A low-energy storage container for food and agriculture products

Francesco Barreca, Pasquale Praticò, Giuseppe Davide Cardinali

Department of Agriculture, Mediterranean University of Reggio Calabria, Reggio Calabria, Italy

Abstract

In 2018, the food, beverages, and tobacco sectors within the EU-27 consumed approximately 27,500 ktoe of energy. The food facilities and the food production plants are responsible for a large part of this energy consumption. Current global strategies focus on energy conservation and natural environmental protection, ascribing a lot of importance to building-related analyses. Areas for food storage are essential within the food production chain, as the indoor thermal parameters determine the characteristics of the final products. In this paper, a low-energy storage container is proposed. The envelope of the container is made from sandwich panels with a polyurethane layer paired with two phase change material (PCM) layers. The container is designed to store perishable materials, such as extra virgin olive oil. A storage container prototype, equipped with a mini-split heating, ventilation, and air conditioning electric system, was built to analyse and assess the energy spent during its use. Moreover, the achievable yearly energy savings with respect to a container without the PCM layers was calculated. The results showed that the PCM layers improve the energy performance of the container at an indoor temperature of 20°C with an energy saving of about 27%, and at an indoor temperature of 17°C with an energy saving of over 22%.

Introduction

In Europe, the building sector is responsible for about 39% of energy consumption and produces over 30% of CO2 emissions; it is the biggest energy-consuming economic sector. The building sector includes a mix of residential and non-residential buildings, where industrial buildings are a large part of the second group. According to Eurostat (2021), in 2018, the food, beverages, and tobacco sectors within the European Union (EU) consumed approximately 27,500 ktoe of energy. A large part of it (over 75%) was used for food processing, distribution, preparation, and cooking (Sims et al., 2016; Ladha-Sabur et al., 2019). Environment control in food facilities and food buildings is responsible for a large part of this energy consumption. Current global strategies focus on energy conservation and natural environmental protection, ascribing a lot of importance to building-related analyses. In fact, in recent years, the EU issued a large number of directives and regulations, such as the European Green Deal (European Commission, 2019), which aim to improve energy efficiency and reduce greenhouse emissions to curb fossil fuel consumption by 2050. Reducing energy consumption in buildings has now become a critical challenge. Building retrofitting activities focus mainly on improving the thermal insulation of external walls. At same time, the building envelope plays an important role in energy savings, as it has to limit thermal loss. The amount of energy required for heating and cooling buildings is primarily determined by the thermal parameters of the external walls, which account for 25-30% of the total energy loss in buildings (Di Perna et al., 2011; Basinska et al., 2021).

Therefore, there is an urgent need to improve the thermal performance of external walls by thermal insulation in order to improve energy performance of buildings and increase energy efficiency (Barbaresi et al., 2020b). There are various solutions available for building thermal passive control, however the most traditional one is the use of high thermal insulation materials together with a high thermal capacity of the building envelope (Barbaresi et al., 2020a). In fact, thermal insulation limits heat loss, whereas thermal capacity improves the thermal inertia of the envelope, taking advantage of the external thermal daily cycle (Rosso et al., 2021).

Over last years, building technologies have proposed innovative green solutions consisting of green materials such as cork, hemp fibres, wool, cellulose fibres, and other high thermal performance synthetic materials, which all have a low thermal capacity (Barreca and Fichera, 2016; Parlato and Porto, 2020). To cope with this problem, new types of materials have been developed based on the capacity to absorb or release heat, when the material changes its phase from solid to liquid and vice versa or when the internal structure of the material changes. These materials are named phase change materials (PCM) (Osterman et al., 2012). There are three main substances that release/absorb sufficient energy during a phase transition: i) organic (carbon-containing) materials derived from petroleum, plants, or animals; ii) inorganic materials such as salt hydrates, which generally use natural salts; and iii) eutectic mixtures with a solid-to-solid phase change (Bousabbata et al., 2018).

When the PCM is solid and the environmental temperature is close to the melting temperature, the incoming energy starts a melting process. When the temperature decreases, the PCM solidifies and returns the heat to the environment (Caprara and Stoppiello, 2012). These two stages are called ‘load’ and ‘unload’.
In theory, this cycle could continue forever, but, in fact, the PCM has a range of melting/freezing cycles from 100 to 10,000 (Gao et al., 2013) (Talašová and Holeček, 2009), which depend on the type of PCM substance (Sutterlin, 2015).

