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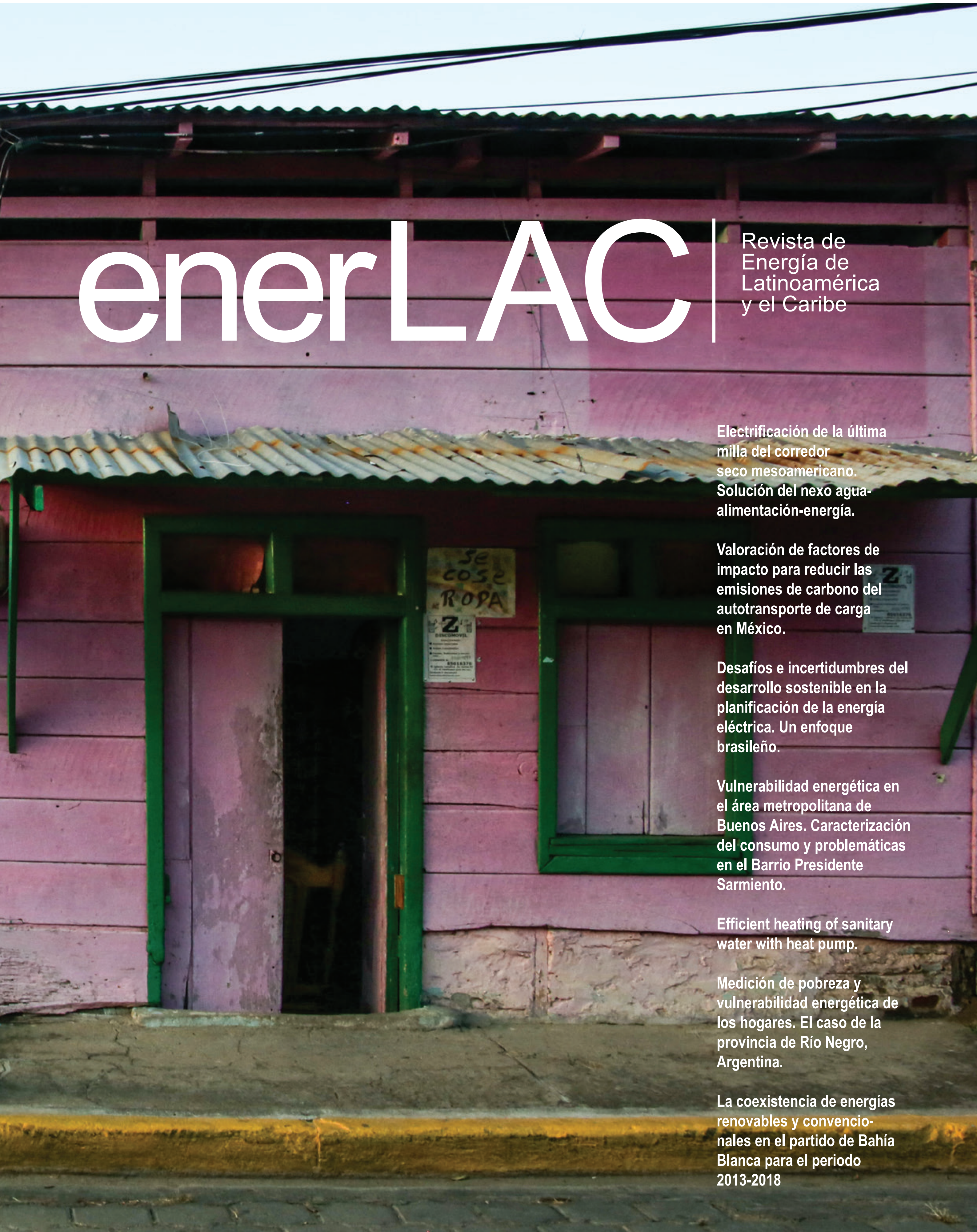


