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Obtaining of SHW with solar energy in the canton Cuenca and analysis of environmental pollution

Obtención de ACS con energía solar en el cantón Cuenca y análisis de la contaminación ambiental

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Abstract

This document contains the analysis to determine the feasibility of implementing solar water heaters to obtain Sanitary hot water(SHW) in Ecuador, in the province of Azuay, in the Canton of Cuenca, in order to reduce the environmental pollution caused by the use of fossil fuels. The project considers the implementation of a meteorological network and data collection of global solar radiation in 16 points located in populated areas of the Canton during the years 2014 and 2015. Then, through a field work a diagnosis is made to establish which are the systems which are currently used to obtain SHW, two solar vacuum tube heaters for SHW production are also located and characterized with their corresponding equations. With the measured radiation data, we stablish the model applying the equations and establishing the feasibility of implementation based on the measured solar energy. Finally, a comparison is made to determine what would be the decrease of CO_2 emissions if the implementation would be carried out. The obtained results indicate that in 82% of households it uses SHW and of these 65% use LPG-based systems, which 44% of the energy demand to obtain SHW can be covered with solar energy.Therefore auxiliary systems can be used to guarantee a constant supply and that with the implementation it would be possible to reduce 108537 t CO_2 eq per year.

Keywords: Solar heater, environmental pollution, solar energy, vacuum tubes

Resumen

En este documento se encuentra el análisis para determinar la factibilidad de implementación de calentadores solares para obtener agua caliente sanitaria (ACS) en el Ecuador, en la provincia del Azuay, en el cantón Cuenca, con el fin de disminuir la contaminación ambiental provocada por el uso de combustibles fósiles. El proyecto considera la puesta en marcha de una red meteorológica y toma de datos de radiación solar global en 16 puntos ubicados zonas pobladas del cantón durante los años 2014 y 2015, posteriormente a través de un trabajo de campo se realiza un diagnóstico para establecer cuáles son los actuales sistemas usados para obtener ACS, también se analizan de manera teórica y práctica las eficiencias de dos tipos de calentadores solares de tubos de vacío para producción de ACS; con los datos de radiación medidos se modela aplicando las ecuaciones de transferencia de calor y se establece la factibilidad de implementación en función de la energía solar medida; finalmente, se realiza una comparación para determinar cuál sería la disminución de emanaciones de CO_2 si se ejecutaría esta propuesta. Los resultados obtenidos indican que el 82 % de familias utiliza ACS, de estas el 65 % emplean sistemas a base de GLP y, que el 44 % de la demanda de energía para obtener ACS puede ser cubierta con energía solar necesitando utilizar sistemas auxiliares para garantizar un abastecimiento constante. La implementación de estos sistemas permitiría reducir 108 537 tn CO_2 eq al año.

Palabras clave: calentador solar, contaminación ambiental, energía solar, tubos de vacío

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1. Introduction

Since the 70s, concern for the environment has been especially intense, generating a series of actions, conferences and international agreements [1], among whose fundamental points is the decrease in the production of CO_2 and greenhouse gases. Their results have remained as good intentions, but efficient action in favor of this large-scale purpose has not been achieved.

The use of renewable energies has generated an increase in technological development, as they have become increasingly reliable and high performance, which has led to constant increases in their production, marketing and implementation, both for domestic and for industrial use.

By the 70s, solar energy began to be used as one of the main options for the benefit of people. Countries such as the United States, France, Germany, Spain, pay great attention to the use of solar energy for thermal and photovoltaic purposes, and present notable percentages of energy generation. By 2016, 94% of the solar thermal systems installed in the world are used to obtain hot water [2].

Because of its geographical location, Ecuador is a privileged country as far as the solar resource is concerned, since the angle of incidence of solar radiation is almost perpendicular to the surface throughout the year, a situation that does not occur in other parts of the planet where the angle varies according to the seasons of the year. This positional advantage translates into the reception of a greater and constant amount of solar radiation (Figure 1), which varies within the national territory only by local geographic conditions. The aforementioned condition has not been considered to take advantage of systems that favor the reduction of CO_2 emissions with special attention regarding the production of SHW, contemplating a constant flow that maintains the comfort conditions obtained with other sources.

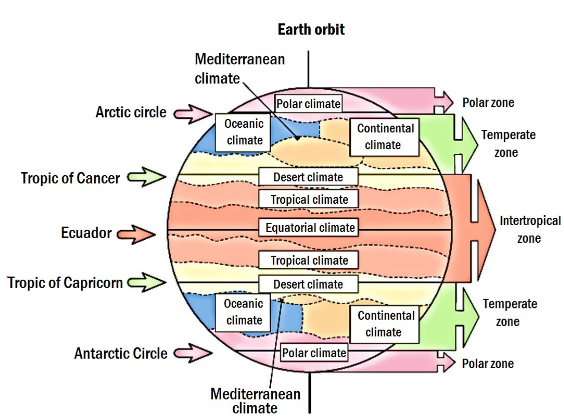

Figura 1. Thermal zones of the Earth [3]

2. Materials and methods

This research is of quasi-experimental nature; since there is no effective control for the selection and development of variables, a set of methodical and technical activities are integrated and carried out to gather the necessary information and data on the subject to be investigated and the problem to be solved [4].

The presented project requires a calculation of the percentage of CO_2 per kg of fuel burned in a defined period without solar thermal systems (control group) and the calculation of the percentage of CO_2 with application of solar thermal systems (experimental group). Four phases have been contemplated for this investigation, as shown in Figure 2.

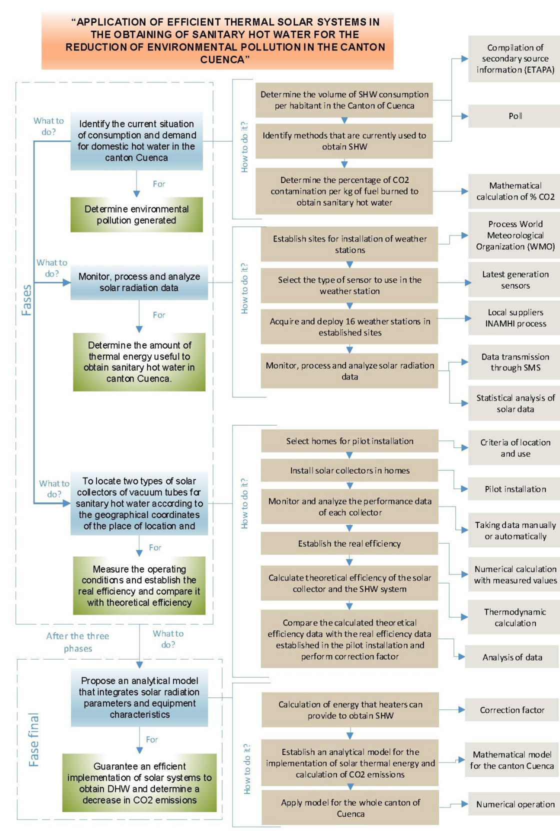

Figura 2. Outline of research design

2.1. Analysis of current SHW consumption and de-mand in the Canton of Cuenca and determination of the percentage of CO_2 emitted into the environment

