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Innovative Organic Thermal Energy Storage for Building Heating

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ABSTRACT

The paper presents the preliminary data collected during the real operation of a Latent Thermal Energy Storage (LTES) filled with an organic Phase Change Material (PCM). The installation was designed for a single dwelling that uses a radiant heating system served by a heat pump. A PV array helps the electricity self-production, and the main control system software detects the household electrical balance between auto-production, home consumptions, and surplus availability. Whenever the surplus makes available energy to run the heat pump, this energy is used to charge the LTES. During evening and/or night, the thermal energy storage releases the stored heat to satisfy the energy demands of the household.

1. INTRODUCTION

It has been estimated that up to 95% of carbon dioxide total emissions worldwide can be related with the exploitation of fossil fuels (Adom et al., 2012). In the last decades, the objective of reducing the greenhouse gas emissions has called the researchers to explore and focus on the development of innovative solutions with the aim of translating them in real applications in the next future. In this scenario, over the last decades, energy management and indoor thermal comfort have become challenging issues. Gagliano et al. (2012) reported that in the European Countries the total cooled floor area is destined to grow up to 2 billion m^2 in 2020 (it was 1000 million m^2 in 2012). Therefore, more than 100 TWh/year will be required for building cooling only. The thermal equilibrium of the buildings' indoor ambient is strictly affected by the thermal fluid-dynamic interaction of the external air with the building envelopes. This has been calling for continuous efforts in studying solutions to prevent the heat from the outdoors to be transferred into the indoor environment.

In an interesting critical review work, Cabeza and Chafer (2020) reported the passive and active strategies needed to achieve zero energy buildings (ZEBs). They can be summarized in four points:

1. Passive sustainable design: building geometry, natural lighting, natural ventilation.
2. Energy saving techniques: building envelope design, heat storage system, lighting design.
3. Renewable energy: photovoltaic system, solar thermal system, geothermal system.
4. Storage or back-up system for renewable energy: fuel cell system, district heating, district cooling, boiler.

With this purpose, Latent Thermal Energy Storage (LTES) systems seem to be a very promising technology. The LTESs take advantage of particular material denoted as Phase Change Materials (PCMs) to store thermal energy. Different PCMs can be retrieved (Sharma et al., 2009). Among the differences, their common feature is the ability of storing energy through the phase change process from solid to liquid or vice versa. In fact, the latent heat of fusion, i.e. the heat exchanged during the phase change, permits to store and/or release a higher amount of thermal energy with respect to Sensible Thermal Energy Storage systems (STESs). Furthermore, the phase change process occurs almost isothermally, stabilising the operating temperature which is beneficial for real applications. Therefore, LTESs can find applicability in diverse fields: from the building thermal management (Zhou et al., 2012) to the power generation systems (Jing et al., 2010), from heating ventilation and air conditioning applications (Rastogi et al., 2015) to the thermal management of electric car batteries (Verma et al., 2019).

This paper presents the preliminary results collected during the real operation of a LTES based on organic PCM for space heating of a household based on radiant floor system served by a heat pump connected to a PV solar array.

2. THERMAL ENERGY STORAGE AND BUILDING INTEGRATION

2.1 Thermal Energy Storage

The thermal storage object of this work is made of a double wall insulated aluminium container with external sizes of 650 x 710 mm and a height of 1400 mm. The container thickness is 50 mm filled with an insulation material to limit as much as possible the thermal losses to the surroundings. Inside the internal tank, sixteen aluminium heat exchangers based on the well-known roll-bond technology specifically designed for this application are positioned and connected in parallel to allow for the charging and discharging of the LTES.

The heat transfer fluid is the water of the heating system that was mixed with a tiny quantity of anticorrosion inhibitor to maintain the water chemical neutrality for a long time. Figure 1 shows a drawing of the designed LTES while figure 2 shows photos of the LTES installation.

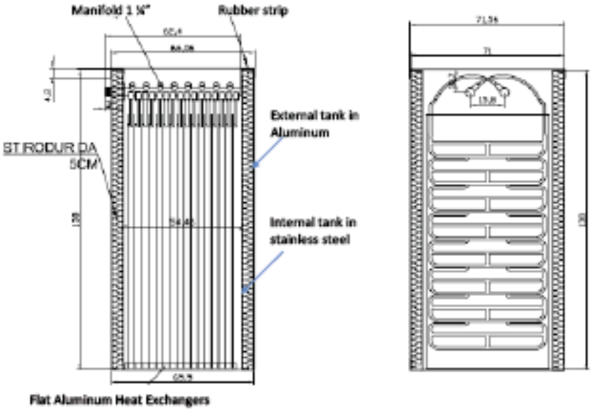


Figure 1: Schematic drawing of the LTES


(a) (b)

Figure 2: Photo of the LTES (a) and of the heat exchangers connected to the inlet and outlet manifold (b).

