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Utilization of an Air-PCM Heat Exchanger in Passive Cooling of Buildings: A Simulation Study on the Energy Saving Potential in Different European Climates

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Abstract: The energy saving potential (ESP) of passive cooling of buildings with the use of an air-PCMheat exchanger (cold storage unit) was investigated through numerical simulations. One of the goals of the study was to identify the phase change temperature of a PCM that would provide the highest energy saving potential under the specific climate and operating conditions. The considered air-PCM heat exchanger contained 100 aluminum panels filled with a PCM. The PCM had a thermal storage capacity of 200 kJ/kg in the phase change temperature range of 4 °C. The air-PCM heat exchanger was used to cool down the outdoor air supplied to a building during the day, and the heat accumulated in the PCM was rejected to the outdoors at night. The simulations were conducted for 16 locations in Europe with the investigated time period from 1 May–30 September. The outdoor temperature set point of 20 °C was used for the utilization of stored cold. In the case of the location with the highest ESP, the scenarios with the temperature set point and without the set point (which provides maximum theoretical ESP) were compared under various air flow rates. The average utilization rate of the heat of fusion did not exceed 50% in any of the investigated scenarios.

Keywords: energy conservation; latent heat thermal energy storage; phase change materials; passive cooling

1. Introduction

Many countries, especially in Europe, have adopted a number of requirements on the energy performance of buildings in the last several decades in order to make the building stock more energy efficient [1]. The early energy saving policies focused mainly on energy consumption for space heating. The requirements on the thermal resistance of building envelopes have been repeatedly tightened. As a result, the transmission heat loss of newly-built and renovated buildings has decreased significantly and so has the amount of energy needed for space heating. As the transmission of heat loss decreased, the ventilation heat loss and its impact on the energy consumption of buildings became more important. Consequently, various approaches to the reduction of ventilation heat loss have been introduced. Mechanical ventilation with heat recovery has become more common in many types of buildings, and various energy saving strategies for building ventilation were developed. "Build tight—ventilate right" [2] is becoming a widely-adopted approach in the building sector. The air tightness testing is now a rather standard procedure during building construction, particularly in the case of passive buildings.

Well thermally-insulated buildings with a high air tightness level brought about problems with thermal comfort during the warm part of year. This is one of the factors contributing to the increasing demand for space cooling in Europe [3]. The actual energy consumption for space cooling in buildings is more difficult to determine than the energy consumption for space heating. The energy consumption for space heating can often be obtained or estimated based on the amount of consumed heat or fuels. On the other hand, the energy used for space cooling is mostly in the form of electricity and needs to be obtained from consumption of electricity [4]. Nonetheless, the consumption of energy for space cooling in buildings is becoming a concern even in climates where space cooling was not an issue several decades ago [5]. This development brought about an interest in passive cooling of buildings. Many studies have been conducted in this area since the beginning of the 21th Century. Artmann et al. [6] assessed the climatic potential for passive cooling of buildings by night-time ventilation. The analysis was carried out for 259 locations in Europe. The authors concluded that there was a "very significant" potential for passive cooling by night-time ventilation in Northern Europe. In Central and Eastern Europe and some parts of Southern Europe, the authors assessed the potential of this passive cooling technique as "significant". However, the authors pointed out that "floating building temperature is an inherent necessity of this passive-cooling concept". Passive cooling by night-time ventilation is thus mostly suitable for the buildings that are not occupied at night and where low air temperatures and relatively high air velocities during night-time ventilation would not cause discomfort.

Another issue with passive cooling of buildings by night-time ventilation is thermal energy storage. For this passive cooling technique to work effectively, cold needs to be stored at night in order to be available for the next day. Cold is usually stored in the building structures, and thus, night-time ventilation works best in buildings with high thermal mass. As many new buildings consist of light-weight building structures, additional thermal mass needs to be provided for passive cooling to work effectively [7].

Some of the problems of passive cooling of buildings (e.g., lightweight construction or large swings in indoor air temperature) could be mitigated by the use of cold storage units. The cold can be stored in the cold storage unit at night and then utilized during the day. This approach has been used in mechanical cooling systems for decades in the form of ice storage. The use of cold storage in passive cooling makes it possible to avoid supplying large volumes of cool outdoor air into the building at night and thus compromising thermal comfort. Cold can be stored in the cold storage unit at night and utilized the following day.

A number of studies have been conducted in the area of energy saving with latent heat thermal energy storage (LHTES) under various climatic conditions. Arkar and Medved [8] reported investigations of PCM-based LHTES integrated into the ventilation system for free cooling of a building. The LHTES unit was a cylindrically-packed bed comprising spherical containers filled with the encapsulated RT20 paraffin-based PCM (Phase Change Material). A mathematical model of the LHTES unit was created as a 2D continuous-solid-phase packed-bed model. The model was validated with the experimental results obtained for the packed bed with spheres of two diameters; 50 mm and 37.6 mm. The developed model was then used to obtain the multi-parametric temperature-response function of the LHTES unit in the form of a Fourier series. The temperature-response function allowed for calculation of the outlet air temperature of LHTES in the case that the inlet air temperature was approximated with a smooth periodic function. The thermal-response function was then used in the TRNSYS simulation tool for the investigation of free cooling in the case of a low-energy house. In the studied case, 6.4 kg of PCMper m^2 of floor area was found as an optimum value. The same authors [9] investigated the correlation between the local climate and the free-cooling potential of LHTES. The same packed bed LHTES, as in the previous paper [8], was considered. The climatic data of six cities in Europe were used in the study, and the simulated time period was from 1 June–31 August. The free-cooling potential was assessed in terms of the cooling degree hours (CDH). As no building characteristics or cooling set point were considered, the adopted approach provided the maximum theoretical cooling potential for the specific climatic conditions and the ratio between the air flow rate and the mass of the PCM. The authors concluded that the wide melting range of a PCM was not a disadvantage in free cooling of buildings. The optimum melting temperature of PCM was 2 °C above the average outdoor air temperature at the location in the investigated time period, and the optimum ratio between the mass of PCM and the air flow rate was 1–1.5 $\frac{kg}{m^3/h}$.

Chen et al. [10] investigated the energy saving potential of a ventilation system with a latent heat thermal energy storage (LHTES) unit under different climates in China. The authors used an in-house-developed model of the LHTES unit (air-PCM heat exchanger). The LHTES unit consisted of 20 parallel PCM slabs, which were 1.5 m long, 0.5 m wide, and 0.01 m thick. The air gaps between the slabs were 0.01 m high. The thermophysical properties of $CaCl_2 \cdot 6\,H_2O$ were considered in the study with the exception of the melting temperature. The optimal melting temperature for each location was obtained by simulations. An isothermal phase change of the PCM was considered. The simulations were done for eight cities in China for the time period from 1 June–31 August. The average outdoor air temperature in the studied locations varied from 21.3 °C (city of Harbin) to 28.0 °C (city of Guangzhou). The study showed that the optimal PCM melting temperature varied from 21 °C in the case of Harbin to 29 °C in the case of Guangzhou. The average utilization rate of the heat of fusion of the PCM ranged from 0.09 in Shanghai to 0.24 in Beijing. Beijing was also the location with the highest electricity savings (87 kWh).

