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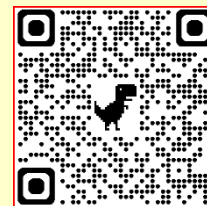
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## Low-energy Passive Thermal Conditioning for Social Housing

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### ABSTRACT

*This study evaluates the performance of a hybrid system as a low-energy alternative for passive thermal conditioning, integrating a paraffin-based phase change material (PCM) and a silica aerogel thermal insulation into a metal ceiling panel, for application in social housing in Atotonilco el Grande, Hidalgo. The methodology combines a systematic literature review and an analysis of the region's climatic conditions, which were incorporated into numerical simulations using the Finite Element Method (FEM) to complement the development of the system. The simulations made it possible to validate the physical behaviors of the materials, including thermal conductivity, density, melting temperature, latent heat of fusion, and thermal convection, as well as thermal comfort within the dwelling. The results show that the integration of PCM and aerogel reduces energy consumption by approximately 29.6% in climates with high heating and cooling demand, representing annual energy cost savings of up to 16,910 RMB. The aerogel acts as a thermal insulator with a conductivity of 0.020 W/mK, retaining more than 90% of the heat flux, which favors the PCM in storing and releasing energy more efficiently, releasing it as the indoor temperature of the dwelling decreases. The economic analysis indicates that, although the system demonstrates technical viability in climates with high energy demand, the payback periods vary significantly by region, ranging from 18 years in cold climates to longer periods in temperate climates. This finding is particularly relevant for the context of Atotonilco el Grande, where 52.4% of the population lives in poverty and access to conventional climate control systems is limited. As the final part of the project, a comparison with conventional heating and air conditioning systems is carried out, analyzing energy consumption and return on investment.*

**KEY WORDS:** Phase Change Materials (PCM), aerogel, thermal conditioning, social housing, thermal comfort, energy consumption.

## INTRODUCTION

Currently, one of the areas of greatest global interest is the development and implementation of renewable and low-energy consumption sources that maintain a cost-benefit ratio, driven by the need to reduce the environmental and economic impact generated by conventional systems. In Mexico, the Federal Electricity

Commission (CFE, 2024) reports that 31.2% of generated electricity comes from clean sources, representing a broad research field for the development of new alternatives that contribute to the efficient use of energy, such as Phase Change Materials (PCMs), which possess the ability to absorb, store, and release thermal energy through a phase transition, primarily between solid and liquid states.

Population growth, urbanization, and technological development have significantly increased global energy demand (UNEP/GlobalABC/IEA, 2024). This increase has led to a higher reliance on climate control systems to maintain suitable thermal comfort conditions in buildings, where at least 64.1% (Jorgensen & Ma, 2025) of residential energy consumption is allocated to indoor thermal regulation, implying greater financial expenditure for families. Cooling demand is projected to grow globally by 150% and by up to 600% in developing countries by 2050 (Jorgensen & Ma, 2025). However, the implementation of such systems remains limited for a significant segment of the population due to costs associated with acquisition, installation, operation, and maintenance; in contexts such as Atotonilco el Grande, Hidalgo, 52.4% of the population lives in poverty and 7% in extreme poverty, restricting access to conventional climate control systems (Kumaraswamy et al., 2024; INEGI, 2020), a situation that predominantly affects social housing.

Given this scenario, the implementation of passive thermal conditioning strategies has gained growing importance within economic and technological domains (Kokatnur et al., 2025; UNEP/GlobalABC/IEA, 2024). Unlike conventional heating and cooling systems, these strategies aim to harness environmental conditions and material properties to reduce energy demand in buildings (Jorgensen & Ma, 2025; Zhou et al., 2025). Among the technologies with the highest potential, Phase Change Materials (PCMs) stand out for their capability to store and release thermal energy during phase change processes (González Espinosa, 2025; Zou et al., 2025), thereby helping to mitigate indoor temperature fluctuations and enhance thermal comfort conditions (Fraga Horton, 2025; Kokatnur et al., 2025; Li et al., 2024).

