Decarbonizing Building Heating Through Solar Thermal Energy and Latent Heat Storage

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Abstract

Maximizing the utilization of solar thermal energy is critical for accelerating the decarbonization of thermal energy systems. This study explores a solar heating and cooling system designed for temporary shelters, incorporating latent heat thermal energy storage (TES) using paraffin-based phase change materials. The system aims to support decarbonization of buildings by replacing conventional heating with sustainable solar heating. A prefabricated test cabin equipped with flat plate collectors and PCM tanks was monitored. Results from the heating season, show effective solar heat storage and recovery. The findings highlight the potential of latent heat TES for delivering thermal comfort in off-grid applications. Future work will focus on improving thermal energy storage performance through advanced control and efficient heat distribution.

Keywords: Buildings, Solar Heating, Decarbonization, Thermal Energy Storage, Latent Heat

1. Introduction

Solar thermal energy is the most important renewable energy source that can replace the fossil fuel-based heating systems. For accelerating transition to green heating and cooling solar thermal should be in the center of systems. For building applications, compact thermal energy storage (TES) storing heat in phase change materials (PCM) is a key component for efficient utilization of solar energy. High storage capacity of latent heat TES systems requires smaller volumes making them suitable for heating residential buildings (Liu et al., 2022).

However, there is a significant lack of long-term monitoring data on latent heat TES systems integrated with solar energy, which limits progress in optimization and broader deployment. Reliable performance data is essential to improve the design, control, and durability of these systems.

Temporary shelters are critically needed for individuals affected by natural disasters or displaced due to environmental degradation and geopolitical conflicts. This paper introduces the solar heating and cooling concept incorporating latent heat TES specifically developed for such shelters. It presents recent findings from the long-term monitoring of the system during the heating season and analyzes the impact of various operating parameters on system performance.

2. Solar heating and cooling system

The solar heating system is integrated into an insulated prefabricated cabin measuring 3.0 × 7.0 × 2.8 meters, representative of the living area found in temporary shelters within refugee camps. Solar energy is harvested using eight flat plate solar collectors (dimensions: 1.940× 0.94 × 0.10 m), each featuring a painted absorber surface and a 0.004 m tempered glass cover. Four fan coil units,

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connected in series, distribute heat throughout the cabin.

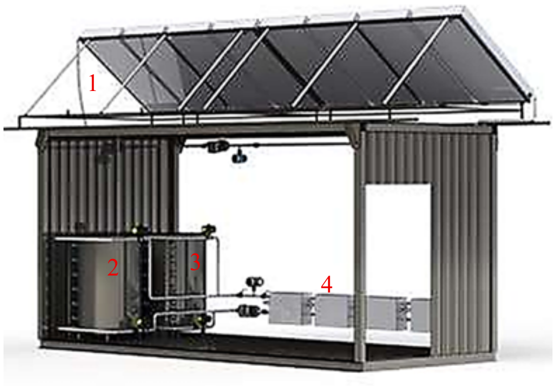


Figure 1: System concept 1) Solar collector, 2) Hot TES tank, 3) Cold TES tank, 4) Fan coils (Paksoy et al., 2024)

Latent heat storage is achieved using two cylindrical tanks (diameter: 1 m diameter, height: 1.5 m) —one designated for hot storage and the other for cold—each equipped with internal heat exchanger coils and filled with approximately 1 ton of PCM (Figure 2).

(a) **(b)**

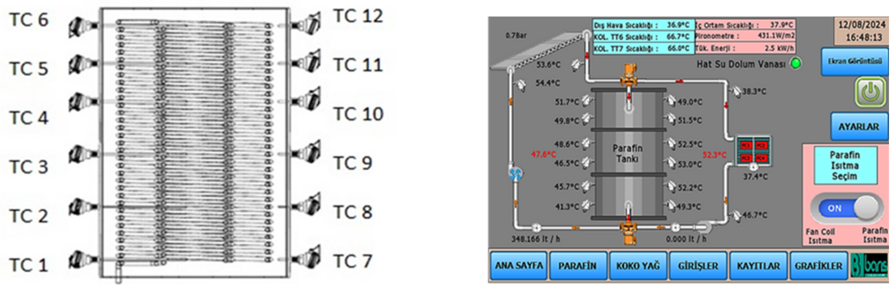
Figure 2: a) TES tanks, b) Heat exchanger coils,

Paraffin (melting range: 45 – 55°C, latent heat: 159 kJ kg^{-1}) and coco oil (melting range: 22 – 34°C, latent heat: 110 kJ kg^{-1}) are used as PCMs in hot and cold TES tanks, respectively. Figure 3 illustrates (1) the paraffin block and (2) the paraffin in its melted state within the TES tank. Two circulation pumps are employed – one for circulating heat transfer fluid (HTF) between solar collectors and TES tanks and the other for circulating HTF between TES tanks and fan coils. Two-way valves regulate HTF flow based on operational modes.

