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The Effects of Using a Trombe Wall Modified with a Phase Change Material, from the Perspective of a Building's Life Cycle

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Abstract: The increasing costs related to the use of primary energy carriers, and greater social awareness related to the need for energy saving, necessitate the use of renewable energy sources, including solar radiation. The Trombe wall (thermal storage wall—TSW) is an indirect passive solar energy system solution, aimed at obtaining, storing, and transferring thermal energy into buildings. However, there is no comprehensive information on the impact of the use of such solutions on environmental performance in the life cycle of buildings, especially those located in temperate climates. The aim of this paper is therefore to determine the environmental impact of the construction of barriers using phase change materials (PCM) from the perspective of the life cycle of a model building conforming to the current Polish energy standard (EP < 70 kWh/(m^2·yr)). The subject of the research is the structure of a TSW using phase change materials and a reference wall with a maximum overall heat transfer coefficient of 0.2 W/m^{2}K. A comprehensive computational model of a residential building located in Rzeszów, Poland, was created, taking into account the thermal parameters of the analyzed structure of the wall and its operation under real, specific climatic conditions, as well as the environmental characteristics. High-quality input data (based on real, long-term measurements) were used to conduct a Life Cycle Assessment of the analyzed variants. As a result, the energetic and environmental efficiency of the analyzed thermal storage wall, from the perspective of the whole building's life cycle, were assessed. According to the analyzed data, a TSW modified with paraffin enables the reduction of the energy requirements for heating by 11.3%, and the payback period of the environmental load does not exceed 1 (GWP) and 5 (IMPACT2002+) years, which were lower than the monitored period of operation.

Keywords: PCM; Trombe wall; LCA; heat flow; thermal storage wall; GWP; IMPACT2002+

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1. Introduction

The issues of great importance which are considered in ongoing scientific research in the area of energy saving in construction include the possibilities of using various systems and solutions which use solar energy to improve the energy balance of buildings. This type of research is conducted in many research centers in various countries. In the area of construction, solar energy can be used, among other forms, by systems integrated within building elements. One type of such solar system is a low-temperature passive system, which enables the improvement of thermal characteristics of the building. This type of system can also contribute to increasing thermal comfort in the internal environment of the building. The passive system solutions that generate indirect gains include the Trombe wall, which is integrated into the structure of a building's external barrier. This wall connects the functions of solar collection (glazing) and thermal energy accumulation (storage wall), creating a single unit [1].

The properties of the materials from which the accumulation layer is made have a significant impact on the ability to store heat in this layer. The use of phase change material in the Trombe wall structure allows increased storage of heat, which is then transferred to the adjacent space [2–4]. In this article, the authors, based on the existing knowledge, propose improving the efficiency of passive solar heating systems by using phase change material in the wall structure. Such a wall was used as a component of a building's envelope for the purpose of improving the heat balance of the model building, taking into account its life cycle.

1.1. Application of PCM in Thermal Storage Wall

The first tests on the use of PCM in Trombe walls were carried out in the late 1970s [5]. The research aimed to determine the possibility of replacing heavy accumulation layers, most often concrete, with a phase change material [6,7]. Replacement of a concrete wall (400 mm thick) with a layer of calcium chloride hexahydrate (81 mm thick) resulted in a six-fold reduction in wall weight and an increase in energy savings of 10% [8].

The choice of PCM depends on its purpose in the barrier. If PCM is used to improve thermal comfort in inner rooms, it should have the highest latent heat. Additionally, when using a Trombe composite wall in a warmer climate, the phase change material should have a higher melting point [9,10]. It is assumed that for human thermal comfort, the melting point range of PCM should be in the range from 22.0 °C to 28.0 °C [11].

Phase change materials are characterized by a low thermal conductivity coefficient, which adversely affects the flow of stored heat in a barrier. This problem is increasingly being solved by the use of additives applied to PCM, such as graphene or other substances based on this material. They improve thermal conductivity and at the same time increase the shape stability of phase change composite materials [12]. Furthermore, appropriate modification of the structure of SiC skeletons, which are used for porous composite phase change materials (CPCMs), can also contribute to increasing thermal conductivity and increasing the robustness of these elements [13]. Research has also been carried out to obtain the stability of the above-mentioned technical features of PCM after many heating and cooling cycles. After the introduced modifications, stability of shape, structure, thermal storage and stability of photo-/electro-/magnetothermal conversion of the phase change material were achieved after 100 heating—cooling cycles [14].

In comparative tests carried out between a concrete layer (200 mm), paraffin (50 mm), and salt hydrate (8 mm), the smallest fluctuations in internal air temperature were demonstrated when salt hydrate was used [15]. Zalewski et al. [5] placed polyolefin containers filled with a mixture of salt hydrates with a melting point of 27.0 °C instead of the massive layer in the Trombe composite wall. The flow of stored heat in the PCM towards the room occurred after 2 h 40 min. Compared to a concrete wall, the time was shorter by more than 3 h. Gracia et al. used ready-made panels filled with salt hydrate with a melting point of 22.0 °C in the ventilated thermal storage wall. The masonry layer was completely replaced with phase change material. The tests confirmed the positive effect of PCM on the thermal comfort of the room and it was found that in this solution there was no need to use mechanical ventilation [16]. Zhou and Pang [17] also replaced the massive wall with inorganic PCM. The time for transfer of the accumulated heat was 17.5 h. During the first 2 h, there was a sharp decrease in heat flow, while for the next 15 h heat flow was slow and extended in time.

The massive wall in the thermal storage wall has also been replaced with glass blocks filled with PCM. This barrier was characterized by the ability to bring daylight into the room.

Experimental tests and computer simulations have confirmed heat gains in winter, while in summer this wall can cause the room to overheat [18]. An interactive glass wall, the structure of which was analogous to the Trombe wall, has been tested under temperate climate conditions. On the basis of the results obtained, it was shown that, as a result of heat flow after sunset, there was a reduction in fluctuations in internal air temperature in the test chamber [19]. The concrete layer in the Trombe wall can also be replaced with

PCM-modified ceramic elements. The use of hollow ceramic bricks reduces the mass of the storage layer, and additionally, the use of phase change material in the structure of these elements increases the accumulation capacity of the barrier. Preliminary studies using this solution were conducted under real climatic conditions. During periods of large temperature fluctuations between the external and internal environment, tests confirmed the reduction in fluctuations and stabilization of the internal air temperature in the test chamber [20]. Most analyses conducted on PCM-modified ceramic composites have mainly been concerned with external barriers without a glazing layer. Research on such solutions is aimed at limiting the flow of heat into a room and stabilizing the internal air temperature.

