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SHORT COMMUNICATION

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Passive room conditioning using phase change materials—Demonstration of a long-term real size experiment

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Summary

The thermal properties of lightweight buildings can be efficiently improved by using phase change materials (PCMs). The heat storage capacity of the building can be extended exactly at the desired temperature level, which leads to an enormous increase in residential comfort. This is shown in the present paper using the example of a prefabricated wooden house. The house was divided into two identical rooms. One of them was equipped with almost one ton of phase change material based on salt hydrates with a melting temperature of approx. 21°C. The material was encapsulated in 1-l Polyethylene containers and installed in two back-ventilated layers inside of the walls. The house was monitored for a period of 87 days in terms of temperatures, solar radiation and air velocity inside the PCM wall system. A considerable temperature buffering could be observed in the PCM room compared to the reference room. An overall reduction of the temperature fluctuations of 57% and a reduction of the day/night fluctuations of 62% compared to the reference room could be obtained. In addition, a prediction regarding the energy demand of such buildings is discussed on the basis of a simulation program. Thus, the annual cooling capacity can be reduced by 36.5% compared to the regular timber construction technique by introducing PCM. Furthermore, the good correlation of the simulation results with the experimental ones allows using the simulation as a tool to design a house with additional thermal storages.

KEYWORDS

latent heat storage, phase change material, salt hydrates, temperature stabilization, thermal comfort temperature, thermal energy storage, wooden house

1 | INTRODUCTION

Due to climate change, the demand for air conditioning systems is growing even in relative temperate regions like central Europe.[1] Therefore, if no new and innovative cooling systems enter the market, global energy demand for cooling systems will increase by 72% by the year 2100.[2] Most traditional air conditioning systems are based on the principle of compression refrigeration systems, which require huge amounts of electrical energy. According to current projections, the increasing cooling demand has great potential to overload the energy supply systems.[1] Besides that, the compressors cause considerable noise and the resulting dry air is linked to higher infection rates of airborne diseases.[3] In many households, especially in more temperate climates, active air conditioning would not even be necessary. Common problems are the low thermal storage capacity of buildings, mainly because of lightweight building materials and longer hot spells as in the past, caused by climate change.[4] One promising solution is to artificially increase the thermal storage capacity of the material, which is in contact with the interior air. This is where phase change materials (PCMs) can help to reduce the electrical energy demand for heating or cooling and consequently decrease the overall energy consumption and thus the carbon footprint. The previously published paper already discussed the possibility of using PCMs with a melting temperature of 21°C as thermal storage material to cut the room-temperature peaks.[5] In this way, PCMs store energy in the transition from solid to liquid and vice versa and thus are able to store high amounts of energy at a desired temperature, which is the melting temperature of the corresponding material.[6] Most people feel comfortable at a temperature between 19°C and 23°C and a humidity of 40%-60%,[7] making the 21°C material highly promising for room conditioning. Many attempts have already been made to use PCMs in building applications.[8-11] In summary, it appears that too little PCM was used in most studies to achieve a significant effect. Additionally, in many studies small test chambers with well-defined boundary conditions were equipped with PCM,[12,13] but there are very few long-term studies with real size and environmental conditions. Various techniques for integrating PCM in houses have already been tested. For example, Ye et al[14] used paraffin wax in a graphite foam matrix to enhance thermal conductivity with a paraffin weight ratio of 40%. Oruc[15] investigated a (PCM)-embedded radiant wall heating system with different kinds of PCMs and found out that a commercially available PCM with a melting point at 26°C leads to a significant increase in both energy and exergy efficiency. Concrete blocks designed by Xu et al[16] contained 7.5% of a form-stable PEG/SiO_2 composite PCM and Voelker[17] equipped a lightweight building test room with PCM. Overall, they compared paraffin and a salt hydrate mixture based on $CaCl*6H_2O$ and achieved a reduction of the indoor peak temperature of 4 K with a combination of both. These methods are all very innovative, but unfortunately, they all have in common that they either allow only a very low amount of PCM or are associated with very high costs. Another popular example are gypsum boards with integrated microencapsulated paraffins.[18] Microencapsulation is a smart solution to integrate PCM in buildings, but, due to the maximum weight ratio of microencapsulated PCMs that can be incorporated in drywall panels, which is around 30%,[19] it is almost impossible to get enough PCM into a room to see a perceptible effect on room temperature conditions.[20,21] In addition, paraffins are combustible and therefore a questionable building material for modern buildings. Depending on the local regulations, the higher fire load can lead to significant modifications of the building. Finally, the significantly higher price of paraffins is one of the main arguments to prefer salt hydrates for PCM building integration. The price may also increase in the future, as paraffins are byproducts of fossil fuel rectification. Salt hydrates are generally much cheaper, have a higher volume-specific heat of fusion and are non-combustible. However, salt hydrates have some disadvantages, too. One has to overcome the following challenges in order to be able to use them:

- Avoid phase separation: Many salt hydrate mixtures tend to phase separation caused by gradual decomposition into undesired hydration stages.[22]
- Diffusion-tight packaging: Salt hydrates are hygroscopic. Contact with air humidity would cause dilution of the materials. Deviations from the stoichiometric water content can reduce the melting enthalpy significantly.[23]
- No contact with corroding metals: Salt hydrates are highly corrosive. Stainless steel or additional coating is required for long term stability.[24]

The salt hydrate based PCM can either be integrated into the building structure or centrally stored and actively loaded and unloaded.[25] In this respect, it can not only function directly at room temperature, but can also be integrated into the heating circuit.[26] In all cases it needs to be encapsulated in a way that it is sealed against diffusion.[27] In this paper, a possibility of direct room integration for passive air conditioning is presented and tested over a long period to achieve important key figures for future building designs. The main difference to the mentioned publications is the much larger PCM mass used in this study.

2 | MATERIALS AND METHODS

2.1 | The test environment of the house

The test house is located in Bisingen in south Germany at the company premises of *Willi Mayer Holzbau*

(48.304000°N, 8.923458°E). It is a prefabricated wooden house in timber frame construction technology, which meets the German Energy Saving Ordinance (EnEV). All outer walls, as well as the floor and the ceiling, are insulated with 100 mm rock wool between the wood frames, with an additional 60 mm wood fiber insulation on the outside. Furthermore, the house is divided into two equally sized rooms and a hallway as separation. Both rooms have one window of the same size on the south/west side of the house. All other windows have been subsequently insulated for the time when the measurements took place. A construction drawing of the house and its most important dimensions is shown in Figure 1 and Table 1, respectively. The physical properties of the building materials can be found in Table 2.

One of the rooms acts as a reference, while the other one has been provided with PCM boxes. Both rooms were equipped with temperature sensors located at three height levels in the middle of each room. In addition, the ambient temperature on the north side of the house was measured on two different levels (2 and 0.1 m above the ground). The temperatures shown below are average values from the sensors in a room or outdoor. The solar radiation was measured on the unshaded roof. All data were recorded every 5 minutes.

2.2 | The phase change material used

The PCM that was used is a salt hydrate mixture consisting of $CaCl_2 \cdot 6H_2O$ and $MgCl \cdot 6H_2O$. Its melting temperature is between 21°C and 22°C. The liquid ($c_{p,l}$ and solid heat capacity $c_{p,s}$ are 2.1 and 2.0 kJ/kgK respectively. The latent heat of fusion Δh is given as 83.5 kJ/kg.

TABLE 1 Dimensions of the investigated test house

Description	Dimensions (m)	Area (m^2)
Whole house	5.32 × 3.33	17.72
Each room	3.33 × 1.90	6.33
Average height of rooms	2.80	30.74
Windows (each room)	1.49 × 1.14	1.70

Because of the lower price for future broad applications, the raw materials are of technical grade and therefore do not have a high purity. Seed crystals are added to minimize the effect of super cooling. The salt hydrate mixture tends to phase separation. An upper and a lower phase are usually formed, while the upper phase acquires a clear and the lower phase a reddish color. The red color is probably caused by iron parts. Both phases were investigated for their thermal properties after segregation. The melting point of both phases is still within the desired range of 21°C to 23°C and the latent heat has not changed either.

