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TECHNICAL-ECONOMIC STUDY OF FLAT COLLECTORS AND EVACUATED TUBE COUPLED TO A HEAT PUMP FOR HEATING SYSTEMS

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Abstract. *This work presents the comparison between the flat solar collector and the evacuated tube combined with a heat pump for a heating system. The analysis performed is done through an algorithm in the MATLAB software that simulates the operation of the heating system in the city of Porto Alegre, where water must be supplied to a residential building. The consumption profile established for the simulation is 20 m³ per day. The model of the water heating system is the ASHP, which consists of two fixed volume reservoirs, an air-liquid heat pump, an auxiliary heater, and the collectors. The study of the thermal performance was formed based on the efficiency of collectors and the performance indicators. The economic analysis was done by calculating the LCS of each system, which was solved using method $P_1 - P_2$. From the system analysis, a set of differential equations was obtained, which were solved by the finite difference method. The simulation resulted in a set of graphs that show system indicators according to the area of collectors. The flat collector presented the highest financial return among the collectors and good performance for areas over 330 m². The evacuated tube reached a maximum LCS of around 190 m².*

Keywords: *evacuated tube collector, flat solar collector, ASHP, heat pump, heating system*

1. INTRODUCTION

Brazil is a country with great potential for harnessing solar energy due to its high levels of irradiation. Nevertheless, solar energy is responsible for only 1.6% of the Brazilian electrical matrix (ABSOLAR, 2020). This solar potential has also been used to heat fluids for the industrial and residential sectors.

The fluid heating systems that use solar energy, has gained more and more prominence in the market. The most common application of this system is heating water for domestic use. Bearing in mind that elements such as the electric shower present a share of 24% of the electricity consumption in the residential sector, it is of great importance to study systems that use solar energy to make them more efficient and economical (PROCEL, 2007).

The main component of water heating systems is the solar collectors. They are in charge of heating the fluid using energy from the sun. The flat solar collector is the most used type, as it has a lower cost when compared to other options. Another kind of solar collector is the evacuated tube, this equipment consists of two concentric tubes that are united by the ends where the space between them is evacuated. This collector has better thermal insulation and is more suitable for operating in cold environments.

Given its high cost, the use of the evacuated tube collector is restricted to applications where high temperatures are required. However, in recent years this type of collector has been gaining more space in the market becoming an attractive alternative. (Manea *et al.*, 2013).

The replacement of flat solar collectors with evacuated tube collectors has many benefits for water heating systems. Concerning application in colder locations, evacuated tube collectors perform better than flat collectors, which makes this type of collector suitable for operation in the coldest regions of Brazil. The superior heating capacity of the evacuated tube can reduce the need to use the auxiliary heater, generating a better economy. Another important benefit provided by this type of collector is the space savings since its heating capacity allows it to achieve satisfactory heating using a smaller collector area than the flat collectors (Budihardjo and Morrison, 2009). It is worth mentioning that one of the greatest difficulties in the application of water heating systems is the space available for the collectors, which can be very restricted.

The objective of this work is to analyze the technical and economic performance of flat-type solar collectors and evacuated tubes applied to a residential heating system. The analysis is performed based on graphs generated by an algorithm in the MATLAB software. This algorithm simulates a residential heating system based on a model of heating systems.

2. METHODOLOGY

To analyze the performance of solar collectors an algorithm was developed that performs a simulation of the functioning of a residential heating system. The methodology adopted for this work is based on transient numerical simulations performed with the MATLAB software. The differential equations generated by the energy balance of the system were solved using the finite difference method.

The set of meteorological data used in the simulation originates from the LabEEE (Laboratório de Eficiência Energética em Edificações) base. The selected data correspond to the city of Porto Alegre (Rio Grande do Sul) and data such as day, month, hour, dry and wet bulb temperature, and the different forms of irradiation are included in the table. This data is used to calculate the total irradiation incident on the collectors. The weather data comes in TMY (Typical Meteorological Year) format.

The model of the water heating system selected for the simulation is ASHP (Air-source heat pump). This system consists of two thermal reservoirs, an air-liquid heat pump, an auxiliary heater, and solar collectors. The system layout can be viewed on the Fig. 1.