Costanzo et al. [11] used the EnergyPlus simulation tool to investigate the contribution of the PCM mats, installed behind the plasterboards, on the energy need for cooling and also thermal comfort in an air-conditioned office building with a large glass area. The PCM considered in the study was a fatty acid-based organic material. Three commercially-available variants of the material with the peak melting temperatures of 23 °C, 25 °C, and 27 °C were considered. The non-isothermal phase change without hysteresis with the melting range of about 2 °C was assumed. The summer climatic conditions of three cities in Europe (Rome, Vienna, and London) were used in the study. The authors concluded that the peak values of the operative temperature were reduced by about 0.2 °C when the PCM was used in comparison to a basic scenario without the PCM. The average reduction of the peak cooling load was around 10%, and the cooling energy need was reduced by 6%–12%.

An inverse method to estimate the average air flow rate through the air-PCM heat exchanger in free-cooling operation was proposed in [12]. The air-PCM heat exchanger (HEX) consisted of PCM slabs separated by air gaps. The air flow rate was estimated with the use of experimentally-obtained temperatures at the exit of the heat exchanger. MATLAB and COMSOL Multiphysics were used in the simulations. Considering the plane symmetry, only a half of the PCM slab thickness and a half of the air gap were modeled. Different apparent heat capacity curves were considered in melting and congealing of the PCM (i.e., phase change hysteresis). The authors reported fairly good agreement between the measured air flow rates and the air flow rates obtained by the proposed inverse method. The investigation was the first step in the optimization of the air flow rates with regard to the melting and congealing processes.

The goal of the present simulation study was to assess the energy saving potential of passive cooling of buildings, with the use of an air-PCM heat exchanger, when considering a cooling set point that would allow addressing both the ventilation cooling load and the internal cooling loads. In the study conducted by Chen et al. [10], the temperature set point for the utilization of stored cold was 26 °C as the ventilation cooling load was addressed. Moreover, an isothermal phase change of the PCM was assumed, which is rather rare in the case of most real-life PCMs. A lower temperature set point makes it possible to utilize the stored cold for the removal of indoor cooling loads, and it leads to higher utilization rates of the available cold storage capacity of the air-PCM HEX. In the simulation study presented by Medved and Arkar [9], no temperature set point was considered for the utilization of stored cold. Such an approach provides the maximum theoretical utilization rate of cold storage capacity, but it overestimates the real-life potential of passive cooling (particularly in cold climates). These issues were the motivation for the present simulation study, and the authors aimed at taking them into account. The air-PCM HEX considered in the present study was different from the one (a packed bed) considered in [9]. The present study revealed significant difference between the "optimal" ratio between the mass of the PCM and the air flow rate in the case of the air-PCM HEX consisting of parallel PCM slabs (panels) and the cylindrically-packed bed of spherical containers filled with the encapsulated PCM [9].

2. Simulated Scenario

The need for space cooling in buildings depends on many factors; most of them building-specific (thermal resistance of the building envelope, area of glazing, ventilation rates, internal heat gains, cooling set point, etc.). Certain assumptions about the operation of cold storage had to be made in order to assess the energy saving potential of passive cooling with an air-PCM heat exchanger (air-PCM HEX) without considering building-specific parameters. The actual amount of cold that can be stored in and released from an air-PCM heat exchanger depends on the temperature of air passing through the air-PCM HEX. In the case of passive cooling, the outdoor air flows through the air-PCM HEX during both rejection of heat (at night) and utilization of cold (during the day). For that reason, the outdoor air temperature was the most important factor in the study. The lower the outdoor air temperature, the larger the amount of cold that can be stored in the air-PCM HEX. On the other hand, when the outdoor air temperature is below a certain value during the day, the outdoor air does not need to be cooled down in the air-PCM HEX. For these reasons, it was assumed that the cold stored in the air-PCM HEX would be utilized only when the outdoor air temperature is above 20 °C. Though the set point of 20 °C seems arbitrary, there are justifiable reasons for choosing this value in the case of passive cooling. Many buildings may need space cooling when the outdoor air temperature is above 20 °C because of the internal heat gains, solar heat gains, and other factors. On the other hand, when the outdoor air temperature is below 20 °C, unconditioned outdoor air can be supplied to a building to provide passive cooling. With the upper limit of a good thermal comfort level at about 26 °C, the supply air temperature below 20 °C provides sufficient cooling capacity in many cases. Once again, cooling loads are very building-specific, and a thorough analysis of a particular case would be needed before actual application of passive cooling with cold storage.

The energy saving potential of the air-PCM HEX in passive cooling was determined from the mass flow rate of air and the difference between the outdoor air temperature and the outlet air temperature of the air-PCM HEX. The investigations were performed for 16 locations in Europe (described in Section 4) and for the time period from 1 May–30 September. Six nominal phase change temperatures of PCM were considered (16 °C, 18 °C, 20 °C, 22 °C, 24 °C, and 26 °C). The phase change temperature of the PCM providing the highest energy saving potential for a particular location could thus be identified.

An air-PCM heat exchanger, described in detail in the next section, was considered in the study. The simulated scenario was as follows. The rejection (discharge) of heat from the air-PCM HEX took place at night between midnight and 6:00. The air flow rate through the heat exchanger was 800 m^3/h during the discharge phase. The air passing through the air-PCM HEX during the discharge (rejection) of heat was assumed to return to the outdoor environment. The cold stored in the air-PCM HEX was utilized during the day. Several conditions were set for the utilization of the stored cold. The outdoor air would be supplied to a building through the air-PCM HEX between 8:00 and 20:00, but only if the outdoor air temperature was above 20 °C and the outlet air temperature of the air-PCM HEX was lower than the outdoor air temperature. When the air was supplied to a building through the air-PCM HEX, the air flow rate was 400 m^3/h (Figure 1). The simulation model of the air-PCM HEX allows for the calculation of the heat loss/gain to/from the surrounding environment, but the adiabatic walls of the exchanger were considered in the study. Considering a relatively small temperature difference between the inside of the air-PCM HEX and the ambient environment in the passive cooling operation, almost adiabatic walls can be achieved in practice with an appropriate level of (inexpensive) thermal insulation.

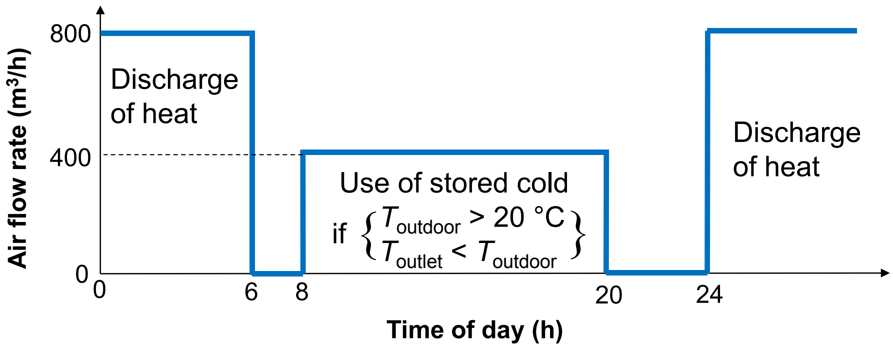

Figure 1. Operation of cold storage.

3. Model of the Air-PCM Heat Exchanger

The model of the air-PCM HEX, previously developed by the authors [13], was used in the study. The exchanger (heat storage unit) consisted of aluminum panels filled with a PCM. The unit contained a total of 100 CSM panels (compact storage modules) in five rows of 20 panels with each CSM panel containing 0.5 kg of the PCM (the total weight of the PCM was 50 kg). A schematic of the air-PCM heat exchanger can be seen in Figure 2. The configuration with 100 panels arranged in five rows of twenty panels was chosen because it was previously investigated both experimentally and numerically [13].

