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# Financial Analysis of Low-Temperature Solar Thermal Energy Storage Systems to Supply Hot Water and Heating for Rural Colombian Households

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In order to mitigate the effects of climate change, contribute to energy autarky and improve the quality of life of the population, Colombia has adopted the energy transition to renewable energy as a state policy. In this context, the use of solar thermal energy, which is abundant in the tropical zone, should be considered as one of the alternatives to be prioritised. A solar thermal energy storage system (STESS) has been developed for the supply of hot water and heating in paramo areas. The system is capable of storing energy in the form of latent heat using a renewable phase change material (PCM). The PCM reaches a maximum temperature of 70° C, allowing enough energy to be stored to take several hot showers and maintain a comfortable temperature in a room. This paper evaluates the performance of the developed STESS from a financial point of view, analysing the associated capital and operational costs. It is also compared with alternative technologies available in the area based on electric heaters and propane gas heaters. The operating cost analysis concludes that the performance of the STESS allows savings of variable operation cost up to 90 % compared to electric energy-based systems. These results become even more relevant considering that many of these areas are not connected to the national electricity grid and almost none of them have a reliable supply of propane gas. Regarding capital costs, although STESS requires an initial investment up to 20 times the value of alternative systems, its long lifetime, low operating costs and reliability make it an attractive alternative in this scenario.

## 1. Introduction

Many population centres in the South American Andean region are in high mountainous areas and have low temperatures throughout the year despite the high availability of solar radiation. In the case of Colombia, the high concentration of moorlands and the high number of population centres located in them stand out (Morales et al., 2007). In addition to the need to meet the heat demands of the inhabitants of these areas, there has been a growing interest in sustainable tourism in these sites (Pérez Forero, 2019). This is why the development, evaluation, and financial analysis of solar thermal energy storage systems for hot water supply and heating is of interest. While it is known that district heating can achieve higher efficiency (Burzynski et al., 2012), it is necessary to evaluate smaller capacity systems as it is a technology that is barely applied in the country, especially in configurations that allow heat storage. Solar thermal energy storage systems, which employ phase change materials, and supply heat even during nighttime hours (Hyman, 2011) can be an attractive alternative for inhabitants of high mountain regions, as well as for tourism developments, especially those with a focus on sustainability. The analysis of this type of systems implies different aspects besides the financial one, such as: emission reduction, energy, and exergy analysis. These aspects, although relevant during the development of the technology, are of greater interest once the technology is established in the market (Fraisse et al., 2009). An example of this is the financial and energy analysis of a solar system for indoor heating, which allows a reduction of up to 67 % in electricity consumption. The analysis of different configurations, including collector area and amount of PCM employed, is also reported in this paper (Plytaria et al., 2019). As variants of this

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technology, some papers report the combined use of solar thermal energy and biomass burning for hot water supply. Some of these systems allow a greater use of renewable resources, although the complexity of design and operation is considerably increased(Krarouch et al., 2020). This paper evaluates the financial feasibility of a solar thermal energy storage system to supply heating and hot water for two rooms and two showers in a house located in the Páramo de Santurbán, Colombia.

## 2. Description of case study location

The analysis presented in this paper is geographically located in a house in the Páramo de Santurbán, Santander, Colombia. The site at the coordinates (7° 8' 52.9224", -72° 54' 36.9036") has an altitude of 3,200 m.a.s.l. Its elevated location and the fact that it is in a tropical zone result in high solar radiation all year round, reaching temperatures of up to 21 °C in the hottest months, while at night temperatures as low as - 10 °C can be recorded. Figure 1 shows the average hourly profiles of direct normal irradiation at study site. Data in Figure 1 was obtained from the Global Solar Atlas 2.0, a free, web-based application is developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP) (Solargis, 2023).