2.3 | Integration of the Phase Change Material within the house

The material is macro-encapsulated in 1-l polyethylene-boxes with a size of 280 × 190 × 28 mm (*co. Fasel Innovations, Germany*). Underneath the lid, the boxes are thermally sealed with an aluminum layer. The boxes are

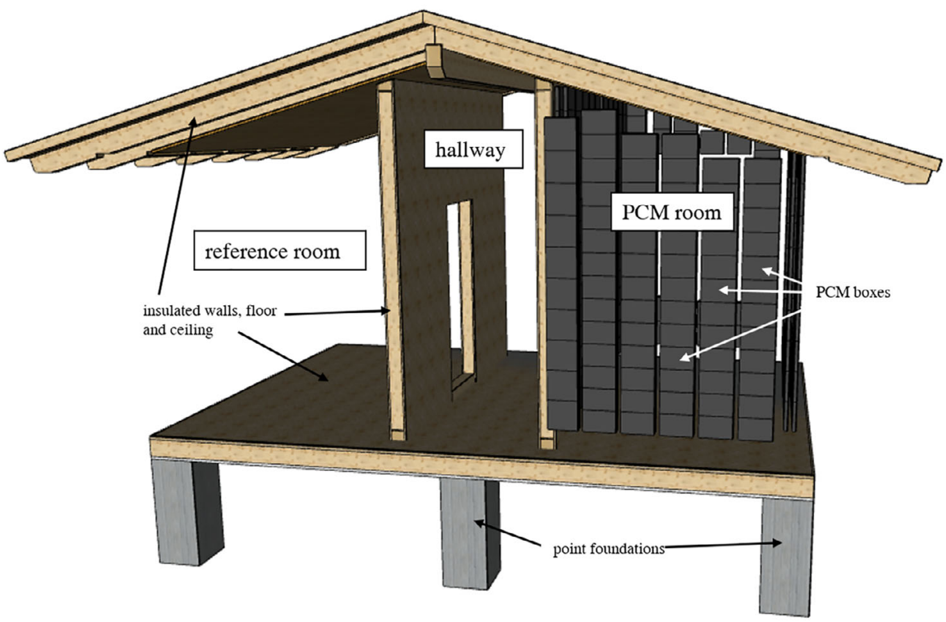

FIGURE 1 Construction drawing of the test house without outer walls [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Physical characteristics of the used construction materials

Material	Heat conductivity [W/(m K)]	Heat capacity [kJ/(kg K)]	Density [kg/m³]
Timber	0.13	2.50	500
Wood-fiber insulation	0.04	2.10	140
PCM (solid)	0.60	2.50	1580
PCM (liquid)	0.60	3.00	1580

Abbreviation: PCM, phase change material.

placed in two layers all around the "PCM room," as it can be seen in Figure 2. Through a ventilation gap on the floor and a distance of 40 mm between the PCM layers, the boxes are back-ventilated. To observe the behavior of the PCM walls more closely, an additional temperature sensor and a hot-wire anemometer velocity sensor were placed inside one wall, directly in between the PCM containers. Overall, 628 boxes with a total PCM-mass of 992 kg were integrated into the room.

2.4 | Fourier analysis

Fourier analysis is a method of expressing a function as the sum of periodic components. If both the function and its Fourier transform are discrete—for example, a digital transient signal—a discrete Fourier transform (DFT) is performed instead.

