Experimental Solar Thermal Storage System for Hot Water and Space Heating Under Moorland Climate

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Abstract:

Some factors, such as the growing demand for thermal energy, the need for energy autarky by countries, and climate change issues, boost the development of renewable energy systems. According to the Sustainable Development Goals (SDGs), solar thermal energy is considered one of the most promising renewable energy sources, with a particularly challenging scenario for its implementation being moorland areas. This paper presents the results of the design and start-up of a solar thermal storage system (STSs) located in a Colombian moorland with an altitude of 3,200 meters above sea level (m.a.s.l.) to supply hot water and space heating for a bedroom. This experimental setup implements an indigenous phase change material (PCM) of renewable origin and a robust measurement and control system, including 39 temperature sensors and a control system based on the microcontroller board Arduino MEGA. This configuration also allows for the implementation of a remote monitoring system. The constructed STSs employs 140 collector tubes and 550 kg of PCM, running at a maximum temperature of 82 °C. The system can raise the average temperature of the phase change material to values above 70°C, while preventing the limiting temperature of 82°C from being exceeded at any point in the system. Additionally, the control system can prevent freezing damage due to low temperatures at night by recirculating hot water. Finally, the methods implemented for real-time visualization, storage and analysis of data allow effective monitoring of equipment performance and analysis of the different variables.

Keywords:

Arduino microcontroller; Automation; Energy storage; Hot water; Phase change material (PCM).

1. Introduction

Currently, the residential sector represents 40% of global energy needs, with the supply of hot water and the adequacy of environments being relevant factors in this area [1]. In the worst-case scenarios, global energy demand for domestic heating and water heating is expected to double the value achieved in 2010 by 2050 [2], while considering the best passive thermal management scenarios, heat demand for heating could still be between 20% and 30% of current demand [3]. For the South American Andean region there are no precise data on this demand, but it is estimated that 52.5% of the current population lives in areas above 1000 meters above sea level [4]. In Colombia, this percentage exceeds 70% of the population, of which an important part lives in paramo areas, currently having 32 populated areas and 400 municipalities located totally or partially in these areas [5].

Low temperatures and different socioeconomic factors mean that many households in these areas currently use wood or diesel as fuel for water heating and heating, despite the environmental and health problems that this entails [6]. Although rural electrification or the use of natural gas may be presented as the first alternatives, in the long term the impact of climate change on electricity production by hydroelectric plants [7] or the uncertainty about the fossil fuel market [8], among other factors, project energy diversification as the best solution [9].

This diversification of technologies must in turn be framed in the activities and goals defined within the framework of the Sustainable Development Goals (SDGs) in order to achieve positive impacts on social, environmental and economic aspects. Bearing in mind the proposed SDGs, meeting the needs of hot water and space heating, directly impacts objectives such as health and well-being, affordable and clean energy, sustainable cities and communities and climate action [10]. Likewise, decisions in this area will have an effect on the goal of reducing CO_2 emissions by 20% by 2030, compared to the BAU scenario, proposed by Colombia after the climate change conference held in Paris in 2015 [11].

The elevated location and tropical zone of the moors, creates a climate of low temperatures and high solar radiation [12]. Therefore, an alternative for heat supply is the use of solar radiation through low-temperature solar thermal energy storage systems (STSs), which accumulate thermal energy, releasing it in a controlled manner during the day and even at night [13]. Among the main applications of these systems are water heating in houses, residential units, hotels, swimming pools, as well as in domestic heating [14].

Although STSs have been implemented in various scenarios, accumulating vast knowledge about geometries and efficiencies, it is still necessary to perform extensive design and calculation work when evaluating performance under specific conditions [15].

In STSs, the storage of latent heat is preferred over sensible heat, using materials known as phase change materials (PCM), which must have some desirable characteristics such as: high value of enthalpy of fusion and specific heat per unit volume and weight, melting point suitable with the application, low volatility at working temperature, non-corrosivity, chemical stability; it must not be hazardous, highly flammable or poisonous, solidification without degradation, low degree of overcooling, small volume variation during solidification, high thermal conductivity value and be abundant and inexpensive [16].

Many of the characteristics mentioned above are present in agro-industrial materials, so in recent years the development of PCMs of animal or vegetable origin has been investigated, as substitutes for paraffin waxes traditionally used. Fatty acids, mixtures of fatty acids, fatty esters, polymers, polyols, sugars and various residues and by-products are outlined with a high potential [17]. The use of organic materials of animal or vegetable origin preferably autochthonous allows, among other things: cost reduction, lower risk of environmental contamination and increase in the value chain of various agro-industrial products [18]. Additionally, this trend is presented as an opportunity to take advantage of Colombia's agro-industrial potential since this country is currently recognized as the second most biodiverse in the world, the second in plant diversity and the third in palm biodiversity [19].

Due to the above, this proposal proposes to develop a sustainable solar thermal energy storage system in high mountain conditions using indigenous phase change biomaterials.