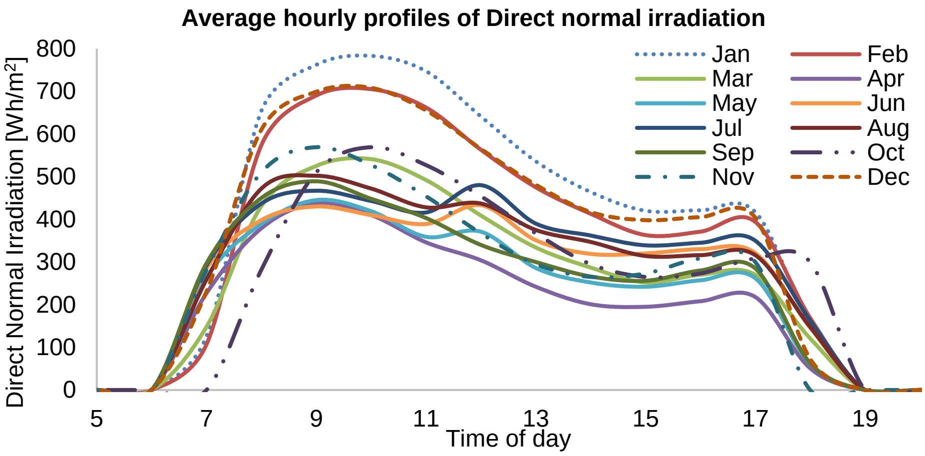


*Figure 1: Average* hourly *profiles of Direct normal irradiation. Source: Global Solar Atlas 2.0*

For all months, a minimum of 11 h of sunshine is reported, with January having the highest average daily radiation with a value of 6.1 kWh/m$^2$, while April is the month with the lowest radiation, with a value of 3.2 kWh/m$^2$. Due to its elevated location and high availability of solar radiation, the average daily maximum temperature is around 12 °C, while the minimum temperature is around 4 °C. However, some temperature measurements made by the authors indicated that in the hottest months temperatures of up to 21 °C can be reached, while during frost periods minimum temperatures of down to - 9 °C were measured. These conditions mean that the local population needs hot water at different times of the day and heating at night when staying overnight. The selected house currently meets these needs with a 1,500 W electric heater per room, which is used to provide comfort at night. For domestic hot water supply, a gas heater is used for each bathroom in the house, with an average consumption of 0.4 m$^3$/h each.

## 3. STESS sizing and design

The sizing of the solar thermal energy storage system was carried out based on 3 main aspects: Amount of energy to be delivered with the heating system, amount of energy to be stored in the phase change material and amount of solar energy to be captured in the collectors. In addition, the technical specifications and some design parameters are based on a pilot research STESS that was built and is installed at the case study site. In order to obtain a version of STESS closer to a commercial product, only the sensors involved in the control system are considered and not those used for scientific data generation. Also, the use of a stainless-steel tank for the storage of the PCM is replaced by the use of a brick reservoir, which is more economical in the Colombian market.

### 3.1 Amount of energy to be delivered with the heating system

It was taken as a calculation basis that the STESS should be able to deliver 2 times the amount of energy delivered by the electric heater currently used. The power of the heater currently used is 1,500 W. Considering the use of a linear finned tube type convector with a pipe diameter of 3/4", through which water circulates at 50 °C with a flow rate of 3.79 L/min, its energy transfer rate will be approximately 206.73 W/m. To reach a power of 3,000 W or 3 kJ $s^{-1}$ requires the installation of 14.5 m of linear convector in each room. Steady-state operation is assumed, so an average water temperature through the convector and the minimum possible water flow were selected.

### 3.2 Amount of energy to be stored and delivered by the PCM

Hydrogenated palm stearin has the following thermal properties: Melting temperature range between $T_{i,fus}$ = 46.52 °C and $T_{f,\ fus}$ = 67.95 °C, $H_f$ = 226.36 J $g^{-1}$, crystallization temperature range between $T_{i,cris}$ = 45.59 °C and $T_{f,cris}$ = 37.19 °C, $H_c$ = 188,15 J $g^{-1}$, $Cp_s$ = 6.4 J $g^{-1}$ $°C^{-1}$, $Cp_l$ = 8.6 J $g^{-1}$ $°C^{-1}$. Under normal operating conditions, the STESS will raise the temperature of the PCM daily from 30 °C to 70 °C, to cool down at night from 70 °C to 37.19 °C. The amount of energy stored and released can be calculated by considering the sensitive heat of solid, sensible heat of liquid, and the latent heat of fusion (Lizcano-González et al., 2023). Considering the use of 700 kg of hydrogenated palm stearin as a phase change material, approximately 289.6 MJ of energy, equivalent to 80.5 kWh, would be stored during its heating from 30 °C to 70 °C. During the cooling process, the PCM releases 278.5 MJ of energy equivalent to 77.4 kWh. This value is significantly higher than the energy required for the operation of the electric heaters which delivers 30 kWh during 10 h of operation, however, due to heat transfer limitations and energy losses, this oversizing is necessary.