At this point, water consumption per inhabitant is determined through secondary source data that is, in this case, collected from the Municipal Public Company for Telecommunications, Drinking Water, Sewerage and Environmental Sanitation (Empresa Pública Municipal de Telecomunicaciones, Agua Potable, Alcantarillado y Saneamiento Ambiental, ETAPA) and the analysis is completed with a survey where the consumption and demand of SHW is identified. In addition, the methods used to produce hot water are identified: gas heaters, electric heaters, solar heaters, others. Finally, a mathematical calculation will determine the percentage of CO_2 contamination per kg of fuel burned to obtain SHW.

For conducting the survey, the projection of the population for the year 2016 is performed using the parabolic method [5], based on the information from the censuses of the years 1990, 2001 and 2010 [6] as shown in Table 1.

Tabla 1. Projected number of inhabitants in the canton of Cuenca for the year 2016

Year	Urban	Rural	Total
1990	194 981 hab.	136 047 hab.	331 028 hab.
2001	277 374 hab.	140 258 hab.	417 632 hab.
2010	331 888 hab.	173 697 hab.	505 585 hab.
2016	**361 781 hab.**	**210 986 hab.**	**572 767 hab.**

The population under study is made up of the number of households in the canton of Cuenca. It is estimated that an average household is composed of 5 members, which results in a total of 114 553 households for the whole canton divided into 72 356 for the urban area and 42 197 in the rural area.

To determine the sample, equation (1) is applied considering reliability level k = 95%, error limit e = 0.06, probability of success p = 0.6 and probability of failure q = 0.4.

$$n = \frac{k^2 \times p \times q \times N}{(e^2 \times (N-1)) + k^2 \times p \times q} \tag{1}$$

The significant sample to be used is 531 households divided into 266 in the urban area and 265 in the rural area. In the latter, a stratification is carried out according to the number of inhabitants of each parish due to the geographical particularities presented by each one; the urban area it is not stratified because the conditions of all the parishes are similar.

A questionnaire is used to obtain instrumental information. Taking into account the variable transit to its dimensions or components, then to the indicators and, finally, to the items or reagents [4], the established analysis is shown in Table **??**.

Tabla 2. Analysis of transit of variables for questionnaire

<table>
<tr><th colspan="4">Analysis on the use of SHW in the Canton of Cuenca</th></tr>
<tr><th>Variable</th><th>Dimension</th><th>Indicators</th><th>Items</th></tr>
<tr><td>Uso of SHW</td><td>Daily cleaning activities</td><td>If use or do not use</td><td>Use hot water for regular activities such as bathing, washing hands, washing dishes, washing clothes, etc. (Mark with an "X" your answer)
YES ……. NO……..</td></tr>
<tr><td>No use of SHW</td><td>Consideration factor</td><td>Hierarchy of preference why does not use SHW considering cost, pollution and ease of purchase and installation.</td><td>If your answer is NO, write in the box that the numbers from 1 to 4 are blank, considering 1 to the most important and 4 least important.
Very expensive…………
It contaminates the environment……
Difficult to buy……
Difficult to install……….</td></tr>
<tr><td>Number of inhabitants per household</td><td>Accountant</td><td>Number of inhabitants per household</td><td>Including you, how many people live in your house?
……………… people</td></tr>
<tr><td>Type of system used to obtain SHW in the home</td><td>Identification of the type of system for SHW</td><td>Determination of the current system to obtain SHW considering: Gas (LPG); electrical resistance, electric induction, solar heater, solar and gas, solar and electrical resistance, other in regular activities: shower, sink, kitchen sink and laundry</td><td>Indicate the type of water heating system you use in your home for the following activities. (Mark with an "X" only in those that use hot water)
<table>
<tr><th>Activity
System</th><th>Shower</th><th>Handwash</th><th>Kitchen sink</th><th>Laundry</th></tr>
<tr><td>Gas (LGP)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Electric resistance</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Electric induction</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Solar heater</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Solar and Gas (LPG)</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Solar - Electric resistance</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Other</td><td></td><td></td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Time used for cleaning activities with SHW</td><td>Determination of time</td><td>Time range for regular activities: shower, sink, kitchen sink and laundry</td><td>Considering what is marked in the previous table, determine the total daily time for each activity by adding up the time occupied by each family member. (Mark with an "X" your answer).
<table>
<tr><th>Time Activity</th><th>30 to 45 min</th><th>45 to 60 min</th><th>60 to75 min</th><th>More than 75 min</th></tr>
<tr><td>Shower</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Handwash</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Kitchen Sink</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Laundry</td><td></td><td></td><td></td><td></td></tr>
</table></td></tr>
<tr><td>Quality of the SHW system used</td><td>Attribution of performance</td><td>Degree of perception of the quality of the SHW system used</td><td>How do you rate the current water heating system that you have? (Mark with an "X" the corresponding answer, the same one that is unique).
Very good…… Good…… Regular….. Bad…..</td></tr>
<tr><td>Factors to choose system</td><td>Implementation allocation</td><td>Degree of perception and ranking of factors to choose a DHW system for housing</td><td>What are the factors you considered when choosing your current water heating system? (Write in the box that the numbers from 1 to 4 are blank, considering 1 to the most important and 4 least important).
Low cost…… Easy to install……
Does not pollute…… Easy to buy……</td></tr>
</table>

For data collection, the questionnaire is applied ac-cording to the analysis made in the previous paragraphs. A group of interviewers visited the homes and re-quested that it be completed.

The amount of energy that is required to cover the demand, considering the average values of SHW consumption in the shower, sink and in the kitchen sink determined in the survey, is obtained from equation (2):

$$D_{ACS} = V_{ACS} \times \rho_a \times C_p \times (T_{uso} - T_{red}) \quad (2)$$

Where:

D_{ACS}= Demand for SHW (J)
V_{ACS}= Volume of SHW consumption (m^3/month)
ρ_a= Water density 1000 kg/m^3
C_p= Specific heat of water (4187 J/(kg·°C))
T_{uso}= Temperature of use (°C)
T_{red}= Network temperature (°C)

To calculate CO_2 emissions generated when obtaining SHW, the energy required to obtain SHW is multiplied by an emission factor of 0.234 kg CO_2 eq/kWh for LPG and 0.385 kg de CO_2 eq/kWh for electricity [7].