The techno-economic analysis of PCM-based systems has shown promising results in various climatic contexts. Zou et al. (2025) developed an elastic PCM/SEBS composite with a latent enthalpy of 178.2 J/g and a melting temperature of 25.1 °C, demonstrating that its integration into building envelopes can reduce HVAC energy consumption by up to 29.6% in cold climates, with payback periods of 18 years in regions with high energy demand (Zou et al., 2025).

In social housing contexts in Mexico, sustainability analysis has shown that although solutions using low-carbon materials and prefabricated systems can increase construction costs by up to 59%, improvements in energy efficiency (a reduction to 82.93 kWh/m<sup>2</sup>-year compared to 132 kWh/m<sup>2</sup>-year in conventional dwellings) and reductions in CO<sub>2</sub> emissions (13.20 kg/m<sup>2</sup>-year compared to 23.88 kg/m<sup>2</sup>-year) justify the long-term investment (Velazquez, 2023). Furthermore, studies in low-income communities in Mexico show that combining passive strategies with efficient HVAC systems can reduce primary energy consumption by up to 57%, although initial investment costs may increase by 125% to 150% (Flores et al., 2025), underscoring the importance of incentive programs and subsidies for the economic viability of these technologies in the social housing sector.

According to the National Water Commission (CONAGUA, 2026), the national mean temperature reached 25.4 °C, representing an anomaly of 1.3 °C above the baseline average recorded during the

1991–2020 reference period, which was 24.1 °C. This increase highlights the necessity of developing thermal conditioning alternatives capable of addressing current climatic conditions without escalating energy consumption. In this context, PCMs represent a viable option for application in regions with extreme climate conditions and in housing where economic constraints prevent the installation of conventional climate control systems. Nonetheless, the implementation of these materials in Mexico remains limited due to scarce dissemination and a low volume of research focused on their application in the residential sector (González Espinosa, V., 2025).

For this reason, this research proposes the design of a hybrid passive thermal conditioning system to improve thermal comfort conditions in social housing. To achieve this, the compatibility of different Phase Change Materials with various insulating materials will be analyzed, evaluating their thermal behavior within the dwelling. Furthermore, different PCM alternatives will be studied to select the most suitable configuration and subsequently compare the thermal, energetic, and economic performance of a conventional dwelling, a dwelling integrated with the proposed passive system, and a dwelling equipped with conventional climate control systems. The study adopts a quantitative approach, based on the collection and analysis of literature data regarding the thermal properties of materials, such as melting point, thermal conductivity, density, and latent heat, among other variables of interest. Subsequently, a simulation model will be developed to evaluate the thermal behavior of the dwelling under different scenarios, complemented by an economic feasibility analysis considering investment costs, estimated energy savings, and payback periods—fundamental aspects for implementing these technologies within the context of social housing in Mexico.

## RESEARCH DEVELOPMENT

This section details the scientific foundations and the methodology for the design, simulation, and analysis of the hybrid passive thermal conditioning system for social interest housing. The development is organized into seven stages, starting from the review of the state of the art to the numerical validation, with the main focus on the use of computational simulation tools (FEM, CFD, and transient thermal models) to validate the system's performance. The specific study variables, materials, design criteria, and simulation parameters of the proposed solution are defined to understand the technical feasibility of the solution.

### State of the Art

The PRISMA protocol was adopted in four phases. In Identification, 189 records were obtained from Scopus, WoS, ScienceDirect, Springer, and Google Scholar (2015–2025), reduced to 112 after filtering. In Screening, 30 articles were selected, excluding studies without PCM/aerogel application in buildings or without numerical/experimental analysis. In Eligibility, priority was given to works combining simulation-validation, hybrid systems, and PCM (15–30 °C). In Inclusion, the 30 articles are synthesized into thermal performance, insulating materials, and simulation.