### 3.3 Requirements for solar thermal collectors

The use of evacuated tube solar thermal collectors was selected, which allow temperatures above the required 70 °C to be reached, with an efficiency of 93 % in energy capture. Every evacuated pipe has dimensions of 0.058 m x 1.8 m. The cross-section area is 0.1044 $m^2$. Considering a direct solar radiation of 4 kWh/$m^2$ (14.4 MJ/$m^2$), which is close to the annual daily average, each tube would capture 1.4 MJ of energy per day. To deliver the 289.6 MJ required during the PCM fusion process, a total of 211 tubes are required.

*Table 1**:** Generic project costs for Solar Thermal Energy Storage System.*

| Item | Description | Price (USD) |
|---|---|---|
| **Infrastructure** | | |
| Underground reservoir | Brick storage tank for PCM. | 1,429 |
| **National Equipment** | | |
| Big coil | 5/8” copper pipe with a total length of 100 m | 1,190 |
| Small coil | 5/8” copper pipe with a total length of 60 m | 762 |
| Thermal insulation | Expanded polystyrene layer and sealant to prevent leaks. | 119 |
| PCM | 700 kg of phase change material | 3,333 |
| CPVC Pipping | 150 m of 1/2 inch CPVC pipe | 136 |
| CPVC Accessories | Includes elbows, universal joints, pipe unions, T-connections, etc. | 83 |
| Check valves | 5 gate type non-return valves with 3/4" thread. | 50 |
| Finned pipe | 29 metres of finned pipe with 3/4" pipe diameter. | 101 |
| **Imported Equipment** | | |
| UPS | Short-term battery power supply - 1000 W. | 71 |
| Box for electrical connections | IP65 Plastic Enclosure with UV Protection 544x454x186 mm | 119 |
| PT100 module | Converter board MAX31865 PT100 | 43 |
| PT100 sensor | Temperature sensors type PT-100 3-wire. | 86 |
| Arduino Mega 2560 | Microcontroller board. | 48 |
| Digital relay | 1 channel 12v relay module with optocoupler isolation | 24 |
| Pump contactor | Contactor 1810 18 Amp Coil 110v or 220v | 10 |
| Wire | 3-wire low resistance wiring. Wiring for connection of electronics. | 71 |
| Solar collectors | 11 solar collectors with 20 vacuum tubes of dimensions 1.8x0.15 m | 11,786 |
| Hot water pump | Hot water recirculation pump. | 83 |
| Solenoid valves | 3/4" Inch 110V AC Stainless Steel Solenoid Valves | 190 |
| **Engineering** | | |
| Labour and installation | Transport and installation costs at the final site. | 1,071 |
| | **Total** | **22,711** |

### 3.4 STESS specifications

Table 1 presents in detail the components of the solar thermal energy storage system and gives an estimated cost for each item, based on commercial quotations.
It should be noted that 66.5 % of the investment costs correspond to only two items, the solar collectors, and the phase change material. Any effort to reduce the costs of these two components will be a major step forward for the implementation of the technology. It is noted that the cost value for this system is lower than others reported in literature, where for a system with sensible heat storage its construction cost in 2016 was estimated at EUR 28,334 (Colclough and Griffiths, 2016).