2. Methods

2.1. System sizing

The sizing of the solar thermal energy storage system was performed considering 3 main factors: 1. Heat demand for heating a room during a 12-hour period, 2. Specific heat required to heat 1 kg of the selected phase change material from 20°C to 70°C and the energy released during the reverse process from 70° C to 37° C and 3. In situ solar radiation and efficiency of selected solar collectors.

Heating energy consumption was calculated based on secondary data reported for residential buildings and during the winter season. The reported data were analysed for daily energy consumption per square meter and adjusted according to the target room dimensions.

Hydrogenated palm stearin (HPS), a novel renewable PCM obtained from palm stearin, which is a by-product of crude palm oil refining, was used as a phase change material. The thermal characterisation of this PCM was carried out by Differential Scanning Calorimetry where the temperatures and enthalpies of fusion and crystallisation were measured, as well as the solid and liquid heat capacities. The results were previously published as an undergraduate thesis [20].The energy required to increase the temperature of the selected phase change material was calculated by Eq. (1):

$$E_s = \int_{T_0}^{T_1} m * Cp_s * dT + m * \Delta H_f + \int_{T_2}^{T_3} m * Cp_l * dT \quad (1)$$

Where E_s is the energy stored, m is the mass of the PCM (1 kg). Cp_s is the solid's specific heat capacity, ΔH_f is the enthalpy of fusion and Cp_l is the liquid's heat capacity. (T_0) corresponds to the temperature at which the heating starts, (T_1) is the temperature at which melting starts, (T_2) is the temperature at which the material is fully liquid and (T_3) is the maximum heating temperature. The same expression can be applied to calculate the energy released (E_r) during the crystallisation process of a substance, following the reverse process. Possible hysteresis phenomena must be considered, so that the values of T_1 and T_2 may vary with respect to the heating process. Also, the value of ΔH_f must be replaced by the enthalpy of crystallization ΔH_c. The operating ranges for heating (20° C - 70° C) and cooling (70° C - 37° C) were set based on the STSs operating conditions and the temperature at which HPS solidifies completely.

Finally, the availability of solar radiation at the system installation site was obtained from the atlas of solar radiation in Colombia, elaborated by the Colombian Institute of Hydrology, Meteorology and Environmental

Studies (IDEAM). The efficiency of the solar thermal collectors was provided by the supplier of these components.

The final sizing calculation consisted of 1. estimating the heat required to heat a room over a 12-hour period, 2. this amount of heat must be stored in the phase change material and 3. the heat to be stored in the PCM will be supplied by the installed solar thermal collectors.

2.2. Piping diagram, elements, and control algorithm

The design of the piping system and the selection and configuration of the control elements had as its main objective the reliable supply of hot water and heating using the minimum number of components and reducing the production and installation costs of the system. To achieve this, work was carried out to analyse solar thermal energy storage systems, especially those focused on improving heat transfer. It was decided to design a heat exchanger that would allow for maximum natural convection during the melting process. For the selection of construction materials and final control elements, we worked closely with the industrial sector to receive feedback on prices and availability.

The following principles were prioritised for the structuring of the control algorithm: 1. Safety: the system must avoid temperature peaks and troughs that could cause damage due to overheating or freezing of water. 2. Speed: the response of the actuators should be as fast as possible based on real-time temperature measurement. 3. Stability: Temperature increases or decreases in the system should be gradual, avoiding stress on the materials due to abrupt temperature changes. For the development of the control algorithm, MATLAB software (MathWorks Inc.) was used, where multiple simulations of its operation were carried out. Finally, the control algorithm was implemented in the system on an Arduino Mega 2560 microcontroller.

2.3. Data visualization and storage

For visualisation and storage, it was decided to separate the data into two groups: 1. Temperatures measured inside the PCM storage tank and 2. Other temperatures and flow rates measured in the solar thermal energy storage system. It was also decided to have a remote access device to the solar thermal energy storage system to monitor its operation. Finally, the data processing will be carried out at a later stage using dedicated software.

2.4. Solar thermal energy storage testing

For the initial start-up phase of the STSs, activities focused on: 1. Evaluating the control system to avoid temperatures above the safety temperature. 2. Evaluating the control system to avoid temperatures below the freezing point of the water. 3. Analysing the average maximum temperature in the PCM and the heat losses during the night period.

Currently the calculation stage of the STSs performance during hot water supply and heating has started.

3. Results and discussion

3.1. System sizing

According to values reported in the literature, the daily energy consumption per square metre of building for winter periods has been reported as: 20.4 (MJ/m^2) [3], 2.6 (MJ/m^2) [21], 2.72 (MJ/m^2) [1] and 0.39 (MJ/m^2) [22]. As can be seen, the data vary considerably from one study site to another. Since the system is intended to be implemented in a tropical moorland area with an elevation of more than 3,200 metres above sea level, an average daily heat consumption of 10 (MJ/m^2) was assumed. The room where the system will be installed has an area of 16 m^2, so the system will have to supply 160 MJ of energy during night-time.

Table 1 shows the thermal properties of Hydrogenated Palm Stearin and the theoretical value of energy store and release during the heating and cooling process from 20° C to 70° C and contrariwise from 70 °C to 37° C.