As shown in Figure 2b, the aluminium heat exchangers are connected in parallel to two distribution manifolds made of stainless steel. The inlet and return manifolds are connected directly to the heating system through a circulation pump activated by the storage control.


(a) (b)

Figure 3: Roll-bond heat exchanger manufacturing process: (a) ink application before bonding process; (b) finished Roll-Bond Heat Exchanger.

The roll-bond technology is an efficient and performant solution that produces one of the thinnest flat (only 1,5 mm. thickness) heat exchanger, consisting of two sheets of aluminium bonded at very high pression while leaving an appropriate designed inked circuit between the two layers. The bonded plate is then inflated by compressed air in order to create a channel between the two sheets of Aluminum. The heat transfer fluid (in this case water) circulates into this circuit and it activates immediately the whole aluminium flat panel that assumes an average temperature similar to the one of the fluid. The fast heat transfer (commonly less than 2 minutes) makes this solution smart, efficient and promising for the LTES application. The aluminium panels are light and can be easily positioned as a battery into the container internal volume. Figure 3 shows two manufacturing phases of the roll bonding process. The heat exchangers are embedded in 300 kg of organic PCM that presents a nominal melting temperature of 48°C and a melting range between 47°C and 52°C. The most important thermophysical properties are listed in Table 1.

Table 1. Most important thermophysical properties of the organic PCM

Property	Values
Nominal melting temperature	48°C
Melting temperature range	47-52 °C
Latent heat of fusion	240 kJ/kg
Solid density	810 kg/m^3

The current LTES was designed for an energy capacity of 20 kWh but the modular concept at the basis of the present design permits to flexibly increase or decrease the storage capacity according to the requirements of the application.

2.2 Building integration

The LTES was inserted in the heating system of a newly built building that was integrated with an existing refurbished one becoming an energetically efficient residential complex, thus obtaining a harmonious modern architecture built according to the most recent regulations. The dwelling is located in Castelfranco Veneto, in North-Est of Italy (45° 40' 37" N, 11° 55' 37" E). The heating and cooling system uses radiant floors for the new built part while radiant ceilings for the renovated exiting building. A schematic of the heating system is shown in Figure 4. The thermal power plant is based on a 22 kW brine-water heat pump which provides heating, cooling, and domestic hot water (DHW). The primary circuit uses a brine as heat transfer fluid and it exchanges heat with the ambient through two external finned coil heat exchangers. The secondary circuit is connected to a 400 L water storage tank

(TANK1 in Figure 4), which disconnects the heat pump and the LTES (LTES). A second 400 L water storage tank (TANK2) is used to store the excess of heat (i.e. so called de-superheating heat) to produce DHW.