The DFT of a vector $(x_0,\ldots,x_{2n-1})$ of dimension $2n$ is given by Equation (1).

$$f_m = \sum_{k=0}^{2n-1} x_k e^{-\frac{2\pi i}{2n}mk} \quad m = 0\ldots,2n-1 \tag{1}$$

DFT is a widely used method, not least because of a very fast algorithm, the Fast Fourier Transform (FFT) developed in its present form by Cooley and Tukey.[28] For an overview of the FFT, the reader is referred to Press et al.[29]

Applied to the analysis of discrete and finite measurement signals, the FFT input signal is inherently truncated. This truncation can be expressed as the multiplication of an infinite signal with a rectangular window function. To overcome this issue, windowing the signal with a special window function is a common procedure in signal processing, see, for example, Harris.[30] In this work, the Hann window function has been found to be suitable and will be used for the following analyses. The window function according to Hann is given by Equation (2).[31]

$$\omega[n] = 0.5\left[1-\cos\left(\frac{2\pi n}{N}\right)\right] = \sin^2\left(\frac{\pi n}{N}\right) \tag{2}$$

2.5 | The simulation tool

To forecast temperature profiles within the house a simulation tool especially developed for prefabricated wooden houses with PCM wall integration is used. It is based on a one-dimensional finite difference method and takes into account heat exchange through thermal conductivity, air exchange and solar radiation through windows.

FIGURE 2 Two-layer integration of the phase change material (PCM) boxes in the test-room [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

The calculation field is derived in $m = 720$ time steps and $j = 50$ grid points for the finite difference transition calculation. The calculation was performed with the explicit finite difference method shown in Equation (3)

$$T_j^{m+1} = T_j^m + \mu\left(T_{j+1}^m - 2T_j^m + T_{j-1}^m\right) \quad (3)$$

with T as the temperature, μ as the dimensionless Fourier number and m and j as the continuous indexes for space and time respectively. Therefore, the entire temperature field was calculated for each time step. After $m = 720$ time steps (one time loop), new weather data are loaded for the next loop. A Cauchy boundary condition was used for the outer wall and a Neumann boundary condition for the symmetry axis in the middle of the house. Additional heat sources like air ventilation and radiation are all added to the first grid point next to the symmetry axis ($m = 2$) as demonstrated in Equation (4)

$$\underbrace{T_2^{m+1} = T_2^m + \mu\left(T_3^m - 2T_2^m + T_1^m\right)}_{Transition} + \underbrace{\frac{\dot{Q}_{rad,win} * \Delta t}{A_{house} * \Delta x * \rho_{in} * C_{p,in}}}_{Radiation} + \underbrace{\frac{\dot{V} * \rho_{rad} * C_{p,air} * \left(T_A - T_1^m\right) * \Delta t}{A_{house} * \Delta x * \rho_{in} * C_{p,in}}}_{Air\ ventilation} \quad (4)$$

with $\dot{Q}_{rad,win}$ as the radiative heat flux through the windows, A_{house} as the area of all boundarys of the house, ρ_{in} and $c_{p,\ in}$ as density and heat capacity respectively, $\dot{V}$ as air flow rate and Δx and Δt as grid length and time step respectively. The simulation is supplied with either real measurement data, for the ambient temperature T_a and the solar radiation I_r, or with climate data from the official German meteorological service called Test-Reference-Year data (TRY/Deutscher Wetterdienst), which are especially arranged records that offer year-round hourly meteorological data. The simulation tool enables a determination of the theoretical heating and cooling requirements for both rooms as well as for fictitious scenarios. Besides the geometry of the house (Table 1) and physical properties of the building materials (Table 2), the program is equipped with a constant air exchange rate of 1.5 $hours^{-1}$, which is a limit value of EnEV and usually always targeted by the buildings of *Willi Mayer Holzbau*. The inner and outer heat transfer coefficients are assumed to be 5 and 10 W/(m^2 K), respectively, taking the expected average wind speed into account.[32] More detailed information about the simulation tool can be found in Ref. 5.

3 | RESULTS AND DISCUSSION

3.1 | Temperature measurements—comparison of the rooms

Figure 3 shows the temperature curves of the outside and both inside room temperatures of the house in the period between May 14, 2019 and August 9, 2019. The room temperatures are mean values of the three height levels in each room. The gaps in the graph where no data are visible are caused by failures of the measuring system. It becomes clear that the day/night fluctuations are strongly buffered by the integration of the PCM. Even outside of the melting range, the heat is buffered caused by the increase of the sensible heat due to a higher thermal storage by adding PCM to the room.