Table 1. Thermal properties of Hydrogenated Palm Stearin.

Sample	$Cp_s\ (J/g\ K)$	$Cp_l\ (J/g\ K)$	$\Delta H_f\ (J/g)$	$\Delta H_c\ (J/g)$	$E_s\ (MJ)$	$E_r\ (MJ)$
HPS	6.4	8.6	226.36	188.15	0.41	0.40

Note: Modified data from [20]

The difference between the enthalpies of fusion and crystallisation is typical of organic materials, which exhibit hysteresis for these phase change processes. In the case of hydrogenated palm stearin, this hysteresis phenomenon was so strong that even a single signal was obtained for the crystallisation process at 43.6 °C, while two signals were obtained for the melting process at 48.45 °C and 59.17 °C. The enthalpies of fusion and crystallisation were calculated by integration of the signals, using TRIOS software (TA Instruments). Since each kilogram of HPS delivers $0.4\ (MJ)$ of energy during the cooling process and considering a 10% of heat loss, the minimum required amount of PCM would be: $PCM\ (kg) = 160\ (MJ) \div 0.4\ (MJ) = 400$. Considering the energy required to heat 1 kilogram of PCM from 20°C to 70°C, a total of 164 (MJ) of energy is required to be transferred daily from the collectors to the PCM.

Finally, the following parameters were considered to calculate the required collector area: 1. Evacuated tubes were selected with a cross-sectional area of 0.1044 m^2 and a heat retention efficiency of 93% and 2. According to the Atlas of Solar Radiation in Colombia, published by the country's Institute of Hydrology, Meteorology and Environmental Studies, the average solar irradiation at the site is 500 W/m^2 with 7 hours of sunlight per day and an average daytime temperature of 12° C. With these parameters, each tube would provide 1.2234 (MJ) of energy per day for a total of 134 tubes required. As the selected commercial collector pipe system comes in groups of 20 pipes, a total of 140 pipes will be worked with. Additionally, since the lowest radiation value reported for the area was used and the calculations did not consider heat losses, it was decided to increase the amount of PCM to be used from 400 kg to 550 kg in order to take advantage of these radiation peaks and to guarantee an excess of stored heat.

3.2. Piping diagram, elements, and control algorithm

The increase in material prices as well as the cost of labour, especially in the welding requirements, led to the selection of a shell-coil configuration for the heat storage tank. This configuration has several advantages, including no need to drill holes in the sides of the tank or require welding in different materials, in this case, copper and stainless steel. Figure 1 shows the design of the STSs developed in Solidworks (Dassault Systèmes), where the shell-coil scheme used can be seen.

The technical specifications of the heat storage tank are detailed below:

Internal measurements of chamber for PCM storage Deep: 1332 mm; Width: 880 mm and Height: 760 mm with a volume of 0.89 m^3. 304 stainless steels with a thickness of 1.5 mm were used. Structural reinforcement profiles of 1020 steel were placed on the outside of the chamber. Mineral wool was used to insulate all six sides of the chamber. In addition, a double-walled PVC outer skin was installed. The chamber was located 40 cm above the ground, supported on a fixed metal structure. In order to distribute the coil piping over the entire volume of the PCM, it was decided to install two copper coils, each connected to a group of solar thermal collectors. For both the internal and external coils, 5/8-inch internal diameter copper tube was used. The dimensions of the coils were calculated considering that they must always be immersed in the phase change material. Measures of the large coil: 560 mm wide, 510 mm high and 990 mm deep. 27 turns for a total length of 57 meters of pipe. Measures of the small coil: 360 mm wide, 310 mm high and 736 mm deep. 20 turns for a total length of 27 meters of pipe.

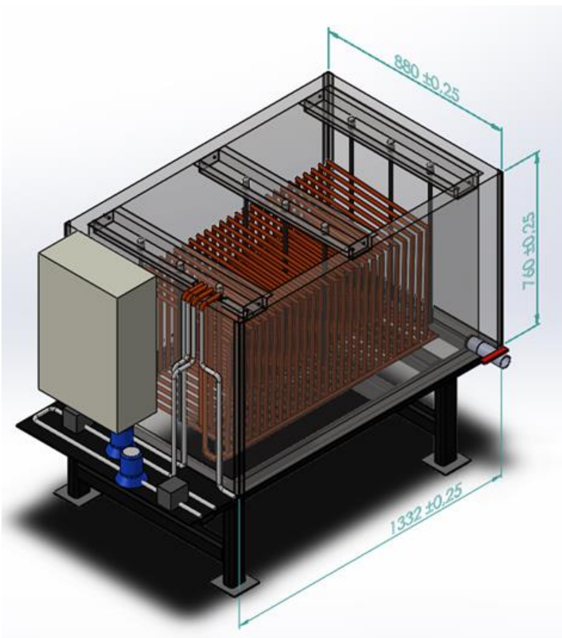

Figure 1. *STSs design in Solidworks. The final internal dimensions of the heat storage tank, required to hold the 550 kg of PCM, are shown.*

A square profile was selected for the coils to maximize the effect of natural convection during the PCM melting process. This phenomenon is due to the fact that vertical pipe sections generate a temperature gradient in the same direction in the molten material. This temperature gradient in turn generates a density gradient which causes the less dense (hotter) material to move to the top. Several studies have demonstrated the positive contribution of the natural convection effect on heat transfer either by observing the difficulty in melting PCM located at the bottom of the storage tanks [23], the low thermal conductivity values of organic PCM, especially when in solid state [24], or by employing buoyancy factors in the heat transfer equations used to simulate the melting process [25].