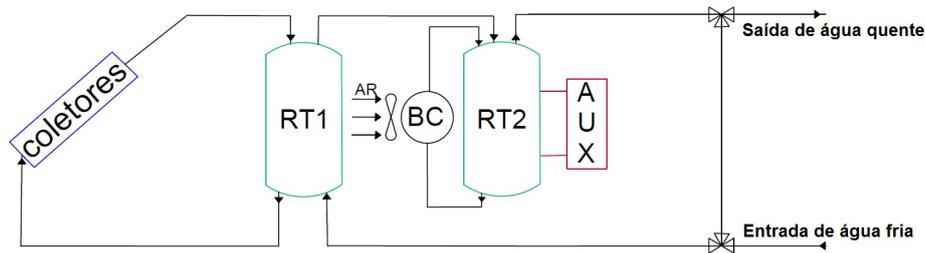


Figure 1. Simplified schema of ASHP system. Adapted from Gonçalves (2016)

In the reservoir, isothermal nodes were established to simulate stratification using five nodes. The reservoir has an auxiliary gas-based heater and an air-liquid heat pump that also functions as a heater. In the ASHP system, Reservoir 1 is connected to collectors only, while Reservoir 2 is connected to heaters and is responsible for sending hot water to homes. The volume of the two reservoirs is fixed and does not vary with the increase in the area of collectors.

The air-liquid heat pump takes heat removed from the environment to the water inside the reservoir. The heating capacity was calculated based on the COP (performance coefficient) of the pump and the data provided by the manufacturer. The heat pump model is the Aquasnap by CARRIER, which has a COP of 3.16 and a nominal heating capacity of 42000 W.

Two types of solar collectors were selected for the study: flat plate and evacuated tube. These collectors were selected because they are the most requested models on the market, the first being the most economically advantageous.

The flat solar collector is a simple model that consists of a set of absorber tubes that are thermally protected by a matte plate. This model for being simple to build ends up being cheaper. It is also the most used in residential heating systems, however, depending on the water demand it can take up a lot of space.

The evacuated tube solar collector is a more complex model that consists of two concentric tubes, usually made of glass, in which the space between them is evacuated. This kind of collector minimizes the heat exchange through conduction and convection, to reduce thermal losses. The disadvantage of using this model for heating residential water is in its price. However, the participation of countries like China in the production of this type of collector has been heating the market, causing the price to have a reasonable fall.

To make the simulation more realistic, it was defined that the water heating system will be installed in a residential building. A consumption profile was established based on the profile presented by Salazar (2004), which indicates the consumption of 150 liters per day. The water consumption profile has been increased to 20000 liters, as the objective is to supply a residential building (Gonçalves, 2016). The system also has a water recirculation system that works during periods of low consumption.

3. MATHEMATICAL MODEL AND SIMULATION PARAMETERS

3.1 Solar collectors

To calculate the useful heat provided by the collectors, the mathematical model described by Duffie and Beckman (2006) in Eq. (1) was selected. According to the authors, this model can be applied to flat solar collectors and evacuated tubes.

$$\dot{Q}_u = \dot{m}_c c_p (T_{c,o} - T_{c,i}) \quad (1)$$

The c_p is the specific heat at a constant pressure of water, the \dot{m}_c represents the mass flow inside the tubes, $T_{c,o}$ and

$T_{c,i}$ are the outlet temperature and the inlet temperature of the water, respectively. The Eq. (2) represents the instantaneous efficiency of the system, that is, it represents the collector's ability to absorb the incident radiation. The component $(\tau\alpha)_n$ is the transmittance-absorbance product of the collector, F_R is the heat removal factor from the fluid and U'_L is the global heat loss coefficient. The Eq. (2) can also be written in the form of Eq. (3), where $a_0 = F_R(\tau\alpha)_n$ and $a_1 = F_R U'_L$ are data provided by the manufacturer.