The effect is even stronger when the room reaches the melting temperature of the PCM. A clearly visible stabilization of the room temperature near the melting range can be observed. The behavior of the phase change material can be better determined by looking closer at a meaningful area, which for example can be seen in Figure 4, where the period from June 14, 2019 to July 3, 2019 is illustrated. The average outside temperature is increasing in those days that both rooms have passed the melting temperature of the PCM. The graph shows again the temperature of the PCM room, this time compared to the temperature inside the wall, in the gap between the two PCM layers.

It is visible that the PCM is solid at the starting point, due to its temperature lower than 21°C. Later, when the temperature begins to increase, the PCM starts to melt and therefore keeps its melting temperature until it is completely liquid. When observing the temperature in the gap between the boxes, one can see very well when this process is finished. This happens around June 25, 2019 when the temperature inside the PCM wall suddenly starts to fluctuate in the same way as the room temperature. Additionally, the air velocity in the gap between the PCM boxes is plotted in Figure 4. As can be seen, a measurable air flow exists inside of the wall. The flowrate correlates to the temperature difference between

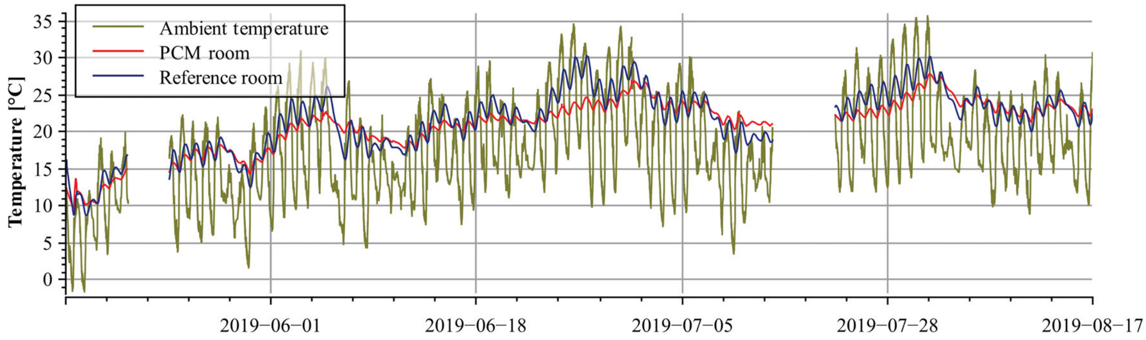

FIGURE 3 Temperature curves in the phase change material (PCM) room (red), the reference room (blue), and at the ambient of the house (green) in the time from May 14, 2019 to August 9, 2019 [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

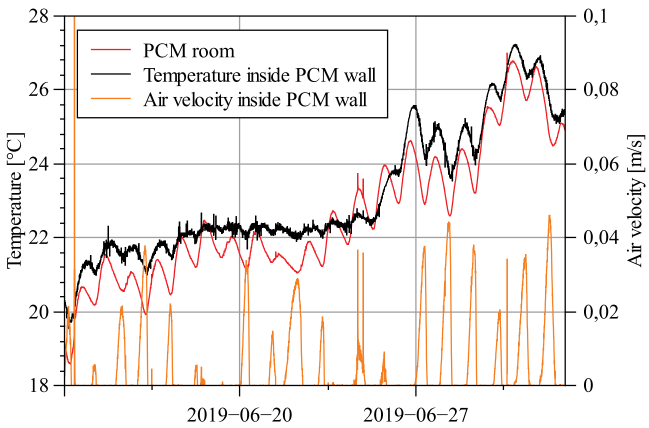

FIGURE 4 Comparison between temperature of the phase change material (PCM) room and the PCM wall in the period of June 14, 2019 and July 3, 2019 [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

the room and the gap, which is a proof for the functionality of the back-ventilated PCM wall system. The velocity inside the wall reaches maximum values of around 0.04 m/s for the period shown. Assuming a homogeneous flow in all of the walls, this equals a flowrate of 60 m^3/h for the whole room.