(a) **(b)**

Figure 3: a) Paraffin block, b) Paraffin melted in TES tank

The system includes a comprehensive monitoring setup that includes temperature sensors at 12 points within each TES tank (Figure 4.1), and at the inlet/outlet of collectors, indoor and outdoor spaces, and fan coils, flow rate meters in solar and fan-coil networks and energy consumption meters of pumps and fans. All system parameters, including temperature, flow rate, can be monitored and recorded in real time through the monitoring interface shown in Figure 4. System concept aims to provide 24 kWh cooling or heating when requested, which makes it possible to provide thermal comfort during 10-hour period.



(a) **(b)**

Figure 4: a) Temperature measuring points in TES tank, b) Monitoring screen

The concept developed in this study utilizes thermal energy storage (TES) to enable solar-based heating and cooling, capitalizing on the temperature difference between day and night. During the heating season, solar energy collected during the day is stored and then used to heat the shelter at night. Conversely, in the cooling season, the system exploits night-time radiative cooling—chilled water produced by nocturnal heat loss is stored and used to cool the shelter during the day. Solar thermal collectors serve a dual purpose: harvesting solar heat during the day and facilitating radiative cooling at night. In the heating season, the collectors are adjusted to an optimal tilt angle for maximum solar gain, while fan coils are used to recover the stored heat and maintain indoor comfort conditions, as shown in Figure 5. During night-time operation, infrared radiation emitted by the collectors lowers the temperature of the heat transfer fluid (HTF) near the ambient air temperature. To enhance radiative cooling efficiency, the collectors are positioned horizontally during night-time operation. A flexible piping system is integrated into the collector assembly, allowing adjustment of the tilt angle as required for optimal performance.

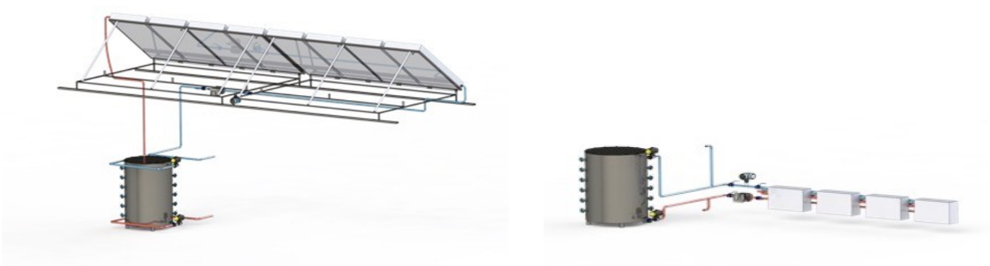


Figure 5: Collector and Fan-Coil Operation During the Heating Season

The operation of the system is divided into two primary modes: storage and recovery. In the storage mode, the process begins when the collector temperature exceeds 45°C and continues until the TES outlet temperature becomes higher than the TES inlet temperature. In the recovery mode, operation starts when the indoor temperature drops below 23°C and TES outlet temperature is less than indoor temperature, the recovery process stops when the indoor temperature rises above 25 °C.

3. Results and Discussion

Results from the long-term monitoring of the system for the heating system in the period 15 October 2024 - 1 April 2025 in Adana, Turkey is reported here. Figure 2 shows indoor and outdoor air temperatures for this period. There were some cuts in the monitoring due to maintenance or power cuts.

According to international standards (ASHRAE 55, EN 15251), the comfort temperature in buildings is expressed by equations derived from long-term monitoring of outdoor temperature data. According to ASHRAE 55, the indoor comfort temperature ($T_{comfort}$) is expressed by Equation 1, and according to EN 15251, by Equation 2 (Taleghani et al., 2013).

$$T_{comfort} = 0.31T_{out} + 17.8 \qquad \text{(eq. 1)}$$

$$T_{comfort} = 0.33T_{out} + 18.8 \qquad \text{(eq. 2)}$$

Equation 1 is determined for office buildings and equation 2 is for buildings. Based on the minimum and maximum outdoor temperatures during the period shown in Figure 2, comfort zone shown between dashed lines can be accepted to vary between 20 – 30°C.