Interesting research has been conducted in Algeria. On the basis of their analysis, the authors concluded that the most favorable reduction in total heat flux within 24 h occurred for the ceramic hollow bricks in which the phase change material was located in the middle and outer rows of the element [21]. The numerical and experimental studies showed that location of the PCM in the inner part of the ceramic hollow brick is most preferable for reducing heat flow in peak time intervals. Regarding the average values of the daily heat flux density, the results were similar to the values obtained for the variant without PCM [22].

To obtain a time delay of heat flow through the barrier, Mahdaoui et al. [23] proposed integrating cylindrical PCM capsules with a diameter of 4 mm into a ceramic element. Numerical analyses confirmed the influence of PCM on reducing the thermal amplitude, and the appearance of a time delay in the heat flow through the barrier. The authors concluded that the higher the latent heat, the greater the accumulated gains of the barrier [23].

Research carried out under hot climate conditions also confirmed that incorporation of phase change material, enclosed in tight aluminum tubes, into the bricks reduced the temperature in the room by 4.7 °C. Heat transfer to the room was also delayed by 2 h compared to bricks without PCM [24]. Analysis of thermal phenomena and physical parameters of barriers made of composite ceramic elements [25] increases knowledge about the integration of ceramic elements with PCM and the possibility of using them in a thermal storage wall.

The above solutions present various ways of using phase change material incorporated into the external wall barrier. One of the factors that should be taken into account when using a PCM relates to the climatic conditions in which it will be able to achieve the highest efficiency. Further research should be conducted over longer time periods in local climate zones. The authors of this article conducted long-term laboratory tests on a Trombe wall of special construction, equipped with phase change material, which was tested by real climatic factors in subsequent research periods. The aim of further scientific considerations in this article is to analyze the thermal efficiency of the wall described in the article, over a long period of time, taking into account the building's life cycle.

1.2. Energetic and Environmental Costs of Thermal Energy Storage

The energy balance and environmental impact of integrated building systems are commonly verified using Life Cycle Assessment [26,27]. Current LCA studies regarding the use of PCM in buildings often rely on thermal energy storage in building heating systems and generally confirm their positive energy and environmental balance [28,29]. In particular cases, for heating systems in buildings, PCM is less beneficial than hot water storage, while in the case of cooling systems, PCM has a better environmental performance than cold water storage [30]. Studies on the use of palm oil-based organic PCM for application with domestic hot water showed that it allowed the reduction of GHG emissions by 16 Mg over ten years, while having a payback period of less than 2 years [31]. Moreover, a design based on a circular economy (recycling and reusing resources and materials in buildings with PCM), can significantly reduce the overall environmental impact [32].

Regarding the purpose of this study, extensive literature searching included identifying the particular cases of building-integrated TSWs and their environmental balances. The research by Sobolciak et al. [33] was based on LCA, including the Ecoinvent database used for the evaluation of paraffin wax-based phase change materials, composed with the use of linear low-density polyethylene (LLDPE) and expanded graphite (EG), incorporated into brick walls. The results showed that compared to brick walls made of rock and glass wool, the integration of PCMs into brick walls decreases their total environmental impact by more than 15%.

Some studies have focused on a material's production, embodied energy, carbon footprint, and the number of cycles necessary to receive its payback. A study on an alveolar brick construction system incorporating phase change materials [34] included the energy consumption rates for both heating and cooling which have been measured and registered in two experimental cubicles located in Puigverd de Lleida (Spain). The decrease in the environmental impact, based on LCA, due to the energy savings achieved during the operational phase of these cubicles compensates for the increase in environmental impact that is induced during the manufacturing phase, and the reduction in the overall global impact of the wall containing PCM ranges from 12% to 14% in comparison with the other constructions without PCM.

Incorporation of PCM into building materials such as concrete, asphalt and roofing materials can support temperature regulation, extending the useful life and efficiency of these materials [35]. However, there are comments in the literature regarding the impact of thermal ageing caused by paraffin-based PCMs. Wax-based PCMs (paraffin and beeswax) were tested with respect to the technical parameter of the latent heat of phase change in [36]. As the authors stated, after thermal aging treatment, the charge and discharge performance for both PCMs were degraded. Paraffin wax (PW) experiences performance degradation of around 14.7% in the case of charging rate, but the aging effect can vary for different PCMs, and the possibility of an increase in the latent heat of the phase change is apparent in certain circumstances [37].

The common problem with LCA studies on building TSWs is a low number of articles including the effect of thermal storage on the whole building, as well as the lack of real data on its operation. Some papers focusing on LCA of thermal storage systems simply include no degradation of materials in time. For example, in the study by Bari et al. [30], the entire LCA platform for thermal energy storage systems was presented. However, as the authors emphasize in the limitations section of the paper, no degradation of the PCM thermal properties was considered over thousands of cycles, which would affect the LCA results. Although the thermal properties of paraffin have previously been studied [38], no articles introducing this effect into the LCA model were found when searching the terms "degradation", "paraffin", "Life Cycle Assessment", and "PCM" together in Web of Science databases. Some studies on paraffin use as a PCM included its recycling [39], with no focus on quality deterioration, while EC reports include a scenario of paraffin replacement twice a year due to the aging process [40]. Therefore, in the current study, in addition to modeling a building's life cycle, laboratory tests of PCM (paraffin) were performed to verify its thermal storage properties (latent heat of phase change) after 6 years of operation in an existing TSW. This, together with long term measurements and real data on material and energy balance, deepened with a detailed computational model of the building, will allow the presentation of high-quality LCA results of TSW application in a model detached house. The authors will contribute to the current state of knowledge in terms of TSW application in a temperate climate (Rzeszów, Poland) by presenting a holistic perspective of energetic and environmental balance in the life cycle period, as well as precise data on energy balance and PCM characteristics after many cycles of work. Due to the shortage of this type of study, there is a knowledge gap in terms of the applicability of TSWs in Poland as a result of the limitations in the maximal overall heat transfer coefficient, regardless of the energy balance of the barrier.