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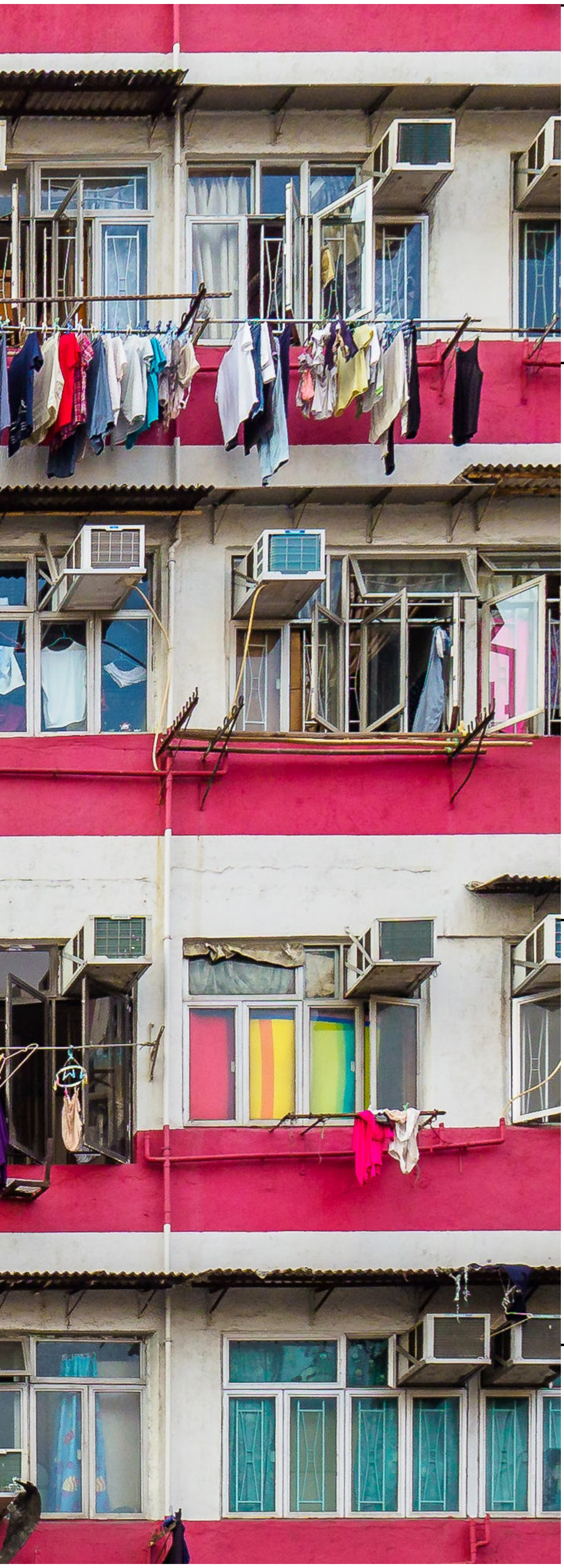