2.2. Monitoring, processing and analysis of solar ra-diation data for the canton of Cuenca

For this second phase of the project, work is carried out for the selection and location of meteorological stations in accordance with the recommendations made by the World Meteorological Organization (WMO). Data quality control and corresponding ad-justments are carried out to finally quantify the exist-ing energy in each of the sectors where the meteoro-logical stations are located and which are associated with the urban and rural parishes of the canton of Cuenca.

2.2.1. Location of weather stations in the canton of Cuenca

In 2013, Universidad Politécnica Salesiana, UPS, and the National Institute of Energy Efficiency and Renewable Energies, INER installed a network of 16 me-teorological stations distributed in strategic points of the canton of Cuenca with the purpose of measuring meteorological variables and use the data in projects for the implementation of energy systems based on renewable energies [8].

For the correct geographical definition of the site sites of the stations, work was conducted in six stages as listed below [9].

- Determination of data of possible areas for placement.
- Field visits
- Selection of criteria.
- Spatial analysis
- Assessment and choice of location sites.
- Selection and location of weather stations

2.2.2. Characterization of solar radiation in the canton of Cuenca during the years 2014-2015

For this process, the global radiation information measured by the meteorological station is collected and a quality control of the obtained data is carried out, given that, due to the conditions of the location sites or due to uncontrolled circumstances of the equipment, there may be missing data in certain dates. Then, the corresponding complementation is carried out, the existing radiation is quantified and the energy contribution that the radiation offers in the different zones for each month in 2014 and 2015 is calculated.

The missing information is completed using the Angström – Prescott mathematical model modified by Page, which enables the estimation of the solar re-source in a given area [10]. The procedure consists of making use of several equations correlated to each other, which allow for the calculation of extraterrestrial radiation (He) according to the geographical location of the area of interest, to then use the Page equation and obtain the radiation on a horizontal surface (Ho). The Angström – Page correlation to determine the missing global solar radiation on a horizontal surface is shown in Table 3.

Tabla 3. Angström – Page correlation to determine global solar radiation [10]

Description	Equation
Theoretical hours of solar brightness (h)	$N = \frac{2}{15} cos^{-1}(-tan\ \phi \cdot tan\ \delta)$
Extraterrestrial radiation (J/m^2)	$H_e = \frac{24}{\pi} I_{sc} \left[1 + 0.033 cos \frac{360 \times z}{365}\right] \cdot \left[cos\ \rho \cdot cos\ \delta \cdot sin\ h_s + \frac{2\pi h_s}{360} sin\ \phi \cdot sin\ \rho\right]$
Real hours (h)	$HSP_{Ecuador} = 9$
Solar radiation on horizontal surface (Wh/m^2)	$H_0 = H_e \left(a + b \frac{n_{reales}}{N}\right)$

To make the corresponding calculations, the daily supplemented values and the established sun hours are added to find the daily total, and the daily totals of each month are added to obtain the monthly total, fi-nally, the monthly totals are used to obtain the total incident annual energy value.

2.3. Characterization of vacuum tube and heat pipe solar collectors

For the case under study, two types of solar collectors are used, which are installed in two houses in the canton of Cuenca; the first is a vacuum tube heater and the other is a vacuum tube heater with a heat pipe, which are commercially available in Ecuador; For each one, the corresponding theoretical analysis is carried out applying the principles of thermodynamics and heat transfer. With the collectors installed, real effi-ciencies are determined and compared with the theo-retical data calculated, the corresponding correction is established, and the specific mathematical model is obtained for each one.

The useful heat (Qu) that would be equal to the in-cidental heat (Qinc), that is, the one obtained from solar radiation minus heat losses (Qper) that occur in the process of heat transfer, is calculated with equation (3).

$$Q_u = Q_{inc} - Q_{per} \tag{3}$$

To determine the efficiency η of the solar collectors, equation (4) is used:

$$\eta = \frac{Q_u}{Q_{inc}} \tag{4}$$

2.3.1. Characterization of a vacuum tube solar heater.

To calculate the incident heat in Watts, we have equation (5)

$$Q_{inc} = I_p \times \alpha_s \times A \tag{5}$$

Where:

I_p is the average irradiation in the city of Cuenca.
A is the radiation collection area multiplied by the num-ber of tubes.
α_S is the correction factor of the incident radiation that reaches the vacuum tubes and is determined by equation (6):

$$\alpha_s = \frac{\tau\alpha}{1-(a-\alpha)\rho_d} \tag{6}$$

Where:
τ is the transmissivity of glass tubes.
α is the absorptivity of the tubes.
ρ_d is the diffuse reflectance of the tubes.

For the calculation of the incidence area (m^2), it must be taken into account that solar radiation, whatever the location of the sun, will only affect half of the vacuum tubes, therefore only half of the periphery will be taken into account as shown in equation (7):

$$A = \frac{d_i \times \pi \times number\ of\ tubes}{2} \tag{7}$$

The next process is to determine the conduction, con-vection and radiation losses in the entire heater as shown in Figure 3.

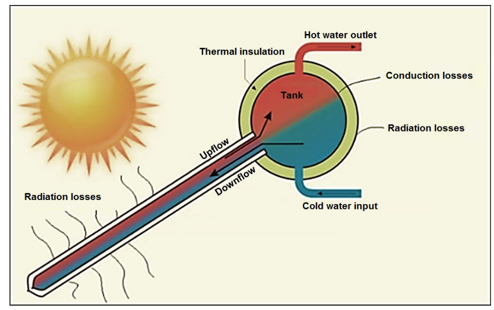

Figura 3. Heat losses in a solar vacuum tube heater [11].

The total of the losses (TQ_{loss}) (W) is given by the sum of the losses obtained in the vacuum tubes ($Q_{p\text{-}Tubes}$) and the losses of the accumulator tank ($Q_{p\text{-}Tank}$). Therefore, the expression for the calculation of the total losses is given by equation (8):

$$Q_{loss} = Q_{p-Tubes} + Q_{p-Tank} \tag{8}$$

In the case of vacuum tubes, losses are generated only by radiation [12], since this is their advantage over other systems; to calculate the losses in the tubes, we have equation (9):

$$Q_{p-Tubos} = U_{lr} \times A(T_c - T_a) \tag{9}$$

Where:

U_{lr} is the coefficient of heat loss by radiation of the tubes.
A is the catchment area.
T_c is the temperature of the cover.
T_a is ambient temperature.