2. Methods

The study presented here was based on the Life Cycle Assessment of a model building (a detached house) located in Rzeszów, southern Poland. In the life cycle inventory, both real data on thermal storage walls operation in this location as well as detailed material and energy balances were included. Moreover, laboratory tests of a PCM (paraffin) were conducted to incorporate the possible material aging into the model. Therefore, several scenarios of the life cycle differing in terms of energy balances were implemented.

2.1. The Subject of the Study

The subject of this study is a detached house located in Rzeszów (50°02′ N. 21°59′ E). A model of this building was created in InstalSystem 5 (InstalSoft, Chorzów, Poland), a software package used in designing and engineering calculations for buildings, including energy calculations. As presented in Figure 1, the building has a typical construction with one usable floor and unconditioned attic space. The external wall in yellow (Figure 1) is oriented south, which makes it possible to absorb the energy from solar radiation throughout the TSW. The basic technical parameters of the model building are presented in Section 3.1. The design of the building included two variants:

1. V1 with a traditional southern wall made of clay brick and rock wool with no modification, U = 0.2 W/(m^{2}K);
2. V2 with a PCM-modified southern wall made of light clay brick and paraffin located in the middle layer, U = 0.401 W/(m^{2}K).

Figure 1. Orientation of the building modeled in InstalEditor 5 (own elaboration).

More details on construction of the V2 variant can be found in Section 2.2.

The detached house designed for this study conforms to the Polish standards for thermal insulation of barriers and primary energy consumption, calculated as 67.7 kWh/(m^2·yr) in the basic variant of construction. The external ground floor dimensions are 12.48 m and 9.99 m. A gas boiler, in conjunction with supply and exhaust ventilation with 80% heat recovery, was assumed as a heat source.

2.2. Real Data Collection

The research results analyzed in this article were collected during the study of the thermal storage wall (TSW), with its surface facing south (in order to obtain maximum sunlight). The research stand used for testing building barriers which use solar radiation is located at the Rzeszow University of Technology, in Poland. The chamber (Figure 2a) in which the tests were conducted has dimensions of 4.00 m × 2.20 m × 3.50 m (length × width × height).

(**a**) (**b**)

Figure 2. Research stand: (**a**) solar-active chamber—view from the outside; (**b**) view of the accumulation layer during the construction of the stand.

The structure of the TSW barrier consisted of several main elements. Outside the barrier, there was glazing with an overall heat transfer coefficient of U = 0.6 W/(m^{2}K) and a transmittance coefficient of g = 0.50. Behind the glazing, there was an accumulation wall made of ceramic blocks with wide holes. The gaps in the blocks were filled with PCM in the two outer rows (Figure 2b), while the next two rows of gaps were filled with brick flour, obtained as a recycling material from the same ceramics. The thickness of a single PCM layer results from the dimensions of the cavity of the block into which the PCM was applied. The thickness of the hole is 0.038 m. The wall surface on the glazing side was painted black to obtain the highest value of the absorption coefficient.

The most important technical parameters of the barrier materials are presented in Table 1.

Table 1. Technical parameters of the materials used to make the TSW.

Material/Parameters	Melting Range	Solidification Range	Specific Heat	Thermal Conductivity	Heat of Phase Change (Latent Heat)	Density
-	°C	°C	kJ/(kg·K)	W/(m·K)	kJ/kg	kg/m^3
ceramic hollow brick	-	-	1.0	0.266	-	(gross) 702
PCM RT25HC	22–26	26–22	2.0	(both phases) 0.2	230 ± 7.5%	solid state 880 liquid state 770
ceramic brick flour	-	-	-	0.456	-	1700

During field tests, the temperature values inside the accumulation layer, the internal air temperature in the chamber and the external air temperature were recorded. The temperature measurements were made using temperature sensors (Figure 3a). The heat flux density values measured on the inner surface of the wall were recorded using plate heat flow sensors (Figure 3b). The value of the total solar radiation intensity falling on the horizontal surface was determined using a pyranometer (Figure 3c).

(**a**) (**b**) (**c**)

Figure 3. Research equipment: (**a**) temperature sensor; (**b**) heat flow sensors on the wall surface; (**c**) weather station with the pyranometer.

All measurement values were recorded throughout the calendar year with a recording frequency of 5 min. Data were saved using a recorder in the format of text files and spreadsheets.

2.3. Laboratory Tests of Paraffin

Laboratory tests were performed in order to determine the characteristics of aging of PCM. The latent heat of melting/solidification and melting/solidification temperature were determined. The measurement of the heat flows was performed by differential scanning calorimetry, using Mettler Toledo DSC 822e apparatus. The temperature interval was from 0 °C to 50 °C (+/−0.2 °C) with a heating and cooling rate of 5 °C/min and with a 5 min isothermal regime before and after linear heating/cooling. The samples (about 10 ± 5 mg) were placed into an aluminum crucible with a lid and a volume of 40 mm^3. All the measurements were performed in an air atmosphere with a flow rate of 50 mL/min. Every test was repeated three times using three samples of the studied paraffins.

2.4. Modeling of Building Energy Balance in TMY

The quasi steady-state calculation method (based on the EN ISO 13790 [41]), commonly used for energy performance checking, was applied to calculate the seasonal energy demand of the model building. The method of calculating energy demand included in the ISO 13790 standard was created during the PASSYS research project, aimed at the development of a method for determining heat demand that would make it possible to include passive solar systems in the energy balance. The standard presents two calculation methods—full and simplified—differing in their basic assumptions and method of taking into account solar gains in the solar space and adjacent heated rooms. The quasi-stationary methods included in the standard are based on the assumption of a steady heat flow in building barriers. Calculations are performed by averaging the parameters of climatic conditions for quite long periods of time (e.g., one month). The phenomena related to the dynamic behavior of a building, such as solar energy accumulation and heat release, are taken into account, indirectly owing to the introduction of a dimensionless energy gain utilization factor [42]. Validation of this method is published in [43].

The model building was represented in graphical form and its details (construction, orientation and location) were characterized in the InstalSystem 5 software package, including the calculation of energy balance on the basis of the EN ISO 13790 method. The assumed length of the heating season equaled 222 days, from the last days of September until the first days of May.