Figure 2 shows the configuration of the water circuits in the STSs and the final control elements. There are two groups of collectors, each connected to a coil, however, the two circuits are driven by a single recirculation pump.

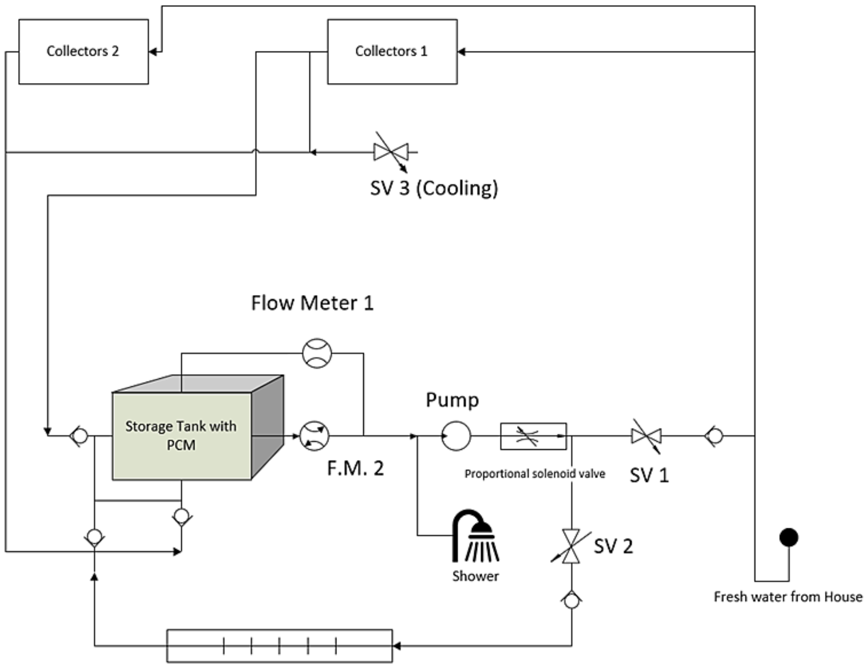

***Figure 2**. Configuration of the water circuits in the STSs and the final control elements. Two groups of collectors, 3 solenoid valves, a recirculation pump, two flow meters, a proportional valve, 5 one-way valves and the representation of finned tubes used as heaters inside the room are observed. Created using Microsoft Visio software.*

The control system was implemented in an Arduino Mega 2560 microcontroller and operates based on the temperature readings at the inlet and outlet of the collectors, the temperatures at the outlet of the coils and the temperature of the pump. Additionally, it is considered whether hot water is being supplied for the heaters or hot water for the shower. The logic of the control algorithm is presented in Figure 3. The algorithm shows the different stages of the implemented control system. Initially, it is checked that the temperatures at the collector outlets are below 82°C to avoid overheating. If this is not the case, solenoid valve 3 is opened to allow cold water to flow through the collectors. It is then checked that the temperature is not lower than 8° C at any point in the system. If this condition is met, the stored heat is used to raise the water temperature in the pipes. Once the safety stages have been passed, the system moves on to the operation stage. If the user has indicated that hot water is required for showering (HDW), the system switches off the pump and closes the valves and the flow is manually controlled by the user. If HDW is not required, a check is made to see if the user requires space heating, in which case hot water is circulated through the finned pipes. The user indicates the requirement for HDW or heating by means of a physical switch. If HDW or heating is not required and if solar radiation is available (Toutc > Toutcoils+5), the system will be storing heat in the PCM. The algorithm runs continuously generating a data set every 20 seconds.