$$\eta_c = F_R(\tau\alpha)_n - F_R U'_L \left(\frac{T_{c,i} - T_{amb}}{G_T} \right) \quad (2)$$

$$\eta_c = a_0 - a_1 \frac{\Delta T}{G_T} \quad (3)$$

To make the collector's operation closer to reality, it is necessary to use three corrective factors. The first of these factors is the incidence angle modifier (IAM), which establishes a relationship of dependency between the transmittance-absorbance product, $(\tau\alpha)$, and the irradiation angle that affects the collector, θ . This relationship varies according to the kind of collector. According to Duffie and Beckman (2006), the incidence angle modifier of the flat collector and the evacuated tube is expressed by Eq. (4) and Eq. (5), respectively.

$$K_{\tau\alpha} = 1 - b_0 \left(\frac{1}{\cos\theta} - 1 \right) - b_1 \left(\frac{1}{\cos\theta} - 1 \right)^2 \quad (4)$$

$$K_{\tau\alpha} = (K_{\tau\alpha})_t (K_{\tau\alpha})_l \quad (5)$$

The b_0 and b_1 are the first and second order coefficients of the collector, $(K_{\tau\alpha})_t$ and $(K_{\tau\alpha})_l$ they are, respectively, transverse and longitudinal IAM. These terms, with the exception of θ , are data provided by the collector's performance test (Tüv, 2009). The IAM values are shown in Tab. 1.

Table 1. Longitudinal and transverse incidence angle modifier for an evacuated tube collector.

Angle of incidence (°)	0	10	20	30	40	50	60	70	80	90
$(K_{\tau\alpha})_l$	1.00	1.00	0.99	0.98	0.95	0.91	0.84	0.69	0.00	0.00
$(K_{\tau\alpha})_t$	1.00	1.00	1.06	1.23	1.24	1.37	1.53	1.02	0.00	0.00

The data used in the simulation of the evacuated collector were taken from an analysis of the behavior of the collector produced by Tüv (2009). The selected flat solar collector was the JFS10 model manufactured by TOSI Ltda. Collector parameters are shown in Tab. 2.

Table 2. Collectors simulation parameters.

Flat Solar Collector		
Parameter	Value	Unity
Test flow	70.00	kg/(m ² .h)
Linear coefficient of the efficiency curve – a_0	0.77	-
Angular coefficient of the efficiency curve – a_1	4.27	W/(m ² .K)
First order coefficient – b_0	0.1065	-
Second order coefficient – b_1	0.00	-
Evacuated Tube Collector		
Parameter	Value	Unity
Test flow	72.00	kg/(m ² .h)
Linear coefficient of the efficiency curve – a_0	0.765	-
Angular coefficient of the efficiency curve – a_1	1.66	W/(m ² .K)

3.2 Energy efficiency indicators

Performance indicators are used to analyze the system's execution. The Free Energy Fraction (FEF) establishes the energy demand that is obtained from the environment through the air through the heat pump and the solar radiation captured by the collectors. This indicator is represented by Eq. (6):

$$FEF = \frac{\int (\dot{Q}_{solar} + \dot{Q}_{evap}) dt}{\int \dot{Q}_{DHW} dt} \quad (6)$$

Where \dot{Q}_{solar} is the radiation absorbed by the collectors, \dot{Q}_{evap} is the heat removed from the environment by the air-liquid heat pump and \dot{Q}_{DHW} is the total system power. Another performance factor is the demand fraction of the auxiliary heater, which represents the fraction of energy that is delivered by the auxiliary heater. This factor is expressed by Eq. (7), where \dot{Q}_{cond} is the rate of heat exchanged in the condenser.

$$F_{d,HeatPump} = \frac{\int \dot{Q}_{cond} dt}{\int \dot{Q}_{DHW} dt} \quad (7)$$

Finally, we have the demand factor for the heat pump Eq. (8). This equation expresses the division between the energy delivered by the heat pump condenser and the total energy of the system.

$$F_{d,HeaterAux} = \frac{\int P_{aux} dt}{\int \dot{Q}_{DHW} dt} \quad (8)$$

3.3 Economic analysis

The objective of the economic analysis is to relate the initial investment to the cost of operation to determine which area of collectors provides the greatest financial return. This study is important due to the high financial investment that is made in the addition of a water heating system that uses solar energy. Thus, the analysis carried out allows us to know which type of collector will give the greatest financial return and which collector area is suitable for investing.