In order to make the recorded data suitable for the estimation of the energy balance in a typical meteorological year, subsequent corrections have been made, extending the basic model as follows (1)–(3) [41]:

$$Q_{H,nd} = Q_{H,ht} - \eta_{H,gn} \cdot Q_{H,gn}, \tag{1}$$

where (for each month)

$Q_{H,nd}$ is the building energy need for space heating, MJ;

$Q_{H,ht}$ is the total heat transfer for the heating mode, MJ;

$Q_{H,gn}$ is the total heat gains for the heating mode, MJ;

$\eta_{H,gn}$ is the dimensionless gain utilization factor.

$$Q_{H,ht} = Q_{tr} + Q_{ve}, \tag{2}$$

where

Q_{tr} is the total heat transfer by transmission, MJ;

Q_{ve} is the total heat transfer by ventilation, MJ.

$$Q_{tr} = H_{tr,adj} \cdot (\theta_{int,set,H} - \theta_e) \cdot t, \tag{3}$$

where

$H_{tr,adj}$ is the overall transmission heat transfer coefficient, W/K;

$\theta_{int,set,H}$ is the set-point temperature of the building zone for heating, °C;

θ_e is the temperature of the external environment, °C.

The simplification included by the authors in order to complete the model by using the solar gains accumulated in PCM modified TSW as follows:

$$Q_{tr,TSW} = H_{TSW} \cdot (\theta_{int,m} - \theta_e) \cdot t = A_i \cdot U_t \cdot (\theta_{int,m} - \theta_e) \cdot t, \tag{4}$$

$$Q_{H,TSW} = Q_{tr\_TSW} - \eta_{gn\_TSW} \cdot Q_{SOL\_TSW}, \tag{5}$$

where

$Q_{tr,TSW}$ is the total heat transfer by transmission through the PCM modified TSW, MJ;

H_{TSW} is the overall transmission heat transfer coefficient of the PCM modified TSW, W/K;

$\theta_{int,m}$ is the mean measured temperature of the building zone for heating, °C;

A_i is the area of element i of the building envelope, in m^2;

U_i is the overall heat transfer coefficient (thermal transmittance) of element i of the building envelope, W/(m^{2}K);

$Q_{H,TSW}$ is the TSW energy balance (energy need/surplus for space heating), MJ;

η_{gn_TSW} is the dimensionless efficiency factor for the use of solar radiation expressed as the ratio of the amount of energy stored in the TSW to the energy per unit on the horizontal plane;

Q_{SOL_TSW} is the energy per unit on the horizontal plane related to the TSW area, MJ.

To unify the further LCA calculations, MJ was recalculated to kWh using relation factor 3.6. Regarding Equations (1)–(5), η_{H,gn_wall} was estimated on the basis of the measured climate data and energy flow (see Section 2.2) throughout the PCM-modified barrier with the overall heat transfer coefficient U = 0.401 W/(m^{2}K). The estimated potential of solar energy accumulation and known parameters of temperature, dimensions and thermal conductivity of materials, together with the monthly sum of solar radiation on the horizontal plane, allowed recalculating the measured, real energy balance into TMY.

2.5. LCA Specifications

Life Cycle Assessment is a widely used technique with its roots dating back to the late 1960s. The ISO 14040 [44] standard define the technical scheme, methods of balancing inputs and emissions, the scope of activities at individual stages of analysis and the necessary input data. In the present study, the model of a detached house was the subject of the study, while the functional units depended on the aim of analysis and included the yearly operation of the heating system in a building, the whole building construction, and the construction of a TSW with modifications in the implemented model. The majority of functional units aimed at the calculation of payback periods of environmental burdens resulting from replacing the classic version of the external wall V1 with a V2 thermal storage wall, which, together with identification of the main impact categories, was the main goal of the study. Taking into consideration the heating needs, the material and energy balances were only focused on the construction (affecting the thermal properties of the cubicles) and operation of the heating system during the assumed 50 years of building operation.

The software used for the calculations was SimaPro v. 8.0.5.13 (PRé Consultants B.V., Amersfoort, The Netherlands) with the Ecoinvent v3 database.

The main assumptions of the data collection and further calculations are included in Figure 4.

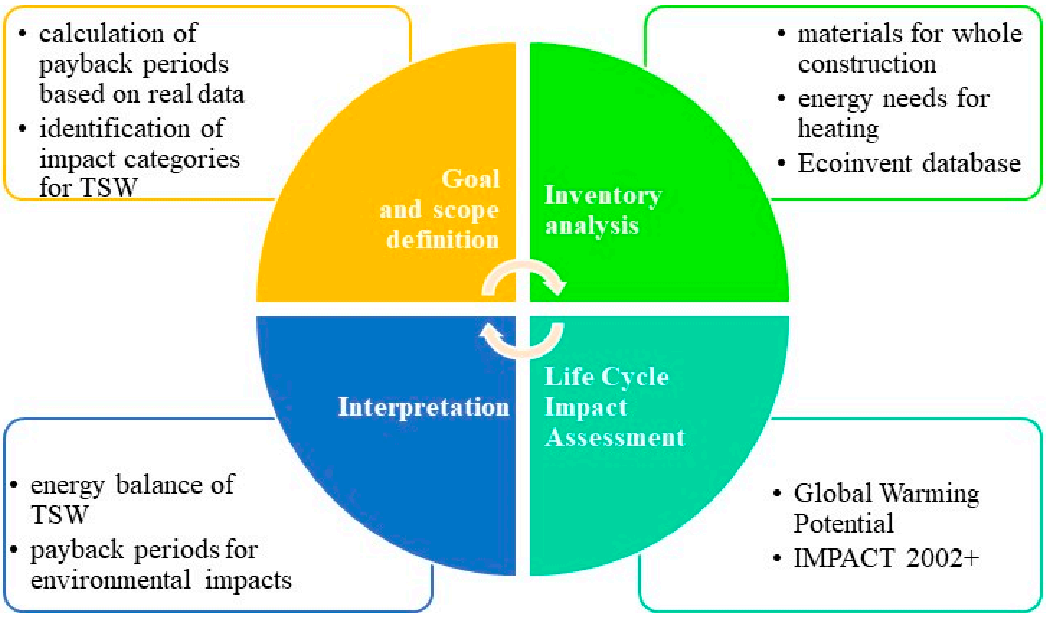


Figure 4. Technical scheme of the building LCA in the presented study.

