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# Comparison between Air-Exposed and Underground Thermal Energy Storage for Solar Cooling Applications

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**Abstract:** Solar energy is one of the main alternatives for the decarbonization of the electricity sector and the reduction of the existing energy deficit in some regions of the world. However, one of its main limitations lies in its storage, since this energy source is intermittent. This paper evaluates the potential of an underground thermal energy storage tank supplied by solar thermal collectors to provide hot water for the activation of a single-effect absorption cooling system. A simulator was developed in TRNSYS 17 software. Experimentally on-site measured data of soil temperature were used in order to increase the accuracy of the simulation. The results show that the underground tank reduces thermal energy losses by 27.6% during the entire hot period compared with the air-exposed tank. The electrical energy savings due to the reduction in pumping time during the entire hot period was 639 kWh, which represents 23.6% of the electrical energy consumption of the solar collector pump. It can be concluded that using an underground thermal energy storage tank is a feasible option in areas with high levels of solar radiation, especially in areas where ambient temperature drops significantly during night hours and/or when access to electrical energy is limited.

**Keywords:** underground thermal energy storage; UTES; thermal energy storage tank; solar thermal energy storage

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## 1. Introduction

Solar energy is recognized as one of the main alternatives for decarbonizing the electricity sector and reducing the energy deficit that exists in several regions of the world. In places with high levels of solar radiation, the energy collected by a solar capture system (i.e., photovoltaic panels, solar collectors) can be higher than the energy demand during sunny hours; however, the maximum demand can occur during non-sunny hours. Therefore, energy storage technologies have an important role in such applications.

The implementation of an energy storage device allows mitigating/reducing the intermittency of renewable energy sources such as solar energy. The inadequate design of an energy storage device can have negative impacts on the initial investment and/or the operating cost of the whole system. For this reason, the efforts of different research groups are focused on designing energy storage devices that provide an optimal matching between the temporal variation of users demand and the availability of the solar resource.

The selection of an energy storage technology depends directly on the type of solar energy application. In systems for electrical energy generation mainly with photovoltaic technologies, the electrical energy is generally stored in a battery bank. In systems for solar thermal energy collection, thermal energy is generally stored in a volume of fluid inside a container called a "tank". Thermal energy storage can contribute significantly to meeting society's desire for more efficient, environmentally benign energy use, particularly in the areas of building heating and cooling and electric power generation [1]. In addition, their high thermal power density has increased their implementation in industrial thermal processes [2].

Despite the fact that thermal storage systems have a low initial investment, long useful life, and simplicity of operation, they still present areas of opportunity to improve their efficiency. Some authors have studied the implementation of two thermal energy storage tanks with the purpose of storing fluid at low temperatures and feeding it into the solar collectors to increase its energy content and store it in another high-temperature tank.

Dannemand et al. [3] used two tanks to store thermal energy provided by PVT collectors to activate a solar-assisted heat pump. The authors report that compared with the single-tank thermal energy storage, the power consumption of the double-tank thermal energy storage system was reduced by 23%, and the heat loss was reduced by 11%.

They have also implemented phase change materials because they offer high thermal storage density with moderate temperature variation. Abdelsalam et al. [4] reported that increasing the number of PCM modules can increase the efficiency of heat storage and delay the time of water temperature drop. However, when the volume fraction of PCM reaches a certain value, it will affect the heat transfer of the heat exchange coil, and the heat storage efficiency becomes no longer sensitive. Therefore, increasing the charge rate requires an increase in the surface area of the heat exchanger coil.

Shen et al. [5] conducted a literature review on three types of solar-driven short-term low-temperature thermal energy storage technologies: thermal energy storage water tanks, thermal energy storage with phase change materials, and thermochemical thermal energy storage. The authors conclude that from an economic point of view, thermal energy storage water tanks are completely feasible in the global market. The application prospect of phase change material thermal energy storage in moderate climates is obviously stronger than that of tropical climates, while the thermochemical heat storage system can be economically feasible around 2030.

Other authors have proposed to take advantage of soil thermal inertia to improve the efficiency of the thermal storage subsystem. For this reason, they are called underground thermal energy storage systems (UTES). These underground storage systems are classified according to their geometry and enclosure material; the main technologies are: aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), pit thermal energy storage (PTES), and tank thermal energy storage (TTES).

The first attempt to store thermal energy in an underground tank occurred in 1939 in Cambridge, Massachusetts, with the purpose of storing solar thermal energy in the summer months to supply heating to a residential building during the winter months [6]. Since then, different UTES technologies for hot water storage have been investigated and proposed, with the main use being long-term storage between seasons.

Yumrutaş et al. [7] studied a space heating system consisting of a heat pump driven by flat-plate solar collectors and an underground cylindrical thermal energy storage tank. The authors developed an analytical computational model to determine the annual variation of the water temperature in the underground tank, the earth temperature field surrounding the tank, and the annual performance of their heating system. Based on their results, the authors report that their heating system is an alternative to fossil-fuel-fired heating systems. In addition, they mention that the soil surrounding the tank behaves as an additional storage medium, since it absorbs energy during summer and rejects the absorbed energy to the tank in winter.

Banjac [8] presented a sizing methodology for a space heating and cooling system which consists of a heat pump, solar collectors, and an underground thermal storage tank for seasonal (or long-term) thermal energy storage. Numerical calculations show that the size of the underground tank has the greatest impact on water temperature variation, and that the amplitude of temperature oscillation decreases with the increase in the tank volume. Furthermore, it is shown that the tank burial depth had a minor effect on the change of water temperature in the tank.

