through the new Brazilian proposal, the calculation of emissions would be done by multiplying the total consumption of electric energy and thermal energy by their corresponding emission factors of equivalent carbon dioxide - a method similar to the one presented in this article. It should be noted that the quantification of emissions of greenhouse gas emissions is important to highlight the environmental impact caused by the use of energy in buildings and consequently increase the awareness of users the owners and users.

4. Final considerations

Formulating of incentives policies for energy conservation measures, such as the certification program for energy efficiency in buildings, can reduce energy consumption and greenhouse gas emissions originating from buildings.

The use of solar water heater in a typical Brazilian dwelling, compared with the electric shower, presented internal return rate of approximately 26% per year; simple payback around 4.5 years; net present value about US$ 2,194.00 and cost of conserved energy around US$ 0.12 kWh^{-1}. In addition, it was verified through a sensitivity analysis that the installation of solar water heater presents maximum economic viability for annual solar fractions between 80 and 90%. It is emphasized that this study was done for the city of Vicosa, Minas Gerais, and the viability indicators can vary depending on local conditions, being essential make an economic viability analysis for each specific case when considering to adopt this technology.

The installation of the solar water heater in a typical Brazilian dwelling resulted in the emissions reduction of approximately 95 and 256 $kgCO_{2equivalent}year^{-1}$ compared with electric and gas heating, respectively. The use of solar water heating systems has the potential of reducing greenhouse gas emissions originating from the Brazilian residential sector, estimated in 5.75 million of $tCO_{2equivalent}year^{-1}$ by this study. Although the GHG reduction potential per dwelling was relatively small for Brazil, due to the large share of renewables in the national energy matrix, the total reduction potential of greenhouse gas emissions in the Brazilian residential sector was substantial, as a result of the country's large population.

The popularization of solar water heaters in Brazilian dwellings, encouraged by buildings energy certification, may bring benefits to end-users, which would have lower costs with energy consume; to the environment, due to the reduction of greenhouse gas emissions; and to the government, because of reduction of the national electric energy demand.

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