The phase change of the PCM occurs at a constant temperature, and therefore, it promotes the stabilization of the environmental conditions delay the decline of polyphenols and the loss of valuable food. For this reason, a specific storage container was designed to contain extra virgin olive oil (EVOO) (Barreca and Praticò, 2019) in optimal thermal environmental conditions (Tinti et al., 2017). In this study, we proposed an innovative portable container, with a sandwich structure and two PCM layers joined to a polyurethane foam panel with two PCM layers joined to a polyurethane foam panel for the container envelope. The application of the PCM to only one side of the envelope is widely used in residential buildings and performs well as it ensures a high thermal inertia. In this paper, we analysed an innovative sandwich panel with two PCM layers, one on the inside and on the outside of the envelope. The external PCM layer was applied to absorb outdoor daytime heat and release it when the temperature cools down during the night. The internal PCM layer was applied to absorb and release heat to maintain a constant temperature around 20°C, which is a temperature value largely adopted by local olive oil producers.

The analysis and sizing of the sandwich panels were conducted by ‘PCM express’ (developed by Dr. Valentin Energie Software GmbH), a planning and simulation software for the use of PCM materials (Gourlis and Kovacic, 2016).

This prototype was monitored and analysed during use. Subsequently, we calculated the achievable annual energy savings of this innovative container.

### Thermal simulation and design of the container

The most important characteristic of PCMs are latent heat and temperature at fusion. In fact, the PCM is activated (absorbs or releases heat) only when it reaches the phase change characteristic temperature. Therefore, it is advisable to choose and maintain the correct transition temperature depending on the temperature of the indoor environment (Özonur et al., 2006). The design process requires a dynamic thermal model that takes into consideration the external heat flux and the PCM latent heat curve (Barbaresi et al., 2014). For the specific EVOO storage container, an analysis was conducted on the possible combinations among three PCM layers of the product by INSOLCOR® with different transition temperatures, i.e., 18, 21, and 25°C. These temperature values were chosen because they were the values closest to the reference temperatures on the market. The PCM software is a commercial software based on a finite difference mathematical method to simulate PCM behaviour. For the analysis, an indoor temperature value of 20°C, constant in winter and summer, and an electric HVAC with a maximum cooling output of 100 W m⁻² were considered. The International Weather for Energy Calculations file (IWE 164200) was used to calculate the external temperature. A simulation was carried out by means of PCM express for each layered combination to calculate the yearly energy spent to maintain a constant temperature of 20°C inside the container. The thermal characteristics of the different layers of the container envelope are reported in Table 1. The panels with PCM21+Pu+PCM25 layers and with PCM21+Pu+PCM21 proved to be the best solutions. For both, the amount of energy used per annum was around 1160 kWh. The first

### Materials and methods

This innovative portable container was conceived for temporary storage of EVOO bottles and cans and was kept outside an olive oil company in Rizziconi, a small town in southern Italy. Generally, the best conditions for storing EVOO for a long period of time are a dark environment with a temperature in the range of 8-22°C with low humidity and no direct sunlight. These environmental conditions delay the decline of polyphenols and the loss of the nutritional and taste qualities of this important and valuable food product. For this reason, a specific storage container was designed with a size of about 14 m², a rectangular shape of about 2.50 x 6.00 m, and an internal height of 2.4 m (ISO container measure) (Figure 1).

Temperature control is guaranteed by means of a 1.25 kW HVAC mini electric split with an inverter system. It was chosen to

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**Figure 1. Layout of the low-energy storage container designed for food and agricultural products.**

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**Table 1.** The panels with PCM21+Pu+PCM25 layers and with PCM21+Pu+PCM21 proved to be the best solutions. For both, the amount of energy used per annum was around 1160 kWh. The first
solution (1158.91 kW h) is slightly lower than the second. The one with the lowest consumption was chosen (Table 2).

### Prototype monitoring

The container prototype with a building envelope made of three layers (PCM 21 + Pu + PCM 25) (Figure 2B) was built and positioned on free land and exposed to weather conditions (Lat. 38.40° N; Long. 15.95° E.). It was equipped with a 1.25 kW HVAC split system, with an energy efficiency ratio equal to 2.81, a coefficient of performance in heating (COPh) equal to 3.95, and a coefficient of performance in cooling (COPc) equal to 2.84 (Figure 3). The weather parameters of the site were surveyed by means of a first class Piranometer (LSI-LASTEM DPA 154 model) for solar irradiance measurement, a thermohygrometer completed with a natural ventilation anti-radiant shield (LSI-LASTEM DMA 672 model) for measuring air temperature and relative humidity. The inside thermal parameters were measured by means of a net of sensors linked to a data logger that recorded the thermal parameters every 15 min. The indoor net was composed of a Psychrometer sensor with wet and dry bulbs and forced ventilation to measure the inside air temperature. Two plate sensors, one heat flow meter to measure the envelope surface temperature, and one heat flow meter to measure the heat flow that crossed the envelope were used. An energy cost measuring device (Voltcraft Energy Logger 4000) that recorded data every 15 min was connected directly to the electric grid to monitor the energy usage by the HVAC system.