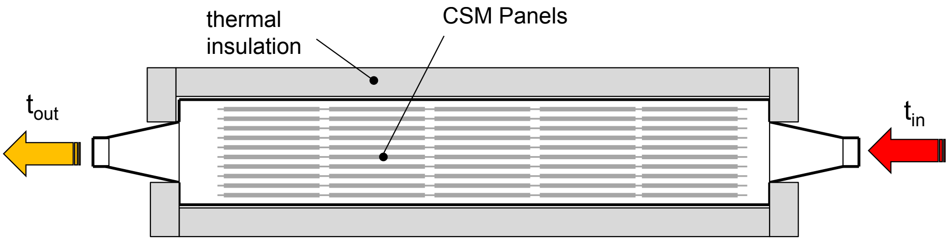

Figure 2. Schematic of the air-PCMheat exchanger. CSM, compact storage module.

The application of such a or similar designs of the latent heat thermal energy storage (LHTES) unit for cold storage has been investigated by many researchers; see, e.g., [14]. The main advantage of the design is its flexibility. The overall thermal energy storage capacity of the air-PCM HEX increases with the number of compact storage modules (panels). The doubling of the number of CSM panels in the air-PCM HEX theoretically doubles its overall thermal energy storage capacity. However, not all arrangements of the CSM panels provide the same performance of the air-PCM HEX. The heat charging and discharging characteristics can be adjusted by the arrangement of the panels in columns and rows.

A PCM exhibiting non-isothermal phase change, but without a phase change hysteresis was considered in the study. The thermophysical properties of the PCM are shown in Table 1. Though no specific PCM was considered in the study, the thermophysical properties were similar to those of paraffin-based PCMs [15]. The model of the heat storage unit was devised as quasi-two-dimensional. It consisted of a set of sub-models of the CSM panels, which were coupled with an energy-balance sub-model for the air flowing between the panels. The sub-model of the CSM panel was devised for the 1D solution of heat conduction in the CSM panel. The conductive heat transfer in the PCM was considered only in the direction of the thickness of the CSM panel (perpendicular to the air flow), while the conductive heat transfer in the other two dimensions was not taken into consideration (as the dominant temperature gradient was in the direction of the thickness of the CSM panel). The effective heat capacity method was used for the phase change modeling. The governing heat transfer equation solved by the sub-model of the CSM panel reads [16]:

$$\varrho c_{\text{eff}} \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) \quad (1)$$

where ϱ is the density, c_{eff} is the effective heat capacity, T is the temperature, τ denotes time, k is the thermal conductivity, and x is the spatial coordinate. The bell-shaped effective heat capacity defined as a function of the temperature was adopted (e.g., [17]):

$$c_{\text{eff}}(T) = c_0 + c_{\text{m}} \exp \left\{ -\frac{(T - T_{\text{mpc}})^2}{\sigma} \right\} \tag{2}$$

where c_0 is the heat capacity outside the temperature range of the phase change, $c_m = 110\,\text{kJ/kg}$ is the increment of the heat capacity corresponding to the latent heat of the phase change, T_{mpc} is the mean phase change temperature, and $\sigma = 1.05\,(°\text{C})^2$ is a parameter characterizing the range of the phase change. The curve of the effective heat capacity according to Equation (2) for the PCM with these parameters, with $T_{\text{mpc}} = 22\,°\text{C}$ and other properties shown in Table 1, can be seen in Figure 3.

Table 1. Thermophysical properties of the PCM considered in the CSM panels

Parameter	Value
Phase change temperature range	$\langle T_{\text{mpc}} - 2, T_{\text{mpc}} + 2 \rangle$ °C
Mean phase change temperature T_{mpc}	{ 16, 18, 20, 22, 24, 26 } °C
Amount of latent heat	200 kJ/kg
Specific heat	2 kJ/kg °C
Thermal conductivity	0.2 W/m °C
Density	730 kg/m^3

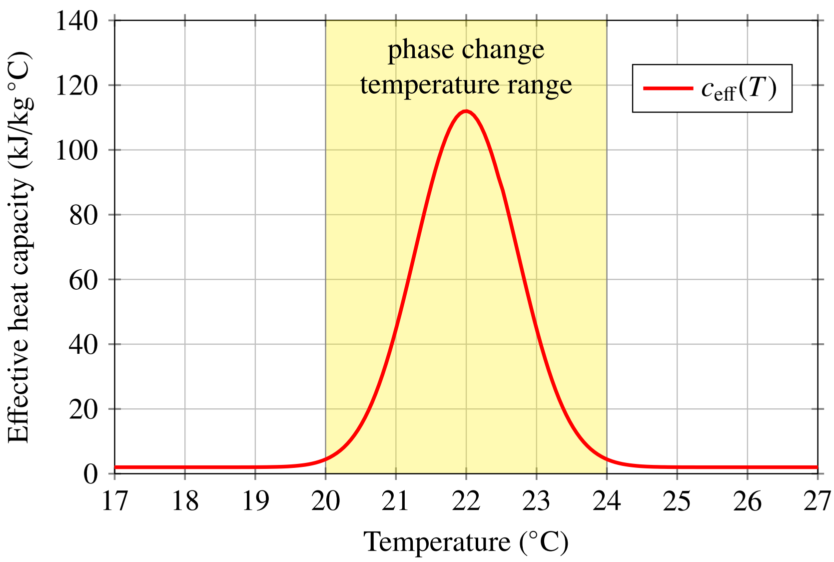

Figure 3. The curve of the effective heat capacity for the considered PCM.

Equation (2) provides a flexible approximation of the distribution of the effective heat capacity of PCMs. Even though most PCMs have an asymmetrical distribution of the effective heat capacity with regard to the mean phase change temperature [18], the approximation by Equation (2) is far more realistic than the assumption of an isothermal phase change considered in some phase change models [19].

The 1D sub-models of heat conduction in the CSM panels interact with each other, as well as with the air flowing in the channel by means of the sub-model of the air flow in the channel. The idea is that each 1D sub-model of the CSM panel is coupled with one node of the air flow sub-model by means of the CSM-air boundary condition. The sub-model of the air flow is devised for the solution of the movement of air in the channel including heat transfer interactions with the sub-models of the CSM panels. A description of this approach was already published by the authors of the paper, and is not repeated here. Readers interested in a detailed description are referred to [20].

4. Considered Locations

The climate in Europe varies significantly, not only with the latitude, but also with other factors such as altitude or the proximity of the sea or ocean. Considering the assumptions and simplifications adopted in the simulated passive cooling scenario, the main factor in the study was the ambient (outdoor) air temperature, which influences the potential of LHTES in passive cooling of buildings. Since the total energy saving potential increases with the number of buildings adopting a particular energy saving measure, only the locations of densely-populated areas were considered in the study. To keep the selection of the locations relatively simple, four cities with their latitude above 55° N were chosen to represent the cold European climate; eight cities with their latitude between 45° N and 55° N represented the mild to cool regions, where the majority of the European population lives; and four cities with their latitude below 45 ° N represented warm European climates.

Figure 4 shows the boxplots of outdoor air temperature of four cities located above the 55th parallel. A box plot is a graphical representation of numerical data by means of their quartiles. The red horizontal line indicates the median, and the blue box represents values in the second and third quartile (between the 25th and 75th percentiles). The whiskers reach the most extreme values (maximum and minimum values), which are not considered outliers, while the outliers are plotted individually as red plus signs. The outliers had values that were 1.5-times the interquartile range below the 25th percentile or above 75th percentile.

The locations above the 55th parallel provide very good potential for passive cooling of buildings by the supply of unconditioned outdoor air into a building. As can be seen, the outdoor temperature rarely exceeds 20 °C. For that reason, the potential for the use of cold storage in passive cooling is rather limited, as will be further demonstrated by the results of the study.