Nhut et al. [9] established a mathematical model for the study of a residential heating system activated by solar thermal energy with a buried thermal tank for seasonal storage. Their results revealed that the optimum volume of the underground tank is 5 m3 and that on days with clear sky, intermittent cloudy sky, and cloudy sky, the solar fraction obtained was 45.8%, 17.26%, and 0%, respectively. The authors recommend that a residential house solar-assisted heating system with a thermal storage tank should be replaced by the solar-assisted heating system with a boiler and a seasonal underground thermal energy storage tank, because it will increase the solar fraction.

Meister and Beausoleil-Morrison [10] experimentally studied a solar thermal system with a 36 m3 underground thermal energy storage tank for seasonal storage. The authors report that low efficiency of solar collectors has the most detrimental effect on system performance. The results indicate that the system can achieve 100% solar fraction for space heating loads (15 GJ) and 86% for domestic hot water loads (13 GJ). The authors report that the seasonal storage tank achieves an annual energy storage efficiency of 42%.

The main application of the UTES is for seasonal or "long-term" thermal energy storage, in order to have solar thermal energy availability in places where the solar radiation decreases significantly during autumn–winter months. Their main application is to provide heating services in buildings. This research gap presents an opportunity to evaluate the potential of UTES for daily or "short-term" thermal energy storage for solar cooling purposes in zones with hot climates. This paper evaluates the potential of a UTES for short-term thermal energy storage supplied by solar thermal collectors to provide hot water for the activation of a single-effect absorption cooling system, considering as a case of study the off-grid remote community of Puertecitos, located in northwest Mexico where rational consumption of electrical energy is essential and solar radiation levels present high values throughout the year.

## 2. Case of Study

This work considers as the case of study the current conditions of the solar absorption cooling system (35 kW) of Puertecitos school reported by Aguilar-Jiménez et al. [11]. The solar absorption cooling system is activated by a solar thermal energy collection and storage subsystem shown in Figure 1, consisting of 25 evacuated tube heat-pipe solar collectors with 110 $m^2$ of collection area (arrangement of five collectors in series and five in parallel) and a thermal energy storage tank exposed to the ambient air with a height of 2.5 m, glass fiber insulation thickness of 0.025 m, and a volume of 12 $m^3$.

**Figure 1.** Solar thermal energy collection and storage subsystem (Aguilar-Jiménez et al., 2020) [11].

Figure 2 shows schematically the arrangement of the thermal energy storage tank. Thermal energy input comes from solar collectors, increasing the water temperature inside the tank and positioning the water with higher temperature in the upper part of the tank through the physical phenomenon of stratification caused by the density differential. The water with lower density and higher temperature inside the tank is used for the activation of the solar absorption cooling system. The water with higher density and lower temperature is used for energy capture in the solar collectors.

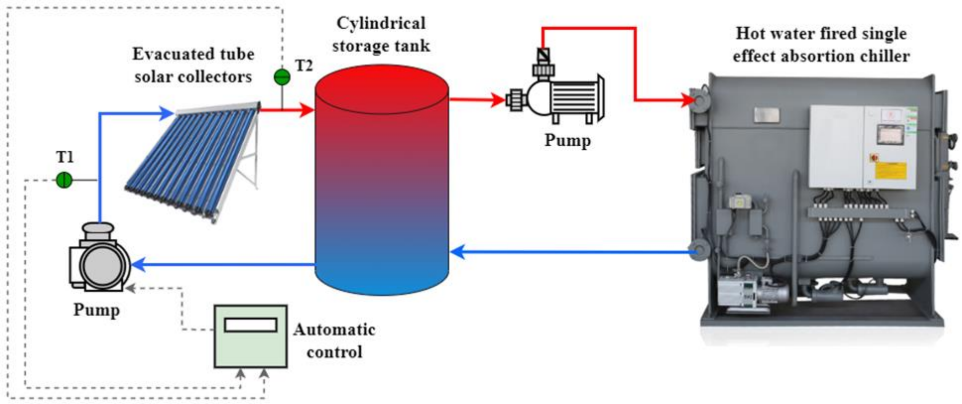



**Figure 2.** Schematic diagram of the system under study.

During weekdays, the solar absorption cooling system operates during the occupancy hours of the Puertecitos school, which are from 8:00 h to 15:00 h. During weekends, the absorption cooling system does not operate, but the solar thermal energy collection and storage subsystem may be turned on to increase the water temperature in the thermal energy storage tank. Sunny hours in this community generally range from 6:00 h to 18:00 h. Therefore, during weekdays the solar energy collection and storage subsystem begins collecting energy before the solar absorption cooling system is turned on and can be found working after school hours to increase the water temperature in the thermal energy storage tank.

The pump that circulates water between the thermal energy storage tank and the solar collectors has a rated power of 3.5 HP (≈2612 W) and starts up when the water temperature at the outlet of the solar collector rows is higher than the average temperature of the hot water tank.

Figure 3 shows the variation of daily ambient temperature, soil temperature, and solar radiation averages during the warm season (May–October), since these are the two surrounding mediums with which the thermal energy storage tank of the solar absorption cooling system exchanges heat. Although the ambient temperature reaches values of 40 °C during sunny hours in the period from June to September, at night it presents values between 25–30 °C, which increases the temperature difference with respect to the tank temperature (≈90 °C) and, subsequently, the heat losses.

The community of Puertecitos is a coastal remote community without access to the electrical grid. The electrical energy supply comes from a solar PV microgrid with electrical battery storage. For this reason, it is important to develop and implement actions and/or strategies to reduce the energy consumption of electrical devices that consume electrical energy from the microgrid. The proposal of burying the thermal energy storage tank of the solar absorption cooling system aims to reduce the heat losses dissipated to the surrounding ambient air, and thus maintaining the desired temperature in the tank (≈90 °C) for a longer period. As a result, reducing the operation time of the pump that circulates water between the thermal energy storage tank and solar collectors, decreases its electrical energy consumption.