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# EFFICIENT HEATING OF SANITARY WATER WITH HEAT PUMP

## *CALENTAMIENTO EFICIENTE DE AGUA SANITARIA POR BOMBA DE CALOR*

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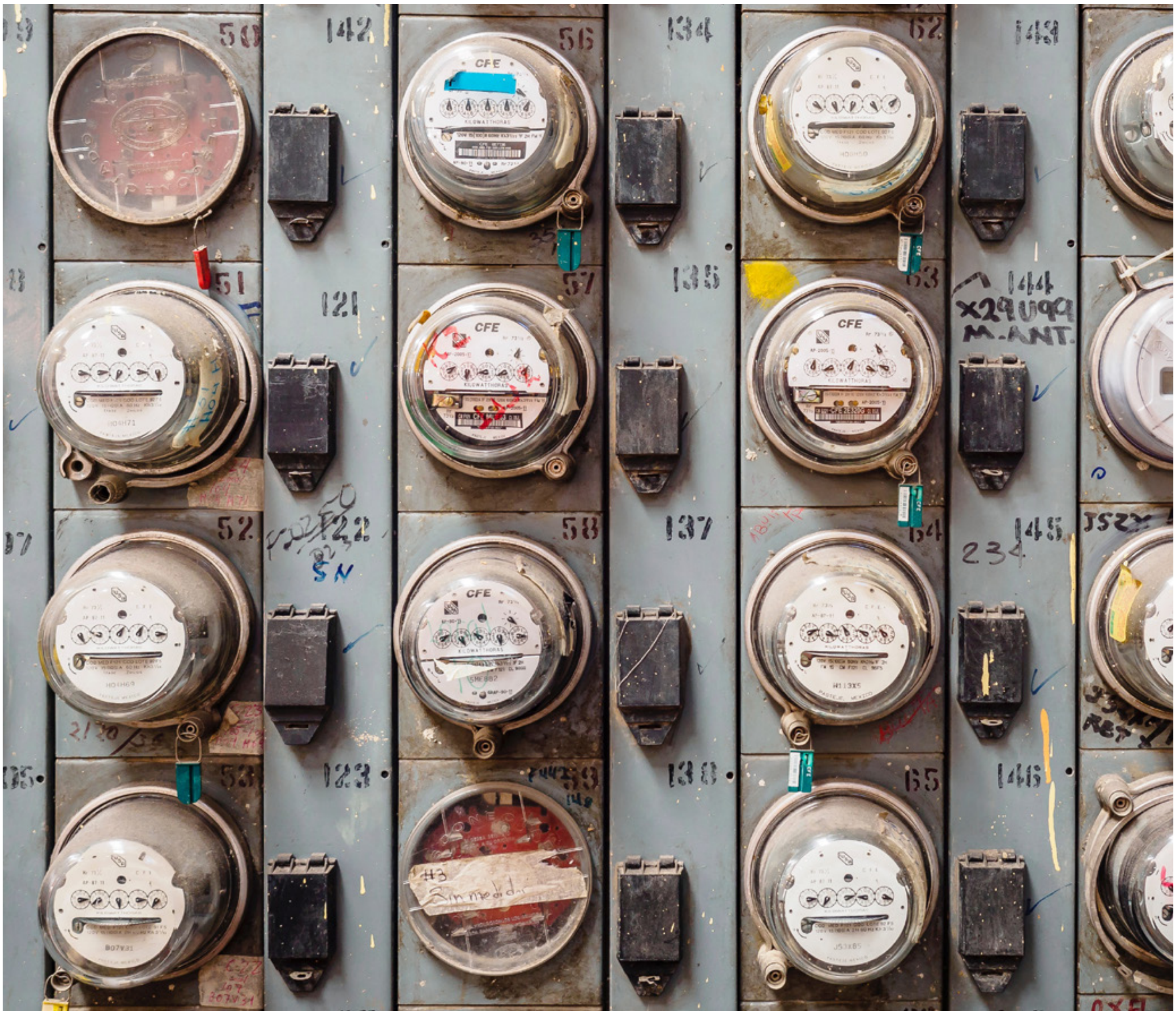

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**ABSTRACT**

This work presents a thermal and economical assessment about replacing the conventional household water heater with a heat pump water heater, which efficiency is several times higher than the previous one. Thus, the efficiency calculated for capitals of Latin-American countries has obtained average values ranging from 298% to 434%. However, the payback period obtained is also related to the electricity tariff and the temperature of the cold-water grid, which varies from 0.064 US$/kWh in Paraguay to 0.233 US$/kWh in Costa Rica, and from 10 °C (La Paz) to 26.8 °C (Costa Rica). Thus, a ranking of payback period (replacing/new installation) was performed for average consumption of a five-person family, obtaining values ranging from 2.4/1.4 years (Montevideo) to 10.5/6.1 years (Asunción), and also it was calculated the energy annual saving obtaining from 1,436 kWh (Costa Rica) to 2,660 kWh (La Paz). Consequently, we have found great potential for household energy saving in Latin-American countries by substituting the conventional water heater with a heat pump.

**Keywords:** Thermal Modeling, Household Electric Water Heaters, Heat Pump for Water Heating, Energy Efficiency, Economic Analysis.

***RESUMEN***

*Se presenta un análisis térmico-económico sobre la sustitución del termotanque hogareño convencional por una bomba de calor, cuya eficiencia es varias veces mayor. Así, la eficiencia promedio calculada en las capitales de países latinoamericanos varía del 298% al 434%. Sin embargo, y como será analizado, el período de repago obtenido depende también de la tarifa eléctrica y de la temperatura del agua fría de red, yendo desde 0.064 US$/kWh (Paraguay) hasta 0.233 US$/kWh (Costa Rica), y desde 10 °C (La Paz) hasta 26.8 °C (Costa Rica). Para una familia promedio de 5 personas se calculó un ranking (recambio/nuevo) con períodos de repago que van de 2.4/1.4 años (Montevideo) a 10.5/6,1 años (Asunción); además, se calculó el ahorro anual de energía, desde 1,436 kWh (Costa Rica) hasta 2,660 kWh (La Paz). Así, hemos encontrado un gran potencial de ahorro energético en los hogares de los países latinoamericanos al sustituir el calentador de agua convencional por una bomba de calor.*