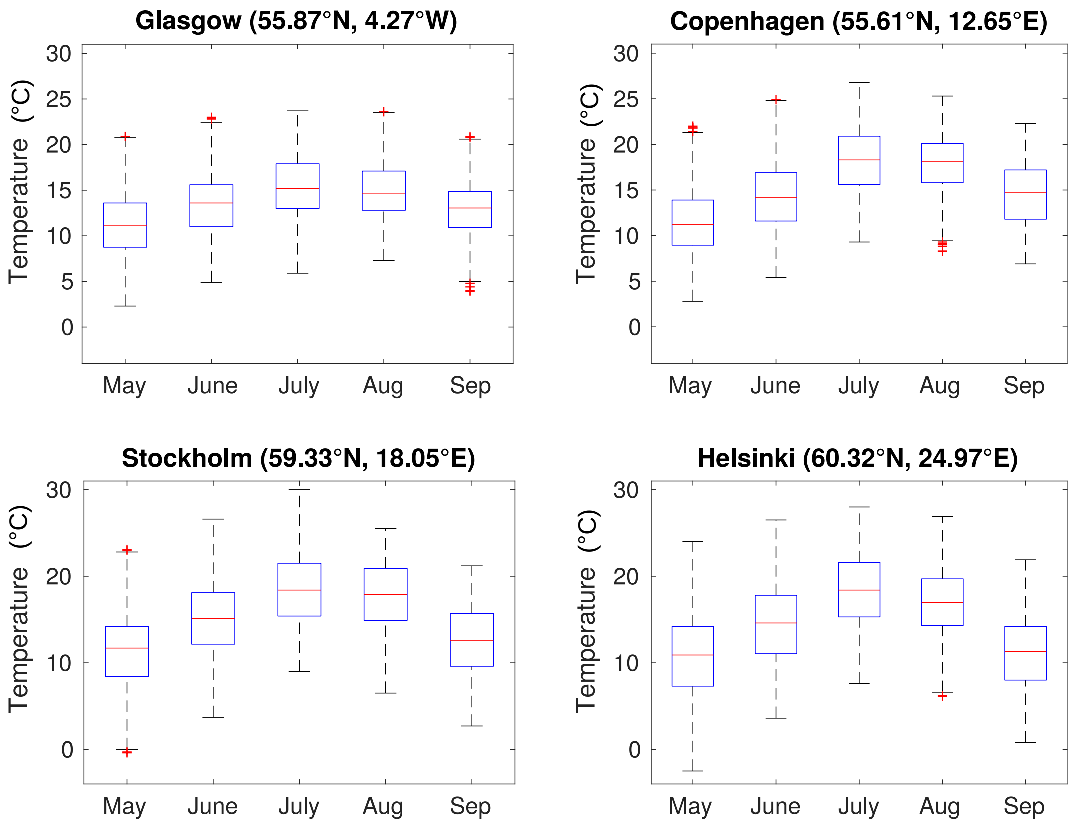

Figure 4. Outdoor air temperatures in the cities located above the 55th parallel.

The box plots of outdoor air temperatures for eight cities located between the 45th and 55th parallels are shown in Figures 5 and 6.

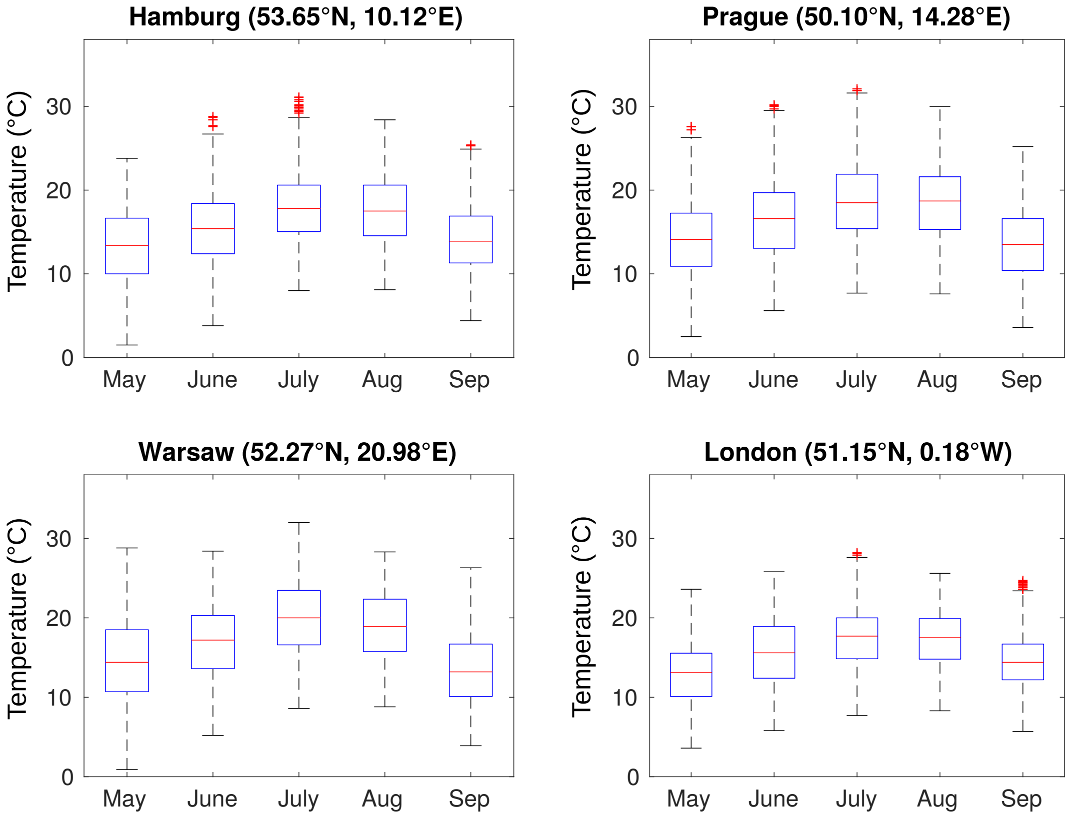

Figure 5. Outdoor air temperatures in the cities located between the 50th and 55th parallels.