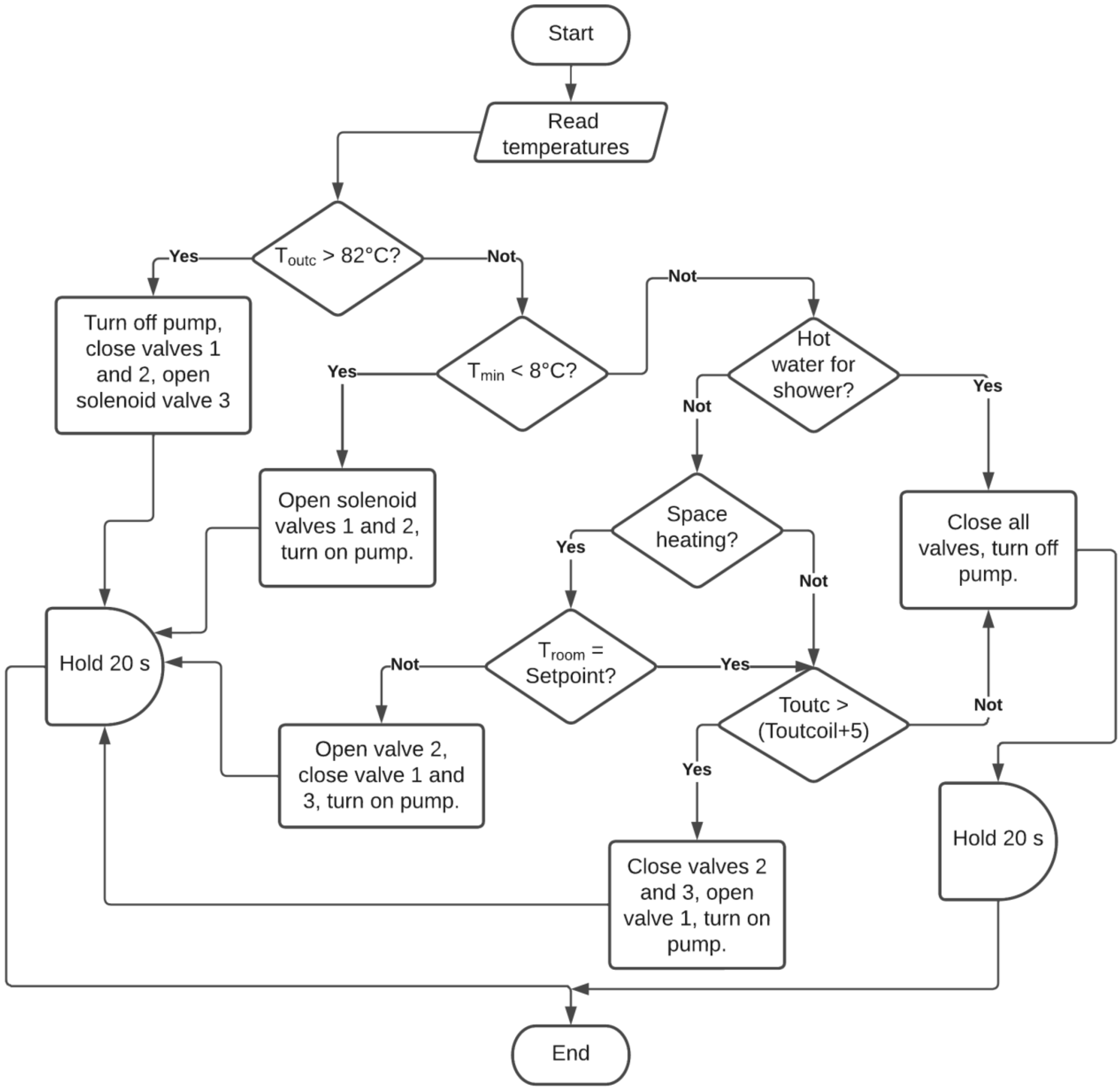

Figure 3. *Logic of the control system implemented in the solar thermal energy storage system for hot water supply and space heating.* T_{outc} *represents the two temperatures measured at the outlet of the collector groups.* T_{min} *is the lowest temperature measured in the pipes of the system.* T_{room} *is the temperature of the air inside the room.* $T_{outcoil}$ *represents the two temperatures measured at the water outlet of the coils.*

The final control elements used were: Aquapak hot water pump with 1/6 HP and a maximum flow rate of 20 L/min and solenoid valves model 2W-040-08. The proportional valve was developed for this project.

3.3. Data visualization and storage

At STSs, 27 pt-100 temperature sensors were installed inside the heat storage tank and 11 at different points in the pipelines. In addition, there are two ultrasonic flow sensors, 3 solenoid valves, two switches and a pump. To handle this amount of data, it was decided to treat the temperature measurements taken inside the storage tank separately from the other elements. Figure 4 shows an image of the electronic control board implemented in the STSs.

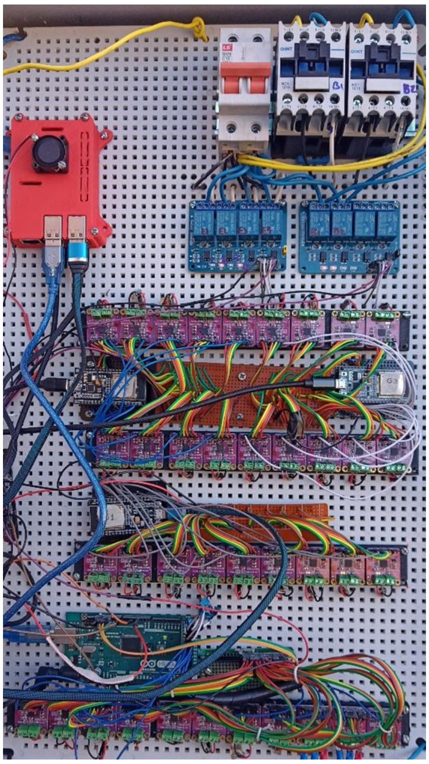

***Figure 4**. Control board. Each purple module is a transducer of one of the 38 PT-100 sensors. At the bottom left, in green, is the ArduinoMega 2560 microcontroller in charge of the control system of the unit. At the upper left, in red, is the RaspberryPi 3 minicomputer, used for visualization and storage of the central control data. The 3 ESP32 microcontrollers, in charge of transmitting the temperature data to the heat storage tank, can also be seen. In the upper left side, there are digital and analogy switches for turning on and off the final elements of high-power control.*