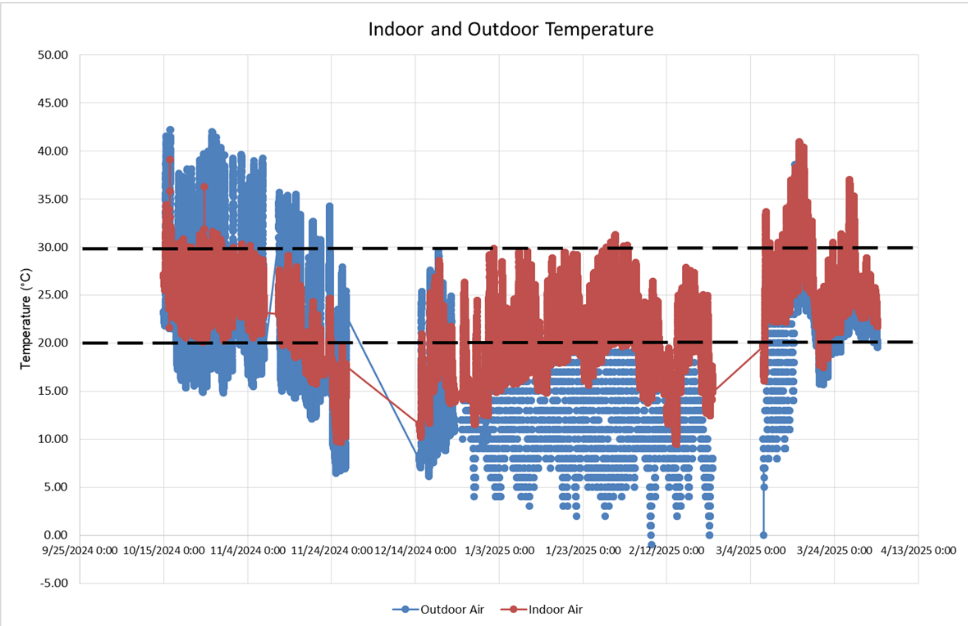


Figure 6: Indoor and outdoor temperatures during monitoring period 15 October 2024 - 1 April 2025

The performance of the system is analyzed for two days in February with high heating demand. For the days February 7th – 8th given in Figure 7, inlet (TES_{bottom}) and outlet (TES_{top}) temperatures of hot TES tank, with indoor and outdoor air temperatures are shown. During these days, outdoor minimum and maximum temperatures were -1°C and 16°C whereas, indoor temperature was minimum 12°C and maximum 27°C. The results show that indoors was kept in thermal comfort conditions for 15 hours, keeping indoor temperatures about 10°C higher than outdoors.

During this period the cabin was kept within thermal comfort zone about 65% of the time, which corresponds to a significant reduction of CO_2 emissions that can be achieved in comparison with conventional heating systems.

The green zone in Figure 7 corresponds to paraffin phase change. The encircled regions in the green zone show the melting and freezing ramps of paraffin. These indicate storage and recovery of solar heat was achieved to provide thermal comfort in the building.

The PCM stores solar heat via internal heat exchanger coils (Figure 2) in the TES unit. Mean temperature difference between TES_{bottom} and TES_{top} was 17°C during this period. This shows that effective heat transfer in the TES tanks during storage could be achieved.