Two techniques were selected as impact assessment methods. Taking into account the arising and expected climate changes, the Global Warming Potential method in a 100-year perspective (IPCC GWP 100a) was applied. It is based on the comparison of how much energy could be absorbed by 1 ton of any released gas to the potential of energy absorption over 100 years in relation to the energy potentially absorbed by 1 ton of carbon dioxide (CO_2) in the atmosphere [45]. All kinds of substances released into the environment with a predicted negative impact on climate stability are calculated into the equivalent amount of CO_2 within the equivalent global warming potential factor ($kgCO_{2eq/kgemission}$). The full IPCC GWP 100a method includes an inventory of the stage of emissions into the atmosphere, including the life cycle of materials and energy built into the system, categorization (selection of substances with the potential to create a greenhouse effect) and characterization, i.e., conversion into the mass equivalent of carbon dioxide using a simple relationship involving multiplying the mass of emissions by the characterization factor for each identified greenhouse gas [46].

The second method (IMPACT 2002+) was used in order to show the range of various environmental impacts. This method includes implementation of a combination mid-point/damage approach that gathers all types of inventory results through fourteen mid-point categories. Subsequently, four damage categories,—human health, climate change, ecosystem quality, and resources—facilitated optimization, finally, into a single result. The method includes a characterization stage, conducted through the use of coefficients expressed in midpoint units, describing the impact of the analyzed emissions and the resources used in a specific damage category, e.g., Disability Adjusted Life Years for the human health category. The characterization indicator is then multiplied by the normalization level, then by the weighting factors equal for all damage categories, and then the weighted indicators are summed up to a single value expressed in points. Generally, a higher value of the IMPACT2002+ indicator means a more intense environmental impact [47].

3. Results

3.1. Material and Energy Balance of the Analyzed TSW

3.1.1. Material Balance

The material balance included detailed quantities of the construction materials available in the design introduced into the InstalSystem software, where the complex model of the building was created. The amounts of the materials used were then implemented into a SimaPro model. The basic characteristics are included in Table 2.

Table 2. Technical parameters of barriers in the model building.

Type of External Barrier	Surface Area	Overall Heat Transfer Coefficient U	Materials for Construction
-	m^2	$W/(m^2K)$	-
External walls	101.9	0.14	Light clay brick, rock wool, base plaster, alkyd paint
Southern wall (V1)	20.2	0.2	Light clay block, rock wool, base plaster, alkyd paint
Southern wall (V2)	20.2	0.401	Light clay block (block plus recyclate), paraffin in PP cover, window frame, alkyd paint, flat glass
Floor on the ground	105.95	0.2	Sand, poor concrete, PE foil, PS, wood
Insulated ceiling	105.95	0.15	Base plaster, reinforced concrete blocks, PE foil, PS, poor concrete
Internal wall	130.2	0.98	Lightweight concrete blocks, base plaster, alkyd paint
Roof	121.8	0.15	Steel, PE membrane, rock wool, wood, base plaster
Windows	15.2	0.6	Window frame, flat glass
Doors	2.1	0.9	External doors

3.1.2. Energy Balance and Stability of Properties

The energy calculations were based on the measured data (Section 2.2) and modeling of the building's performance (Section 2.4).

To begin with, the results of calculations of the building's energy needs for space heating Q_h in variant V1 are presented in detail in Table 1. Q_h is divided into energy need for covering the loss through external walls—Q_{ew}, unheated attic—Q_{ua}, floor on the ground—Q_{fl}, and ventilation—Q_{vent}, and diminished by internal—Q_{int} and solar energy gains—Q_s (Table 3), with the gain-to-loss ratio changing in the range from 0.354 (in January) to 2.537 (in May). The results obtained in the calculations allowed for identification of the part of the energy demand related to specific barriers, thus the share of the southern barrier could be identified.

Table 3. Energy balance of the model building (V1).

Month	Q_{ew} [kWh]	Q_{ua} [kWh]	Q_{fl} [kWh]	Q_{vent} [kWh]	Q_{int} [kWh]	Q_s [kWh]	Q_h [kWh]
January	637.0	449.8	158.0	760.9	0.0	0.0	1337.6
February	460.7	325.3	144.3	1981.4	−1270.1	−1496.7	824.1
March	492.0	347.4	158.0	2115.8	−1406.2	−2645.2	734.9
April	300.7	212.3	148.4	1293.2	−1360.8	−3740.3	293.2
May	31.3	22.1	23.7	134.7	−226.8	−819.4	19.9
June	0.0	0.0	0.0	0.0	0.0	0.0	0.0
July	0.0	0.0	0.0	0.0	0.0	0.0	0.0
August	0.0	0.0	0.0	0.0	0.0	0.0	0.0
September	23.8	16.8	21.9	102.4	−226.8	−492.8	17.9
October	341.8	241.3	140.6	1469.9	−1406.2	−2029.2	469.2
November	451.0	318.5	142.3	1939.8	−1360.8	−1127.2	844.2
December	548.9	387.6	153.4	2360.8	−1406.2	−961.2	1134.3
Sum	11,834.0	8355.6	3926.0	14,137.2	−10,069.9	−14,462.7	5675.1

In the next stage of the calculations, based on Equations (3)–(5) and the measured data on the energy balance in the monitored time period and conditions, calculation of thermal characteristics of the analyzed TSW in variant V2 in relation to TMY (temperature and solar irradiation on the horizontal plane) was conducted. As presented in Table 4, monthly sums of energy (plus means loss and negative value means energy gain) are strongly dependent on both temperature and solar irradiation. It is clearly visible in the case of V2 in January, where in the measured period with higher temperatures (column 3) the analyzed TSW showed an energy gain, while under TMY conditions (column 4), due to the lower average temperature in the month, the V2 variant recorded a loss.

Table 4. Climate data and unit energy balance of the analyzed walls in typical meteorological year.