The calculation of U_{lr} is carried out using the formula proposed by Duffie & Beckman [13] in which they relate the losses by radiation of the surface from the receiver tube to the cover tube ($h_{r,\ r-c}$) and radiation losses from the cover tube to the environment ($h_{r,\ c-a}$) as shown in equation 10.

$$U_{ir} = [\frac{A_r}{h_w + h_{r,\ c-a} \times A_c} + \frac{1}{h_{r,\ r-c}}]^{-1} \tag{10}$$

Where:

A_r represents the area of the receiving tube.
A_c is the area of the cover or outer tube.
h_w is the convection coefficient depending on the wind.

For the calculation of the convection coefficient $\left(\frac{w}{m^2 \times °C}\right)$ Equation (11) will be used:

$$h_w = N_u \times \frac{K}{D} \tag{11}$$

Where:

N_u is the Nusselt number.
K is the coefficient of thermal conductivity.
D is the diameter of the tube.

The heat transfer coefficient between the two concentric tubes, the receiving tube and the cover tube $h_{r,\ r\text{-}c}$ $\left(\frac{w}{m^2 \times °C}\right)$ is not attenuated by the vacuum between them, therefore, its value will be calculated by equation (12):

$$h_{r,\ r-c} = \frac{\sigma(T_r^2 + T_c^2) \times (T_r + T_c)}{\frac{1-\varepsilon_1}{\varepsilon_1} + \frac{1}{F_{12}} + \frac{1-\varepsilon_2 \times A_r}{\varepsilon_2 \times A_c}} \tag{12}$$

Where:

ε_1 is the emissivity of the receiver tube.
ε_2 is the emissivity of the cover tube.
F_{12} is the vision factor.
T_c is the temperature of the cover.
T_r is the temperature of the receiver.

For the calculation of losses in the accumulator tank an analogy is made with thermal resistance networks since the tank is made up of three materials as shown in Figure 4.

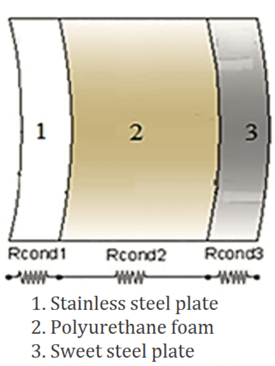

Figura 4. Resistor analogy for the multilayer accumulator tank [11].

Losses are produced in the storage tank by conduction, convection and radiation; ($Q_{p\text{-tanque}}$) and are giv-en by equation (13):

$$Q_{p-Tank} = Q_{p-cond} + Q_{p-conv} + Q_{p-rad} \tag{13}$$

For the conduction losses in the periphery of the tank, equations (14) and (15) are considered:

$$Q_{p-cond} = \frac{T_i - T_a}{R_{Total}} \tag{14}$$

$$R_{Total} = R_{cond1} + R_{cond2} + R_{cond3} \tag{15}$$

Where:

T_i is the temperature inside the tank.
T_a is the temperature of the environment.
R_{Total} is the sum of the thermal resistances by conduction in each of the layers in the accumulator tank.

Equation (16) is applied to the calculation of each of the conduction resistances:

$$R_{cond} = \frac{ln\frac{D}{d}}{2 \times \pi \times L \times K} \tag{16}$$

Where:

D is the largest diameter of the layer being analyzed.
d is the smallest diameter of the layer.
L is the length of the cylinder.
K is the coefficient of thermal conductivity of the materials.

For the losses in the tank tops, an analogy with thermal resistance networks is used since the tank consists of three materials as shown in Figure 5.

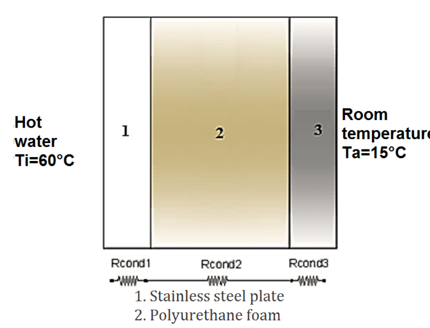

Figura 5. Resistor analogy for the multilayer tank lid [11].

The calculation procedure is the same as explained in the previous paragraphs, but the expression of the re-sistances is modified by equation (17) considering that the surfaces are flat.

$$R = \frac{e}{K \times A} \tag{17}$$

Where:
e is the thickness of the different layers of insulation.
K is the coefficient of thermal conductivity.
A is the conduction area of the insulation layer.

By summing the total resistance of the cylinder and that of the lids, total resistance is obtained, which implemented in equation (14) allows for the calculation of total losses of conduction in the tank (Q_{p-cond}).

For losses by convection in the tank, equation (18) is used.

$$Q_{p-cond} = hA_t(T_t - T_a) \tag{18}$$

Where:

h is the coefficient of heat transfer by convection.
A_t is the cross-sectional area of the storage tank.
T_t is the temperature on the outer surface of the tank.
T_a is ambient temperature.

To calculate the coefficient of heat transfer by convection, equation (19) is used:

$$h = \frac{N_u \times K}{D} \tag{19}$$

Where:

N_u is the Nusselt number.
K is the coefficient of thermal conductivity of air.
D is the outside diameter of the storage tank.

Equation (20) is used to calculate the radiation losses in the tank:

$$Q_{rad} = \varepsilon\sigma A_t(T_t^4 - T_a^4) \tag{20}$$

Where:

ε is the emissivity of the tank's surface.
σ is the Stefan Boltzman coefficient.
A_t is the cross-sectional area of the storage tank.

2.3.2. Characterization of solar heater of vacuum tubes with heat pipes.

The process of calculating efficiency and losses in the tank is the same as for vacuum tubes; the difference for this type of heater is in the vacuum tube system with heat pipes, where an additional element inter-venes in the exchange that will modify the efficiency value in the system. For this particular case the U_{lr} will now be U_l, which is the coefficient of heat losses by radiation of the tubes.