In the analysis the method used is Life Cycle Savings (LCS), it establishes the difference in costs generated between a system that uses traditional energy and the system that uses solar energy (Fernandes, 2018). This method also considers the costs generated by each type of system throughout its life cycle. To calculate the LCS, the P_1 - P_2 method is used, which considers the present value of all associated costs, thus calculating the PWF (Duffie and Beckman, 2006).

For systems that have heat pumps the LCS can be calculated by Eq. (9). This equation is composed of the following terms: the consumption fraction of the auxiliary heater, $F_{c,aux}$, the consumption fraction of the heat pump, $F_{c,hp}$, collectors area, A_c , and the sum of other costs that are not proportional to the area of the collectors, C_E . The terms $P_{1,1}$ and $P_{1,2}$ correspond to P_1 which is the ratio between economies, whereas P_2 represents the ratio between expenditures.

$$LCS = ((1 - F_{c,aux}) C_{F,aux} P_{1,1} - F_{c,hp} C_{F,ele} P_{1,2}) L - P_2 ((1 + C_{inst,A}) C_A A_c + (1 + C_{inst,hp}) C_{hp} + C_E) \quad (9)$$

The other components are defined in the Tab. (3), which presents some selected values for the LCS calculation. It is worth noting that electricity and natural gas costs are based on the values of companies located in Porto Alegre - RS. The market's annual discount rate is 4.5, corresponding to the rate at the beginning of the year 2020 (Banco Central do Brasil).

Table 3. Economic parameters.

Symbol	Parameter	Value	Unity
C_A	Cost of flat solar collectors per square meter	300.00	RS/(m ²)
C_A	Cost of evacuated tube solar collectors per square meter	1050.00	RS/(m ²)
$C_{inst,A}$	Installation cost/Flat solar collector cost	0.1	-
$C_{inst,A}$	Installation cost/Evacuated tube solar collector cost	0.1	-
C_{hp}	Heat pump cost	2871FR+3323	R\$
$C_{inst,hp}$	Installation cost/Heat pump cost	0.1	-
C_{RT}	Reservoir cost	3500V _S +4052	R\$
C_{aux}	Auxiliary heater cost	1900.00	R\$
$C_{F,aux}$	PCS = 9400kW.h/m ³ 3.6492R\$/m ³ price	0.334	R\$/(kW.h)
$C_{F,ele}$	Conventional residential class fare (above 220 kWh)	0.5476	R\$/(kW.h)
	ICMS (above 50 kWh)	0.3	%

4. RESULTS AND DISCUSSION

The first factor to be analyzed is the average efficiency of the collectors as a function of the collector area, expressed in Fig. 2. The graph shows two curves that decrease with the increasing area, this phenomenon occurs due to the increase in the heating capacity of the system. A greater number of collectors implies higher temperatures inside the reservoir, which ends up generating a decrease in the average efficiency of the collectors.

The evacuated tube collector is more efficient than the flat solar collector in the interval of 50-440 m². In the interval 50-150 m² the curve of the evacuated tube decreases slowly, this interval must represent the phase in which the temperature inside the Reservoir 1 is not yet high enough to affect the performance of the collector, that is, the energy absorbed