The prototype was monitored from 01.08.2020 to 30.11.2020. The monitoring period was divided into two phases, the first was from 01.08.2020 to 30.09.2020 and the second was from 01.10.2020 to 30.11.2020. The indoor temperature was maintained at round 20°C during the first period. To test the pro-

### Table 1. The thermal characteristics of sandwich panel layers.

| Materials               | Thickness (mm) | Density (kg·m⁻³) | Specific heat capacity (kJ·kg⁻¹·K⁻¹) | Thermal conductivity (W·m⁻¹·K⁻¹) | Resistance (m²·K·W⁻¹) | Melt point temperature (°C) | Latent heat (kJ·kg⁻¹) |
|-------------------------|----------------|------------------|-------------------------------------|---------------------------------|-----------------------|-----------------------------|-----------------------|
| Polyurethane core       | 40             | 35.00            | 1.59                                | 0.02                            | 1.82                  |                             |                       |
| PCM 25°C                | 6              | 900.00           | 3.14                                | 0.54 (liquid phase)              | 0.0111 (liquid phase) | 25                          | 2.32                  |
|                         |                |                  | 1.09 (solid phase)                  |                                 | -0.0055 (solid phase) |                             |                       |
| PCM 21°C                | 6              | 900.00           | 3.14                                | 0.54 (liquid phase)              | 0.0111 (liquid phase) | 21                          | 2.32                  |
|                         |                |                  | 1.09 (solid phase)                  |                                 | 0.0055 (solid phase)  |                             |                       |
| PCM 18°C                | 6              | 900.00           | 3.14                                | 0.54 (liquid phase)              | 0.0111 (liquid phase) | 18                          | 2.32                  |
|                         |                |                  | 1.09 (solid phase)                  |                                 | 0.0055 (solid phase)  |                             |                       |

### Table 2. Energy consumption for different sandwich panel layer combinations (internal, intermediate, and external).

| In                 | M  | Ex | Temperature (°C) | Heating energy consumption (kW-h) | Cooling energy consumption (kW-h) | Yearly energy consumption (kW-h) |
|--------------------|----|----|------------------|----------------------------------|----------------------------------|---------------------------------|
| Pu                 | 20 |    | 20               | 782.59                           | 988.74                           | 1771.33                         |
| PCM18              | Pu | PCM21 | 20              | 435.76                           | 916.35                           | 1352.11                         |
| PCM18              | Pu | PCM25 | 20              | 566.69                           | 907.40                           | 1474.09                         |
| PCM18              | Pu | PCM18 | 20              | 311.31                           | 921.85                           | 1233.66                         |
| PCM21              | Pu | PCM25 | 20              | 254.96                           | 903.95                           | 1158.91                         |
| PCM21              | Pu | PCM21 | 20              | 259.85                           | 903.84                           | 1163.69                         |
| PCM25              | Pu | PCM25 | 20              | 324.01                           | 936.81                           | 1260.82                         |

In, internal; M, intermediate; Ex, external; PCM, phase change material.
totype at different temperatures, the indoor temperature was maintained around 17°C during the second period.

For each month during the monitoring period the average daily trend of the global sun radiation, and the indoor and outdoor air temperature were calculated using Equation (1). These thermal parameters described the conditions of a monthly ‘generic day’ (Figure 4).

\[
G(t_i) = \frac{\sum_{k=1}^{n} G_k(t_i)}{n}
\]

where:

- \( G(t_i) \) is the mean value of the parameter \( G \) at a generic time \( t_i \) for the ‘type of day’,
- \( G_k(t_i) \) is the value of the parameter \( G \) at a generic time \( t_i \) of day \( k \), and
- \( n \) is the number of the monitored days during the period.

Results and discussion

August was the hottest month during the experimental period. The external weather sensors detected a maximum sun radiation of about 1200 W·m\(^{-2}\) and a maximum air temperature of 32°C.