Table 1: Thermal Performance (own elaboration).

| Author(s)                 | Configuration / Strategy                   | Key Results                                        | Main Contribution                                     |
|---------------------------|--------------------------------------------|----------------------------------------------------|-------------------------------------------------------|
| Kumaraswamy et al. (2024) | PCM in corrugated sheet roofs              | Indoor $T$ reduction: 2-3 °C; Savings: 28-40 %     | Experimental validation in climate similar to Hidalgo |
| Zou et al. (2025)         | PCM/SEBS panels in 5 Chinese climates      | Peak reduction: up to 5.5°C; Savings: up to 30.9 % | Techno-economic evaluation of elastic PCM             |
| Li et al. (2024)          | Dynamic integration of mobile PCM          | Summer reduction: up to 5.35x; Winter: up to 58 %  | Innovative strategy with mobile air layer             |
| Kokatnur et al. (2025)    | Combined strategies                        | Savings: up to 86%; Comfort hours: +17.6 to 74.5 % | Combined outperform individual strategies             |
| Albelwi et al. (2026)     | CMU with pentadecane ( $T_m=10$ °C) at 9 % | Fluctuation reduction: 27 %; Consumption: 12-15 %  | Critical $T_m$ selection for climate                  |
| Iruri-Ramos et al. (2023) | Roof insulation (10 cm rock wool)          | Reduction: 23 % (individual); 29 % (combined)      | Roof insulation is most effective intervention        |

Studies demonstrate reductions of 2-5.5 °C and savings of 20-86 % with combined strategies. Kumaraswamy et al. (2024) reported 28-40 % with PCM in roofs. Zou et al. (2025) achieved peak reductions up to 5.5 °C. Kokatnur et al. (2025) confirmed combined strategies outperform individual ones with savings up to 86 %. Iruri-Ramos et al. (2023) identified roof insulation as the most significant single intervention (23 %).

Table 2: Insulating Materials (Aerogel and Composites) (own elaboration).

| Material / Configuration        | Key Results                                                             | Main Contribution                       |
|---------------------------------|-------------------------------------------------------------------------|-----------------------------------------|
| Slentex aerogel blanket         | Conductivity: $0.019 \frac{W}{m \cdot K}$<br>; Stable after 250 °C      | Thermal and structural characterization |
| Cellulose + aerogel (50 % vol.) | $\lambda$ : $0.0307 \frac{W}{m \cdot K}$ ; Reduction: 42 %              | Sustainable low-cost composite          |
| Cellulose aerogel               | $\lambda$ : $0.024 \frac{W}{m \cdot K}$ ; Cost: USD 4-30/m <sup>3</sup> | Review of lignocellulosic materials     |

Silica aerogels stand out with 0.015-0.020 ( $W/m \cdot K$ ). Ali et al. (2025) achieved 0.0307 ( $W/m \cdot K$ ). with cellulose composites. Cellulose aerogels report 0.024 ( $W/m \cdot K$ ). and attractive costs (USD 4-30/m<sup>3</sup>). Nishad et al. (2026) achieved thermal delay of ~2 hours.

Table 3: Simulation Tools and Validation (own elaboration).

| Author(s)                       | Tool / Method                    | Key Results                                       | Main Contribution                    |
|---------------------------------|----------------------------------|---------------------------------------------------|--------------------------------------|
| Vedrtam et al. (2025)           | CFD (ANSYS) + FEM (FEniCS)       | Error: 7.74 %; $T$ reduction: 5.06 %              | Validated CFD-FEM methodology        |
| Fraga (2025)                    | FEM-ANSYS with PCM RT21          | Error <1 °C; $R^2=0.98$ ; Phase improvement: 42 % | Hotbox validation                    |
| Hou et al. (2025)               | COMSOL with dynamic conductivity | Error <5 %; Plateau +147 %                        | Dynamic effective conductivity model |
| De Masi et al. (2026)           | MATLAB-EnergyPlus for PDRC       | $T_s > 30$ °C; Cooling: -75 %; Heating: +24 %     | Seasonal trade-off analysis          |
| Mousazadeh Aghoei et al. (2024) | DesignBuilder + MATLAB           | PCM savings: 5.6 %; Nano-paint: 1.8 %             | Exergetic and economic comparison    |

Methodologies achieve errors <5-8 % and  $R^2 > 0.95$ . Fraga (2025) validated with error <1 °C and  $R^2=0.98$ . Hou et al. (2025) demonstrated the importance of dynamic conductivity models. De Masi et al. (2026) evidenced that seasonal balance is critical.