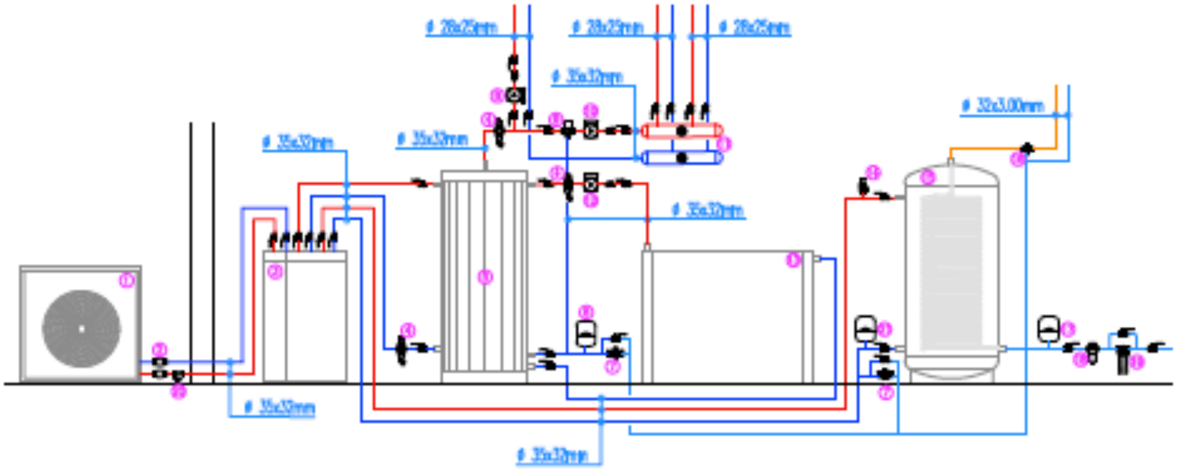
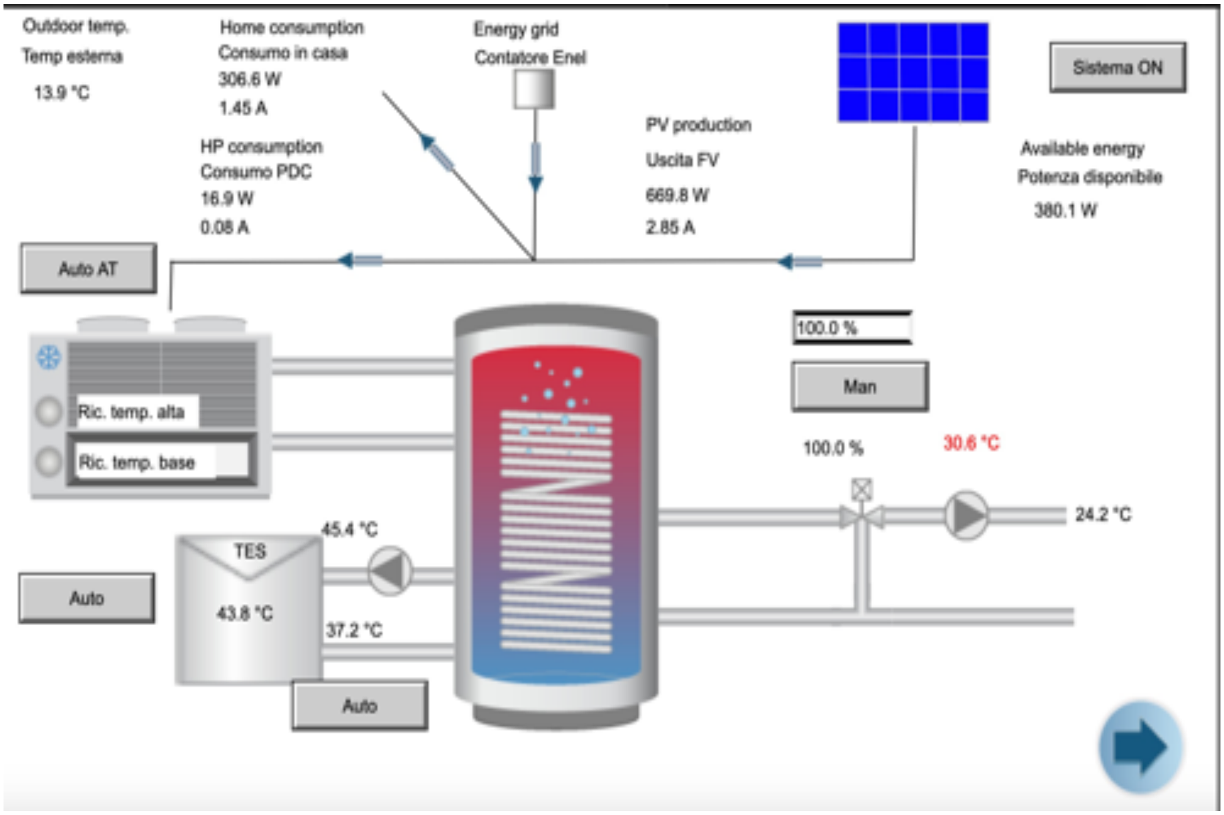


Figure 4: Schematic of the heating system.

2.3 Controlling system


Outdoor temp.
Temp esterna
13.9 °C

Home consumption
Consumo in casa
306.6 W
1.45 A

Energy grid
Contatore Enel

HP consumption
Consumo PDC
16.9 W
0.08 A

PV production
Uscita FV
669.8 W
2.85 A

Available energy
Potenza disponibile
380.1 W

TES
43.8 °C
45.4 °C
37.2 °C

100.0 %
100.0 %
30.6 °C
24.2 °C

Figure 5: Screenshot of the in-house software developed to control the entire heating system including the LTES.

Figure 5 shows a screenshot of an innovative in-house software developed to manage the entire building by continuously monitoring the measurements of the instruments used to monitor the main operating conditions. The control system analyses the instantaneous:

- power produced by the solar PV array located on the roof of the building;
- household energy consumption;
- the available energy excess that can be used to charge the LTES by running the heat pump;
- heat pump energy consumption.