For remote monitoring and access to the control system data, the Node-Red language is used to store the data as a .txt file by creating a local server on a Raspberry Pi 3. For the visualization and storage of the temperatures inside the heat storage tank, 3 ESP32 sensors transmit the data to an external server using the ThingSpeak software (Mathworks Inc.). Remote monitoring of the equipment's operation was implemented through the VNC Server and VNC Viewer applications. These applications also allow remote access to the data file generated by Node-Red. Figure 5 shows an example of how the values of the main temperature sensors are observed in real time.

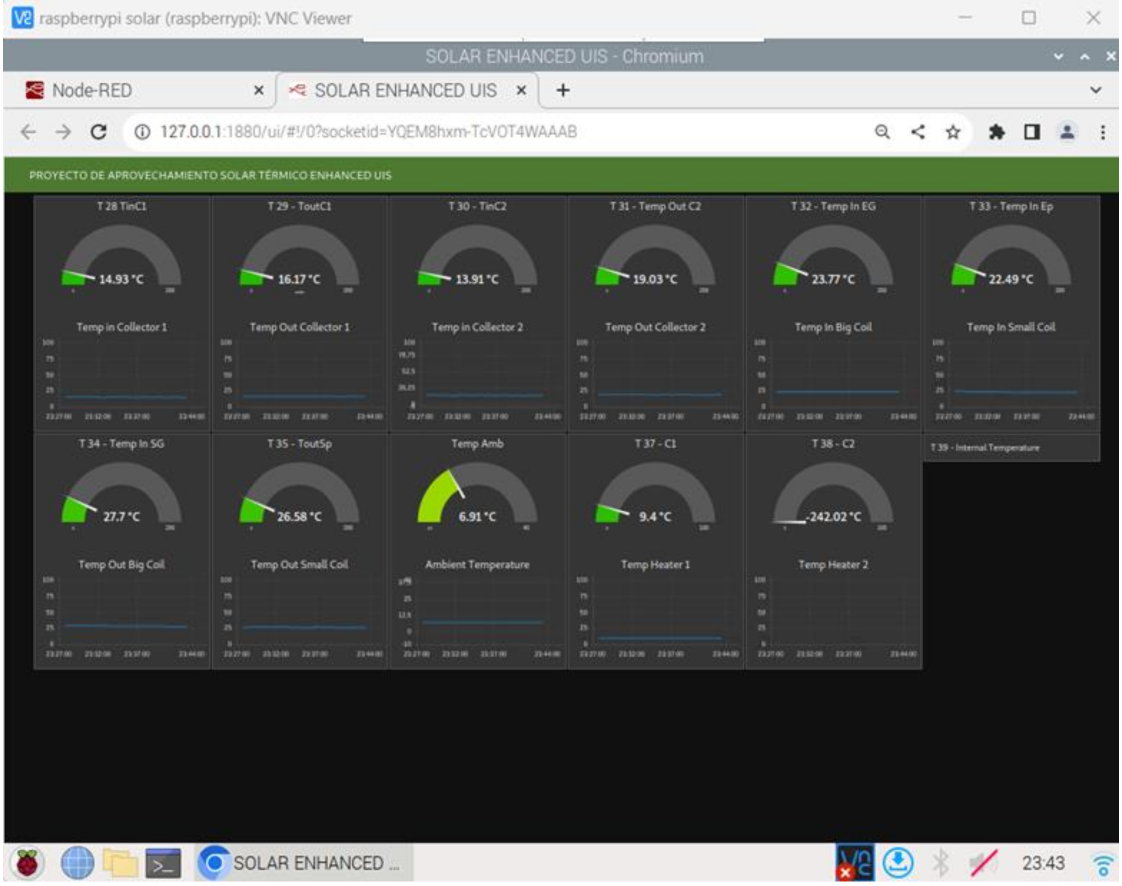

Figure 5. Example of remote monitoring via VNC Viewer application. Through Node-Red, a local server is configured on the RaspberriPi 3 minicomputer, with access to programming and data visualization through cloud. The temperatures at the inlet and outlet of the two groups of collectors, the temperatures at the inlet and outlet of the coils, the ambient temperature and the temperatures at the inlet and outlet of the heaters (the latter used momentarily for the antifreeze control system) are observed.