Table 4: Summary of Key Findings(own elaboration).

| Area                  | Key Finding                      | Key Authors                                                         |
|-----------------------|----------------------------------|---------------------------------------------------------------------|
| Temperature Reduction | 2-5.5 °C indoor                  | Kumaraswamy et al. (2024); Zou et al. (2025); Albelwi et al. (2026) |
| Energy Savings        | 20-86 % with combined strategies | Kokatnur et al. (2025); Li et al. (2024); Kumaraswamy et al. (2024) |

|                      |                                                   |                                                            |
|----------------------|---------------------------------------------------|------------------------------------------------------------|
| Aerogel Conductivity | $0.015\text{--}0.0307 \frac{W}{m \cdot ^\circ K}$ | Lakatos (2025); Lakatos & Lucchi (2024); Ali et al. (2025) |
| Thermal Delay        | 2-10 hours                                        | Nishad et al. (2026); Fraga (2025)                         |
| Simulation Accuracy  | Error <5 %, $R^2 > 0.95$                          | Vedrtnam et al. (2025); Fraga (2025); Hou et al. (2025)    |

Most suitable PCM: Paraffin RT28 with macroencapsulation. Approximately 70 % of studies use paraffins due to stability, high enthalpy (170-237 J/g), and compatibility. The 21-28 °C range aligns with Atotonilco el Grande (14-25 °C). Macroencapsulation is more economical for social housing.

Most suitable aerogel: Silica aerogel blanket. Offers the best performance-practicality ratio ( $\lambda=0.015\text{--}0.020 \text{ W/m } ^\circ K$ ). A vapor barrier is recommended due to moisture susceptibility.

### Limitations

As part of the limitations of this project, the first phase consists solely of simulations, while the fabrication and experimental validation of a prototype are reserved for a subsequent phase. The study is limited to the use of data from social housing units located in the municipality of Atotonilco el Grande, Hidalgo, to carry out these simulations. Furthermore, the research is restricted to the analysis of thermal comfort and the payback period of the proposed system. Structural analysis, acoustic analysis, and indoor air quality assessment are beyond the scope of this study.

### Conclusion and Implications for the Project

The literature confirms the high potential of hybrid PCM + aerogel systems to improve thermal comfort and reduce energy demand in temperate climates. Combined strategies outperform individual ones with reductions of 2-5.5 °C and savings up to 86 %. Calibrated simulation tools offer the necessary accuracy for design.

Identified gaps: (i) scarcity of studies in the semi-arid/temperate climate of Hidalgo; (ii) limited cost analysis for social housing; (iii) few works integrating PCM and aerogel in a single envelope.

Paraffin RT28 (macroencapsulated) and silica aerogel blanket (with vapor barrier) are recommended, modeled with validated tools (ANSYS, COMSOL, or EnergyPlus), prioritizing experimental validation under local climate conditions

## Methodology

The research was conducted in Atotonilco el Grande, in the state of Hidalgo, Mexico, where the system was applied to social housing in the town. This area was selected due to the region's inherent economic and climatic vulnerabilities. However, these homes share a common characteristic: their architecture is designed solely to provide shelter for a family without considering thermal comfort. Consequently, families are forced to acquire conventional heating and air conditioning systems to meet this need.

Within this context, Atotonilco el Grande became the focus of this study. Therefore, it was necessary to determine whether the community perceives thermal comfort as a problem related to climate change and the systems that contribute to it. The statistical analysis proposed by Bernardo et al. (2024) allows for obtaining the sample size, which is considered to have a 96% confidence level, a 4.5% margin of error, and a finite population of 30,140 obtained from data from INEGI (2020), yielding a sample size of 467. However, a sample of 31 participants was selected because it allowed for a more focused study, optimizing available resources and ensuring that the information was relevant to both the research

and the population.