The developed algorithm is able to predict the best conditions to run the heat pump as a function of several boundary conditions and constraints, for example: enough available energy to be consumed; lower energy tariffs; external ambient temperatures for higher heat pump performance, and other advantageous conditions.

The typical operation of the LTES system includes a charging phase, which usually occurs in the morning when the solar irradiation is enough to guarantee a surplus of power that can be used to run the heat pump and store the energy. In "charging mode" the hot water temperature is typically set at a temperature 5-10 K higher than that of the PCM melting point. As listed in Table 1, in this specific study, a PCM with 48 °C of melting temperature was used and thus the inlet water temperature was set at 55°C. A constant water flow rate of 29 l/h was also imposed. The charging phase ended when the water temperature measured at the outlet of the LTES was about 0.2 K lower than the inlet one, meaning that no more heat was exchanged inside the LTES.

Then, the energy stored in the LTES could have been used when requested for space heating (discharging phase) typically over the afternoon or during the evening/night. In this phase, the cold water coming back from the radiative floors was pumped through the LTES heat exchangers. Once the LTES was completely discharged (i.e. the PCM completely solidified), the heat pump guaranteed the energy required by the household.

The temperature of the LTES is monitored by means of a PT100 installed at the centre of the PCM mass in order to follow the phase change process during both the charging and discharging phases.

3. RESULTS

This section reports the results collected during the charging and discharging phases of the LTES. The system was set to charge the LTES only when a surplus of electrical power produced by the solar PV array was available. The present data was recorded over two consecutive day, February 17th and 18th 2021. Figure 6 shows the data recorded during the charging mode from completely discharged LTES. As it clearly appears, the storage temperature (i.e. the temperature measure inside the PCM in the middle of the LTES) decreased during the night with a constant slope because of the thermal losses to the surroundings. Then, at around 8:00 am there was a pre-heating phase in which the warm water from the TANK1 storage was used to increase the LTES temperature from around 25°C to 33°C. This phase lasted at 10.15 am when the electrical power generated by the solar PV was used to start the charging phase.

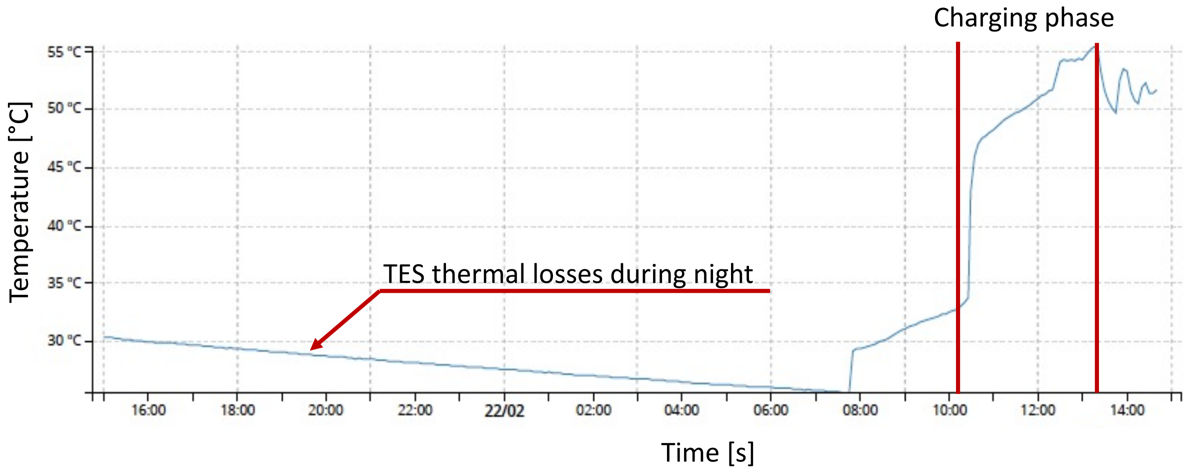


Figure 6: LTES charging phase: storage temperature as a function of the time.

A sudden increase of the storage temperature is noticeable because the hot water immediately warmed up the solid PCM, then when the lower melting temperature was achieved, the PCM temperature curve changed slope and the solid to liquid phase change started. At around 12:15 pm, the PCM temperature sharply increased because the liquid front passed through the temperature sensor and the charging process proceed until the outlet water temperature approached the inlet one, meaning that the no more heat was exchanged in the LTES. Thus, at 1.15 pm, the charging phase can be considered concluded. Immediately after the end of the charging phase, the temperature dropped down. It was possible to visually verify that the superheated liquid tended to melt a few PCM which did not melt before. The control system turned the heat pump on again to supply additional heat to the LTES. This operation was repeated until the LTES showed a constant plateau. The LTES was fully charged and the stored heat could be used to supply heat when requested by heating system of household.