For this month, the daily mean heat flux was below 4 W·K\(^{-1}\)·m\(^{-2}\) until 2:00 pm and was followed by an increasing trend until 6:15 p.m., up to 7.17 W·K\(^{-1}\)·m\(^{-2}\), and a decreasing trend below 4 W·K\(^{-1}\)·m\(^{-2}\) until 11:15 pm.

The daily sun radiation reached a peak of 1.028 W·m\(^{-2}\) at 1:15 pm when, at the same time, the daily outdoor air temperature reached a max value of 33.24°C.

The average daily temperature in August highlighted a temporal phase shift of about 5 hours between the daily sun radiation trend and the daily heat flux trend (Figure 5).

This temporal phase shift was determined using the external layer of PCM which, at a temperature of 25°C, started to melt and to absorb the heat and delayed the incoming heat flow. When the temperature decreased, the PCM solidified and released latent heat into the environment (Figure 6).

![Figure 4. The global radiation, and indoor and outdoor air temperature of a generic day in August (A), September (B), October (C), and November (D).](image)

![Figure 5. The mean daily global radiation and mean daily heat flux in August.](image)

![Figure 6. Operating principle of the container during the seasons. PCM, phase change material.](image)
The monthly energy used by the HVAC split system to condition the temperature of the indoor environment and to maintain a constant temperature of 20°C for the first monitoring period is reported in Table 3. The maximum energy measured was about 6.18 kWh on 20th August, while the total consumption during the period was 221.06 kWh.

During the second monitoring period, the daily energy used by the HVAC split system was measured to condition the temperature of the indoor environment and to maintain a constant temperature of 17°C to evaluate the performance of the prototype with a different design temperature.

The max monthly energy measured was 45.71 kWh in October, and the total measured energy consumption was around 63.05 kWh (Table 4).

The prototype was modelled by means of the DesignBuilder software. DesignBuilder is an Energy Plus-based software tool used for energy measurement in buildings and is a transient heat conduction solver (Jaffal and Inard, 2017). The calculation was carried out with the finite-difference method. For the accuracy of the model, it is important to define the envelope thermal material parameter values such as thickness, density, specific heat capacity, thermal conductivity, resistance, and melting point temperature of the PCM (Table 1) (Barreca et al., 2017). In particular, it is important to define the correct function of the temperature enthalpy for the PCM (Figure 7), which is adopted in the energy model, because it is specific for each PCM product (Zastawna-Rumin et al., 2020). The producer of the PCM has to release this data, because they are very important for the numerical simulation.

The accuracy of the energy analysis is also correlated with the meteorological data set precision. A thermal analysis simulation was conducted with reference to the climate parameters surveyed on site during the first monitoring period. The electric energy consumption was estimated by the analysis simulation to control the indoor air temperature at around 20°C.

These results were compared with the real energy consumption values that were measured during the first monitoring period (Figure 8). A comparison between the measured values and the calculated values confirmed the reliability of the prototype energy model. In the ASHRAE guidelines 14 (Haberl et al., 2005), two statistical indices are used to determine the compliance of the simulation model and the uncertainty of the analysis. The first is the mean bias error (MBE), which is found by first calculating the difference between measured energy consumption and simulated energy consumption for a given time period. The differences are then summed up and divided by the sum of the measured energy use over the same time period. The second statistical index, which indicates the uncertainty of the model results, is the coefficient of variation of the root mean squared error CV(RMSE).

\[
MBE = \frac{\sum_{i=1}^{n} (m_i - s_i)}{\sum_{i=1}^{n} m_i}
\]

where
\(m_i\) is the measured value,
\(s_i\) is the simulated value, and
\(n\) is the number of measure data points.

\[
CV(RMSE) = \frac{1}{\overline{m}} \sqrt{\frac{\sum_{i=1}^{n} (m_i - \overline{s})^2}{n}} \times 100\%
\]

where
\(m_i\) is the measured value,
\(s_i\) is the simulated value,
\(n\) is the number of measure data points, and
\(\overline{m}\) is the mean of measured values.

Table 3. Energy consumption measured to maintain an indoor temperature of 20°C with an envelope composition with layers of PCM21+Pu+PCM25.

| First monitoring period | Energy [kWh] |
|-------------------------|--------------|
| August                  | 136.87       |
| September               | 80.56        |
| Total                   | 217.43       |

Table 4. Energy consumed to maintain a temperature of 17°C inside the prototype with an envelope layer composition of PCM21+Pu-PCM25.

| First monitoring period | Energy [kWh] |
|-------------------------|--------------|
| October                 | 45.71        |
| November                | 17.34        |
| Total                   | 63.05        |

Figure 7. The enthalpy curve of phase change material at 25°C.

