

Design of Solar Thermal District Heating for Andean Region Communities, Based on Chemically Modified Renewable PCM

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In Colombia more than 70% of the population lives in areas above 1.000 m above the sea level, with large urban settlements such as the country's capital, with 10 million inhabitants and elevation of 2.600 m. The cold climate of these places creates a high demand for heat throughout the year, especially at nighttime. However, many of these communities have an average annual solar radiation of 4.5 kWh/m², which allows considering the use of solar thermal storage systems for heat generation. In 2022, the Universidad Industrial de Santander, together with Northumbria University and with financial support from the Royal Society, installed the first solar thermal unit in Colombia, which provides hot water and heating to a rural house located in a highland area. Based on the knowledge acquired, this work presents a novel methodology for the sizing of a solar thermal system for the supply of hot water and heating. This methodology, the first of its kind, allows through the application of basic principles the estimation of the main parameters of the system, including the amount of phase change material required. The proposed system should be capable of supplying the heat demand of 20 rural houses located in high mountain areas, considering the use of vacuum tube-type solar collectors and the use of hydrogenated palm stearin as a novel Phase Change Material (PCM). The daily heat demand for this group of houses was calculated at 1,878 MJ, requiring a minimum of 9,000 kg of PCM and a collection area of 283 m², using evacuated tube type solar thermal collectors. Therefore, a simple and effective methodology is presented that allows obtaining the main parameters for the sizing of solar thermal systems, being the basis for the simulation of the performance of these systems.

1. Introduction

Among the different types of solar thermal energy storage systems (STESS), the most widespread are those with low temperatures, used to supply hot water and/or heating. The four main components of these systems are: solar thermal energy collectors, control system, energy storage tank and an auxiliary system for heat supply (Modi et al., 2023). Heat storage can be as sensible heat or latent heat. In general, energy storage as latent heat is preferred because it provides a higher energy density, using different phase change materials (PCMs). PCMs are used to store energy during the melting process and release it during solidification (Kant et al., 2018). The development and implementation of a new renewable PCM obtained by hydrogenation of palm stearin (HPS) has recently been published. The technical feasibility of this material for the storage of solar thermal energy in green energy systems capable of supplying the heat needs of houses located in high mountain areas, characterized by climates with high levels of solar radiation and low temperatures, has been demonstrated (Lizcano-González et al., 2024). Regarding the design of STESS, this has been extensively studied when water is used as heat storage material, with several guides on their sizing and installation and even correlations between the amount of water to be stored and the required collector area (Idae & ASIT, 2020). In contrast, there is a significant lack of information for systems for the supply of domestic hot water or domestic heating using phase change materials for heat or cold storage. Although there is some variety of scientific literature, especially books (Hyman, 2011) and scientific articles (Lin et al., 2020), there is no guide on the procedure for designing this type of system. This paper presents estimates of the amount of phase change material and collector area of a solar thermal system for hot water and space heating supply with a capacity to cover the space heating and

hot water needs of 80 people living in 20 houses located in high mountain conditions in the Colombian Andes. The use of evacuated pipe solar collector, hydrogenated palm stearin for heat storage, and heat demand estimates based on primary and secondary data were considered. The analysis of solar radiation at the study site was performed with data reported in the POWER/NASA database. It is expected that the methodology presented here will be useful for STESS design decisions and that the estimated ranges for the parameters will serve as a starting point for system performance simulations that consider the variation of climatic data, heat exchanger designs and heat losses in the different stages.

2. Methodology

The methodology for estimating the system parameters is divided into four stages: solar radiation characterization at the study site, heat demand estimation, PCM quantity calculation and, finally, estimation of the number of solar thermal collectors required.

2.1 Characterization of solar radiation availability at the study site

The data was obtained from the POWER Project's Hourly 2.4.3 version on 2024/12/13. The available information on Direct normal irradiance (DNI), Diffuse horizontal irradiance (DHI) and Global horizontal irradiance (GHI) was compiled for the period from January 1, 2023, to December 31, 2023. This database considers the effect of the azimuthal angle for the calculation of the hour-to-hour GHI based on the DNI and DHI. Subsequently, the daily irradiance received was calculated and the calculation of the monthly daily and annual daily averages for the variables was performed.