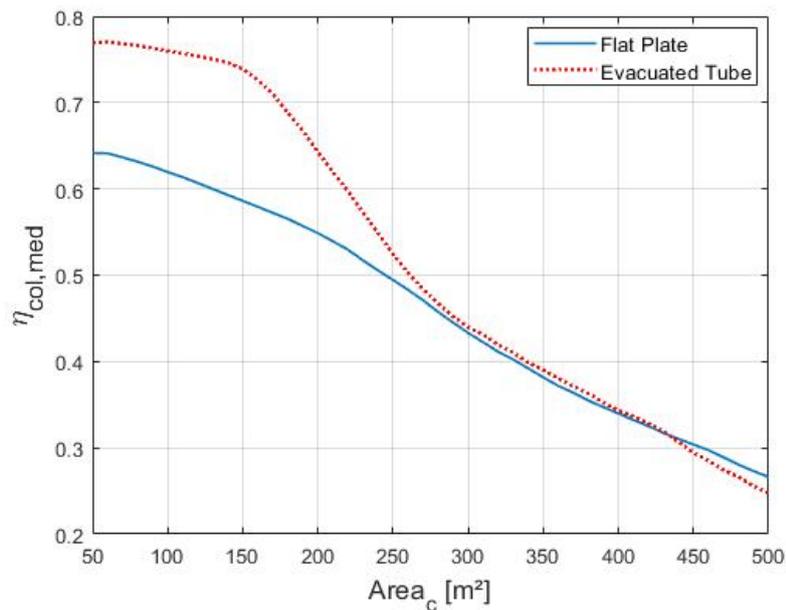


Figure 2. Comparison of systems in terms of average collector efficiency as a function of area collectors

by the collector is almost totally used. However, after 150 m^2 the curve decreases more quickly, which can be explained by the greater heating capacity of the collector, generating more energy accumulated in the reservoir. At that point, the temperature of the water entering RT1 is not low enough to maintain good functioning for the collector.

From 440 m^2 onwards, the flat solar collector has superior efficiency, because as its heating capacity is lower, even generating high temperatures at RT1, this temperature does not affect the flat collector as the evacuated tube, so that it still operates reasonably well.

The second factor to be analyzed is the FEF, it represents the ability to generate energy savings for the system. Based on Fig. 3, it is possible to analyze how the behavior of the FEF in relation to the area is affected by the type of collector.

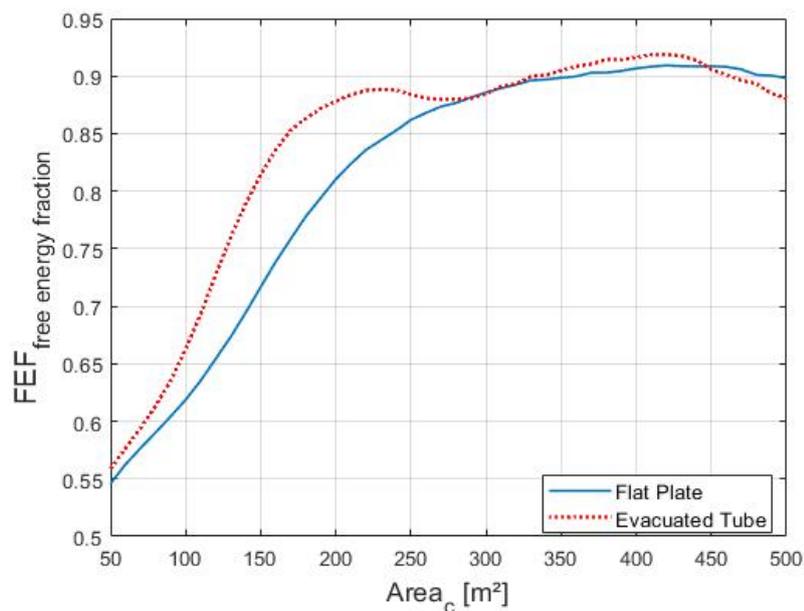


Figure 3. Comparison of systems in terms of FEF as a function of area collectors

The system that has the evacuated tube collector has higher FEF values in the range of $50\text{-}230\text{ m}^2$. This behavior was already expected due to the superior heating capacity of the evacuated tube, however, for areas above 230 m^2 , there is a decline in the curve. This means that the energy of the system is used only in a specific interval of the area and for higher values, the performance of the system is negatively affected.

The curve of the flat solar collector has a more uniform behavior than that of the evacuated tube collector. Such behavior can be explained by the relationship between the heating capacity and the level of stratification inside the reservoir. For a lower heating capacity, the reservoir can achieve satisfactory stratification levels, so as not to hinder the operation of the collector. On the other hand, a reservoir of the same volume tends to present less stratification and higher temperatures for greater heating capacity.

The next factor to be analyzed represents the demand for auxiliary heating of the system. The ASHP system has two types of auxiliary heaters: the gas system and the air-liquid heat pump. This factor is represented by two graphs presented in Fig. 4.