Experimental data are stored in two ways, generating two different files. The data of the temperatures measured inside the heat storage tank are stored in the Thingspeak (MathWorks Inc.) application, which allows exporting a comma-separated file (.csv). The data of the other temperatures, as well as the flows are stored in a text file (.txt). To process, visualise and analyse the data, codes were developed in MATLAB (MathWorks Inc.) software. The code for the analysis of the control system data, once executed, asks the user for the date range to be analysed and the variables to be plotted.

3.4. Solar thermal energy storage testing

The first stage of the tests focused on determining the effectiveness of the control system to prevent overheating in the system. Figure 6 shows the behaviour of the temperatures at the inlet and outlet of the collectors and the ambient temperature. Once 82°C is reached at some point in the system, cold water is taken from the domestic circuit and circulated through the collectors. It is observed that the temperatures at the inlet of the collectors drop sharply below 30°C, while the temperatures at the outlet drop to around 50°C. On a sunny day like the one in the example, the system is activated several times, which shows the availability of energy in the area.

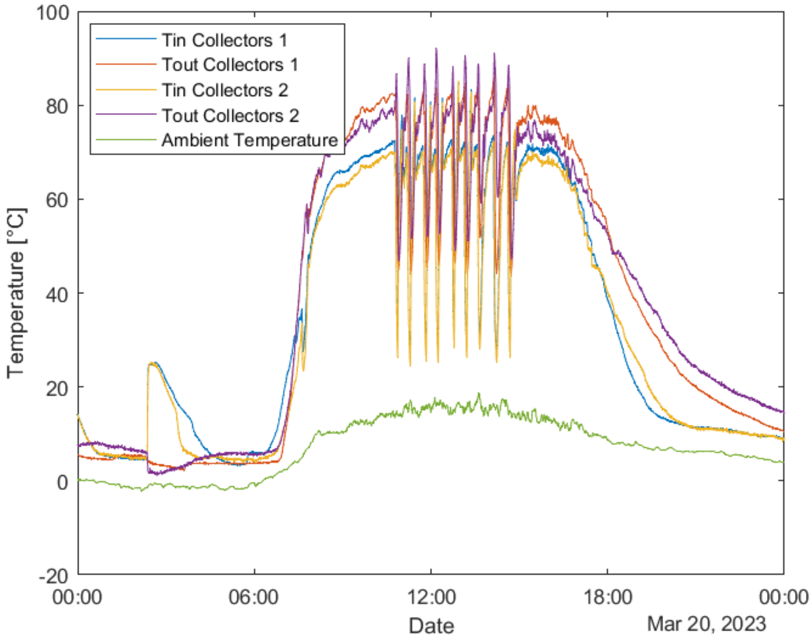

Figure 6. *Operation of the control system in the prevention of overheating. The inlet and outlet temperatures at the solar collectors and the ambient temperature are observed. Once 82°C is exceeded at some point, cold water is circulated through the collectors.*

Subsequently, tests were carried out to assess the effectiveness in preventing water freezing in the pipes. Figure 7 shows the behaviour of the temperature of the water in the pump and the ambient temperature, where, despite temperatures below zero degrees, the system prevented the temperature of the water in the pump from dropping below 8°C.

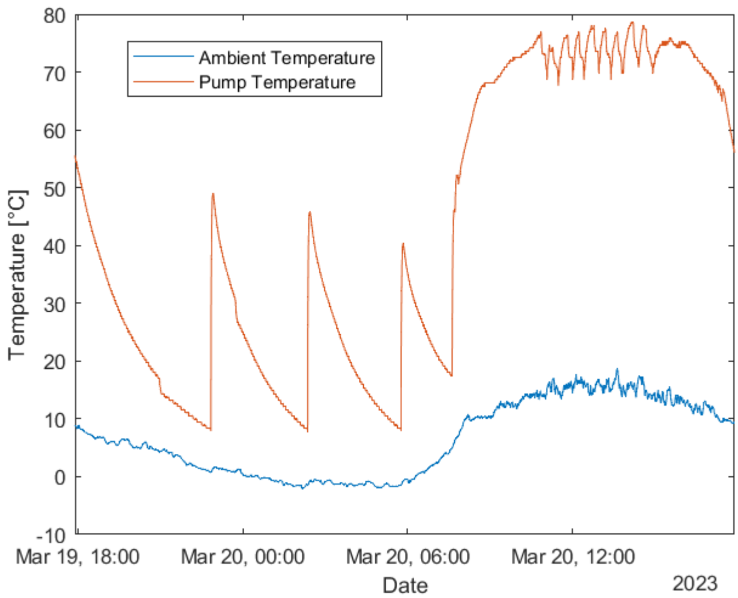

Figure 7. Behaviour of pump and ambient temperatures. The system recirculates hot water when the water temperature in the pump is below 8°C.

Finally, the temperatures measured inside the heat storage tank are analysed. Figure 8 shows the values measured during a 24-hour cycle. Temperatures above 70° C are observed at most of the points measured. Also, at some points the temperatures decrease close to 40° C, indicating that improvements in heat storage can be implemented.