2.2 Heating and hot water demand estimation

The heating energy load was calculated from the power and time of use of a typical electric heater available at he study site, according to Eq (1).

$$Q_{prod} = W_{elec} * \Delta t \quad (1)$$

Where W_{elec} is the electrical power of the device and Δt is the operating time. This produced heat (Q_{prod}) equation is derived from the presence of the Joule effect in electrical conductors, where some of the energy of electrons is dissipated as heat as they pass through a conductive material (Dincer & Ezan, 2018). The heat demand for hot water was estimated from the average daily amount required per person for a single-family dwelling, this value being approximately 55 l of water at 60 °C per person per day (Bertinat & Navntoft, 2024). The heat required to raise the water temperature to 60 °C can be estimated according to Eq (2):

$$Q_{HW} = m * C_p * \Delta T \quad (2)$$

2.3 Estimation of the amount of heat released and absorbed during solidification and melting of hydrogenated palm stearin

The calculation of the amount of phase change material required was performed under the consideration that during the crystallization process an amount of heat should be released equal to or greater than the heat demand identified for the case study. HPS melts between 49.7 °C and 59.9 °C, while its solidification occurs between 46.6 °C and 38.3 °C. This leads to the need to calculate independently the amount of energy required to increase the temperature of the material in a specific range and the amount of energy released during the cooling of the material for this same temperature range (Goderis et al., 2024). For this, Eq (3) was applied considering hysteresis in the process, i.e., for the same temperature range, the energy required to raise the temperature will be different from the energy released during the cooling of the material.

$$Q = m \left[\int_1^{Tm_0} C_{p_s} dT + L + \int_{Tm_f}^2 C_{p_l} dT \right] \quad (3)$$

Q is the heat required to generate the temperature change or heat released during the solidification or melting process, 1 and 2 are the initial and final temperatures of the heating or cooling process, Tm_0 is the temperature at which the melting process starts, Tm_f the temperature at which the melting process ends, C_{p_s} is the solid heat capacity, L the heat of fusion or solidification and C_{p_l} the liquid heat capacity.

The influence of the amount of PCM and the average maximum temperature reached on the amount of heat stored was analysed. For this purpose, the minimum temperature in the PCM was taken as 40 °C and the maximum temperature was varied from 60 °C to 95 °C. The mass of PCM was varied from 7,000 kg to 13,000 kg.

Table 1: Thermal properties of hydrogenated palm stearin (HPS)

Melting temperature (°C)	Solidification temperature (°C)	Heat of fusion (kJ/kg)	Solidification heat (kJ/kg)	Solid heat capacity kJ/(kg K)	Liquid heat capacity kJ/(kg K)
49.7 – 59.9	46.6 -38.3	228	188.6	1.98	1.98

2.4 Evacuated tube collector area

Daily, the system goes through energy loading and unloading cycles, where the heat used for heating and hot water must be replenished. The following considerations were considered when estimating the required collecting area: Solar radiation is transformed into heat in the collectors which transfer it to the heat transfer fluid, which in this case will be water. The heat transport from the collectors to the tank with the PCM will have a heat loss of nearly 5% by using proper insulation, approximately half that one for hot water pipes in large buildings where the heat losses can be as low as 9.36 % (Bocian et al., 2022). The GHI irradiation corresponding to the annual average for the study site will be considered. The parameters of the collector used were supplied by a local supplier, selecting the Allyce HSC20 model. This collector has a quantity of 20 tubes, with a collection area of 1.6 m² and a conversion factor of 0.7.

3. Results and Discussions

3.1 Characterization of solar radiation availability at the study site

Figure 1 presents the minimum daily zenith angle during the year 2023 at the test site. On April 13 and October 10, the two minimum values are presented, indicating that during these periods, the sun reaches its maximum height. At the end of July there is a local maximum of the minimum daily zenith angle and during the month of December there is a maximum zenith angle value. Table 2 presents the monthly average daily DNI, DHI and GHI for the study site.