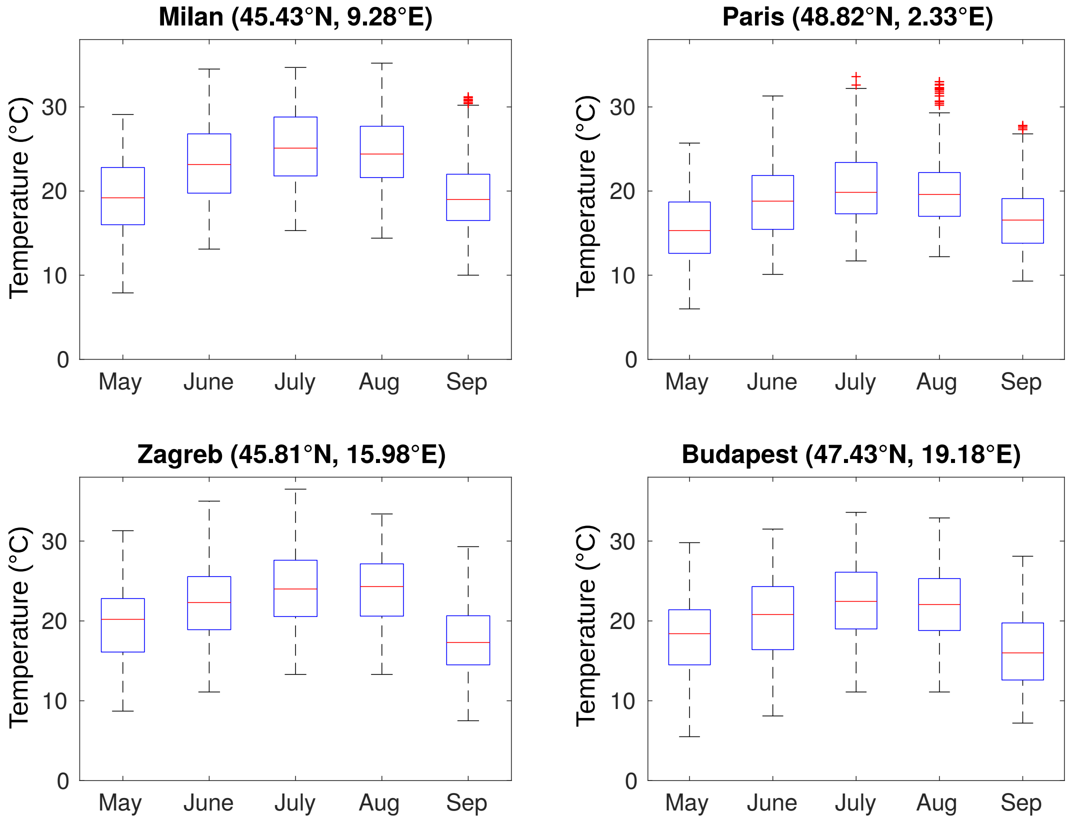

Figure 6. Outdoor air temperatures in the cities located between the 45th and 50th parallels.

The outdoor air temperatures for the four cities located below the 45th parallel are shown in Figure 7. Unlike in case of the four cities above the 55th parallel, there is a high potential for utilization of cold storage in the south of Europe. The problem is the rejection of heat at night as the air temperatures remain rather high all day long.

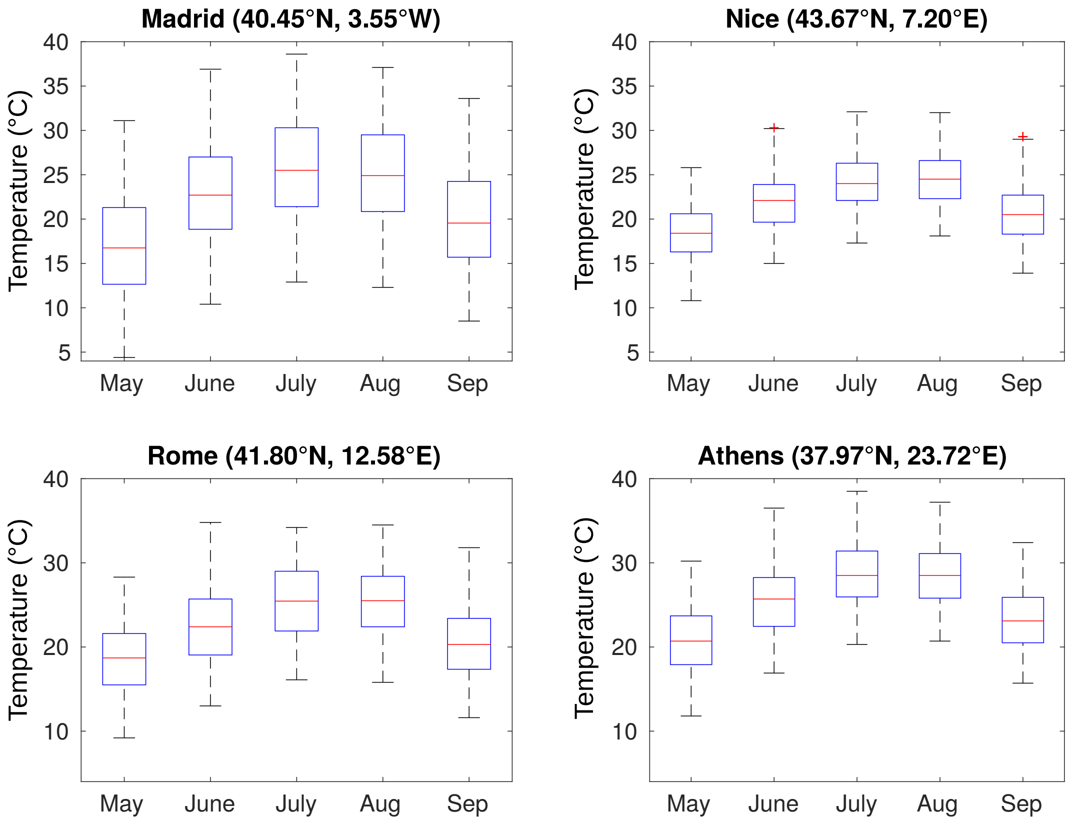

Figure 7. Outdoor air temperatures in the cities located below the 45th parallel.

5. Results and Discussion

The considered air-PCM HEX could store 10,000 kJ (2.78 kWh) of heat or cold in the phase change temperature range of the PCM (Figure 3). The specific heat of the PCM was 2 kJ/kg °C and, thus, 100 kJ/°C could be stored in the form of sensible heat outside of the phase change temperature range. Cold storage in the air-PCM HEX worked in daily cycles, and this means that the maximum amount of cold theoretically available for passive cooling on one day was about 3 kWh. This total heat storage capacity could not be exploited every day as passive cooling was not needed on some days or the heat accumulated in the PCM could not be fully rejected at night.

The amount of cold available for passive cooling of a building was evaluated from the mass flow rate of air $\dot{m}_{\mathrm{air}}$ and the temperature difference between the outlet air temperature of the air-PCM HEX T_{outlet} and the outdoor air temperature T_{outdoor} according to:

$$\dot{Q} = \dot{m}_{\mathrm{air}} c_{p,\mathrm{air}} (T_{\mathrm{outdoor}} - T_{\mathrm{outlet}}) \tag{3}$$

where $\dot{Q}$ is the time-dependent heat transfer rate in which cold is transferred from the HEX to the building. The amount of cold (energy saving potential (ESP)) was obtained as:

$$\mathrm{ESP} = \int_{t \in \mathcal{T}} \dot{Q} \, \mathrm{d}t \tag{4}$$

where $\mathcal{T}$ is the set of time instances during the day satisfying the conditions $T_{\mathrm{outdoor}} > 20\,^{\circ}\mathrm{C}$ and $T_{\mathrm{outlet}} < T_{\mathrm{outdoor}}$ for the utilization of cold from the air-PCM HEX, as explained in Section 2.

The utilization rate of the heat of fusion utilization rate of the heat of fusion (URHF) was obtained as the ratio between the ESP in a 24-h cold storage cycle and the heat of fusion of the PCM in the air-PCM HEX:

$$\mathrm{URHF} = \frac{\mathrm{ESP}_{24}}{m_{\mathrm{PCM}} H_{\mathrm{m}}} \tag{5}$$

where m_{PCM} is the weight of the PCM in the air-PCM HX and H_{m} is the enthalpy of fusion of the PCM. Table 2 shows the results for the cities located above 55° N. The largest energy saving potential was in case of Helsinki (82.4 kWh) for the PCM with the nominal phase change temperature of 18 °C. This phase change temperature provided also the largest energy saving potential at other two locations, Copenhagen and Stockholm. Despite a lower latitude than Helsinki and Stockholm and a similar latitude to Copenhagen, the ESP in the case of Glasgow was rather small (proximity of the ocean influencing summer temperatures, as could be seen in Figure 4).

Table 2. Energy saving potential in kWh (cities above 55° N).