The calculation of U_l for this type of heater is carried out using the formula proposed by Duffie & Beckman [13], in which they relate the radiation losses from the surface of the receiver tube to the cover tube ($h_{r,\ r\text{-}c}$), radiation losses from the cover tube to the environment ($h_{r,\ c\text{-}a}$) and, in addi-tion, losses between the heat pipe and the receiver tube ($h_{r,\ tc\text{-}r}$) are considered as shown in equation (21):

$$U_l = \left[\frac{A_r}{h_w + h_{r,\ c-a} \times A_c} + \frac{1}{h_{r,\ r-c}} + \frac{1}{h_{r,\ tc-r}}\right]^{-1} \tag{21}$$

The incorporated term considers the losses between the heat pipe to the receiver tube ($h_{r,\ tc\text{-}r}$) and is calculated with formula (22):

$$h_{r,\ tc-r} = \frac{\sigma \times 4 \times T^3}{\frac{1-\varepsilon_1}{\varepsilon_1} + 1\frac{(1-\varepsilon_2)A_1}{\varepsilon_2 A_2}} \tag{22}$$

Where:

ε_1 is the emissivity of copper.
ε_2 is the emissivity of the glass tube.
A_1 is the area of the heat pipe.
A_2 is the area of the glass tube.
σ is the Stefan Boltzman coefficient.
T is the temperature of the receiver.

2.3.3. Practical determination of the efficiency of the vacuum tube collector and the vacuum tube collector with heat pipes.

For the two types of heaters installed, the following variables are monitored:

- Room temperature [°C]
- Water temperature in the storage tank [°C]
- Temperature of water that enters from the supply network [°C]
- Water volume [liters]

The values measured throughout a year are used to calculate the efficiency of the heater using formula 23:

$$\eta_s = \frac{\dot{m} \times C_p \times (T_s - T_t)}{Q_{inc}} \tag{23}$$

Where:

$\dot{m}$ is the mass flow of water that circulates through the heater [kg/s].
C_p is the specific heat of water [J/kg·K].
T_s is the water outlet temperature [°C].
T_i is the water intake temperature [°C].
Q_{inc} is useful energy coming from the sun [W/m^2].

Finally, the measured data are compared with the calculated data and the correction is made in the theoretical analysis.

2.4. Feasibility of implementation of solar systems to obtain SHW and determination of reduction of environmental pollution

At this point, the feasibility of implementing systems to obtain SHW will be defined considering the amount of solar energy measured during the years 2014 and 2015 for the parishes of the canton of Cuenca.

For the analysis, data on measured solar radiation are used to calculated the energy that the two types of heaters are able to provide to obtain SHW based on radiation, to then be compared with the energy demand determined in the field work. The percentage of contribution that these systems could generate and the decrease that could occur in emanations of CO_2 with their implementation is also calculated.

In addition, the amount of energy that should be generated with complementary conventional sources to guarantee a constant supply of hot water in the residences is determined.

3. Results and discussion

In the first stage, equation (1) is applied to determine the sample.

By replacing the values, the size of the sample is 531 households.

The applied survey shows that 82% of households in the canton of Cuenca use SHW and 18% do not. (Figure 6)

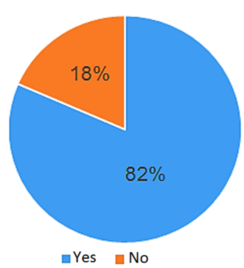

Figura 6. SHW in homes in the canton of Cuenca.

Those who do not use SHW consider that it is a costly implementation, while potential environmental pollution was not considered as an important factor at all (Figure 7).

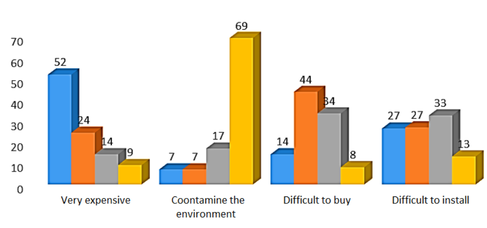

Figura 7. Reasons why a Cuenca household does not have SHW.

In Cuenca, the number of inhabitants per household is between 3 and 6, as shown in Figure 8; the trend of the curve is to the right and is maintained for the urban and rural areas, so the value of five members per household considered is a valid alternative for the analysis.

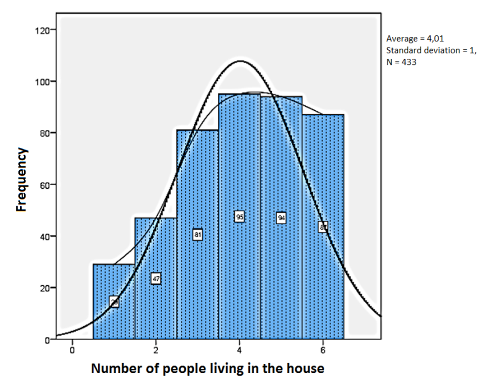

Figura 8. Number of inhabitants per household in the canton of Cuenca.

With regard to the systems used to obtain domestic hot water, the LPG heating system predominates (Figure 9).

SHW is used mainly in showers, sinks and kitchen sinks, and the frequency of use for the five members in sinks and kitchen sinks is between 30 to 45 min daily, and for the shower it is between 30 and 60 minutes (Figure 10).

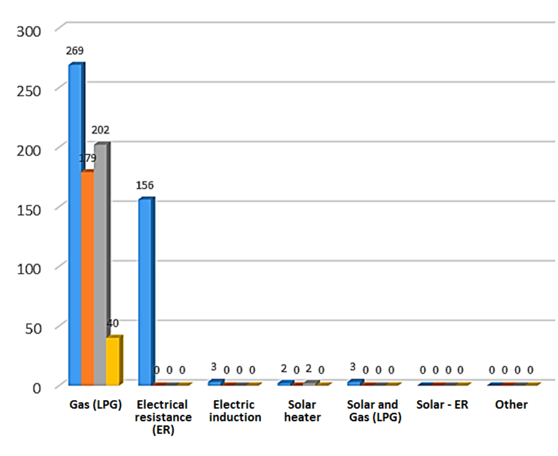

Figura 9. Systems used to obtain SHW.

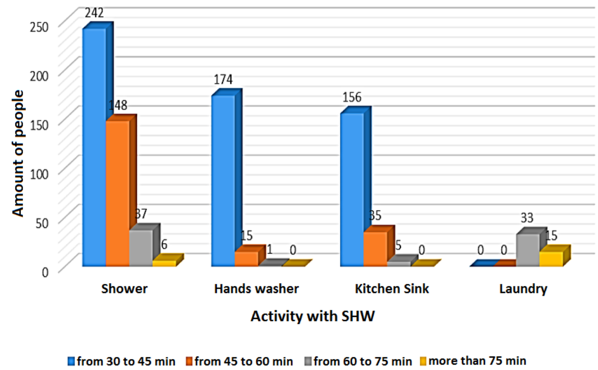

Figura 10. Type of activity with SHW and time spent

The systems currently used to obtain SHW are effi-cient since the population qualifies them as good and very good (Figure 11).