Figure 8. A comparison between the measured and estimated electric usage for a container with a single Pu layer and phase change material (PCM) 25-Pu-PCM 21 sandwich panels during the first monitoring period.
The CV(RMSE) is calculated by dividing the root mean squared error by the measured mean of the data. MBE=0.70% and CV(RMSE)=14.34% were obtained for the case study. The same energy model was also considered for the second monitoring period. The values of MBE=-0.03% and CV(RMSE)=7.26% were obtained. These statistical indices confirmed the model reliability, and allowed us to carry out other energy simulations. In particular, a specific simulation was carried out to assess the thermal performance of the storage container at 17°C without the two PCM layers matched to the envelope layers. The energy calculated for the storage container without PCM was 48.73 kWh (lower by 22.72%) compared to the energy used by the prototype (63.05 kWh) to maintain a temperature of 17°C (Figure 9). A comparison of the energy consumed by the container prototype and the same container without the PCM layers (Figure 6), maintaining a temperature of around 20°C from August to September, led to energy savings of about 59.64 kWh, over 27% of the total energy spent. The same analysis conducted for the months of October and November, but maintaining a temperature of 17°C, showed a higher energy usage (+23%) for the prototype monitored compared to the energy model without the two PCM Layers. During this period, the HVAC used electric energy to heat the indoor environment, because the external mean daily air temperature was lower than the indoor temperature for several hours (Figure 4C and D). It is important to note that the choice of the two PCM layers was made with specific reference to a constant temperature of 20°C. A different temperature range used caused a system malfunction and an increase in energy used to control the temperature. The prototype showed a high performance during the hottest period when it is more important to limit high temperatures for better storage of agriculture and food products. In particular, the surveyed indoor temperature showed a constant trend in both monitored periods. This effect was due to PCM heat stabilization. The constant temperature trend is important to limit food and agricultural product waste and shorten the time during which the HVAC system is in use.

Similar studies highlighted that the PCM can be employed for excess temperature control and to reduce the amount of cooling energy used in houses (Ozdene and Dewsbury, 2016). Its growing application for food and agriculture product storage above all in agricultural farms could be an important way of supporting sustainable agriculture, the farm economic performance, and consumers who will eat safer and healthier products (Barreca and Cardinali, 2019).

### Conclusions

The results showed the high efficiency of the container prototype designed. The PCM layers improve the energy performance of the container by about 30%, although it is necessary to highlight the importance of the choice and use of the correct melting temperature of the PCM. In fact, an incorrect choice of the PCM melting temperature does not lead to energy savings and rather can sometimes increase the energy usage, as was shown by the results. In particular, the two layers of PCM allowed us to obtain a high energy saving for cooling, because the external PCM layer with a melting temperature of 25°C absorbed outdoor heat at the hottest time of day, releasing it into the environment, when the external temperature decreased. The internal PCM layer, which has a melting temperature close to 20°C, stabilized the indoor temperature at around this value; therefore, the HVAC system used less electrical energy to condition the environment. A comparison between the simulated values, in particular of the energy usage, showed the high reliability of the simulation model developed using the Design builder and Energy plus software. It is important to note that the accuracy of the results is correlated with all the model parameters, which mainly depend on the accuracy of the material thermal characteristic values and the weather parameters. For these reasons, in this study it was fundamental to know the enthalpy function of the PCM layers used, which the manufacturer made available to us, and the out-

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**Figure 9. A comparison between the measured prototype energy and estimated energy usage by a container with a single Pu layer and phase change material (PCM) sandwich panels during the second monitoring period.**

**Table 5. Energy consumption measured to maintain a temperature of 17°C inside the prototype.**

| Energy used by Prototype | October [kWh] | November [kWh] | Total  |
|--------------------------|---------------|----------------|--------|
| Measured                 | 45.71         | 17.34          | 63.05  |
| Model with PCM           | 43.51         | 35.34          | 61.64  |
| Model without PCM        | 28.14         | 20.59          | 48.73  |

PCM, phase change material.
door thermal parameters surveyed during the prototype monitoring period. The prototype of the storage unit showed a high energy saving only during the hot season. Future research should be conducted to develop an HVAC split system for the storage unit, fed by a standalone photovoltaic panel system, that will make the storage unit a nearly zero-energy cool space.

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