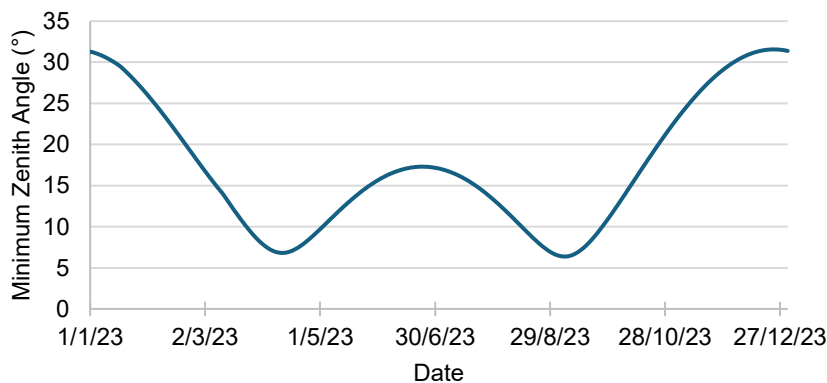


Figure 1 Minimum daily solar zenith angle during the year 2023 at the study site

Table 2: Monthly and annual average daily values of irradiance DNI, DHI and GHI

Month	DNI (kWh/m ²)	DHI (kWh/m ²)	GHI (kWh/m ²)
January	3.6	2.1	4.3
February	3.5	2.1	4.5
March	2.0	2.2	3.6
April	1.9	2.4	3.8
May	2.9	2.6	4.7
June	2.5	2.7	4.6
July	2.6	2.6	4.5
August	3.4	2.6	5.2
September	3.4	2.6	5.3
October	3.3	2.5	4.9
November	2.8	2.3	4.3
December	3.4	2.2	4.3
Annual	2.9	2.4	4.5

The monthly average daily horizontal global irradiance ranges from 3.6 kWh/m² to 5.3 kWh/m², and the annual average daily GHI irradiance is 4.5 kWh/m², equivalent to 16.2 MJ/m². This last value corresponds to a medium-high annual daily average according to the averages for Colombia reported by the Mining and Energy Planning Unit in its report Atlas of solar, ultraviolet and ozone radiation in Colombia. It was established that an annual daily average below 3.5 kWh/m² is considered a low value, while values above 5.5 kWh/m² are considered a high value (Benavides Ballesteros et al., 2017).

3.2 Heating and hot water demand estimation

An average use of the heater of 8 hours per day was considered. Applying Eq (1), the warmth generated by the heater for one night is 12 kWh, equivalent to 43.2 MJ. Although no heat demand characterization is available for a house located in this high mountain area, this value is similar to that reported for houses located in areas with similar climates. For example, for a dwelling located in Riga, Latvia, a city whose monthly average temperature range between -0.3 °C to 20.6 °C, heating energy needs reach values of up to 123.8 kWh/m² per year (Prozuments et al., 2021), which corresponds on average to 5.5 kWh per day for a 16 m² room. In general, it is estimated that for ambient temperatures between -5 °C and 5 °C the heat demand for heating a dwelling range between 350 kW and 100 kW (Naik & Ianakiev, 2021).

Because the entire water supply network is buried, the minimum water temperature is close to ground temperature, which for the study area averages between 4 °C and 8°C (Castro Méndez et al., 2016). Considering the density of water at 60 °C yields a mass of m=216.3 kg for 220 l of water required for four persons per dwelling. The average heat capacity of water was assumed as 4.182 kJ/(kg·K), which allows estimating a heat requirement of up to 50.7 MJ per household for domestic water heating. This value is comparable to that reported for a home in the city of Cantón Cuenca, Ecuador, which is located at an altitude of 2,560 m.a.s.l., with an annual heat demand of 5,562 kWh, equivalent to 20,023 MJ per year or 54.8 MJ per day (Calle Sigüencia & Tinoco Gómez, 2018). A total of 93.9 MJ of heat is the daily energy demand for a house located at the study site. Considering a set of 20 houses, the daily heat demand is 1,878 MJ, which corresponds to the amount of heat to be released by the PCM during its solidification process.

3.3 Estimation of the amount of heat released and absorbed during solidification and melting of hydrogenated palm stearin

Table 3 presents the theoretical values of energy released by hydrogenated palm stearin during a cooling process. The values are presented in MJ and consider different amounts of PCM and different temperatures at the beginning of the cooling process. The minimum temperature of the HPS was taken as 38.3 °C, at which point the material completes its phase transition.

Table 3: Energy released (MJ) by the HPS during solidification, as a function of the mass and the initial temperature of the cooling process

Mass (Kg)	Temperature (°C)							
	60	65	70	75	80	85	90	95
7,000	1,506	1,575	1,645	1,714	1,783	1,852	1,922	1,991
8,000	1,721	1,800	1,880	1,959	2,038	2,117	2,196	2,276
9,000	1,936	2,025	2,114	2,204	2,293	2,382	2,471	2,560
10,000	2,151	2,250	2,349	2,448	2,547	2,646	2,745	2,844
11,000	2,367	2,475	2,584	2,693	2,802	2,911	3,020	3,129
12,000	2,582	2,700	2,819	2,938	3,057	3,176	3,294	3,413
13,000	2,797	2,925	3,054	3,183	3,312	3,440	3,569	3,698

Note: Energy values are given in MJ. Data in blue colour indicate conditions that do not allow the required daily energy to be delivered. Data in red represent configurations that are just above the heat demand value. Data in green shows combinations that allow delivering up to 50% more than the required energy and data in orange those configurations that allow delivering more than 50% excess energy.