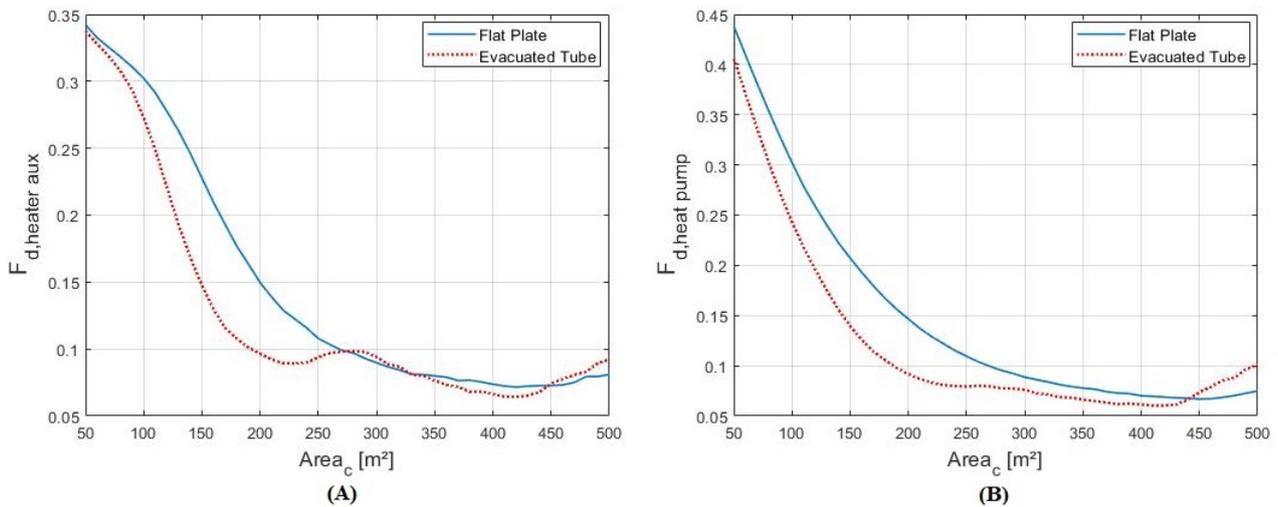


Figure 4. Comparison of systems in terms of: (A) fraction of auxiliary heater demand as a function of area collectors, (B) fraction of heat pump demand as a function of the area of collectors

Both in demand for auxiliary heater and demand for heat pump, the evacuated tube collector has a greater advantage in the interval of 50-440 m². From 440 m² onwards, the system with the flat solar collector will have the advantage.

In both curves, the increase in the collector area reduces the need for the auxiliary heater. For the heat pump, the high temperature inside the reservoir can cause damage in the operation of the system, as the temperature may be outside the operating range of the pump.

Finally, the performance factor that analyzes the savings generated by the system is the LCS (Life Cycle Savings), which is based on method $P_1 - P_2$. The Fig. 5 shows the economy of the life cycle of the system depending on the area of collectors.