		Nominal Phase Change Temperature of PCM (°C)					
		16	**18**	**20**	**22**	**24**	**26**
Glasgow	May	2.0	1.3	0.7	0.2	0.1	0.1
	June	6.1	5.3	3.0	1.1	0.3	0.2
	July	12.0	11.0	7.0	2.3	0.8	0.6
	August	15.5	13.4	8.4	3.3	1.2	0.9
	September	1.2	0.8	0.4	0.1	0.1	0.1
	Total	36.8	31.8	19.4	7.0	2.4	1.9
Copenhagen	May	3.3	2.3	1.2	0.4	0.2	0.2
	June	13.1	14.5	10.6	4.9	1.5	0.7
	July	17.4	24.4	25.2	17.1	7.5	2.9
	August	14.8	21.4	20.2	11.5	3.9	1.3
	September	4.3	5.4	3.3	1.0	0.3	0.3
	Total	52.9	68.0	60.5	35.0	13.5	5.3
Stockholm	May	7.1	5.2	3.0	1.2	0.4	0.3
	June	13.8	16.8	17.1	10.5	4.7	1.8
	July	20.6	28.7	30.7	24.1	14.0	6.6
	August	18.9	26.3	25.5	14.1	5.2	1.6
	September	4.0	2.7	1.4	0.4	0.2	0.2
	Total	64.4	79.7	77.6	50.4	24.5	10.6
Helsinki	May	7.0	5.3	3.1	1.3	0.5	0.3
	June	14.1	14.2	10.8	5.8	2.8	1.3
	July	25.6	33.7	33.5	23.3	11.4	4.3
	August	21.4	26.1	19.9	11.1	4.3	1.8
	September	4.4	3.0	1.7	0.7	0.3	0.3
	Total	72.5	82.4	69.0	42.2	19.3	7.9

The energy saving potentials for the cities between 50° N and 55° N are shown in Table 3. Warsaw was the location with the highest energy saving potential of LHTES in passive cooling; 126.5 kWh for $T_{\mathrm{mpc}} = 20$ °C. The situation for Prague, another city located inland, was rather similar. The energy saving potential in the case of London and Hamburg was influenced by the proximity of the sea, which reduced daily temperature swings.

The energy saving potential of LHTES did not improve very much in the case of the cities located between 45° N and 50° N as demonstrated in Table 4. All four cities in this latitude range were located inland. The highest energy saving potential was reached in the case of Milan; 148.5 kWh for $T_{\mathrm{mpc}} = 24$ °C. The phase change temperature providing the largest energy potential shifted to higher values.

Table 3. Energy saving potential in kWh (cities between 50° N and 55° N).

		Nominal Phase Change Temperature of PCM (°C)					
		16	**18**	**20**	**22**	**24**	**26**
London	May	8.7	6.8	3.9	1.5	0.6	0.4
	June	21.2	21.3	16.4	8.0	2.6	1.3
	July	19.9	22.6	19.6	12.0	6.4	3.2
	August	22.9	26.3	19.6	10.4	4.2	1.8
	September	8.2	10.5	8.1	4.1	1.6	0.6
	Total	80.9	87.5	67.6	36.1	15.4	7.3
Hamburg	May	10.0	8.2	4.7	1.7	0.7	0.5
	June	15.8	17.1	15.4	10.3	5.2	2.2
	July	20.0	25.9	25.8	18.9	11.6	6.3
	August	19.9	26.8	26.9	19.0	10.2	4.5
	September	8.7	9.2	7.3	3.8	1.7	0.7
	Total	74.4	87.1	80.1	53.6	29.3	14.3
Prague	May	17.4	18.5	14.3	7.7	3.4	1.6
	June	17.8	21.3	21.2	17.1	10.6	5.7
	July	23.2	29.2	31.2	24.7	16.3	8.9
	August	24.5	32.6	34.1	25.3	14.9	7.3
	September	13.0	14.6	12.3	6.5	2.7	1.1
	Total	96.0	116.3	113.1	81.4	47.9	24.5
Warsaw	May	20.1	20.9	18.1	12.6	7.5	3.9
	June	22.9	24.4	22.2	17.3	9.2	4.1
	July	23.0	30.1	35.9	33.9	24.6	14.5
	August	23.0	32.4	38.3	29.1	14.9	5.5
	September	13.3	13.9	12.1	6.5	2.8	1.2
	Total	102.3	121.8	126.5	99.4	59.1	29.2

The best energy saving potential among all investigated locations was obtained for Madrid; 188.7 kWh for $T_{\mathrm{mpc}} = 24\,^{\circ}\mathrm{C}$ (Table 5). Other locations below the 45th parallel did not provide much better energy saving potential than the studied locations with the latitude between 45° N and 55° N, but for different reasons. Rejection of heat accumulated in the PCM was a problem in the case of Nice, Rome, and Athens, as can be seen from the rather narrow interquartile temperature ranges (Figure 7).

As mentioned earlier, the overall thermal energy storage capacity of the air-PCM HEX in the phase change temperature range of the PCM was 2.78 kWh. For the time period from 1 May–September 30, this means the theoretical ESP of about 425 kWh. This potential can only be exploited if the PCM completely melts and solidifies in every cold storage cycle (this means every single day). This cannot be achieved in the considered passive cooling operation, where the daily outdoor temperature swings do not always overlap with the phase change temperature range of the PCM. As a result, the heat of fusion cannot be fully taken advantage of in each cold storage cycle. The largest amount of stored cold utilized during the entire investigated time period was 188.7 kWh in the case of Madrid. This means a utilization rate of the heat of fusion (URHF) of about 44%. This value of URHF is higher than the URHF reported for different climates in China [10]. However, the authors considered an isothermal phase change of PCM, which is not an advantage in passive cooling according to [9]. Furthermore, the authors considered a higher temperature set point for the utilization of stored cold, as they focused on the reduction of ventilation cooling load.

Table 4. Energy saving potential in kWh (cities between 45° N and 50° N).

		Nominal Phase Change Temperature of PCM (°C)					
		16	**18**	**20**	**22**	**24**	**26**
Paris	May	11.4	14.5	14.2	8.6	3.5	1.2
	June	16.0	21.4	20.8	16.0	10.1	5.5
	July	10.1	19.1	25.4	24.7	18.7	11.6
	August	11.7	19.2	24.3	21.6	15.1	9.4
	September	13.3	12.0	10.4	8.0	3.9	1.7
	Total	62.5	86.3	95.1	78.7	51.2	29.4
Milan	May	21.8	32.6	35.7	30.7	20.2	10.1
	June	7.5	15.3	25.8	34.3	35.8	30.2
	July	2.8	5.8	13.1	26.4	37.2	42.1
	August	4.2	9.2	17.1	26.7	35.7	37.6
	September	14.4	24.1	30.5	25.7	19.6	12.3
	Total	50.7	87.0	122.3	143.9	148.5	132.3
Zagreb	May	16.3	21.2	23.5	21.5	17.3	11.5
	June	9.8	15.0	19.5	22.8	21.4	18.9
	July	4.6	9.0	15.8	23.9	30.3	30.3
	August	5.3	10.8	16.8	21.7	25.2	26.9
	September	12.5	16.3	14.9	12.0	7.8	3.9
	Total	48.4	72.2	90.5	102.0	101.9	91.6
Budapest	May	24.8	26.7	26.9	23.9	14.6	7.2
	June	23.3	31.7	35.7	30.5	23.0	16.4
	July	11.8	20.3	29.4	35.7	36.6	30.6
	August	11.9	21.3	29.7	34.5	34.0	24.7
	September	21.7	21.7	19.0	13.6	6.6	3.1
	Total	93.5	121.6	140.7	138.2	114.7	81.9

The largest amount of cold utilized in one cold storage cycle (this means during one day) in all locations during the entire investigated time period was 2.67 kWh, meaning URHF of about 95% (Milan, $T_{\text{mpc}} = 16\,°\text{C}$, 13 May). In the vast majority of the cold storage cycles, only a small fraction of the available heat storage capacity was utilized. If the considered air-PCM HEX was used for cold storage in an all-air air-conditioning system, it would be theoretically possible to utilize the entire amount of heat of fusion in the cold storage cycle. Another interesting result of the study is the relatively small difference in the energy saving potential between locations at markedly different latitudes: Helsinki (82.4 kWh) and Athens (107 kWh). Helsinki (latitude 60.32° N) was the northernmost location considered in the study, while Athens (latitude 37.97° N) was the southernmost location.