***Palabras clave:*** *Modelado Térmico, Calentadores Eléctricos de Agua; Bomba de Calor; Calentamiento de Agua, Eficiencia Energética, Análisis Económico.*

## INTRODUCTION

The energy consumption related to sanitary water heating demand (SWHD) represents a major fraction (ranging from 30% to 75%) of total households in warm or temperate climates, as it was pointed out by several authors; for example, Iannelli y Pietro (2016), Sanders and Webber (2015), Keinath and Garimella (2017), Vieira, Beal, and Stewart (2014), Romero (2011), and Raimo (2010). Besides, since this consumption (usually supplied by electrical heaters) is demanded at the peak period (from 5 pm to 11 pm), it also impacts both, the generation and the distribution electrical systems.

The water-storage electrical heater (WSEH) is the preferred appliance in Latin-American countries to provide the SWHD. This appliance heats the water using an electrical resistance submerged into the water tank, which is kept to a constant usable temperature (~45 °C) by the thermostat and is thermally insulated to reduce this standby consumption throughout the whole day. The power consumed by these appliances is about 1,500 W, being this power noticeable lower than for direct-current heaters or showers (that is, without tank), which is about 5,500 W (as the well-known Brazilian shower). This advantage is counterbalanced by the weakness of needing a long heating period when the tank is filled with cold water, or otherwise, it has to waste a stand-by consumption. This stand-by consumption could be enlarged due to the need of keeping the water tank at higher temperatures (up to 75 °C) to extend its capacity (by mixing with cold water), for example, when the dwellers have to take several showers continuously.

The authors have studied the WSEH in detail and developed some new strategies, based on the hourly controlling of the thermostat, to minimize its stand-by consumption (citations deleted A & B). They also developed a numerical code useful for calculating its energetic performance, which will be summarized in the next section. Following these previous works, this paper evaluates the energy-saving achievable for a family by using a new kind of water heater, which is based on a high-efficiency Heat Pump Water Heater (HPWH). Regarding that, the performance of any heat pump is related to the ambient temperature, and in this case, also to the grid-water temperature, we will analyze these factors for the conditions of different Latin-American countries, which vary from temperate to warm climates.

Although the heat pumps have been used in Sweden during last 30 years for industrial applications that are still running (Averfalk et al., 2014), this technology has been generalized for domestic water heating just in the last ten years, as it was pointed out by Stafell, Brett, Brandon and Hawkes (2012), Willem, Lin and Lekov (2017), Pardiñas, Alonso, Diz, Husevåg and Fernández-Seara (2017) and Mengjie, Ning, Yingji and Shiming (2019). This way, every year one million HPWH are installed in Europe. Besides, this technology is continuously improving, achieving efficiencies of up to 700% in some new prototypes (Hua, Ge, and Wang, 2019).

The functioning of every heat pump is similar to any modern air conditioning equipment (like a cooling/heating split air conditioning), which (in its heating mode) takes heat at low temperature from the outdoor ambient by the evaporator unit, and delivers it to the indoor ambient by the condenser, after that the compressor increases the fluid temperature. According to the type of fluid selected and the detailed design of every component, this thermodynamical cycle can be designed for operating from -25 °C (evaporator) to 65 °C (condenser), so that it is very suitable for providing SWHD even in developed countries having cold climates.