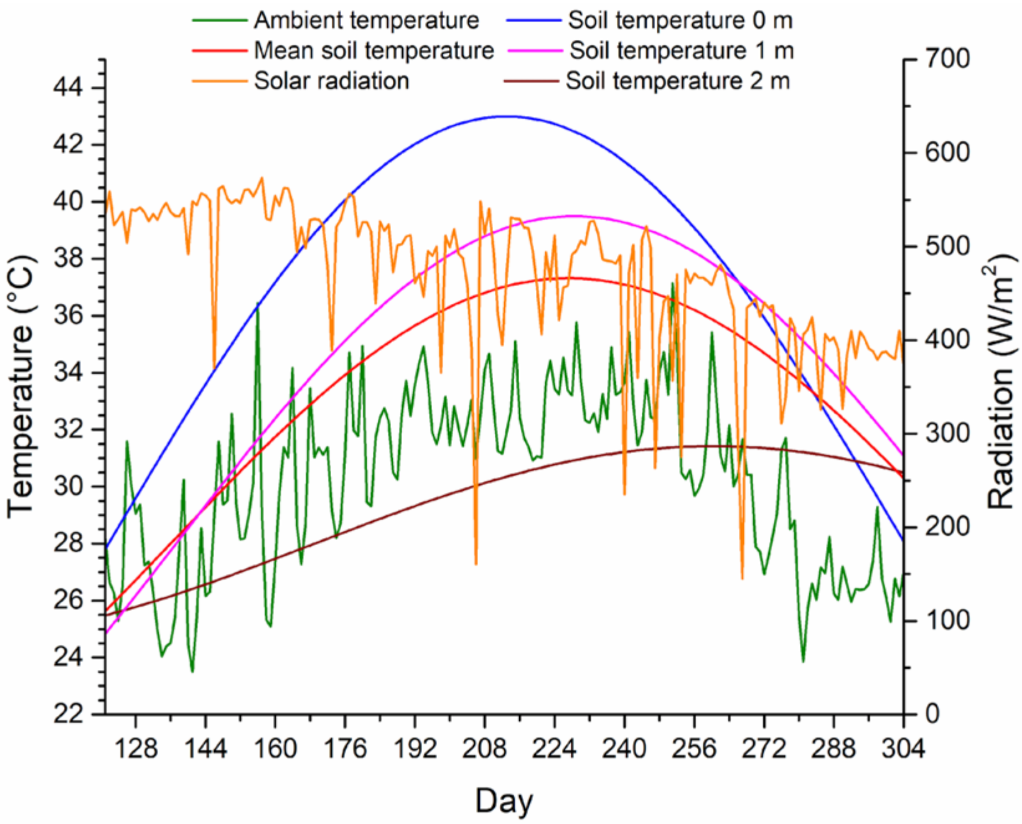



**Figure 3.** Variation of ambient temperature, soil temperature, and solar radiation during the hot period.

## 3. Methodology

This section presents the methods used to carry out an operational study on the performance of the proposed underground thermal energy storage tank, which consists of three main points: features of TRNSYS simulation, experimental validation of soil temperature at the study site, and calculation of the heat transfer coefficients for the air exposed (base case) and the underground thermal energy storage tank cases.

### *3.1. TRNSYS Simulation*

TRNSYS 17 software [12] was used in order to quantify the potential of the proposed underground thermal energy storage tank for short-term energy storage, because this software is suitable for simulating the annual performance of different energy systems.

Meteorological data from Puertecitos, Baja California, Mexico (30.21°, 114.38°) measured during the year 2020 by a weather station were used in this simulation. The data generated by the weather station was entered into the Meteonorm v7 software [13] in order to obtain an Energy Plus Weather file (EPW) compatible with the TRNSYS "Type 15".

Output meteorological variables such as ambient temperature and solar radiation processed by "Type 15" are fed as input variables into the mathematical model of the evacuated tube solar collector (Type 71) and the thermal energy storage tank (Type 534). Subsequently, the solar collector (Type 71) output variables (temperature and mass flow rate) are connected to the thermal energy storage tank (Type 534). The hydraulic pump (Type 3) enables the flow of hot water between the thermal energy storage tank and the solar collectors as shown in Figure 4.

The hot water (≈90 °C) stored in the thermal energy storage tank is pumped to the absorption cooling system (Type 107). Table 1 shows the TRNSYS "Types" used to evaluate both the base case and the proposed underground thermal energy storage tank.

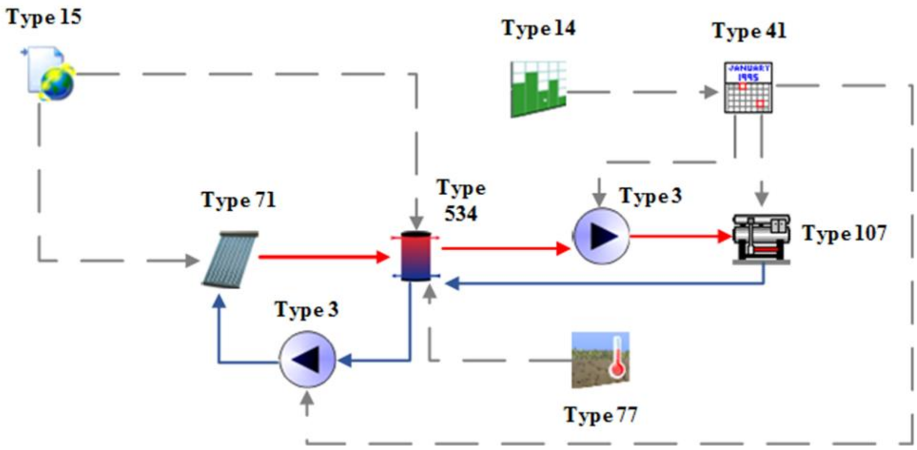
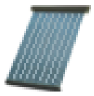
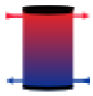
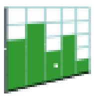
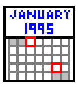
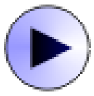
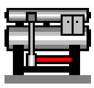