## 4. Financial analysis

The financial analysis of the technology took into account various economic factors. **The inflation rate** is an essential economic indicator representing the average percentage change in the price level of goods and services within a year compared to the previous year. In the cost analysis, both energy inflation (electricity and fossil fuels) and the conventional measurement of goods and services were considered. However, projecting future inflation rates in open economies is challenging due to the dynamic nature of geopolitical, economic, social, and environmental conditions, which can impact the accuracy of any analysis. For instance, events like the COVID-19 pandemic or the Russia-Ukraine war can significantly influence projections. Nevertheless, for the case study, a constant general inflation rate of 7 % per year was established, incorporating projections and averages from the past 30 y.
Regarding **Energy Tariffs**, Colombia, like many other developing countries, heavily relies on fossil fuels for its economy. While the country has made progress in diversifying its energy mix with over half coming from renewable sources such as hydroelectric power, energy reliability remains at risk due to factors like "El Niño" and "La Niña." According to the National Department of Statistics (DANE), the inflation rate for electricity in Colombia was 22.4 % in the past year. In the analysis, an optimistic approach was taken by setting an annual growth rate of 9 % for energy prices throughout the study, which was also applied to determine the growth of gas prices, specifically for water heaters.
A conservative approach was adopted by setting the price of kWh at 0.08 USD. This rate represents the average tariff used in the poorest regions of Colombia, including rural areas. For natural gas, a price of USD 0.81/$m^3$, was considered.
**The Discount Rate** is a crucial figure used in cost analysis to equate future values to their present equivalents. It determines the present dollar value equivalent of a future dollar value. Typically, the discount rate reflects the long-term cost (or value) of money or the alternative investment rate. In this analysis, an annual rate of 9 % was adopted, as stipulated by *El Departamento Nacional de Planeación* (DNP) through resolution 1090/22.
Regarding the **Representative Market Rate – TRM**, it is the exchange rate between the Colombian peso (COP) and the United States dollar (USD). The TRM represents the amount of Colombian pesos required to purchase one US dollar. It is calculated daily by the Colombian Financial Superintendence, based on trading activities of financial intermediaries in the Colombian exchange market, using transactions from the preceding business day. This rate serves as a reference for currency conversion in various financial transactions. For this analysis, a constant TRM of COP 4,200 per 1 USD was established, considering the appreciation of the Colombian currency against the US dollar observed over the past year, and it will remain consistent throughout the analysis period.

### 4.1 Investment costs of solar thermal energy storage system STESS and current technologies

As shown in section 3.4, STESS investment costs amount to USD 22,711. In contrast, the commercial value of a gas water heater capable of meeting the domestic hot water needs of the two showers plus installation costs is USD 310. Likewise, two electric heaters with an output of 1,500 W are sold for USD 429. In total, the investment costs of the technology currently used in the study site is USD 738; approximately 3.3 % of the investment cost of the STESS.

### 4.2 Variable operating and maintenance cost

Electricity and gas consumption was estimated for STESS and conventional technologies. Regarding STESS, the two main contributions to energy consumption are due to the operation of the pump and the electronic components. The pump operates for approximately 17 h/day and has a power of 0.12 kW, for a consumption of 760.6 kWh/y. The electronic components operate 24 h a day, with a power of 30 W, for an annual consumption of 216 kWh. Considering the price per kWh of COP 340, the annual electricity expenditure at STESS is USD 79.
Compared to conventional technologies, each electric heater has an output of 1,500 W and operates for approximately 10 h/day. This gives an energy consumption of 1,800 kWh/y. On the other hand, the gas water

heater has a consumption of 0.83 $m^3$/h of gas. Considering use of 1 h/day, this gives a consumption of 172 $m^3$/y of gas. Considering the costs per kWh and per $m^3$ of propane gas, the variable operating costs of conventional technologies amount to USD 1,014.

### 4.3 Fixed operation and maintenance cost

The lifetime of electric heaters and gas water heater is estimated at 10 y. In addition, these require annual maintenance, which by 2023 costs USD 74 and this value is expected to increase in line with the value of inflation. On the other hand, the lifetime of the STESS is estimated at 30 y, although the water pump will need to be changed every 5 y and the phase change material every 15 y. Additionally, maintenance costs in 2023 are estimated at USD 227 and are projected to increase in line with inflation. Considering the above, annual cost discrimination is projected for both STESS and conventional technologies, as shown in Table 2.