> **This technology is well established for cold developed countries. However it is precisely in the warm climates of Latin-American countries where it would obtain a better performance.**

Up until today, two different kinds of HPWH are available in the market, one is an integrated device, and the other is a split device. The integrated design is suitable for indoor using, and so, it mounts a small and quietly compressor above a big water tank (300 liters), to satisfy a large hot water demand by using a low (375 W) heating power ([BCI for ACS in MLC], 2019). On the other hand, the split design used the external unit (evaporator) of any standard air conditioning system together with an indoor water tank that is heated by using a coiled heat exchanger, instead of the condenser. These tanks (with a copper-coiled heat exchanger and thermal insulations) are nowadays manufactured massively in China (having capacities ranging from 100 to 5,000 liters) as much as the evaporator, and consequently, a split HPWH is cheaper than the previous integrated design. For example, a split HPWH (compressor power of 875 W, the tank of 150 liters) costs 1,200 dollars in Latin-American countries (only 400 dollars in China), meanwhile a less powerful (375 W) integrated HPWH costs 1,800 dollars. ([BCP for ACS in MLU], 2019; [BCP for ACS in MLC], 2019; [BCI for ACS in MLC], 2019). However, to date, these types of equipment are almost unknown in Latin-American countries although they are based on the same technology that any modern heat pump for air conditioning system, and so, there are many technical services that could easily install them.

This technology is well established for cold developed countries, but, precisely in the warm climates of Latin-American countries is where it would obtain better performances, due to several causes: 1) lower temperature gradient for heating water from the water grid; 2) concerns related to freezing on the evaporator on ambient temperatures below 4 °C are not frequent (Song, Deng, Dang, Mao and Wang, 2018); and 3) low electrical tariffs, being noticeably lower than in European countries (i.e., 0.6 US$/kWh Spain). In this work is studied the energetical and economic performance of HPWH in Latin-American countries regarding a standard SWEH, for a 3-person and 5-person average family.

## NUMERICAL MODEL

The thermal modeling of the standard Water-Storage Electrical Heater (WSEH) was developed in previous works, (citations deleted A & B), which is based on the energy conservation on the water tank. Thus, considering a standard (Joule's effect) electrical heater having efficiencies about 100%, the electrical energy daily consumed (Ed) is equal to the sensible heat required so that the hot water mass (M) consumed can be heated from the water-grid cold temperature (Tc) to the desired usable hot temperature (Th), plus the heat daily losses through the thermal insulation of the tank, Ql:

$$Ed = M\,Cp\,(Th - Tc) + Ql \qquad \textbf{(1)}$$

Where $Cp$ is the specific heat of water, and $Ql$ is calculated as the convective heat losses to the indoor ambient (for indoor tanks). Thus, for a tank of external area ($A$) that is kept at a constant temperature set by the thermostat ($Tt$), within an ambient temperature ($Ta$), and having a uniform insulation layer of thermal transmittance K ($W/m^2/°C$), $Ql$ can be calculated by:

$$Ql = A\ K\ (Tt - Ta)\ *\ 24\ \text{h} \qquad \textbf{(2)}$$

From here, by considering a similar heat pump device (that is, having the same tank volume, insulation quality, and thermostat working temperature), this thermal model can be also applied, but taking into account that now the efficiency is determined by the coefficient of production (*COP*), which relates the heating power obtained and the electrical power consumed, by:

$$Eel = [M\ Cp\ (Tc - Tred) + Qper] / COP \qquad \textbf{(3)}$$

The *COP* value on any heat pump depends on the temperature difference (ΔT) between the outdoor ambient (the heat source) and the heated water (the heat sink), which has been fitted by Staffell et al. (2012) by using a quadratic function:

$$COP = 6.81 - 0{,}121 * \Delta T + 0.00063 * \Delta T^2 \qquad \textbf{(4)}$$

On the other hand, regarding that the energy consumed for heating water is related to its starting (cold) temperature, it is relevant to take into account the temperature of the tap-water grid. We have solved the lack of available data on grid temperatures for each city studied here, by using the general modeling developed by the National Laboratory of Renewable Energies of USA (NREL; Hendron, 2006). In this model, the temperature of the water grid follows the monthly average or the mean ambient temperature with an offset of +3.0 °C. We will estimate the heat pump performance by considering only the annual mean temperatures (for both, the ambient and the water grid), and so, neglecting the seasonal variations of these variables. Let us note from eq. (4) that the efficiency of the heat pump does not depend linearly on the temperature difference, and so, our simplified model introduces a seasonal error. However, we have verified that this assumption causes an error lower than 3% in all the studied cases, and so, this simplified methodology is reasonable.