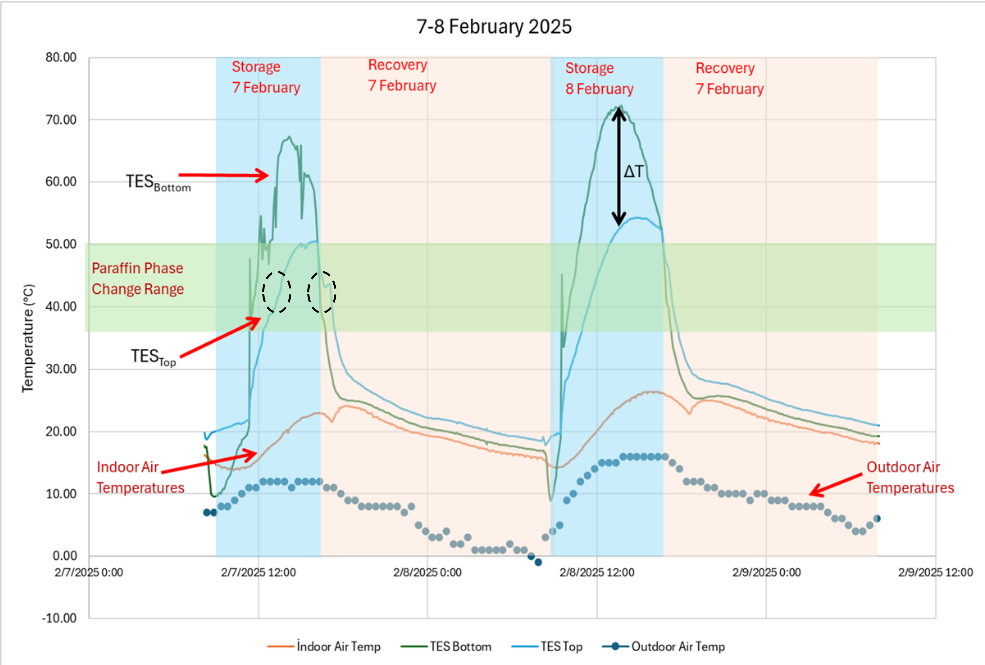


Figure 7: Monitoring results for February 7th-8th, 2025

Using monitored temperature and flow rate data at 5 min intervals total energy stored (Q_{sto}) and recovered (Q_{rec}) can be calculated. Q_{sto} (kWh) and Q_{rec} (kWh) are calculated using Equations 3 and 4.

$$Q_{sto} = \sum_{i=0}^{i=N} mC_p dT_{sto,i} dt \qquad \text{(eq. 3)}$$

$$Q_{rec} = \sum_{i=0}^{i=N} mC_p dT_{rec,i} dt \qquad \text{(eq. 4)}$$

Where dT_{sto} (°C) and dT_{rec} (°C) are delta T in TES tank during storage and delta T in fan coil units during recovery, m (kg/s) is the flow rate for storage in the collector network and recovery in the fan coil network, respectively and dt is the time interval in hours. Cp /kJ/kg°C) is the heat capacity of heat transfer fluid. Total energy stored on February 7th and 8th were 12.6 kWh (45360 kJ) and 18.9 kWh (68040 kJ), respectively. 69% and 49% of the stored energy was recovered during the night time of these days (Figure 8).

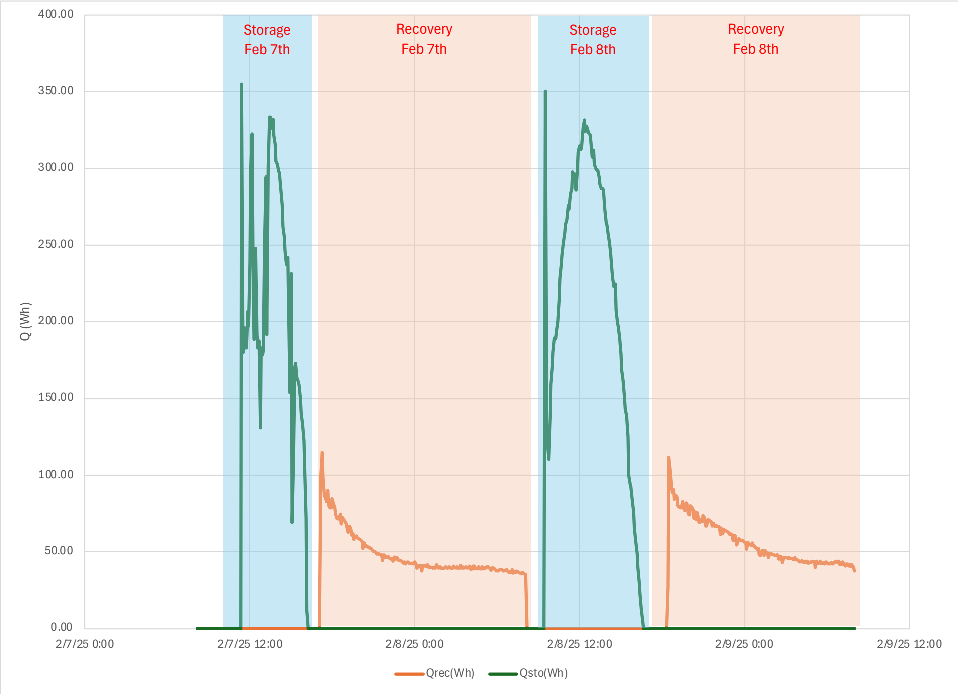


Figure 8: Q_{sto} and Q_{rec} for February 7^{th} - 8^{th} , 2025

4. Conclusions

The solar heating and cooling system integrating latent heat thermal energy storage has been specifically developed for application in temporary shelters. Long-term monitoring during the heating season confirms that solar energy can be efficiently stored in paraffin-based phase change materials (PCMs) and effectively recovered to meet the heating demand. The shelter maintained indoor conditions within the thermal comfort range for approximately 65% of the monitored period, highlighting the system's potential to significantly reduce CO_2 emissions compared to conventional fossil fuel-based heating solutions. Performance analysis of two representative days in February showed thermal storage efficiencies between 49% and 69%. To further improve system effectiveness, future work will focus on integrating high-efficiency fan coil units and developing advanced control strategies for optimized charging and discharging of the TES.

5. Acknowledgments

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