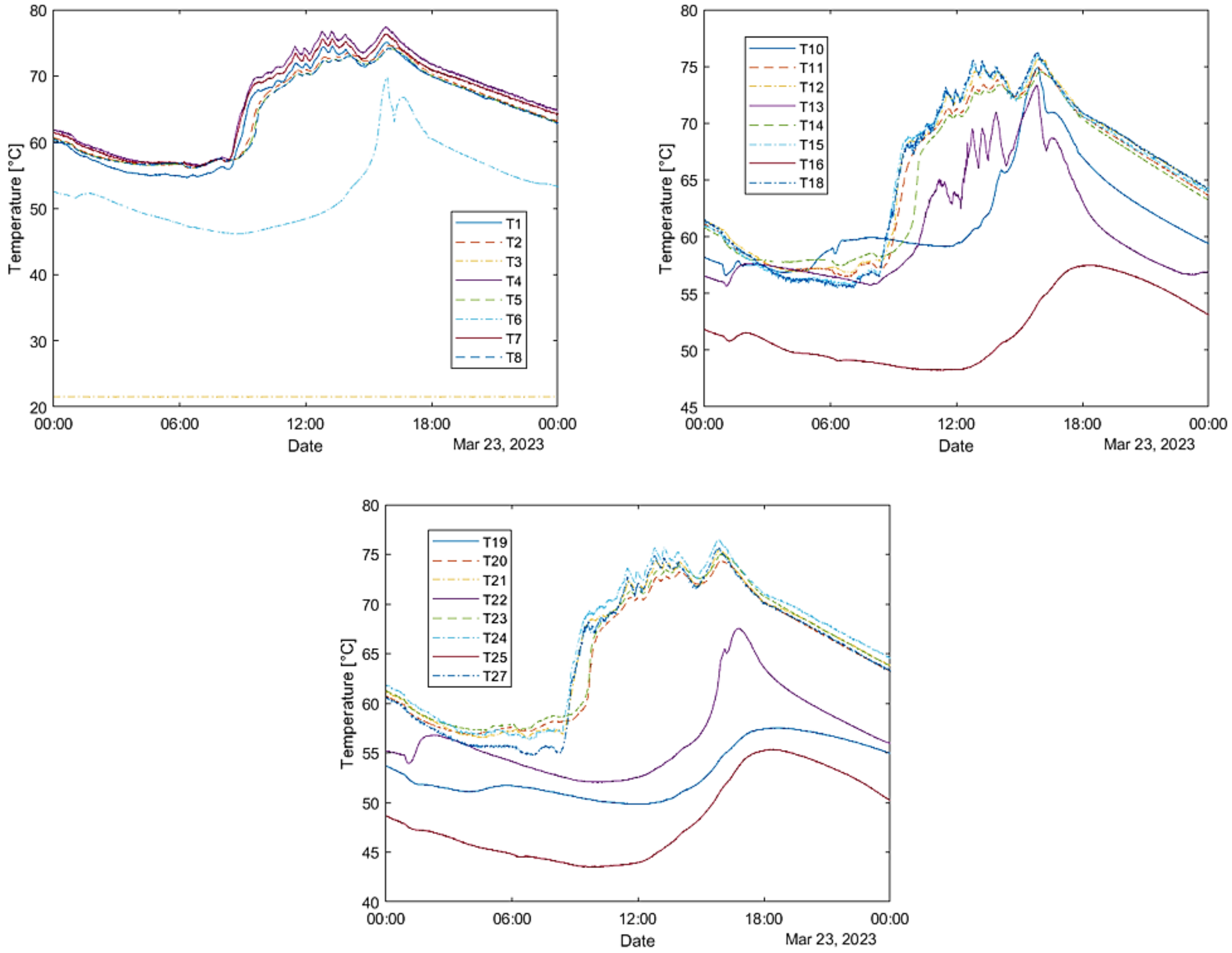

Figure 8. *Temperatures measured inside the heat storage tank. T1, T4, T7, T12, T15, T18, T21, T24 and T27 correspond to temperatures at the top surface of the phase change material. T2, T5, T8, T11, T13, T20 and T23 correspond to temperatures taken at the mid-height of the PCM. T3, T6, T10, T13, T13, T16, T19, T22 and T25 correspond to temperatures at the bottom of the PCM.*

An image of the fused PCM is shown in Figure 9. The solidification observed on the surface is due to the low temperatures while the solidification around the coils is due to tests for the study of crystallisation.

Figure 9. *Molten PCM and detail of the coils. Crystallisation on the surface is evidence of the low temperatures in the area.*

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Conclusions

A solar thermal energy storage system for domestic hot water supply and heating was designed, constructed and evaluated under moorland conditions. The methodology used for the system sizing estimation allowed to successfully estimate the proportion of solar thermal collectors and the amount of phase change material used.

The design of the piping system and the control system allows avoiding overheating in the system as well as freezing problems in pipes. Likewise, temperature stability is observed as heating or cooling is generated in both the collectors and the storage tank.

When the complete fusion of the PCM is achieved, it is inferred that the amount of energy stored is close to 164 MJ. The respective analyses of the heat delivered by the heat transfer fluid and the domestic hot water supply and space heating tests must now be carried out.

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