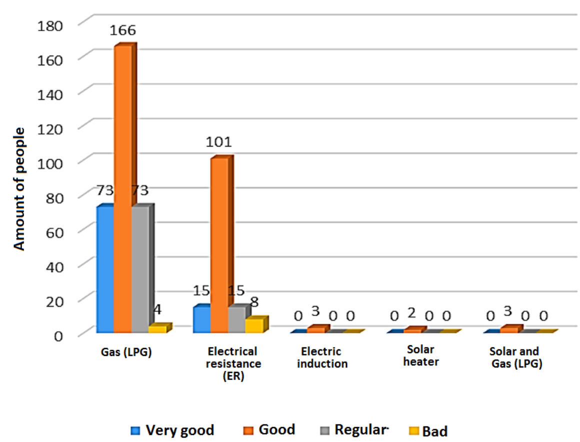

Figura 11. Rating of the SHW system.

When it comes to selecting the system, what is most important is the cost of the system and what is less important is the pollution it may generate (Figure 12).

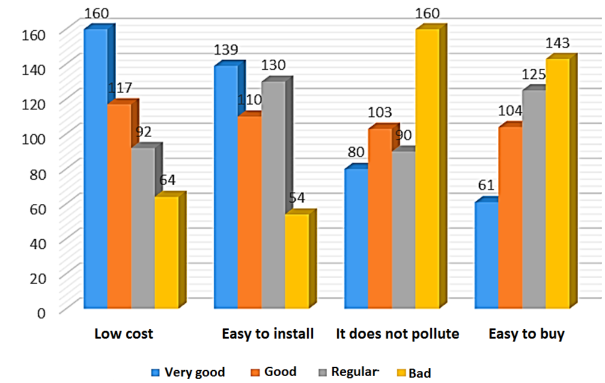

Figura 12. Importance of parameters when choosing a system to obtain SHW.

The average value of SHW consumption is determined with question 4. To accomplish this, the average values of the sum of the times of use for shower, sink and kitchen sink are calculated. The value corresponding to laundry is neglected since the percentage of us-ers in this activity is minimal.

With the aforementioned, SHW consumption is de-termined, multiplying the total time used by the mem-bers of the household by an average consumption of 0.006 m^3/min [14], and by a coincidence factor since all the members bathe every day, or use SHW in the sink or in the kitchen sink. These values have been identified considering the habits of the inhabitants of the canton of Cuenca. The results obtained can be seen in Table 4.

Tabla 4. Calculation of effective SHW consumption per 5-member household in the canton of Cuenca

Activity	Average daily time (min)	Match factor	Efective daily time (min)	Flow in pipe (m^3/min)	Effective consumption (m^3/day)
Shower	44	0,5	22	0,006	0,13
Hands washer	30	0,4	12	0,006	0,07
Kitchen sink	20	0,4	8	0,006	0,05
				Total	**0,25**

To calculate the monthly energy demand, we use equation (2). The value corresponding to Tuso is 60°C, while for Tred it is an average of 8°C, this value is assumed since there is a variation between 6 and 10°C in urban and rural areas; the value of V_{ACS} is 0.25 m^3/day, if the values of the parameters are known, the expression is replaced by considering the days of each month and the monthly and annual value of energy required to produce SHW is determined; the calculated values are shown in Table 5.

Once the value of monthly and annual energy demand required to obtain SHW for a family of 5 members is obtained, CO_2 production is calculated by multiplying the obtained value by the emission index which, in the case of generic LPG, is 0.234 kg of CO_2 eq/kWh [7], resulting in a value of 2141.20 kg of CO_2 eq. per year in an average family of 5 members in the canton of Cuenca, as presented in Table 5.

Tabla 5. Monthly and annual energy demand to produce SHW in a household of 5 members in the Cuenca canton and production thereof CO_2

Month	**Days**	**Consumtion (m^3/day)**	**Consumption total (m^3) monthly**	**Tred (°C)**	**Tuse (°C)**	**ΔT (°C)**	**D_{ACS} (MJ) per month**	**D_{ACS} (kWh) per month**	**kg eq of CO_2**
January	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
February	28	0,25	7,06	8	60	52	1536,26	426,74	164,29
March	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
April	30	0,25	7,56	8	60	52	1645,99	457,22	176,03
May	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
June	30	0,25	7,56	8	60	52	1645,99	457,22	176,03
July	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
August	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
September	30	0,25	7,56	8	60	52	1645,99	457,22	176,03
October	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
November	30	0,25	7,56	8	60	52	1645,99	457,22	176,03
December	31	0,25	7,81	8	60	52	1700,86	472,46	181,9
					Demand per year		**20026,25**	**5562,85**	**2141,7**

Considering the previous data and with 114 553 5-member households, the contribution to pollution is of 245 338 160 kg eq of CO_2 or 245338 of tn $CO_2$2 eq.

With respect to monitoring, processing and analysis of global solar radiation, the process takes into account radiation data measured by a group of 16 meteorological stations installed in the canton of Cuenca according to Table 6.

Complementation of missing data is performed using an Angström – Page correlation for the data of the stations as shown in Table 7.

The complemented tables are obtained; as an example, Table 8 is presented for the station at the rural parish of Chaucha.

Tabla 6. Weather station data

Weather station	**Coordinates**	**Elevation (m s. n. m.)**
Quingeo	729057; 9664602	2893
Molleturo	679708; 9692232	3530
Baños	712899; 9672817	3062
CTS	720504; 9677509	2561
UPS	723584; 9680788	2556
Tixán	723017; 9686678	2725
Cumbe	719190; 9656242	3179
Sayausí	715974; 9681200	2727
Nulti	729704; 9682466	2601
San Joaquín	714405; 9680807	2764
Llacao	730418; 9685180	2542
Santa Ana	730085; 9672006	2651
Chaucha	672859; 9678690	1929
Turi	721103; 9674971	2768
Sinincay	722340; 9685283	2696
Victoria del Portete	713645; 9659192	2665

Tabla 7. Weather stations with missing data

Weather station	**Year**	**Month**	**Days with missing data**
CTS	2014	january	1-9
	2014	march	19-24
Chaucha	2014	november	27-30
	2014	december	9-15
Cumbe	2014	january	1-8
Irquis	2014	january	1-3
Santa Ana	2014	january	1-3
Turi	2014	january	1-7
UPS	2014	january	1-7

Tabla 8. Missing radiation data complemented in the month of december 2014 at the Chaucha station