**RESULTS**

The following assumptions have been used for all cases studied:

a) A constant indoor temperature, set to 20 °C. This is reasonable regarding its modest effect, lower than 5 %, on the standby heat losses.

b) The water tank has average-quality thermal insulation, made by a 5 cm-thickness layer of polyurethane foam, which provides a thermal transmittance K = 0.6 W/$m^2$/°C.

c) A standard cylindrical water tank (150 liters, 0.4 m diameter).

d) Average daily consumption of hot water for each person, which is represented by 45 liters at 40°C (shower) and 10 liters at 50°C (cleaning dishes and others), according to previous works (citations deleted A & B).

e) Thermostat set to 50 °C; this level is enough for satisfying all the household demands, but not causing overheating, which in turn would lead to higher heat losses on the tank.

f) A constant outdoor ambient temperature and equals to its mean annual value for every location studied.

g) The annual mean temperature of the water grid equals to the mean ambient temperature plus 3.0 °C, according to the NREL model (Hendron, 2006).

Hence, based on these simplifications and by using the modeling developed in the previous section, we obtain the results illustrated in Table 1. Here is shown the annual average values of the ambient temperature for fifteen major Latin-American cities (CLIMATE-DATA.ORG, 2020), and the coefficient of performance (COP) that a HPWH would obtain in these cities (in increasing order). Thus, it was obtained a wide range of efficiencies, ranging from 298 % (La Paz) to 424 % (Guayaquil). Besides, here is shown the annual energy consumption of the heat pump for families of 3 or 5 persons; we see that this energy consumption is lower as higher the COP is.

Table 1. Ambient temperatures and annual consumptions for using HPWH in different cities

| City | Ta annual (°C) | COP (50 °C) | 3 pax HPWH (kWh) | 5 pax HPWH (kWh) |
|---|---|---|---|---|
| La Paz | 10 | 2.98 | 769 | 1,221 |
| Bogota | 13.5 | 3.23 | 633 | 998 |
| Quito | 13.9 | 3.26 | 619 | 975 |
| Santiago | 14.6 | 3.32 | 594 | 934 |
| Mexico, ciudad de | 15.9 | 3.42 | 550 | 863 |
| Montevideo | 16.3 | 3.45 | 537 | 841 |
| Buenos Aires | 16.8 | 3.49 | 521 | 815 |
| Lima | 18.7 | 3.64 | 462 | 720 |
| San Jose de Costa Rica | 20.9 | 3.82 | 400 | 619 |
| Brasilia | 21.1 | 3.84 | 395 | 610 |
| Medellin | 21.6 | 3.89 | 381 | 588 |
| Asuncion | 22.7 | 3.98 | 353 | 542 |
| Rio de Janeiro | 23.3 | 4.02 | 340 | 522 |
| Santa Cruz de la Sierra | 23.9 | 4.08 | 323 | 494 |
| Guayaquil | 25.7 | 4.24 | 281 | 426 |

Source: Own elaboration, 2020

Table 2 presents the annual energy consumption of a conventional water heater (WSEH) for the 3-person family (column #1) and the 5-person family (column #2). Besides, taking into account the energy consumptions by using the heat pump (calculated in table 1), table 2 presents the energy saving that could be achieved by installing a heat pump water heater (HPWH), in columns #3 and #4, in increasing order. This new ranking is almost opposite to the one performed in Table 1, due to the energy consumption of the conventional heater increases noticeably in cold climates, since the grid water must be heated much more than in warm climates, and this effect cancels the lower performance of heat pumps in cold climates. Therefore, it is observed that the lower the ambient temperature is, the higher the energy-saving obtained is, for substituting the conventional heater with a modern heat pump.

Table 2. Annual energy consumption by using conventional WSEH and the saving achievable by the new HPWH