**Figure 4.** Simulation diagram in TRNSYS 17.

**Table 1.** Modules used for simulation in TRNSYS 17.

| TRNSYS Type | Component | Description |
|---|---|---|
|  71 | Evacuated tube solar collector | Model the solar collector field. |
|  534 | Cylindrical storage tank | Model the thermal storage tank. |
|  15 | Weather data processor | Climatological database. |
|  14 | Time-dependent forcing function | Controls chiller on/off. |
|  41 | Day-dependent forcing function sequencer | Indicates the day of the week |
|  3 | Pump | Send water to solar collector field. |
|  77 | Temperature probe | Calculate the soil temperature. |
|  107 | Hot-water-fired single-effect absorption chiller | Model the absorption chiller. |

The system simulation was conducted during the hot period of the year at the study site, which starts on 1 May (2880 h) and ends on 31 October (7296 h). Time steps of 1 h were set and "Type 41" was configured to turn off the absorption cooling system during weekends, holidays (15 May and 16 September), and vacations (1 July–25 August). The solar thermal energy collection and storage subsystem pump is turned off during vacations only. The performance analysis of both cases (air-exposed and underground tank) was focused on the operational start-up week of the solar thermal energy collection and storage subsystem (2977–3096 h) and the week with the highest thermal load in the classrooms during the hot period (5833–5952 h). Table 2 shows the parameters specified to "Type 534".

**Table 2.** Specifications of the thermal storage fluid and tank.

| Parameter | Specification |
|---|---|
| Tank volume [$m^3$] | 12 |
| Tank height [m] | 2.5 |
| Fluid specific heat [kJ/kg·K] | 4.2 |
| Fluid density [kg/$m^3$] | 965 |
| Fluid thermal conductivity [W/m·K] | 0.68 |
| Fluid viscosity [kg/m·h] | 1.134 |

### *3.2. Soil Temperature Validation*

The experimental data were measured with HOBO model TMCx-HD temperature sensors (ONSET BRANDS, Norwalk Connecticut, CT, USA) placed at a depth of 2 m in a vertical well drilled at the Puertecitos school. An analog recorder HOBO model UX120-006M was used for data acquisition.

Figure 5 shows the results of the experimental validation for the soil temperature variation in Puertecitos at 2 m depth. The coefficient of determination $R^2$ is equal to 0.9901 and the mean absolute error (MAE) value is 0.1572 which indicates that the TRNSYS model to obtain the soil temperature is representative of the real phenomenon. The largest temperature difference between the model and the experimental measurement occurs at the end of the hot period (7293 h) and it is equal to 0.61 °C.

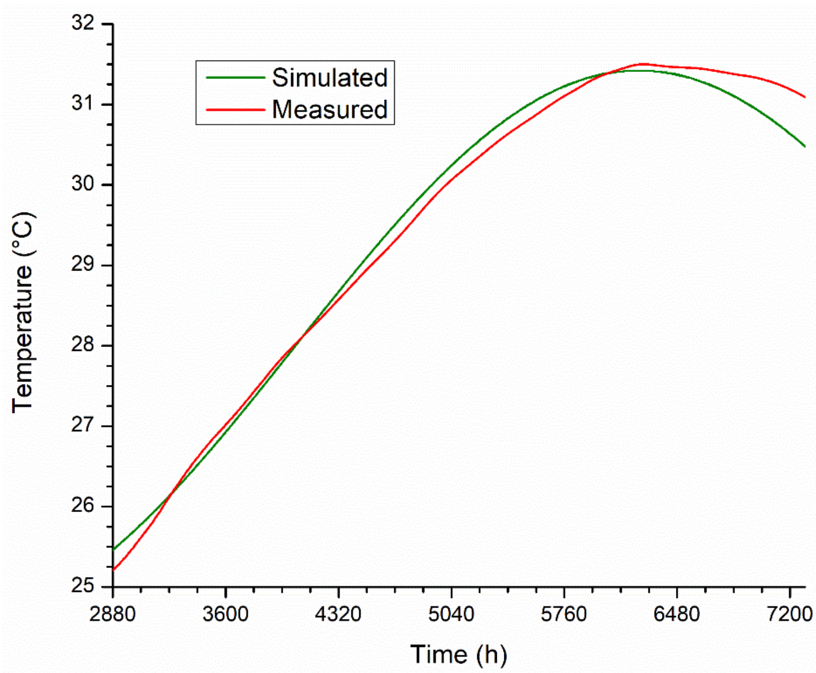



**Figure 5.** Validation of soil temperature modeling at 2 m depth.

The parameters used for "Type 77" to calculate the soil temperature variation based on the Kusuda and Achenbach [14] model are presented in Table 3. The parameters Tm, A0, and t0 represent the annual average ambient temperature (°C), the amplitude of annual ambient temperature variation (°C), and the time at which the lowest annual temperature occurs (°C). The parameters k, ρ, and Cp represent the thermal conductivity, density, and specific heat of the soil, respectively, and were obtained from the ground thermal properties database reported by Dalla Santa et al. [15] considering a wet clayey-silt soil.