The amount of cold that can be stored in the air-PCM HEX (and later utilized) depends on the mass flow rate of air. Small mass flow rates of air mean that the available cold storage capacity cannot be fully utilized. On the other hand, large airflow rates lead to the increases of the necessary fan power and thus decrease the energy efficiency of cold storage. The fan power was not considered in the study, as it depends on the actual integration of the air-PCM HEX in the ventilation or air-conditioning systems.

Table 5. Energy saving potential in kWh (cities below 45° N).

		Nominal Phase Change Temperature of PCM (°C)					
		16	**18**	**20**	**22**	**24**	**26**
Madrid	May	27.6	31.2	31.7	26.0	17.2	9.1
	June	15.9	25.6	34.6	42.3	44.6	38.1
	July	5.6	10.4	19.6	33.1	45.8	54.4
	August	6.9	13.0	23.0	36.2	48.6	53.7
	September	22.8	32.9	41.3	39.4	32.5	22.3
	Total	78.9	113.2	150.1	176.9	188.7	177.7
Nice	May	12.5	20.0	20.5	12.1	4.4	1.6
	June	3.1	10.1	21.2	24.0	16.1	10.1
	July	1.4	2.4	7.5	18.7	29.7	23.8
	August	1.4	2.0	6.5	17.5	27.2	24.7
	September	5.4	13.9	23.8	21.9	12.9	5.3
	Total	23.8	48.4	79.4	94.1	90.3	65.4
Rome	May	24.2	32.3	33.0	26.2	14.7	6.6
	June	7.9	17.1	27.6	33.5	30.4	25.2
	July	2.5	6.2	14.4	27.9	40.6	44.3
	August	2.8	6.4	13.1	24.8	36.8	41.5
	September	12.4	22.3	32.3	30.7	21.3	12.5
	Total	49.9	84.2	120.4	143.1	143.9	130.2
Athens	May	12.0	22.4	30.1	30.3	22.8	11.3
	June	1.9	4.3	10.7	21.8	30.3	29.2
	July	1.8	1.8	2.0	3.6	10.3	23.3
	August	1.8	1.8	1.9	3.8	10.4	24.6
	September	2.2	6.0	15.5	29.1	28.0	18.6
	Total	19.7	36.3	60.2	88.5	101.8	107.0

Table 6 shows the ESP and the URHF for Madrid under various air flow rates in the considered scenario with the temperature set point of 20 °C for the utilization of cold. Both the ESP and the URHF increase with the increasing air flow rates. Table 7 shows the results for the same scenario, but without the temperature set point. The energy saving potential was obtained from Equation (4), but without the condition $T_{outdoor} > 20$ °C. The obtained values of the ESP and URHF were the theoretical maximums that can be reached under the considered conditions. As can be seen, neither the ESP nor the URHF increased very much. The main reason is the frequent occurrence of outdoor air temperatures above 20 °C during the daytime (8:00–20:00) in the studied time period.

Table 6. Energy saving potential (ESP) in kWh for Madrid at various air flow rates for the temperature set point $T_{outdoor} > 20$ °C. The percentage in brackets is the utilization rate of the heat of fusion (URHF).

Air Flow Rate (m^3/h)		Nominal Phase Change Temperature of PCM (°C)					
Daytime	**Night**	**16**	**18**	**20**	**22**	**24**	**26**
100	200	71.4 (16.8%)	94.7 (22.3%)	118.0 (27.7%)	133.8 (31.5%)	139.2 (32.7%)	130.1 (30.6%)
200	400	76.5 (18.0%)	106.7 (25.1%)	138.3 (32.5%)	161.0 (37.9%)	170.0 (40.0%)	159.9 (37.6%)
400	800	78.9 (18.5%)	113.2 (26.6%)	150.1 (35.3%)	176.9 (41.6%)	188.7 (44.4%)	177.7 (41.8%)
800	1600	79.8 (18.9%)	116.3 (27.4%)	155.9 (36.7%)	185.2 (43.5%)	197.7 (46.5%)	186.4 (43.8%)

Table 7. Energy saving potential (ESP) in kWh for Madrid at various air flow rates without the temperature set point. The percentage in brackets is URHF.

Air Flow Rate (m^3/h)		Nominal Phase Change Temperature of PCM (°C)					
Daytime	**Night**	**16**	**18**	**20**	**22**	**24**	**26**
100	200	81.9 (19.3%)	105.5 (24.8%)	127.1 (29.9%)	140.1 (32.9%)	142.8 (33.6%)	131.8 (31.0%)
200	400	90.4 (21.3%)	120.6 (28.4%)	150.2 (35.3%)	168.7 (39.7%)	174.2 (41.0%)	161.3 (37.9%)
400	800	94.6 22.3%)	128.7 (30.3%)	163.1 (38.3%)	185.0 (43.5%)	192.9 (45.4%)	178.7 (42.0%)
800	1600	96.4 (22.7%)	132.5 (31.2%)	169.1 (39.8%)	193.0 (45.4%)	201.9 (47.5%)	187.1 (44.0%)

Figure 8 shows the comparison of the ESP and the URHF, in the case of Madrid, for the daytime air from rates from 50 m^3/h–1000 m^3/h (the air flow rates at night were twice higher, from 1000 m^3/h–2000 m^3/h) for the scenarios with and without the temperature set point. The results in Figure 8 are shown for the nominal phase change temperature $T_{mpc} = 24$ °C. The chart shows a rather significant influence of the air flow rate below about 400 m^3/h (0.125 kg of PCM per 1 m^3/h of the air flow rate). This PCM mass to air flow rate ratio is significantly lower than the 1–1.5 $\frac{kg}{m^3/h}$ reported in [9]. However, it needs to be emphasized that a very different type of air-PCM HEX (cylindrical packed bed) was used in that study. Furthermore, the PCM considered in the study had a smaller melting enthalpy and a wider temperature phase change range than the PCM considered in the present study. This only demonstrates the difficulty of providing quantitative recommendations that would be generally applicable in a latent heat thermal energy storage. Fortunately, with the current state of knowledge and many available models and simulation tools, it is possible to investigate the performance of a particular design of LHTES under a given set of operating conditions.