The implemented methodology consists of 5 phases (Figure 1):

- Selection of the environment and field study: An important phase for establishing a foundation and analysis, mentioned by Ochoa et al. (2020), and implemented in this phase to understand the population's perspective on the problem and also to ensure that the developed proposal has an impact within the state. Meanwhile, a deductive method was chosen for characterizing the community's housing, as Programme (2024) indicate that contextualization reinforces the urgency of implementing a passive system.
- Identification and characterization of materials: After evaluating the field study, the thermo-physical properties of the elements that make up the hybrid system must be considered. Following Lakatos (2025) and Lucchi (2024), the main variables are proposed, which were key in selecting the study variables such as thermal conductivity, specific heat, and melting range. Zhou (2025) provides a comprehensive review of organic PCMs (paraffins) that serves as a basis for characterization, using temperatures of 20°C–30°C and latent enthalpies of 110–220 kJ/kg as a reference, as proposed by Osibidu (2024).
- Simulation and digital modeling: The three-dimensional model of the proposed system was developed using CAD software (SolidWorks). Mazaheri et al. (2025) suggest using modeling to establish boundary conditions before performing the simulation. Horton (2025), on the other hand, develops the implemented structure that allows for an acceptable description of the studied phenomenon.
- Thermal testing and comparison: Similarly, it was mandatory to perform steady-state simulations applied and implemented by Kumaraswamy (2024) at different temperatures, studying the behavior of the PCM and insulating material. Iruru-Ramos et al. (2023) focus on deducing the energy demand and the behavior of the system governing this phase.
- Impact assessment: Finally, the percentage of energy savings established by Gayar et al. (2024) is quantified to determine the energy consumption of the proposed system

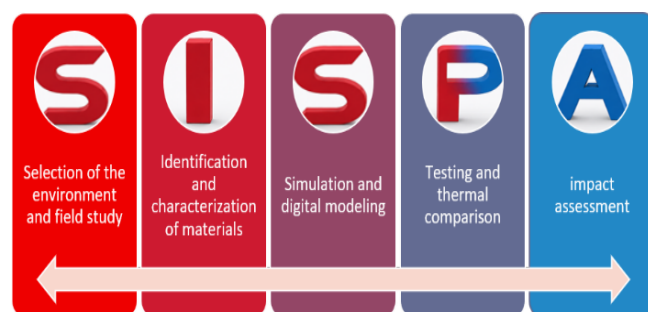


Figure 1: Methodology (own elaboration)

### Identification of the Need

The use of conventional air conditioning systems represents for communities an economic and environmental challenge due to the maintenance, manufacturing, and operation of the system, since they not only provide partial solutions but also require high energy

consumption. In this sense, Gerley et al. (2025) mention various conventional systems and conduct an analysis of each one, from which it can be concluded that these are inefficient systems due to the cost-benefit relationship they present.

In Atotonilco el Grande, climatic conditions are established at temperatures of 11 °C in winter and 25 °C in summer according to CONAGUA (2026). Within the field study, the population is exposed to conditions that compromise their health and well-being. As noted by Ochoa et al. (2022), access to essential energy services such as thermal comfort is strongly related to economic vulnerability, and in Atotonilco el Grande, according to INEGI (2020), 52.4 % of the population lives in poverty, consequently making it impossible to acquire conventional systems or keep them in operation.

To quantify the perception of the inhabitants, a structured survey was applied to identify the perception of homeowners using a five-level Likert scale. The Pareto analysis (Figure 2) revealed that thermal comfort represents the most critical problem. These findings establish the need for a passive system that improves thermal comfort.

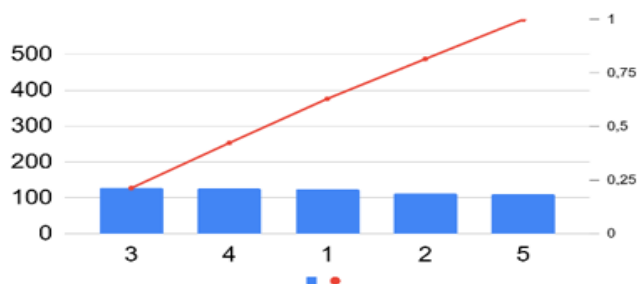


Figure 2: Pareto chart (own elaboration).

The functional analysis was developed through an Ishikawa diagram, organized into six causes (Figure 3), which provides support for examining the causes. Meanwhile, the application of the problem tree (Figure 4) established the logical relationship between the causes, the central problem (inefficient thermal comfort), and the consequences.