**Table 3.** Parameters used for soil temperature calculation.

| $T_m$ (°C) | $A_0$ (°C) | $t_0$ (h) | k (W/m·K) | ρ (kg/m$^3$) | $C_p$ (J/kg·K) |
|---|---|---|---|---|---|
| 28 | 10 | 360 | 1.45 | 2000 | 1200 |

### *3.3. Heat Transfer Coefficient*

#### 3.3.1. Air-Exposed Tank

The heat transfer phenomenon studied to determine the heat losses through the thermal energy storage tank exposed to ambient air is the natural convection on the top and walls. The equations to calculate the heat transfer natural convective coefficient "$h$" depend mainly on its geometry and orientation.

In the literature, a wide variety of correlations and dimensionless numbers are available that vary according to the geometry and orientation of the tank; as reported by Çengel and Ghajar [16], a vertical cylindrical container can be treated as a vertical plate when the condition stated in Equation (1) is met:

$$D \geq \frac{35 * L}{\mathrm{Gr}_L^{1/4}} \quad (1)$$

where "$D$" represents the tank diameter, "$L$" the tank height, and "$\mathrm{Gr}_L$" the Grashof number. The Grashof number must be calculated using Equation (2); this dimensionless number represents the effects of natural convection:

$$\mathrm{Gr}_L = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2} \quad (2)$$

where "$g$" represents the acceleration of gravity, "$\beta$" the coefficient of volumetric expansion, "$T_s$" the plate surface temperature, "$T_\infty$" the temperature of the fluid in contact with the plate surface, "$L_c$" the height of the plate, and "$\nu$" the kinematic viscosity of the fluid.

For this case study, the condition established in Equation (1) is satisfied, and hence the equations corresponding to a vertical plate were used. Subsequently, it is necessary to calculate the Rayleigh number using Equation (3), which describes the relationship between buoyancy and viscosity within the fluid:

$$\mathrm{Ra}_L = \mathrm{Gr}_L \mathrm{Pr} \quad (3)$$

where "Pr" represents the Prandlt number, used to describe the relationship between momentum diffusivity and thermal diffusivity. The last dimensionless number required for the calculation of the convective coefficient is the Nusselt number obtained by Equation (4), which is an empirical correlation in natural convection for vertical plates:

$$\mathrm{Nu} = \left\{0.825 + \frac{0.387\mathrm{Ra}_L^{1/6}}{\left[1 + (0.492/\mathrm{Pr})^{9/16}\right]^{8/27}}\right\}^2 \quad (4)$$

Finally, the natural convection heat transfer coefficient "h" was calculated using Equation (5). Figure 6 shows a flow chart summarizing the methodology used for the calculation of the natural convection heat transfer coefficient.