Hour/Day	**december 14**								
	8	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
01H00	0	0	0	0	0	0	0	0	0
02H00	0	0	0	0	0	0	0	0	0
03H00	0	0	0	0	0	0	0	0	0
04H00	0	0	0	0	0	0	0	0	0
05H00	0	0	0	0	0	0	0	0	0
06H00	0	0	0	0	0	0	0	0	0
07H00	13	7	13	13	24	9	14	3	5
08H00	59	72	67	81	112	89	72	64	76
09H00	123	255	267	495	292	217	151	305	279
10H00	569	309	500	739	331	504	191	633	465
11H00	955	355	719	941	570	719	387	1071	902
12H00	1123	569	940	1085	923	783	555	1054	1187
13H00	1114	453	922	1129	798	536	651	1063	1022
14H00	975	224	670	1128	1004	664	419	325	686
15H00	1059	67	226	432	399	394	790	69	216
16H00	173	57	96	89	383	389	241	78	86
17H00	50	85	31	90	184	177	68	51	57
18H00	11	47	6	54	8	71	62	53	73
19H00	1	4	2	4	1	7	6	5	9
20H00	0	0	0	0	0	0	0	0	0
21H00	0	0	0	0	0	0	0	0	0
22H00	0	0	0	0	0	0	0	0	0
23H00	0	0	0	0	0	0	0	0	0
24H00	0	0	0	0	0	0	0	0	0

With the supplemented data, the total daily, monthly and annual radiation is calculated for each station (Figure 12, example from Chaucha station).

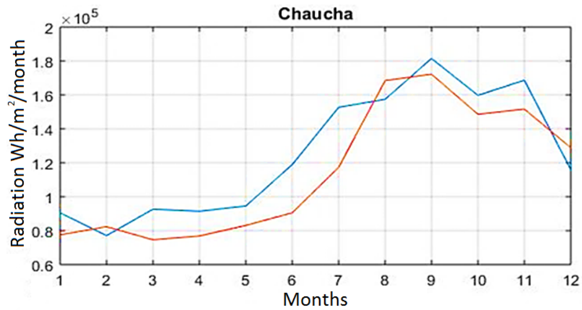

Figura 13. Global Solar Radiation – Chaucha sector

With the averages of all the data measured in the 16 stations, the average global solar radiation curve for the canton of Cuenca is obtained as shown in Figure 14.

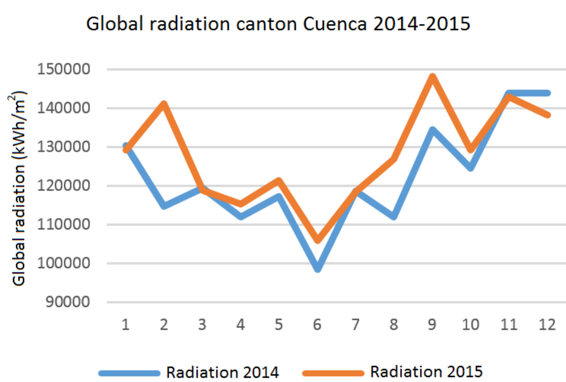

Figura 14. Global Radiation - Cuenca canton 2014-2015

The installed heaters have the following characteristics (Figure 15):

Figura 15. Characteristics of solar heaters installed

The efficiency of the solar collectors is calculated both theoretically and practically and the values are compared, leading to the conclusion that the average of the percentage difference for the heater of simple evacuated vacuum tubes is 5% and that of vacuum tubes with tubes of heat is 2%; (Figure 16) with these values the analysis is corrected and the real efficiency of the collectors is determined, the results being 74% for vacuum tube and 80% for of vacuum tubes with heat pipes.

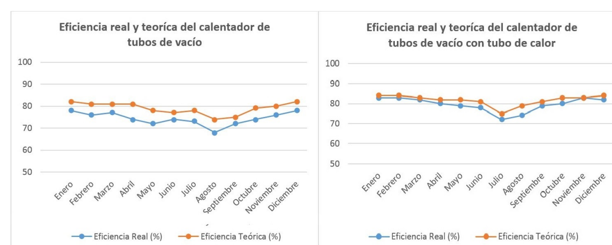

Figura 16. Real and theoretical efficiency of solar heaters

Energy of loss and useful energy that will be used to obtain SHW is compared with the energy demand to establish the missing amount which must be covered with auxiliary systems for each type of heater (Tables 9, 10). The calculation contemplates 9 effective daily hours of sunshine.

Tabla 9. Energy analysis for the vacuum tube heater

Station	Average irradiance kWh/m^2		Incident energy kWh		Lost energy kWh		Useful energy kWh		Demand energy kWh		Missing energy kWh		Missing energy kg (GLP)	
	2014	**2015**	**2014**	**2015**	**2014**	**2015**	**2014,00**	**2015,00**	**2014**	**2015**	**2014**	**2015**	**2014**	**2015**
Baños	1359,11	1349,73	2729,67	2710,82	709,71	704,81	2019,96	2006,00	5562,85	5562,85	3542,89	3556,85	280,32	281,42
Chaucha	1454,31	1372,09	2920,86	2755,73	759,42	716,49	2161,43	2039,24	5562,85	5562,85	3401,42	3523,61	269,12	278,79
CTS	1527,98	1551,79	3068,82	3116,64	797,89	810,33	2270,93	2306,31	5562,85	5562,85	3291,92	3256,54	260,46	257,66
Cumbe	1457,39	1525,81	2927,04	3064,46	761,03	796,76	2166,01	2267,70	5562,85	5562,85	3396,84	3295,15	268,76	260,72
Irquis	1466,93	1509,14	2946,20	3030,99	766,01	788,06	2180,19	2242,93	5562,85	5562,85	3382,66	3319,92	267,64	262,67
Llacao	1609,21	1665,49	3231,97	3345,01	840,31	869,70	2391,66	2475,31	5562,85	5562,85	3171,19	3087,54	250,91	244,29
Molleturo	1823,05	1968,17	3661,44	3952,91	951,97	1027,76	2709,47	2925,15	5562,85	5562,85	2853,38	2637,70	225,76	208,70
Nulti	1691,23	1781,70	3396,70	3578,40	883,14	930,38	2513,56	2648,01	5562,85	5562,85	3049,29	2914,84	241,26	230,62
Quingeo	1472,95	1570,64	2958,31	3154,51	769,16	820,17	2189,15	2334,34	5562,85	5562,85	3373,70	3228,51	266,93	255,44
San Joaquín	1414,30	1364,51	2840,51	2740,51	738,53	712,53	2101,98	2027,98	5562,85	5562,85	3460,87	3534,87	273,83	279,68
Santa Ana	1431,65	1482,57	2875,36	2977,62	747,59	774,18	2127,76	2203,44	5562,85	5562,85	3435,09	3359,41	271,79	265,80
Sayausí	1435,70	1440,54	2883,49	2893,20	749,71	752,23	2133,78	2140,97	5562,85	5562,85	3429,07	3421,88	271,31	270,74
Sinincay	1523,17	1552,78	3059,17	3118,64	795,38	810,85	2263,79	2307,79	5562,85	5562,85	3299,06	3255,06	261,02	257,54
Tixán	1462,79	1472,53	2937,90	2957,45	763,85	768,94	2174,04	2188,51	5562,85	5562,85	3388,81	3374,34	268,13	266,98
Turi	1441,54	1515,15	2895,23	3043,06	752,76	791,20	2142,47	2251,86	5562,85	5562,85	3420,38	3310,99	270,62	261,97
UPS	1640,31	1679,48	3294,43	3373,09	856,55	877,00	2437,88	2496,09	5562,85	5562,85	3124,97	3066,76	247,25	242,64
									Average values		3313,85	3259,00	262,19	257,85
											3286,42		**260,02**	