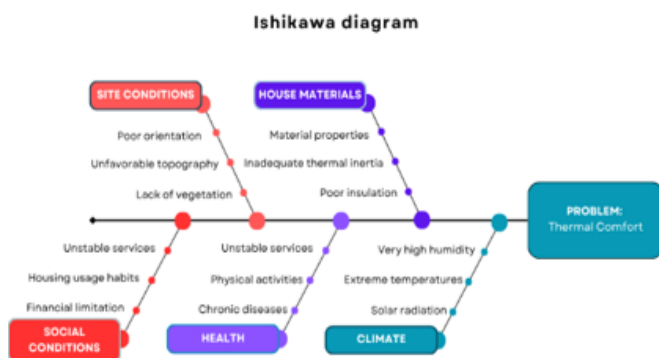


Figure 3: Ishikawa diagram (own source)

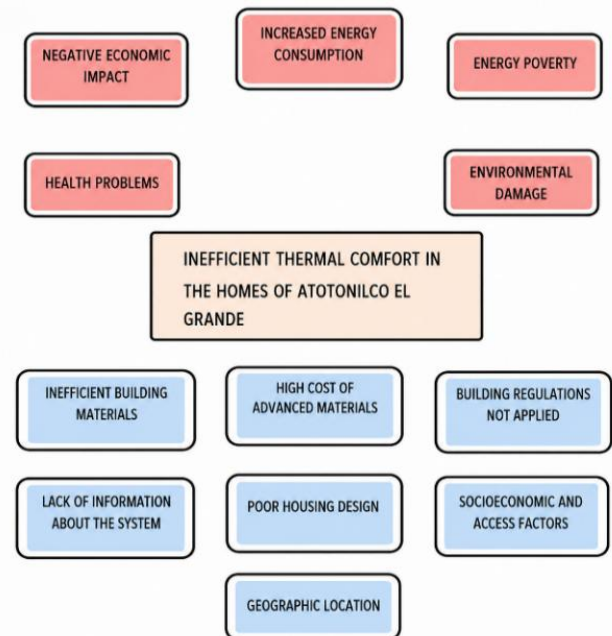


Figure 4: Problem tree (own source)

Through the instruments applied, user requirements were defined and transformed into product characteristics, among which thermal comfort, reduction of extreme temperatures, economic savings, and thermal insulation and storage were prioritized. These requirements established the parameters that guided the design of the hybrid system.

## ENGINEERING DESIGN

The manufacturing drawing of the reinforced gypsum ceiling panel is dimensioned under ANSI standardization in a customized engineering drawing template. Likewise, the drawing is dimensioned with the GD&T standard. This regulation is a standardized system of symbols, rules, and specifications used in engineering drawings to precisely define the geometry, orientation, location, and allowable variation of the part's features. GD&T aims to ensure that components can be manufactured, incorporated, and assembled correctly.

Specifying tolerances with considerable data of functionality and quality, finishes are specified that are intended, as well as the manufacturing method planned for the reinforced gypsum ceiling panel. The reinforced gypsum ceiling panel is manufactured by molding, seeking a surface finish of approximately 50 microns. A high-quality surface finish is not sought since it is a construction material, although it must meet some quality features such as color, to provide a good interior appearance.

The dimensions of 610x610 mm are based on the market, since the ceiling panels that are commercialized are standardized and based on construction standards, so the aim is to have the same properties for good adaptability to the system. Something curious about the design, which is mainly the innovation of the system, is the honeycomb shape of the gypsum ceiling panel. This allows the incorporation of the phase change material (PCM). This shape also enables better convection between the materials and better adaptability in the intended heat transfer. In a precise and condensed way, the reinforced gypsum ceiling panel seeks good heat transfer with its innovative honeycomb shape where the phase change material (PCM) will be located.