$$h = \frac{Nu * k}{L_c} \quad (5)$$

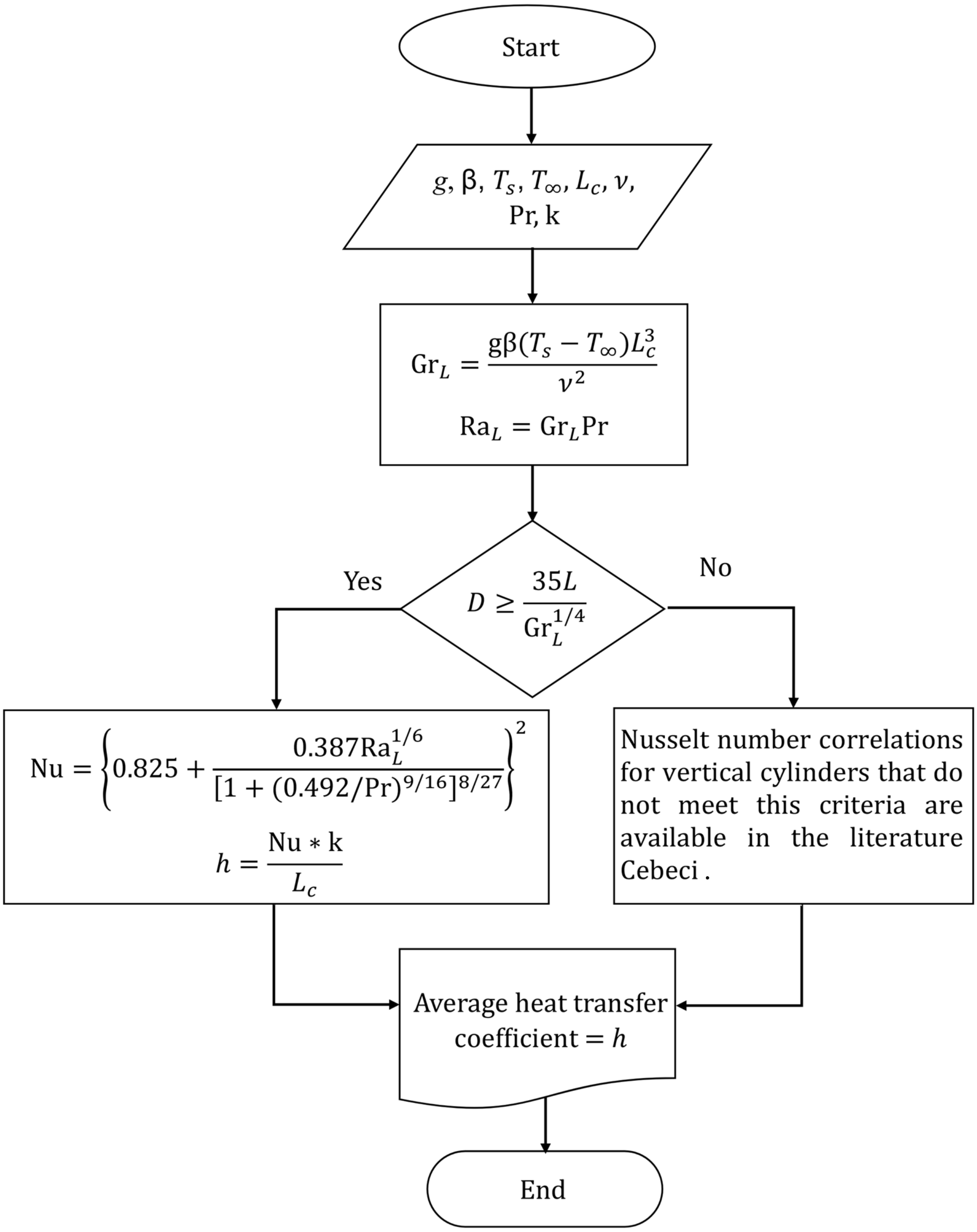



**Figure 6.** Calculation sequence of natural convection heat transfer coefficient (Cebeci, 1974) [17].

#### 3.3.2. Underground Tank

For the calculation of the heat transfer coefficient corresponding to the underground tank case, Equation (6) reported by Big Ladder software (Denver, CO, USA) was used. This software provides software tools, training, support, and consulting services for Energy-

Plus [18] to mechanical, architectural, and design engineering firms focused on the building energy modeling sector.

$$R_{soil} = 0.0607 + 0.3479 \cdot z \quad (6)$$

where "$R_{soil}$" represents the effective thermal resistance of the soil and is the inverse of the heat transfer coefficient, and "$z$" represents the depth into the soil from the surface.

## 4. Results

Figure 7 shows the tank's water temperature behavior during the absorption cooling system in the first week of operation (2977–3096 h). The solar thermal energy collection and storage subsystem started operating at the weekend (2929–2976 h) in order to reach the required temperature (≈90 °C) to activate the absorption cooling system. For Monday, at the beginning of school hours (2982 h) the temperature of the underground tank is 77.6 °C and the air-exposed tank is 72.6 °C; it is worth mentioning that this is the largest temperature difference (≈5 °C) between both cases during this week. During the rest of this week, the temperature of the underground tank is on average 2.1 °C higher than the air-exposed tank at the start of the absorption cooling system operation.

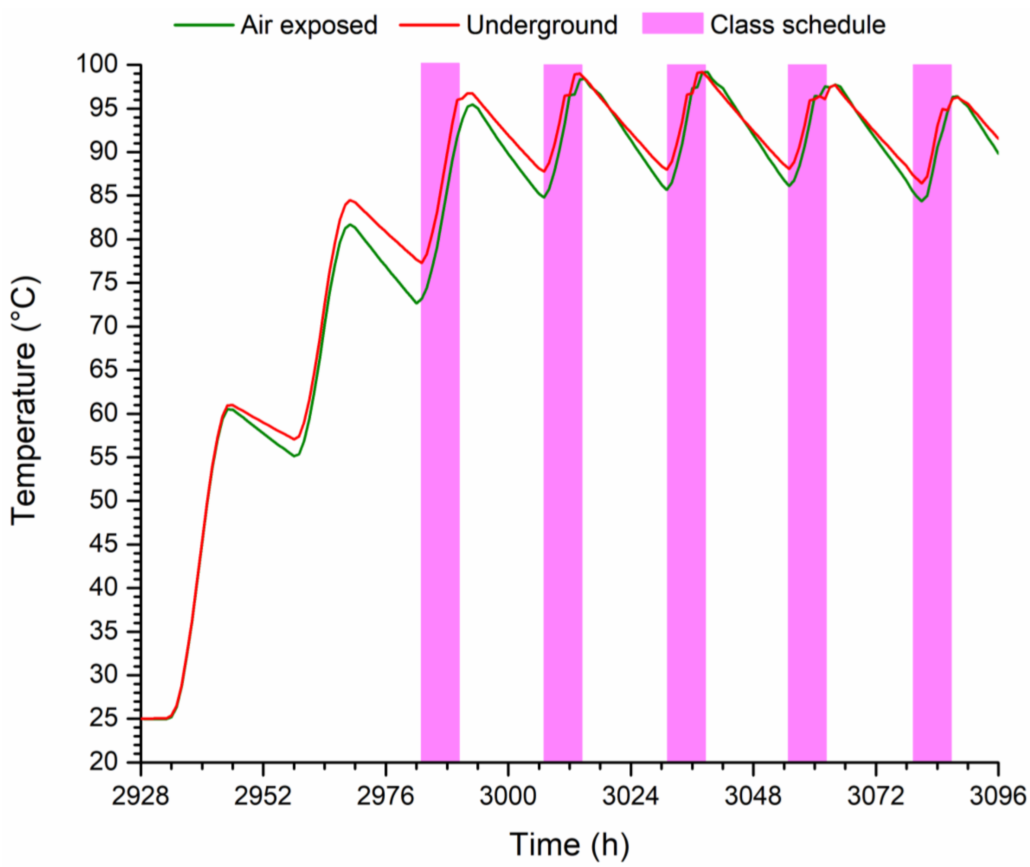



**Figure 7.** Variation of the tank water temperature during the start-up week.

Figure 8 shows that the temperature in the underground tank has a more stable dynamic during the highest classroom thermal load week, and the amplitude of the temperature variation is lower compared with the air-exposed tank. At the first hour of Monday (5833 h), the temperature of the buried tank is 91.6 °C, whereas the temperature of the air-exposed tank is 82.75 °C. During school hours, when water is extracted from the tank to activate the absorption cooling system, the temperature difference in the tanks decreases considerably. At the end of the week, the temperature of the underground tank is 91.1 °C and 85.8 °C for the air-exposed tank.