Tabla 10. Energy analysis for the vacuum tube heater with heat pipes

Station	Average irradiance kWh/m²		Incident energy kWh		Lost energy kWh		Useful energy kWh		Demand energy kWh		Missing energy kWh		Missing energy kg (GLP)	
	2014	2015	2014	2015	2014	2015	2014,00	2015,00	2014	2015	2014	2015	2014	2015
Baños	1359,11	1349,73	2729,67	2710,82	545,93	542,16	2183,74	2168,65	5562,85	5562,85	3379,11	3394,20	267,36	268,55
Chaucha	1454,31	1372,09	2920,86	2755,73	584,17	551,15	2336,69	2204,58	5562,85	5562,85	3226,16	3358,27	255,26	265,71
CTS	1527,98	1551,79	3068,82	3116,64	613,76	623,33	2455,06	2493,31	5562,85	5562,85	3107,79	3069,54	245,89	242,86
Cumbe	1457,39	1525,81	2927,04	3064,46	585,41	612,89	2341,64	2451,57	5562,85	5562,85	3221,21	3111,28	254,87	246,17
Irquis	1466,93	1509,14	2946,20	3030,99	589,24	606,20	2356,96	2424,79	5562,85	5562,85	3205,89	3138,06	253,65	248,29
Llacao	1609,21	1665,49	3231,97	3345,01	646,39	669,00	2585,58	2676,01	5562,85	5562,85	2977,27	2886,84	235,56	228,41
Molleturo	1823,05	1968,17	3661,44	3952,91	732,29	790,58	2929,15	3162,33	5562,85	5562,85	2633,70	2400,52	208,38	189,93
Nulti	1691,23	1781,70	3396,70	3578,40	679,34	715,68	2717,36	2862,72	5562,85	5562,85	2845,49	2700,13	225,14	213,64
Quingeo	1472,95	1570,64	2958,31	3154,51	591,66	630,90	2366,65	2523,61	5562,85	5562,85	3196,20	3039,24	252,89	240,47
San Joaquín	1414,30	1364,51	2840,51	2740,51	568,10	548,10	2272,41	2192,41	5562,85	5562,85	3290,44	3370,44	260,34	266,67
Santa Ana	1431,65	1482,57	2875,36	2977,62	575,07	595,52	2300,29	2382,09	5562,85	5562,85	3262,56	3180,76	258,14	251,66
Sayausí	1435,70	1440,54	2883,49	2893,20	576,70	578,64	2306,79	2314,56	5562,85	5562,85	3256,06	3248,29	257,62	257,01
Sinincay	1523,17	1552,78	3059,17	3118,64	611,83	623,73	2447,34	2494,91	5562,85	5562,85	3115,51	3067,94	246,50	242,74
Tixán	1462,79	1472,53	2937,90	2957,45	587,58	591,49	2350,32	2365,96	5562,85	5562,85	3212,53	3196,89	254,18	252,94
Turi	1441,54	1515,15	2895,23	3043,06	579,05	608,61	2316,18	2434,45	5562,85	5562,85	3246,67	3128,40	256,88	247,52
UPS	1640,31	1679,48	3294,43	3373,09	658,89	674,62	2635,54	2698,47	5562,85	5562,85	2927,31	2864,38	231,61	226,63
									Valores promedio		3131,49	3072,20	247,77	243,07
											3101,85		**245,42**	

With the established values, it is determined that the solar heater of vacuum tubes shows an average coverage with solar energy of 40.92%, and the heater of vacuum tubes with heat pipe 44.23%, this implies an average reduction, in the first case, of 100 397.17 tn CO_2 eq and in the second case 108 537.24 tn CO_2 eq, taking into account that using LPG-based heaters implies the generation of 245 337.84 tn CO_2 eq per year (Figure 17).

The values of coverage and reduction of pollution will vary slightly depending on the area in which they are located, which are assigned to the measurements of the 16 installed meteorological stations [15].

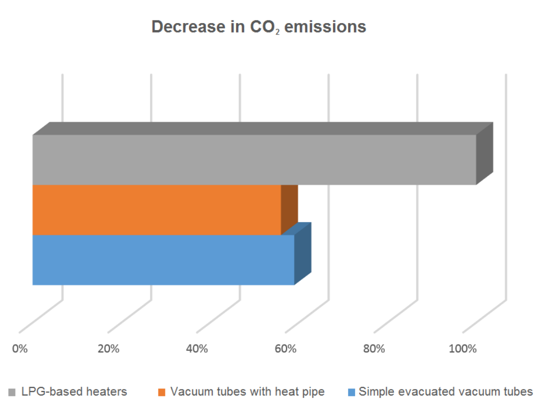

Figura 17. Decrease in CO_2 emissions through obtaining SHW with hybrid heaters with solar technology in contrast to LPG-based heaters

4. Conclusions

To obtain SHW in the canton of Cuenca, its inhabitants mainly use LPG-based systems, causing an approximate contamination of 245,337 tn CO_2 eq.

The amount of hot water used for the different activities, corresponding to 50 l per person per day, is excessive compared to the 30 l per day used in Spain [16, 17] in accordance with the ordinances imposed in that country.

The average radiation in the canton of Cuenca is between 1359 kWh/m^2 and 1968 kWh/m^2 depending on the geographical conditions of each sector. Using solar heaters of vacuum tubes can generate an energy contribution to obtain SHW ranging from 40.92% to 44.23%.

To guarantee a constant supply of SHW the heaters must be hybrid, that is, they must work with solar energy and have an auxiliary system that can be based on LPG or electrical resistance.

If the implementation of hybrid systems with solar technology is carried out, a reduction in contamination of CO_2 of around 44% is obtained, this implies stopping the emanation to the environment of 108 537.24 tn CO_2 eq per year.

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