| City | 3 pax WSEH (kWh) | 5 pax WSEH (kWh) | 3 pax HPWH (kWh) | 5 pax HPWH (kWh) |
|---|---|---|---|---|
| Guayaquil | 1,193 | 1,804 | 912 | 1,379 |
| Santa Cruz de la Sierra | 1,319 | 2,014 | 996 | 1,521 |
| Rio de Janeiro | 1,368 | 2,097 | 1,028 | 1,575 |
| Asuncion | 1,405 | 2,157 | 1,052 | 1,615 |
| Medellin | 1,483 | 2,288 | 1,102 | 1,700 |
| Brasilia | 1,515 | 2,342 | 1,121 | 1,732 |
| San Jose de Costa Rica | 1,528 | 2,363 | 1,128 | 1,744 |
| Lima | 1,683 | 2,621 | 1,221 | 1,901 |
| Buenos Aires | 1,817 | 2,845 | 1,297 | 2,030 |
| Montevideo | 1,852 | 2,902 | 1,315 | 2,061 |
| Mexico, ciudad de | 1,881 | 2,950 | 1,331 | 2,088 |
| Santiago | 1,972 | 3,102 | 1,378 | 2,168 |
| Quito | 2,017 | 3,177 | 1,398 | 2,203 |
| Bogota | 2,045 | 3,224 | 1,412 | 2,226 |
| La Paz | 2,293 | 3,637 | 1,523 | 2,417 |

Source: Own elaboration, 2020

Finally, in Table 3 is presented another ranking, which is related to the payback period of the investment required for substituting a conventional heater by a heat pump heater (costing US$ 1,200), or for installing it in a new house (costing US$ 700 in this case, since the WSEH could cost another US$ 500). In this ranking, the electrical tariffs (OSINERGMIN, 2020) play a major role, and so, it is different from both previous ones. Here, note that a longer payback period is usually found for a lower electrical tariff, but not always, since the energy-saving also depends on the ambient temperature. From these results, we can conclude that although Guayaquil is the warmest city studied (and so, where the heat pump gets the best performance), the best economic performance is obtained in Montevideo. This result is due to the combination of three factors:

1) Having moderate ambient temperature, the COP obtained is moderate too (neither the best one nor the worst one);

2) According to its temperate climate, the energy consumption related to heating water is noticeably increased, and so, we can obtain a noticeable energy saving by substituting the conventional heater;

3) This electrical tariff is the highest one, and so, this noticeable energy saving can be transferred into an outstanding economic performance.

Table 3. Payback period obtained by installing the HPWH

| | | CHANGING THE HEATER | | INSTALLING NEW HEATER | |
|---|---|---|---|---|---|
| **City** | **Tariff (US$/MWh)** | **3 pax payback (years)** | **5 pax payback (years)** | **3 pax payback (years)** | **5 pax payback (years)** |
| Montevideo | 213 | 4.3 | 2.7 | 2.5 | 1.6 |
| Santiago | 156 | 5.6 | 3.5 | 3.3 | 2.1 |
| San Jose de Costa Rica | 180 | 5.9 | 3.8 | 3.4 | 2.2 |
| Lima | 153 | 6.4 | 4.1 | 3.8 | 2.4 |
| La Paz | 116 | 6.8 | 4.3 | 4.0 | 2.5 |
| Bogota | 113 | 7.5 | 4.8 | 4.4 | 2.8 |
| Quito | 98 | 8.7 | 5.5 | 5.1 | 3.2 |
| Medellin | 113 | 9.6 | 6.2 | 5.6 | 3.6 |
| Buenos Aires | 92 | 10.1 | 6.4 | 5.9 | 3.8 |
| Brasilia | 105 | 10.2 | 6.6 | 6.0 | 3.9 |
| Santa Cruz de la Sierra | 116 | 10.4 | 6.8 | 6.1 | 4.0 |
| Rio de Janeiro | 105 | 11.1 | 7.3 | 6.5 | 4.2 |
| Guayaquil | 98 | 13.4 | 8.9 | 7.8 | 5.2 |
| Mexico, ciudad de | 62 | 14.7 | 9.3 | 8.6 | 5.5 |
| Asuncion | 56 | 20.6 | 13.4 | 12.0 | 7.8 |

Source: Own elaboration, 2020; Tariffs were obtained from OSINERGMIN, 4th semester 2018

Let us note that the payback period is the simplest merit figure used on financial analysis to estimate the profitability of potential investments (the number of periods required to mortgage the investment is calculated through dividing the investment by the annual saving obtained by using the modern HPWH instead of the WSEH), instead of, for example, the internal return rate. However, the payback period is suitable for this case considering both, the simplicity involved in this analysis, and the fact that the national discount rate and the evolution of the relative prices of energies sources are quite different between Latin American countries studied.