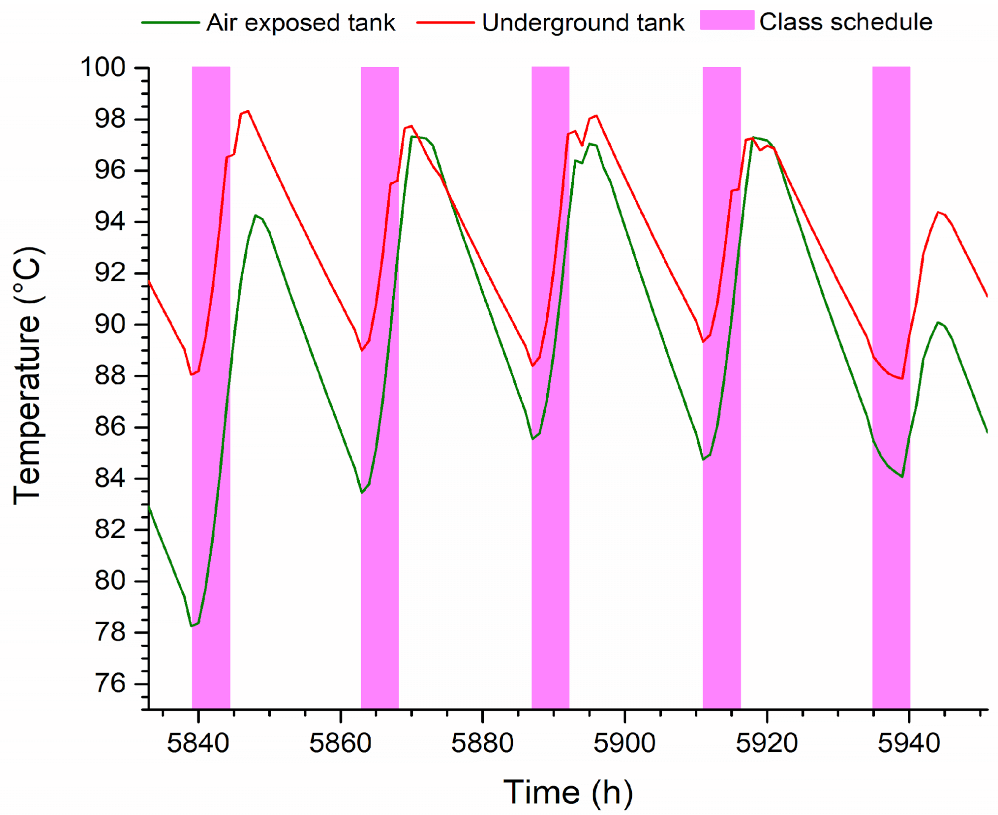



**Figure 8.** Tank water temperature behavior during the highest thermal load week.

Figure 9 shows that the temporal variation of heat losses follows the same trend as the water temperature in the tank, because as the temperature in the tank increases, the temperature difference with respect to the heat sink (air or soil) increases. The underground tank reduces heat losses during the critical week by 27.33% compared with the air-exposed tank. The maximum rate of thermal energy that dissipated to the soil surroundings is 8.1 kWh, while, for the case of the air-exposed tank, this is 11.5 kWh. The increase/decrease in thermal energy dissipated to the soil surroundings has a more linear trend because the soil temperature change during a day is negligible, as opposed to ambient air which has a greater temperature variation.

Figure 10 shows the electrical energy savings generated by the reduction of pumping time, because the pump that circulates water between the tank and the solar collectors turns on when the temperature at the solar collector row outlet is higher than the temperature of the tank. The reduction in thermal energy losses in the underground tank causes its temperature to be higher than the outlet temperature of solar collectors for a longer period of time. Monthly electrical energy savings were 146.21 kWh (22.3%) in May, 193.2 kWh (24.5%) in June, 31.3 kWh (18.7%) in August, 172.32 kWh (24.26%) in September, and 96.6 kWh (25.17%) in October.