| PCM Behavior                            | Symbol           | Value    | Unit                          |
|-----------------------------------------|------------------|----------|-------------------------------|
| Maximum effective heat capacity         | $C_{p,eff,max}$  | 68,667   | $\frac{J}{kg \cdot ^\circ K}$ |
| Energy stored per m <sup>2</sup>        | $Q_{Total}$      | 5,424    | $\frac{kJ}{m^2}$              |
| Energy stored per dwelling              | $Q_{dwelling}$   | 54,240   | kJ                            |
| Thermal lag                             | $\tau$           | 19.165   | hours                         |
| Energy and Savings                      |                  |          |                               |
| Reference annual demand                 | $E_{ref}$        | 2,500    | $\frac{kWh}{year}$            |
| Annual energy savings                   | $\Delta E$       | 625      | $\frac{kWh}{year}$            |
| CO <sub>2</sub> reduction               | $CO_{2,avoided}$ | 281.25   | $\frac{kg}{year}$             |
| Economic                                |                  |          |                               |
| Initial investment (10 m <sup>2</sup> ) | $CapEx$          | 1,709.20 | USD                           |
| Annual economic savings                 | $\Delta C$       | 175.00   | USD/year                      |
| Payback period                          | $Payback$        | 9.77     | years                         |
| Net Present Value (20 years)            | $NPV$            | 1,261.75 | USD                           |
| Internal Rate of Return                 | $IRR$            | 12.7     | %                             |

#### Material data

- PARAFFIN-BASED PCM Thermal conductivity: 0.8 ( $W/m^\circ K$ ).
- SILICA AEROGEL Thermal conductivity: 0.15 ( $W/m^\circ K$ ).
- GYPSUM CEILING PANEL Thermal conductivity: 0.033 ( $W/m^\circ K$ ).

#### Material dimensions

- PARAFFIN-BASED PCM Width: 25 mm Length: 25 mm Height: 30 mm
- SILICA AEROGEL Width: 590 mm Length: 590 mm Height: 10 mm
- GYPSUM CEILING PANEL Width: 610 mm Length: 610 mm Height: 50 mm

#### Simulation criteria

For the simulations, SolidWorks software was used with finite element method (FEM) conditions, in order to analyze the system independently under data collected by INEGI in the area where the composite system is planned to be installed. These temperature data studied by INEGI show average temperatures ranging between 15 to 20 °C, but in recent years average temperatures have reached approximately 23 °C. Based on these data, additional criteria were established for the simulation.

A behavior of natural convection was set for the entire composite material (PCM, AEROGEL, and GYPSUM PANEL), with a convection coefficient of 10 ( $W/m^2^\circ K$ ). This means that all faces of the system present convection in the direction in which the face is oriented.

This criterion was based on the way air behaves inside a dwelling: the hotter the air, the less dense it becomes, meaning that the hotter it is, the higher it will be found in the house

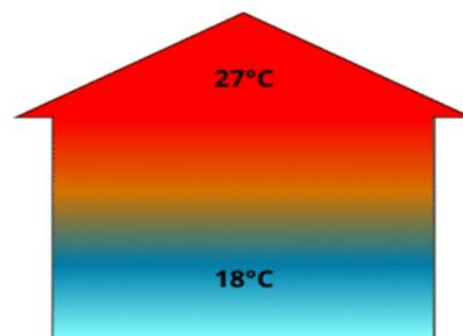


Illustration 9:indoor temperature representation (source: Google)

Therefore, the system works entirely by convection between the system and the hot air inside the home. Despite being FEM elements, different simulations were carried out to achieve various system behaviors.

The silica aerogel functions by absorbing the greatest amount of heat from the hot air, thus reducing its temperature. While the aerogel retains and releases heat over time, the PCM acts as a heat exchanger. This function causes the PCM to change phase and transfer heat to the gypsum ceiling panel. The entire process occurs through natural convection.

This system is planned to be installed as a false ceiling, so between the roof and the system there will be a static air layer without flow, but with a temperature provided by the heat inside the home and convection between the roof and the air.

#### Summary of criteria:

- Static air heated by the home and convection between the roof and the air.
- The system operates entirely by natural convection.
- Aerogel retains 90% of the heat present in the environment.
- PCM functions as a heat exchanger.
- Gypsum ceiling panel releases the temperature transmitted by the PCM into the environment, generating convection between the gypsum panel and the ambient air.

#### Simulation 1:

In the first simulation, it was specified that the system works through natural convection due to the thermal properties of the materials. SolidWorks showed the direction of convection in each system component.