Month	Temperature of Air in Chamber	Mean Air Temperature in Months (Measured)	Mean Temperature in Months (TMY)	Irradiation on Horizontal Plane (Measured)	Irradiation on Horizontal Plane (TMY)	Energy Balance of Wall V2 (Measured)	Energy Balance of Wall V2 (TMY)
	°C	°C	°C	kWh/m^2	kWh/m^2	kWh/m^2	kWh/m^2
January	19.9	1.4	−4.6	32.3	31.1	−0.197	2.952
February	20.1	−3.0	0.3	47.2	41.9	−1.110	−1.188
March	19.8	1.2	1.0	97.1	74.5	−6.003	−3.227
April	20.2	14.9	8.0	151.7	109.8	−11.301	−5.775
May	20.2	17.7	12.5	188.1	150.2	−0.785	−0.245
June	20.3	19.3	16.8	161.3	163.4	0.000	0.000
July	20.3	20.6	16.9	159.6	149.9	0.000	0.000
August	20.4	21.2	17.7	161.9	134.3	0.000	0.000
September	20.0	16.2	14.3	125.4	84.8	−0.524	−0.263
October	20.0	10.5	6.8	61.8	55.8	−7.935	−5.800
November	19.5	4.9	2.0	32.1	30.2	−1.747	−0.554
December	19.3	2.7	−1.2	19.1	25.5	1.203	1.144
SUM							−12.957

The calculations described above allowed comparison of the energy requirements for space heating of the analyzed walls in the V1 and V2 variants. As presented in Table 5, in all the analyzed months of TMY, TSW allowed for a significant decrease in the energy requirements. Except for the two coldest months (January and December), TSW implemented into the model building allowed for a positive energy balance, compensating for the energy lost through transmission and providing additional solar energy gain. The negative values are due to the surplus energy used for space heating.

The effect described above can be easily recognized in Figure 5, where in all the months of a typical heating season, energy requirements for space heating Q_H are lower in the case of the application of PCM-modified walls.

The highest differences in $Q_{H,nd}$ between V1 and V2 can be observed in months of heating season with higher solar irradiation, from April to October, where the reduction in energy demand varied between 32% and 46% (April). In May and September, the reduction in energy needs was also high, but due to the limited time of operation of the heating system these months are not crucial in relation to the seasonal demand.

In total, the decrease in energy requirements for space heating of V2 compared with V1 equaled 11.3%. The results reported in the existing literature are slightly better [48,49], but the analyzed buildings are usually located in different climates. Moreover, it can be seen that the reason for the limited effectiveness of the introduced changes is the increasing insulation of the external barriers and their reduced share in seasonal energy consumption rates.

Table 5. Energy needs of the analyzed walls in a typical meteorological year.

Month	Q_H Wall V1	$Q_{H,TSW}$ Wall V2
	kWh	**kWh**
January	89.05	59.62
February	54.87	−23.99
March	48.93	−65.18
April	19.52	−116.66
May	1.32	−4.94
June	0.00	0.00
July	0.00	0.00
August	0.00	0.00
September	1.19	−5.32
October	31.24	−117.17
November	56.20	−11.20
December	75.52	23.11
Sum	377.83	−261.72

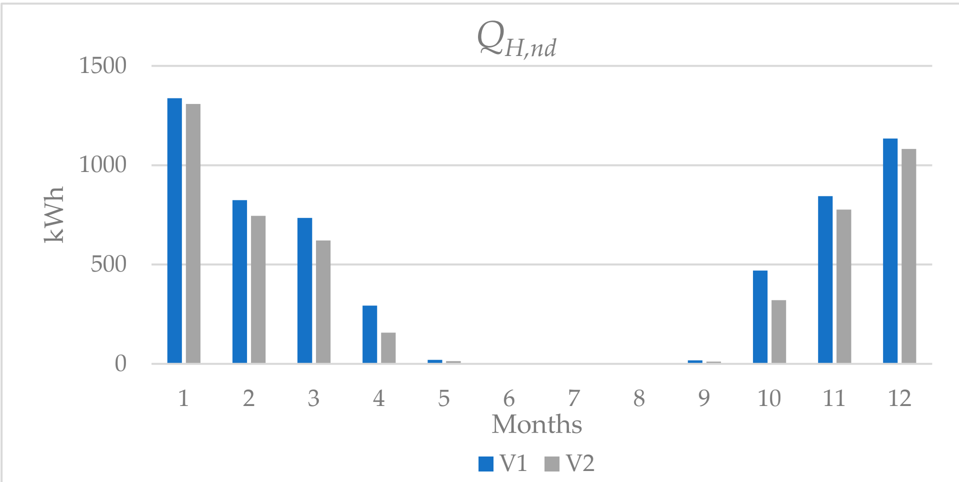


Figure 5. Energy requirements for space heating balanced for the model building in a typical heating season.

This energy balance was accounted for by the efficiency of solar energy storage based on the measuring period. In the case of paraffin used as PCM, some publications report changes to its properties over time. Particularly, some articles report the decrease in the latent heat of phase change in this material [37,50–52] due to multiple cycles of melting and solidification. It is worth underlining that the conditions for laboratory testing found in the literature were significantly different to the typical temperatures for TSW operation. Therefore, the authors of this study decided to provide their own tests of paraffin after 6 years of operation. It is crucial to emphasize that no leakages of material were reported in this period.

The paraffin used for the construction of the TSW was RT25HC, characterized by a latent heat of phase change of 230 J/g ± 7.5% according to the manufacturer's data, which was also confirmed before the construction was raised.

Laboratory tests conducted after the operation period were divided into two parts: one related to the material stored at a stable temperature below melting point with no solar radiation (reference value) and one related to the operating material (samples taken directly from the V2 variant of the wall). The latent heat of fusion was calculated from the area under the curve of the melting/solidification phenomenon, resulting in the values presented in Table 6.

Table 6. Results of laboratory tests of paraffin.