Figure 7 shows another possible operation of the LTES, the data was collected on February 18th 2021, the temperature of the LTES reached around 41°C at 12.00 pm, this means that no pre-heating was needed. The solar PV powered the heat pump and the LTES was immediately warmed up and charged; at around 3.15 pm, the charging phase ended and the LTES reached a temperature of almost 52°C. The heat pump was turned off and the LTES temperature decreased stabilizing at 49°C. This means that not all the PCM was melted in this configuration, but the algorithm of the control system decided that it was not convenient to run the heat pump anymore. The temperature remained constant till 7.30 pm when the heating system of the household request started. During the discharging phase, the LTES temperature decreased almost constantly; at around 8.45 pm, the water flow rate stopped and the LTES temperature slightly increased but at 9:00 pm, heating system demand started again and the LTES continued to supply the requested heat.

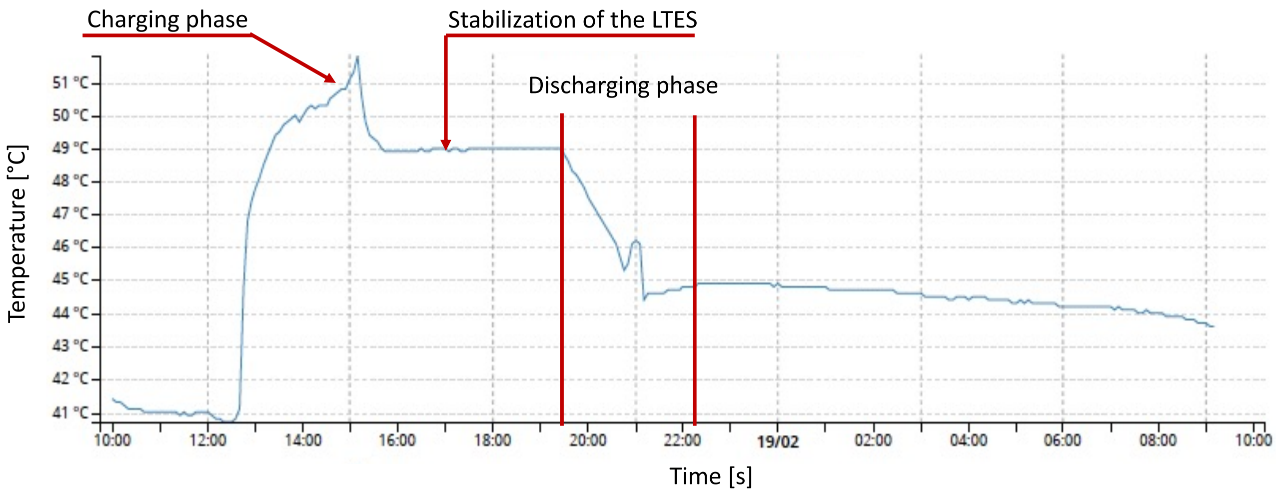


Figure 7: LTES discharging phase: storage temperature as a function of the time.

These two examples demonstrate the capabilities of the present LTES to contribute to the maximization of the self-consumption of the energy generated by the available solar PV array. Nonetheless, they also clearly show that an efficient and multi-parametric control system is needed to maximize the use of the renewable energy and limit as much as possible the energy costs while ensuring an optimized use of the thermal energy stored in the LTES.

4. CONCLUSIONS

This paper presents an experimental assessment of the operation and performance of a 20 kWh LTES integrated in a complex heating system equipped with heat pump and solar PV array of a household located at Castelfranco Veneto in the North-Est of Italy. The data collected in winter, 17th and 18th of February 2021 clearly demonstrate the capability of the LTES to store a great amount of energy using the brine-water heat pump run by the power generated by the solar PV array. The in-house developed control software allows for the maximization of the self-consumption of the renewable source while minimizing the energy costs by running the heat pump only when a surplus of energy from the PV array is available or when the cost of the energy is the lowest. The charging and discharging phases show how is it possible to shift the load and charge the storage when the renewable energy is available and supply it when requested by the heating system, leading to remarkable energy savings. Future development of the present work will involve a full characterization of the LTES at the laboratory of the University of Padova to optimize its performance and the control.

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