3.2 | Results of the Fourier analysis

A Fourier analysis was carried out to better compare the overall impact of the PCM integration as described in Section 2.4. For this purpose, a continuous measuring range of approx. 50 days is extracted from May 23, 2019 to July 14, 2019 and periodically scaled using a Hann window function. The three instances of ambient, reference room and PCM room temperatures are examined.

The results are shown in Figure 5, where the amplitude is plotted over the duration of the period. The maximum value at the periodic duration of unity represents the day/night variation, while the higher values represent the long-term effect on weather variations over several days. The day/night variations are 6.21°C, 1.32°C, and 0.50°C respectively for the ambient, reference room and the PCM room temperatures. This corresponds to a relative reduction in the amplitude for the PCM room of 61.8% compared to the reference room.

The sum of the amplitudes over the entire frequency range is furthermore suitable as an integral measure of temperature fluctuations—both within 1 day and over several days. These are calculated to 89.70°C for the ambient temperature, 15.75°C for the reference room temperature and 6.76°C for the PCM room temperature. This results in a significant relative reduction in temperature fluctuations for the PCM room compared to the reference room, in this case 57.1%.

In addition, the relative reduction of the fluctuations with respect to the ambient temperature over the periodic duration is shown in Figure 5. It can be seen that the reference room is no longer ideally damping the temperature fluctuations for periods larger than 0.8 days and that the damping decreases almost monotonously over longer periods, while the PCM room still shows a reduction in temperature fluctuations of 83.5% even for a period of 7.2 days.

3.3 | Simulation results and year-round observation

In order to validate the program, the period from May 23, 2019 to July 14, 2019 is considered again. The simulation is carried out with the five-minute measurement data for outside temperature and radiation recorded during this period. The results, as well as the input data ambient temperature and radiation, are plotted in Figure 6. The progressions of both curves, simulation and

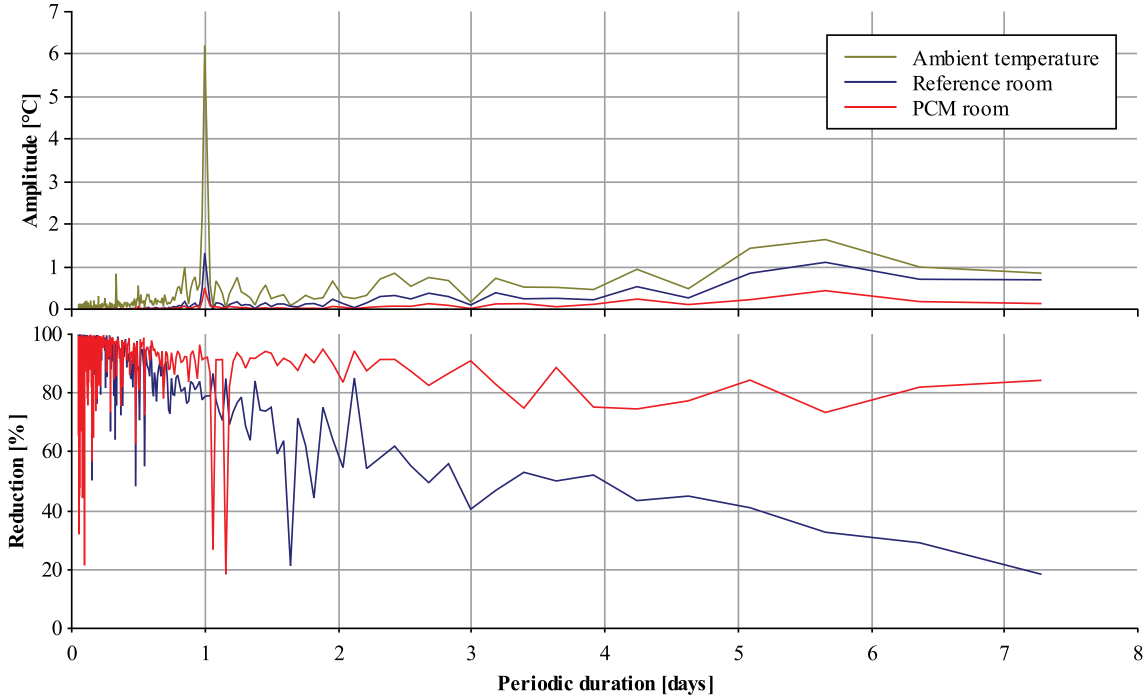

FIGURE 5 Results of the Fourier analysis of a measuring period from May 23, 2019 to July 14, 2019 [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