Sample No.	Melting Temperature (Beginning)	Melting Temperature (End)	Latent Heat of Fusion
	°C	°C	J/g
Stored no. 1	21.01	26.84	232.03
Stored no. 2	21.96	25.98	237.37
Stored no. 3	21.69	26.18	246.66
Working no. 1	22.45	29.89	278.81
Working no. 2	22.19	29.17	278.52
Working no. 3	22.41	29.78	283.64
Stored, mean	21.55	26.33	238.69
Working, mean	22.35	29.61	280.32

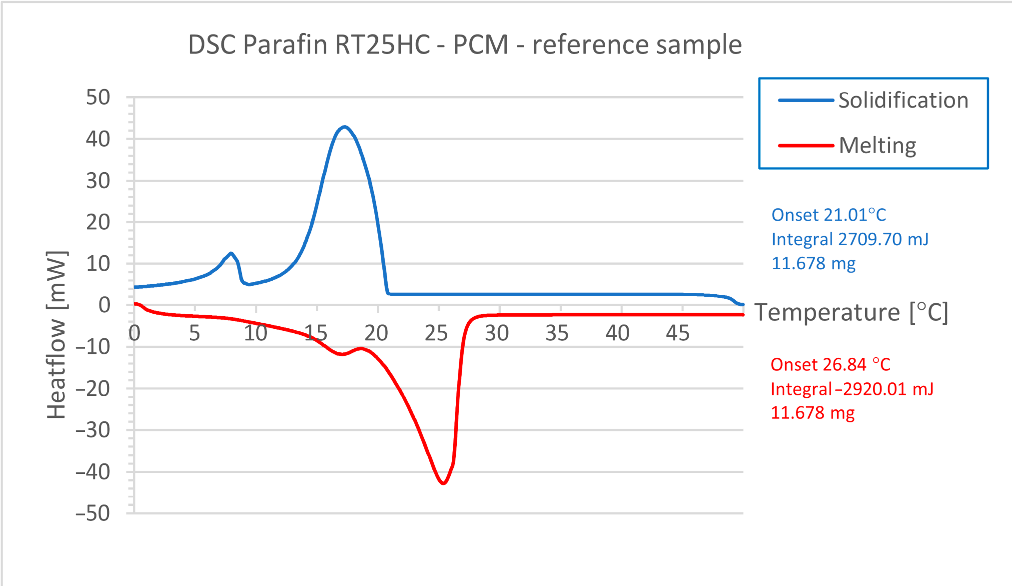
According to the results received, the samples stored under the stable conditions showed no serious changes in their properties, as presented in Table 6. At the same time, the samples taken from the existing TSW were characterized by increased phase change temperatures as well as a rise in the latent heat of phase change, which accounted for 17%. The increase did not cause the deterioration in heat storage capacity, but several changes were noticed, as discussed below.

Figure 6 includes a comparison of the DSC graphs received during melting and solidification of the samples Stored no. 1 and Working no. 1, characterized by similar mass. As can be seen, the process of melting begins and ends with higher temperature in the case of the second sample, which is caused by the deterioration in its properties after the thermal cycles during 6 years of operation. At the same time, the latent heat of phase change increased significantly, which influenced the possible amounts of stored energy. The same results were obtained during solidification of the studied samples.

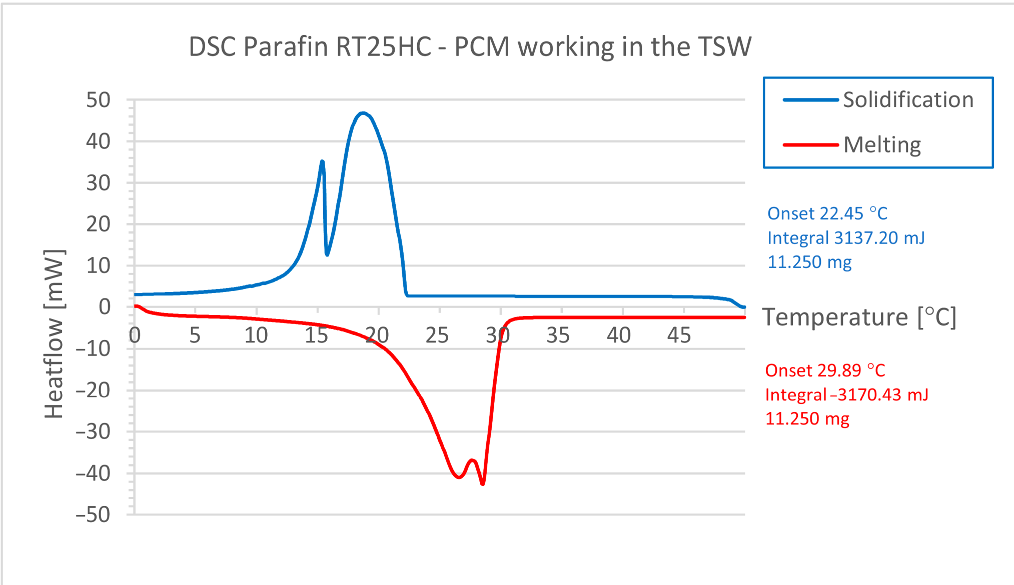
Two endothermic/exothermic peaks were observed during DSC measurement. These two peaks had different melting temperatures, which indicate phase separation in the crystalline structure. It was assumed that the measured samples consist of a large proportion of lower molecular weight crystals and a small proportion of higher molecular-weight crystals, representing various temperatures and enthalpy of fusion, as reported in [53]. This effect may be caused by sample contamination during the operation phase in a real TSW. Furthermore, the supercooling effect could be the reason that the second sharp peak, in the case of the second PCM sample, was observed. Supercooling is a natural phenomenon that keeps PCMs in their liquid state at a temperature lower than their solidification temperature [54].

On the basis of the results of this study and comparison to those in the literature [38], there is an effect of heat capacity increase in certain circumstances, depending on the PCM characteristic as well as the conditions of operation, which may lead to the increase in stored potential energy. At the same time, monitoring of real TSWs leads to the conclusion that a higher melting temperature reduces the amount of energy stored in TSWs [55], since the phase change material with a lower melting point of 35 °C achieved 4% greater reduction in energy requirements than PCM bricks with a melting point of 36–38 °C. In spite of the fact that no significant changes in the operation of the monitored TSW were noticed, the authors applied two models of life cycle energy balance:

- Scenario 1: with no deterioration in thermal properties (constant efficiency of the TSW);
- Scenario 2: with a linear change in efficiency resulting from a 17% latent heat increase and assumed 4% decrease caused by the temperature interval, resulting in a 2% yearly increase in the efficiency of the TSW in the first 6 years of operation (tested period).



(**a**)



(**b**)

Figure 6. DSC graphs of studied PCM samples: (**a**) Stored no. 1, (**b**) Working no. 1.

3.2. Life Cycle Impact Assessment

The Life Cycle Impact Assessment was based on the calculation of the GWP and IMPACT 2002+ indicators. The main results of the GWP calculations for the construction of the building, for 1 year of operation (heating), and 50 years of the lifetime perspective are presented in Table 7.

Table 7. Results of GWP calculation for the model building.