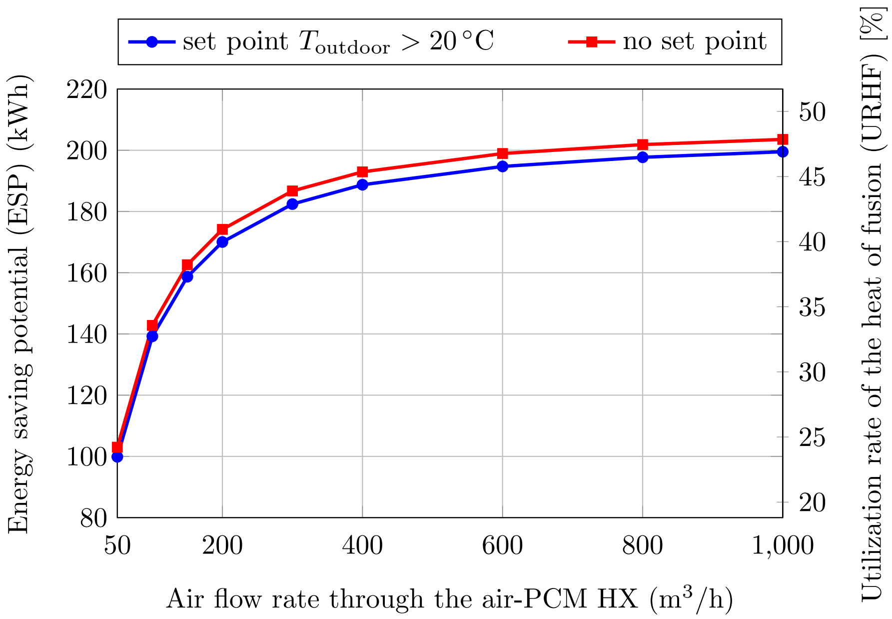

Figure 8. Energy saving potential (ESP) and the utilization rate of the heat of fusion (URHF) for Madrid and the nominal phase change temperature $T_{mpc} = 24$ °C.

The comparison of the URHF for Madrid in the case of the scenarios with and without the temperature set point, in the form of histograms, is shown in Figure 9. Each bar of the histogram represents a URHF range of 5%. The histograms are for the daytime air flow rate of 400 m^3/h and the nominal phase change temperature of the PCM $T_{mpc} = 24\,°C$. As can be seen, the URHF did not exceed 95% in either of the scenarios, but on about 10 days, the URHF was over 90%. As already mentioned earlier, the outdoor temperature set point had only a small impact on both the ESP and the URHF in the case of Madrid.

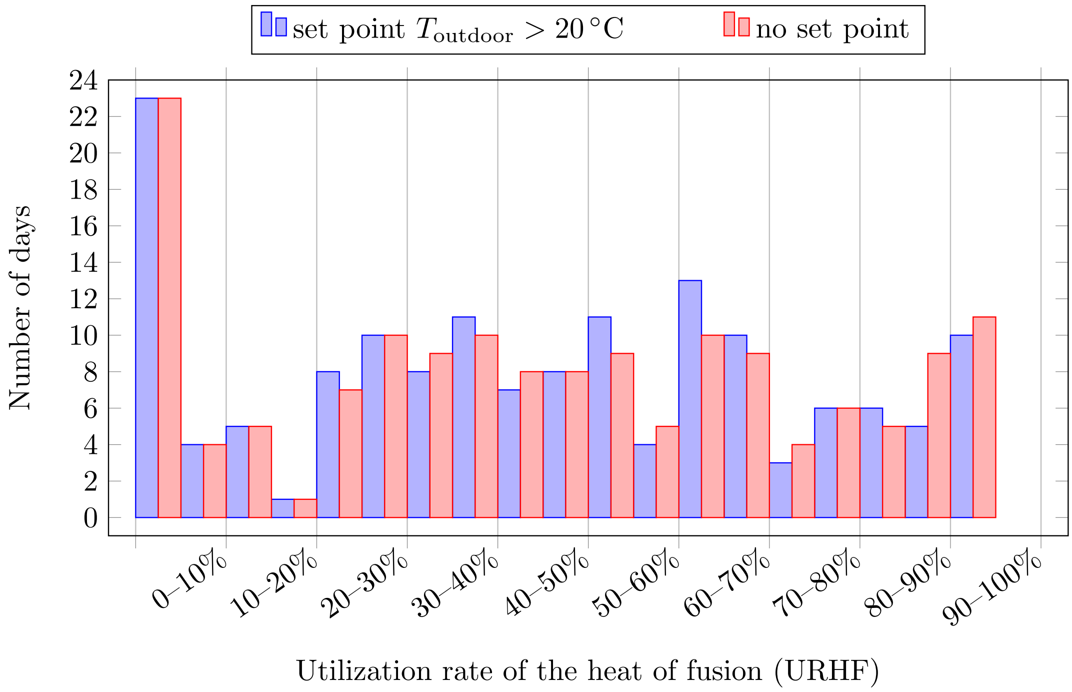

Figure 9. Histogram of the utilization rate of the heat of fusion (URHF) for Madrid and the nominal phase change temperature $T_{mpc} = 24\,°C$; each bar represents a range of 5%.

6. Economic Considerations

Despite many studies demonstrating the energy-saving potential of the PCMs in heat and cold storage, the real-life application of PCM-based LHTES is still lagging behind its potential. One of the reasons is the current economic viability of many solutions employing the PCMs. The economic considerations presented in this section concern only the system investigated in the present paper. A thorough analysis needs to be carried out in each particular case.

Economically, passive cooling is most cost effective if it makes it possible to avoid installation of a mechanical cooling system. In such a case, the benefit of both lower capital costs and lower operating costs can be exploited. If mechanical cooling needs to be installed anyway, the economic benefits of passive cooling are related to lower operating costs and possibly the downsizing of the mechanical cooling system, which can save some capital costs. The more complex the passive cooling system is (e.g., when it includes latent heat thermal energy storage), the less advantage in terms of capital costs it offers in comparison to relatively inexpensive mass-produced air-conditioners.

In the present study, the energy saving potential of passive cooling of buildings with the use of an air-PCM HEX (cold storage unit) was investigated. The economic question was whether the potential energy savings could pay for the cost of the considered air-PCM HEX. The most expensive part of the heat exchanger are the CSM panels. Considering the cost of 10 Euro per panel the total cost of the panels in the air-PCM HEX would be 1000 Euro. The shell of the heat exchanger, thermal insulation, dampers, and other fittings for connecting the heat exchanger to a ventilation system might cost about 200 Euro. The largest amount of stored cold utilized in the entire investigated time period was 188.7 kWh. If a vapor compression cooling system with the coefficient of performance of three (COP = 3) were used for space cooling, the reduction of cooling demand due to LHTES would translate to a savings of about 63 kWh of electricity. With the average price of electricity in the EU being about

0.2 Euro/kWh, the simple payback time would be well beyond the expected lifespan of the air-PCM heat exchanger.

7. Conclusions

As expected, the energy saving potential (ESP) of the air-PCM heat exchanger for cold storage in passive cooling of buildings depends on the climatic conditions. However, the differences between some locations were not as significant as could be expected. The energy saving potential in the case of Athens was only about 30% higher than the ESP in the case of Helsinki. The influence of the air flow rates on the ESP was rather significant. In the considered configuration of the air-PCM HEX and the investigated operating conditions, the ESP decreased rather significantly below about 400 m^3/h.

The average utilization rate of the heat of fusion (URHF) was lower than 50% in all investigated cases. The main reason for that was the daily outdoor temperature swing that does not always overlap (straddle) the phase change temperature range of the PCM. Nonetheless, the URHF exceeded 90% on some days. In the case of Madrid (the location with the highest average ESP), the outdoor temperature set point of 20 °C for the utilization of cold during daytime had only a small influence on the overall ESP, which was very close to the theoretical maximum (without considering any set point). The main reason was the frequent occurrence of outdoor air temperatures above 20 °C during the utilization of cold, which made the set point condition inconsequential most of the time.

From the economic point of view, the considered way of cold storage (an air-PCM heat exchanger) was not economically viable even in the climates with the most favorable conditions.

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