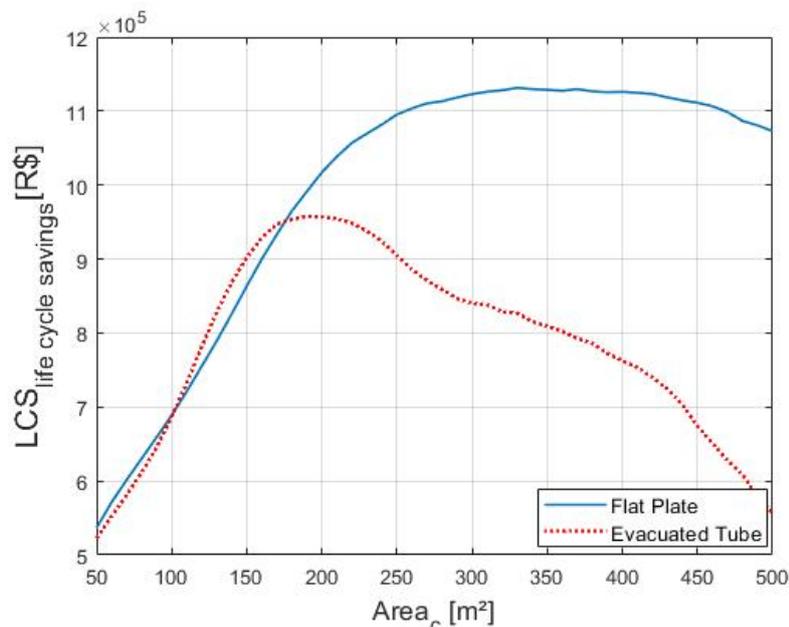


Figure 5. Comparison of systems in terms of LCS as a function of area collectors

Initially in the range of 50-90 m^2 , both curves are very close, being the curve of the flat solar collector is upper. For the flat collector, the greatest cost-benefit is in the range of around 330 m^2 , and for larger areas, the net gain is still advantageous.

In the 90-160 m^2 interval, the evacuated tube curve has the greatest advantage, reaching its greatest financial return in an area close to 190 m^2 . For larger areas, the financial return is no longer advantageous, since the LCS of the evacuated tube system decreases.

5. CONCLUSION

Brazil, despite being a tropical country, still spends a good portion of its energy on heating water. The electric shower is one of the appliances that weigh most on the energy bill, however, with the advancement of technology, this equipment has become replaceable. A more viable option for heating water, from an economic and environmental point of view, is the use of solar energy. Solar water heating systems require a large initial investment and have a good long-term financial return. The principal component of this type of system is the solar collector, which has several types, the main ones being the flat solar collector and the evacuated tube collector.

The study and analysis of evacuated tube solar collectors are often realized, but the price of this equipment is a disadvantage that weighs heavily on your selection. For this reason, the flat solar collector is seen as a more viable option because it has a lower cost and performs the same function, but with less efficiency. However, research shows that both types are good options, but the selection depends on the environment and application to which the collector will be exposed (Rosa *et al.*, 2013).

In this analysis, the flat solar collector and the evacuated tube collector were used to heating water for a residential building in a model of a water heating system called ASHP. The consumption profile established based on the literature is 20 m^3 per day. The region used in this analysis is the city of Porto Alegre in the Rio Grande do Sul, a state that has one of the highest rates of use of the electric shower.

The results presented show that both collectors have a good thermal performance at different intervals in the area of collectors, and the thermal analysis is performed based on the efficiency of the collectors and the efficiency indicators. From an economic point of view, both types also bring net gains at different intervals, with the highest LCS belonging to the flat solar collector.

The evacuated tube solar collector has the best performance in the 50-300 m^2 range. This collector showed good efficiency for smaller areas, the efficiency being much higher than that of the flat collector. This result was already expected since the evacuated tube has better thermal insulation, so the heat losses for the environment are minimal. For areas over 300 m^2 , this collector becomes unviable, as its heating capacity cannot be used. From an economic point of view, the evacuated tube solar collector has advantages in the range of 50-200 m^2 , with a maximum LCS of around 190 m^2 . In some points of this range, the LCS of the flat collector was higher, but the excellent performance of the evacuated tube makes it still the best option. Based on the results, the evacuated tube collector proved to be more suitable for situations in which the area available to the collectors is restricted.

The flat solar collector performed well throughout the range, but its function proved to be superior to the evacuated tube in areas larger than 300 m^2 . In economic terms, this collector gained prominence, as it proved to be superior in almost the entire range, in addition to having the largest LCS between the two types. The maximum financial return of this system is in the area of 330 m^2 . Thus, this collector proved to be the best alternative for situations in which the available area is reasonably large. If the goal in choosing the type of collector is to have the highest possible financial return, the flat collector is also the best option.

For future work it is recommended to study solar collectors made of polymeric material. Collectors of this type have a lower cost, despite having higher thermal losses than the flat solar collector, making it a good competitor in the market.

Finally, it is important to highlight some factors that can distort the study. The economic data may vary according to the time and place of application, and cannot be taken as absolute. The technical data of the collectors may also vary from manufacturer to manufacturer. The consumption profile used was based on a different location, which may differ from the reality of the studied location.

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