## CONCLUSIONS

This work studied a modern high-efficiency system of water heating based on the thermodynamic cycle of the heat pump. These systems have been used for a decade in developed countries intended for household energy efficiency, although their cold climates are a major drawback, regarding that the heat pump performance is proportional to the ambient temperature. This way, for example, the efficiency achieved in Oslo (6 °C) is 270%, meanwhile in the warm Latin-American climates can be obtained efficiencies up to 424%. However, as we have demonstrated here, the potential of saving achievable (by substituting the old conventional heater for a modern heat pump heater) is larger as lower the ambient temperature is. This unexpected result is caused by the major effect related to the lower temperature of the water grid, which in turn causes a higher energy consumption in the conventional heater, and in turn, a larger saving by substituting it by the heat pump.

On the other hand, by performing an economic assessment about this substitution, we have concluded that the residential tariff of electricity also plays a major role, together with the previous ones. These tariffs vary considerably in Latin-American countries, ranging from 55.5 US$/MWh (Paraguay) to 213 US$/MWh (Uruguay). Thus, for a five-person average family, the short payback period for substituting the old appliance was found in Montevideo (2.7 years), due to their very high tariff and temperate climate. In opposition, the longest payback period was found in Asunción (13.4 years), due to their low tariff and although its warm climate.

The sum of all these factors previously analyzed is obtained by the numerical tool developed here, which has proven to be useful for evaluating different configurations and climatic conditions. For example, the payback period also depends on the level of the household demand (that varies with the number of persons, etc.), the temperature of the thermostat (that defines the efficiency achieved by the heat pump, together with the ambient temperature), and other minor variables, such as the volume of the water tank and the thermal insulation quality (that define the stand-by heat losses), which are considered on this model.

Regarding the economic performance, if it is considered as reasonable an investment that can be mortgaged in five years, the substitution of the conventional heater by the heat pump is affordable in six cities (Montevideo, Santiago, San José de Costa Rica, Lima, La Paz y Bogotá) among a total of fifteen cities studied, for a five-person family. However, we also can observe that this figure is reduced to only one city for a three-person family, according to the very low capacity factor of this equipment (running less than an hour per day). This poor performance could partially explain the neglectable penetration of this technology in Latin-American markets. However, we can also be optimist regarding the future, due to:

1) The competitiveness of the heat pump increases when it is considered its application on new houses, in which the investment required is lower (subtracting the cost of the conventional heater). Thus, a good performance is obtained for 12 or these 15 cities for a five-person family.

2) The local price of the HPWH is very high due to its negligible volume of the Latin American local markets (and tax for importation), but the international cost it just one third (US$ 400, FOB Hong Kong).

3) The competitiveness of the HPWH increases noticeably when it is intensively used. For a fully using case (24x7), we could obtain payback periods ranging from 2 to 11 months.

**Fast-growing of renewable low-scale technologies in Latin-America shows the region is now ready for achieving a similar behavior on the development of HPWH, which could enhance the penetration of solar technologies to many reluctant users and could provide a new solution within the portfolio of renewable energies.**

Upon these considerations, we could test now a proposal to Latin-American governments, promoting the fast penetration of this technology for supply sanitary hot water demands. This proposal consists of several executive orders:

1) To make tax-free all the household HPWH, which is based on using renewable energy (let us note that the heat pump uses the ambient heat that comes from the sun, and so, it can be considered as a "solar" technology). Hence, we are suggesting to take for HPWH the same considerations that often are given to solar technologies (photovoltaic panels and thermal collectors).

2) Driving the development of the local market by making several large purchase orders, used to fulfill the demand of governmental buildings (hospitals, etc.) that require a 24x7 demand.

3) Although it is true that one family household cannot represent this case, a large building with a centralized supply of sanitary hot water can certainly be one of these intensive applications.

4) The application of HPWH, although being almost unknown in this region, does not imply any technical challenger, since is similar to any split air conditioning device.

For these reasons, we believe that, regarding the fast-growing of renewable low-scale technologies recently observed here, the Latin-American region is now mature for achieving a similar behavior on the development of HPWH, which could certainly enhance the penetration of solar technologies to many users that maybe are reluctant to install some "estrange devices" over their roofs, or in other roofs where the direct solar irradiation is blocked for neighbor buildings. For all these cases, the HPWH could provide a new solution within the portfolio of renewable energies.

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