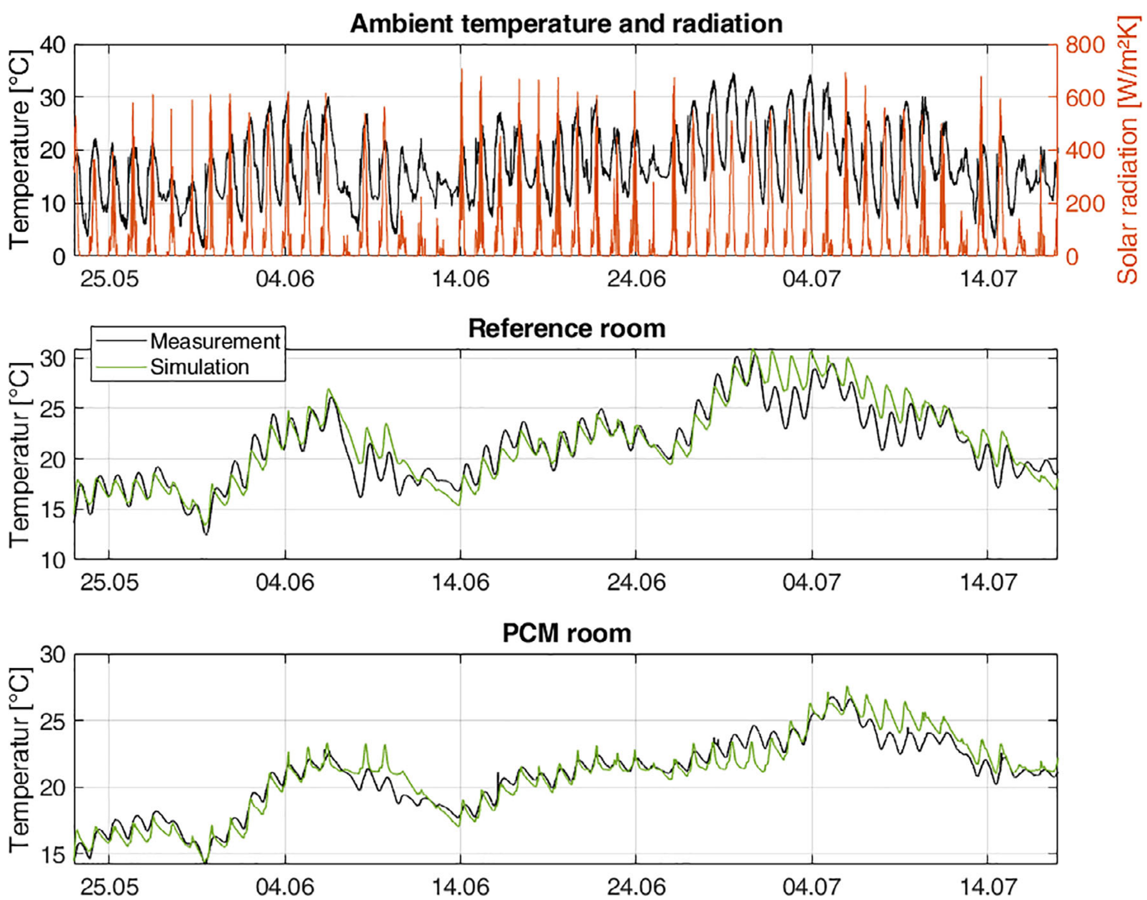

FIGURE 6 Simulation results plotted against measurements for both room temperatures, in the period of May 23, 2019 to July 14, 2019 [Colour figure can be viewed at wileyonlinelibrary.com] [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Heating and cooling demand of different rooms as year-round simulation results

	Thermal cooling demand [kWh/a]	Thermal heating demand [kWh/a]
Reference room	83.9	879.6
PCM room	53.3	864.6
PCM room—double PCM mass	35.5	805.8

Abbreviation: PCM, phase change material.

measurement, are basically very similar for both rooms. Small deviations appear, because the simulations temperature profile seems to react a little slower than the one of the measurements. Nevertheless, the simulation of such a complicated system over such a long period is considered extremely successful.