*Table 2: Annual costs of STESS and conventional technologies.*

| | Annual costs STESS | | | | | Annual costs of conventional technologies | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Maintenance costs | Parts and materials | Cost of electricity | Total annual cost | Net present value | Maintenance costs | Parts and materials | Cost of propane | Cost of electricity | Total annual cost | Net present value |
| 1 | 227 | 0 | 79 | 306 | 281 | 74 | 0 | 140.0 | 874 | 1,088 | 998 |
| 5 | 298 | 0 | 112 | 409 | 266 | 97.0 | 0 | 197.7 | 1,234 | 1,529 | 994 |
| 10 | 418 | 0 | 172 | 589 | 249 | 136.0 | 0 | 304.1 | 1,899 | 2,339 | 988 |
| 15 | 586 | 3,300 | 264 | 4,150 | 1,139 | 190.8 | 0 | 467.9 | 2,922 | 3,580 | 983 |
| 20 | 821 | 0 | 406 | 1,228 | 219 | 267.6 | 0 | 720.0 | 4,495 | 5,483 | 978 |
| 25 | 1,152 | 0 | 625 | 1,777 | 206 | 375.4 | 0 | 1,107.8 | 6,917 | 8,400 | 974 |
| 30 | 1,616 | 0 | 962 | 2,578 | 194 | 526.5 | 0 | 1,704.4 | 10,642 | 12,873 | 970 |
| | | | | **Total** | **8,043** | | | | | **Total** | **29,901** |

Considering the investment costs and the annual fixed and variable costs for the two technologies, the net present value of the investment in a solar thermal energy storage system is USD 30,750, considering the 30 y lifetime of the system. For the same period, conventional electric heating and propane water heating technologies have a net present value of the investment of USD 30,639. These almost equal values demonstrate that solar thermal energy storage systems are not only technically but also economically viable in the long term. A major constraint is the high initial investment cost, so this aspect should be prioritised in the future, hand in hand with local industries. As can be seen in Figure 2, although the two technologies start with very different investment values, as their costs are projected into the future, equality is achieved in a 30 y window, mainly due to the high variable operating costs of conventional technologies. This leads to the deduction that in scenarios with higher kWh costs, in forecast windows longer than 30 y and in an improvement of the economy of scale of STESS, the latter technology would have a greater economic attractiveness over conventional technologies, especially the use of electric heating.

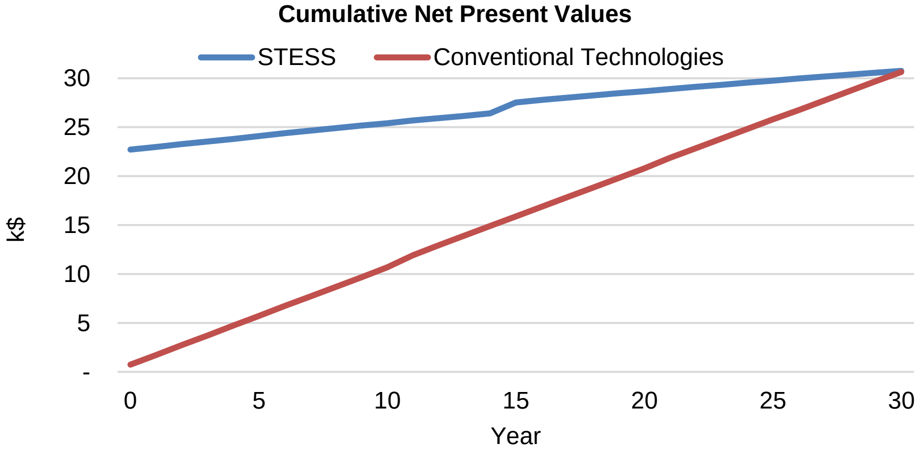


*Figure 2: Cumulative Net Present Values for STESS and conventional technologies*

## 5. Conclusions

The results of the financial analysis of a solar thermal energy storage system for hot water supply and heating under the chosen scenario show that one of the main obstacles to overcome for the massification of this technology is the high investment costs. It is important to note that solar collectors make up the largest proportion of investment costs, so measures such as local production, better import conditions and in general a reduction in their price would have a major positive impact on the financial projection of these systems. However, we hold an optimistic view regarding the implementation of solar heating technologies. These technologies would offer a competitive advantage in both the most vulnerable and affluent regions across Colombia. It is important that in the future the factors considered in the analysis of technologies such as $CO_2$ reduction and exergy analysis are expanded. It is also recommended to include end-use applications such as hot water districts for small settlements, multi-family residential units and commercial applications.

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