Table 4 shows the energy required (MJ) to melt the HPS and bring it back to the initial temperature of the cooling process. By comparing the results of Table 3 and Table 4, it is evident that more energy is required to increase the temperature of the HPS in one temperature range than is released by this material during the cooling process for the same range.

Table 4: Energy absorbed by the HPS during its melting, as a function of the mass and final temperature of the heating process.

Mass (Kg)	Temperature (°C)							
	60	65	70	75	80	85	90	95
7,000	1,755	1,825	1,894	1,963	2,033	2,102	2,171	2,241
8,000	2,006	2,085	2,165	2,244	2,323	2,402	2,481	2,561
9,000	2,257	2,346	2,435	2,524	2,613	2,702	2,792	2,881
10,000	2,508	2,607	2,706	2,805	2,904	3,003	3,102	3,201
11,000	2,759	2,867	2,976	3,085	3,194	3,303	3,412	3,521
12,000	3,009	3,128	3,247	3,366	3,484	3,603	3,722	3,841
13,000	3,260	3,389	3,517	3,646	3,775	3,904	4,032	4,161

3.4 Evacuated tube collector area

Table 5 shows the number of solar thermal collectors type HSC20 required to supply heat to the hydrogenated palm stearin, depending on the amount of PCM and the final temperature that could be reached.

Table 5: Number of HSC20 solar thermal collectors required under a daily GHI scenario of 16.2 MJ and using HPS as PCM.

Mass [Kg]	Temperature [°C]							
	60	65	70	75	80	85	90	95
7,000	102	106	110	114	118	122	126	130
8,000	117	121	126	130	135	140	144	149
9,000	131	136	141	147	152	157	162	167
10,000	146	151	157	163	169	174	180	186
11,000	160	166	173	179	185	192	198	204
12,000	175	182	188	195	202	209	216	223
13,000	189	197	204	212	219	226	234	241

According to the results presented, to store the required energy at the minimum possible temperature (60 °C), at least 9,000 kilograms of HPS and 131 HSC20 vacuum collectors are required. The structure of this collector model occupies an installation space of 1.2 m x 1.8 m, which means that a total area of approximately 282.9 m² is required. With this amount of PCM, four additional solar collectors are required for every 5 degrees Celsius increase in the final temperature that can be achieved. If it is desired to use a 50% oversizing factor in energy storage, the minimum amount of HPS to be used is 13,000 kilograms with 197 solar collectors, reaching an average temperature of 65 degrees Celsius. It is important to highlight that the daily variation in the incident solar radiation will generate differences in the daily amount of stored energy and in the average maximum temperature of the PCM, so it is recommended to simulate the performance of the system, considering meteorological variations. It should also consider the fluctuation in heat demand which is influenced by warm and cold cycles throughout the year. The results of this simulation will allow to know the replacement capacity of the proposed technology in relation to traditional technologies for heating and hot water supply.

4. Conclusions

A simple and efficient methodology for estimating ranges of the main design parameters of a solar thermal system using HPS as phase change material is presented. The daily heat demand for a house in a high mountain area was estimated at approximately 93.9 MJ from secondary data. This methodology, although simple, allows an adequate estimation, in agreement with similar values reported in literature for other study sites. Considering a set of 20 houses, the daily heat demand for hot water production and heating amounts to 1,878 MJ. According to the thermal properties of hydrogenated palm stearin, between 9,000 kg and 13,000 kg of material are required to ensure a daily availability of stored heat considering the minimum required storage or up to 50% additional oversizing. Due to the hysteresis phenomenon of the HPS, it is necessary to deliver between 2,257 MJ and 3,389 MJ of energy per day to the PCM for the same oversizing range. Finally, it was determined that to supply the heat demand at the lowest possible temperature, between 131 and 197 HSC20 solar thermal collectors are required, a range that establishes a starting point for the simulation of the system performance considering variable meteorological conditions.

Nomenclature

HPS – hydrogenated palm stearin

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