As a result, the next step is to carry out year-round simulations with the test reference year data. A lower limit temperature of 20°C and an upper limit temperature of 25°C are selected for this simulation. The corresponding cooling and heating requirements to comply with the temperature limits are added up accordingly. The energy demand for both rooms and an additional fictitious scenario, where the PCM mass included in the room was even doubled, are listed in Table 3.

The required cooling capacity can be reduced by 36.5% compared to the reference room by introducing PCM. By doubling the PCM quantity, a reduction of even 57.7% is possible. However, the heating requirement only decreases by 1.7% or 8.4%, respectively. The PCM is only suitable for shifting the heating or cooling demand over time. In cooling mode, it is possible to store the cold from the night for the day or even to shift it over several days from colder periods to warmer ones. In case of heating, however, it is permanently cold outside. Therefore, stored energy can only be saved during the transition from summer to winter time.

4 | CONCLUSIONS

In the present work, the influence of a very large amount of phase change material in a prefabricated wooden house was investigated with the aim of achieving a significant reduction of the cooling requirements in order to be able to avoid the use of compression refrigeration machines as far as possible. For this purpose, a prefabricated wooden house was built, equipped with a measurement system and monitored for a period of 87 days. The house was divided into two identical rooms with a floor space of 6.33 m^2 each. One of the rooms was equipped with 992 kg of a salt hydrate mixture with a melting point of 21°C. The material is encapsulated in 1-l plastic boxes in a back-ventilated two-layer wall construction. The temperature recording of the two rooms showed a clear stabilization of the temperature in the room equipped with phase change material. Especially in the region near the melting point, but also outside that range, temperature peaks have been cut effectively. A Fourier analysis showed a reduction of the day/night fluctuation of 62% and a reduction of the overall fluctuation of 57% for the PCM room compared with the reference room. The results show, that the PCM has a good contact to the inner room air. The connection to the environment, on the other hand, is poor because the PCM boxes are located inside the insulation. Therefore, especially in the hot periods, even when the outside temperatures at night drop significantly below the melting point of the PCM, only limited regeneration of the salt hydrate takes place. As a result, after a few days of extreme heat, the PCM is completely melted. In a real-life scenario, the working period of the PCM could even be increased by smart room ventilation. Residents of the house would automatically tend to open windows during evening or night time, which would lead to a regeneration of the PCM. In order to achieve an even better utilization, a forced ventilation with automatic control concept could be provided. In principle, it can be noted that a significant reduction in peak temperatures was achieved due to the installation of the phase change material.

Additionally, a year-round simulation of both rooms has been performed in order to determine cooling and heating demand. The simulation program has been successfully validated and, can thus be used for the design of PCM systems in prefabricated houses. For this case, it could be shown that cooling requirements were reduced by 36.5%, whereby a further reduction can be achieved by increasing the PCM quantity. Although the actual heating requirement could only be reduced very slightly, the 21°C PCM can still help to save energy in winter, depending on the heat source. When using renewable energy sources based on solar energy, it can help to transfer excess heat from day to night. It could ensure that the heating can be completely switched off at night instead of having a night setback. However, such scenarios were not considered in the simulation.

In conclusion, the investigations have shown that passive PCM elements can significantly improve the indoor climate, especially in lightweight construction systems. However, the amount of PCM must not be too small. In order to achieve an economical solution with a real effect on room temperature, systems based on salt hydrates are optimal because of their extremely low prices compared to the more frequently used paraffins. Temperature stabilization using phase change materials in building technology is a future-oriented concept with great potential. For this particular reason, it is important to investigate economically viable solutions for the end user. Only in this way, phase change material can succeed in becoming not only a scientific discipline but also an economically significant technology.

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