Variant of LCA	GWP, $MgCO_{2eq}$			
	Construction	1 yr Operation	Cumulated Load, 50 yrs	Avoided Emission
V1	81.028	1.600	161.027	0.000
V2 SC1	81.076	1.420	152.060	8.967
V2 SC2	81.076	1.420–2%diff./yr	150.899	10.128

According to the results of the calculation, the difference between the traditional construction V1 and the PCM-modified TSW incorporated into the southern wall V2 equaled 48 $kgCO_{2eq}$, while the potential yearly savings resulting from the diminished energy consumption was 180 $kgCO_{2eq}$. Therefore, the payback period in the case of this solution does not exceed 1 year, regardless of the scenario of energy efficiency in the life cycle. The possible reduction in carbon emissions was estimated as 8.96 $MgCO_{2eq}$ in Scenario 1 and 10.128 $MgCO_{2eq}$ in Scenario 2 of V2.

Considering the fact that yearly operation (energy required for space heating in the building) is strongly dependent on weather data, additional Monte Carlo statistical analysis was carried out examining the influence of the input data on the final result for the operation stage of the building. According to the implemented model, the maximal difference in energy consumption might equal 15%, which translates into the range of the 90% confidence interval 1.43–1.79 $MgCO_{2eq}$, as presented in Figure 7. Such results do not change the payback time for the construction of the TSW.

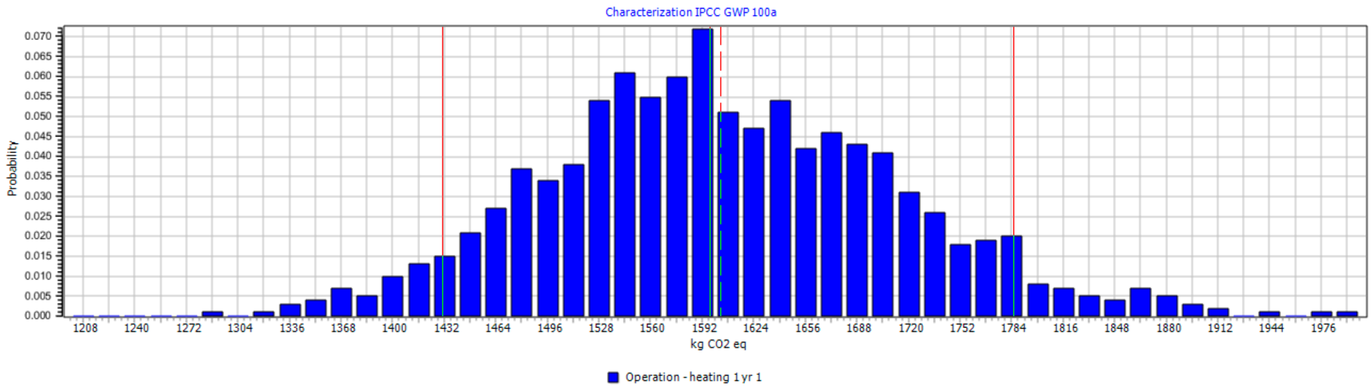


Figure 7. Monte Carlo analysis of 1 year operation of heating system including IPCC GWP 100a characterization.

According to the results of the calculation presented in Table 8, the difference between the traditional construction V1 and the PCM-modified TSW incorporated into the southern wall V2 equaled 0.202 Pt, while the potential yearly savings resulting from the diminished energy consumption were 0.043 Pt. Therefore, the payback period in the case of this solution does not exceed 5 years, regardless of the implemented scenario. The possible reduction in the environmental load reached 1.947 Pt (5%) in Scenario 1 and 2.224 Pt in Scenario 2 of V2 (>5%). According to the share analysis, most of the indicators are related to two of the damage categories—resources and climate change—which correspond to the origin of the heat source for the building being based on fossil fuels.

The results obtained in this study confirm that, under temperate climate conditions, a thermal storage wall modified with PCM can be an efficient solution in terms of energy and environment concerns. The results of the LCA analysis reported for warmer climates [56,57] indicated similar or higher possible reductions in carbon footprint, depending on the conditions of analysis.

Table 8. Results of IMPACT 2002+ calculation for the model building.

Variant of LCA	IMPACT 2002+, Pt			
	Construction	1 yr Operation	Cumulated Load, 50 yrs	Avoided Impact
V1	21.461	0.381	40.533	0.000
V2 SC1	21.663	0.338	38.585	1.947
V2 SC2	21.663	0.338	38.309	2.224

4. Conclusions

Considering the results of this study, it should be emphasized that thermal storage walls applied to a real subject achieves a positive energy balance in temperate climate conditions. Energy efficiency was assessed as an 11.3% reduction in the energy required for space heating, resulting in reduced fossil fuel consumption and a decrease in the carbon footprint of the building. Considering the environmental efficiency of the analyzed solution, it is worth emphasizing that short payback periods were calculated in the case of the analyzed indicators (1 year for the GWP and 5 years for the IMPACT 2002+). The payback period durations did not exceed the real monitoring periods and are many times lower than the predicted building lifetime, which leads to significant possible reductions in the environmental loads of the building. The analysis showed a positive energy balance. However, it has to be mentioned that the possible energy-use reduction could be higher due to the difference in the observed solar radiation increase between the TMY and in recent years.

Reducing the burden on the environment is a key task due to the requirements of the sustainable development of buildings. The presented research has shown that using the proposed solution of the PCM-modified TSW, a short payback period for environmental indicators was achieved while reducing energy consumption during the operation stage of the building. During the tests, brick flour was used as waste material to additionally increase the solar energy accumulation capacity of the barrier. Further research should be focused on maximizing the use of recycled materials and the use of biodegradable materials (e.g., bioPCM), with a possibly lower negative impact on the environment during both their production and disposal.

Moreover, it should be noted that the existing legal guidelines in the area generally do not take into account the possibility of using storage walls due to the current maximum permissible values of the overall heat transfer coefficient and the lack of guidelines on the abolition of these restrictions for barriers with a positive energy balance. Therefore, in the analyzed building model, all the current legal requirements regarding the energy standard were applied, demonstrating the positive impact of a PCM-modified TSW with an overall heat transfer coefficient exceeding the legally permissible value for the energy consumption of the building, which may be informative for decision makers in the field of legislation regarding the implementation of this type of solution.

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