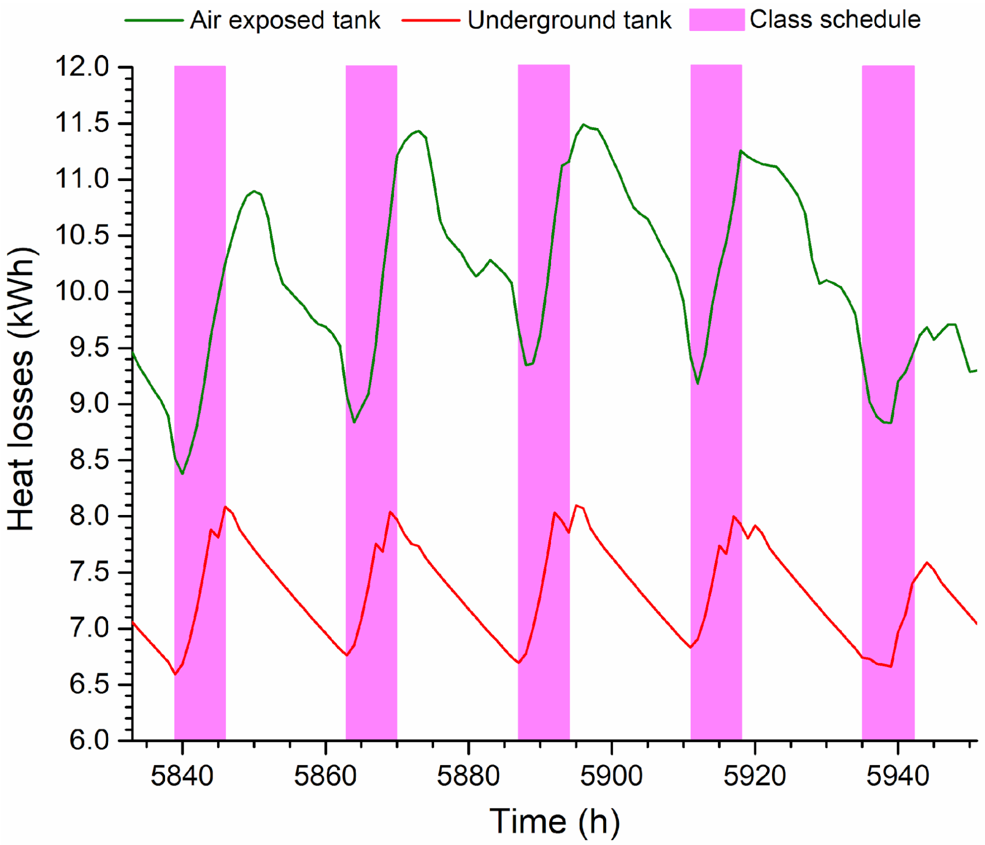



**Figure 9.** Variation of tank heat losses during the highest classroom thermal load week.

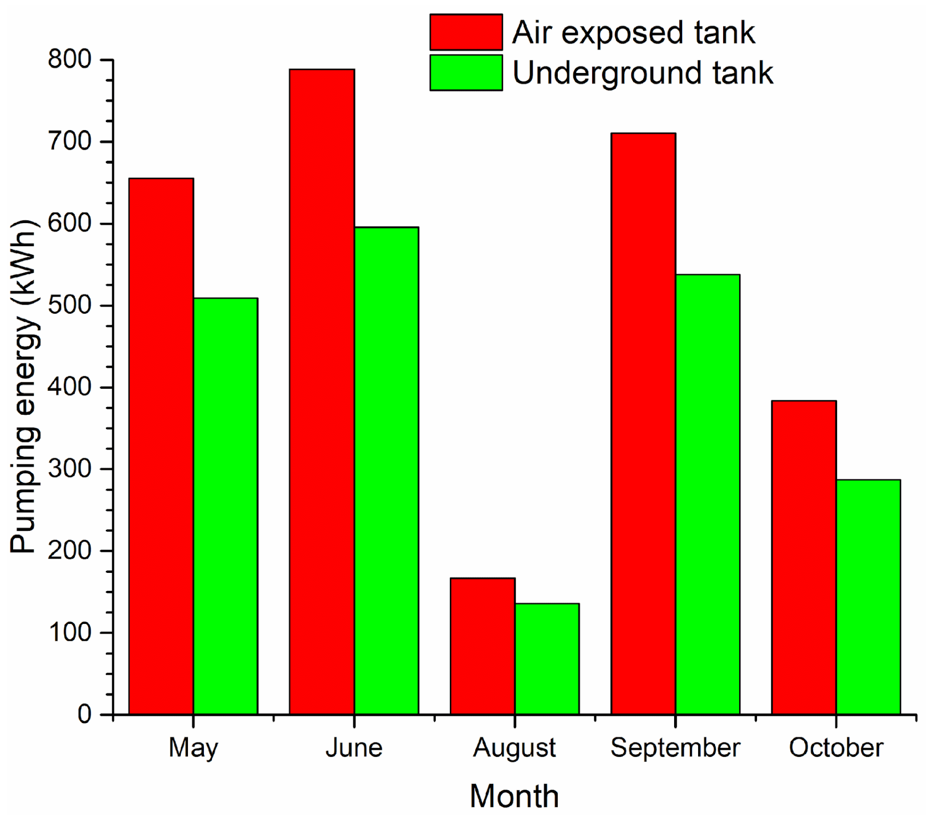



**Figure 10.** Electrical energy savings due to reduction in pumping time.

## 5. Conclusions

This paper evaluates the potential of a UTES for short-term thermal energy storage supplied by solar thermal collectors to provide hot water to activate a single-effect absorption cooling system, considering as a case of study the off-grid remote community of Puertecitos, located in northwest Mexico where rational consumption of electrical energy is essential and solar radiation levels present high values throughout the year.

The results show that the underground tank reduces thermal energy losses by 27.6% during the entire hot period, during the first stage of the hot period (May–June) by 28.1%, and during the second stage (August–October) by 24.9%, compared with the air-exposed tank. The underground tank presented higher savings during the first stage of the warm period (May–June) due to higher solar radiation values but lower ambient temperature values compared with the second warm period (August–October).

The electrical energy savings due to the reduction in pumping time during the entire hot period was 639 kWh, which represents 23.6% of the electrical energy consumption of the pump that circulates water between the tank and the solar collectors. During the first stage of the hot period (May–June), the electrical energy savings was 339.43 kWh and for the second stage it was 300.2 kWh, representing 23.5% and 23.8%, respectively. Although during the second stage the percentage of savings was higher, the performance of the underground tank was better during the first stage because it saved more electricity by 39.2 kWh and its duration was shorter by 8 days.

Based on the results, it can be concluded that using an underground tank for short-term thermal energy storage is a feasible option in areas with high levels of solar radiation, especially in areas where ambient temperature drops significantly during night hours and/or when access to electrical energy is limited. To reduce the initial investment, the excavation for burying the tank can be carried out simultaneously and using the same machinery required for constructing the foundation of a control room or other structure. In addition, the underground tank may have a longer service life by avoiding corrosion due to contact with saline environments in coastal communities; it also increases the availability of space at the installation site and can prevent vandalism.

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