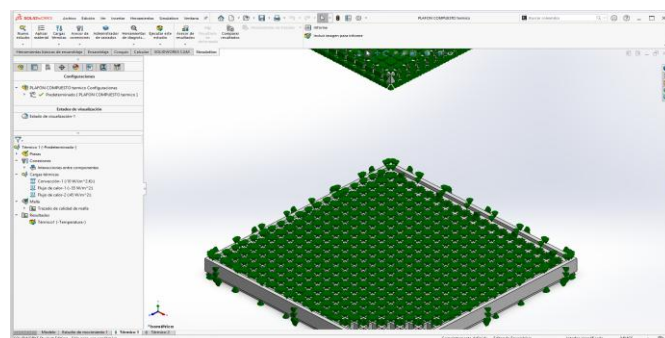


Illustration 10:representation of convection (own source)

Thermal loads applied:

- Heat flux entering the AEROGEL:  $45 \text{ (W/m}^2\text{)}$
- Heat flux exiting the GYPSUM PANEL:  $-50 \text{ (W/m}^2\text{)}$

A medium-fine mesh was generated to observe heat transfer in more detail.

Results:

- The AEROGEL reached a maximum temperature of  $300 \text{ }^\circ\text{K}$ , where most heat transfer occurs since it acts as a thermal insulator.
- The final temperature released at the gypsum ceiling panel was  $293 \text{ }^\circ\text{K}$ .
- In simple terms, the system can take hot air at  $27 \text{ }^\circ\text{C}$  and release it at  $20 \text{ }^\circ\text{C}$ , gradually across the system.

Illustration 11 shows the aerogel in red ( $300 \text{ }^\circ\text{K}$ ) and the gypsum panel in blue ( $293 \text{ }^\circ\text{K}$ ), confirming a reduction of  $7 \text{ }^\circ\text{K}$ . This validates that the PCM and AEROGEL implementation works to reduce ambient temperature.

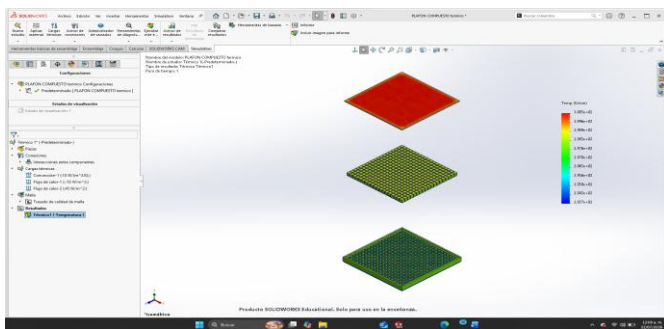


Illustration 11: SIMULATION 1 (own source)

### Simulation 2:

Thermal loads applied:

- Heat flux entering the AEROGEL:  $50 \text{ (W/m}^2\text{)}$
- Heat flux exiting the GYPSUM PANEL:  $-55 \text{ (W/m}^2\text{)}$

Results:

- Increasing the heat flux in the aerogel produced an insignificant change in temperature difference.

The system maintained the  $7 \text{ }^\circ\text{K}$  reduction, confirming thermal comfort and further validating the theory of system viability.

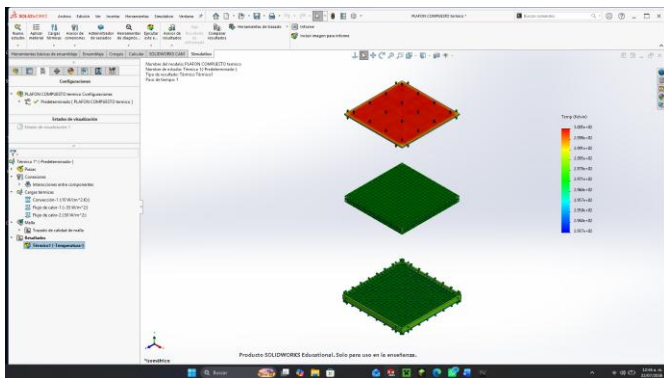


Illustration 12: SIMULATION 2 (own source)

### Simulation 3:

In this third case, this value was added to the heat flux and a condition was changed since the airflow over the aerogel is in

steady-state mode, there is no flow or current that makes it change. In this way, the aerogel absorbs heat by convection from the stationary air at the given temperature:

- Stationary air temperature over the AEROGEL:  $305 \text{ }^\circ\text{K}$
- Heat flux exiting the GYPSUM CEILING at  $-55 \text{ (W/m}^2\text{)}$

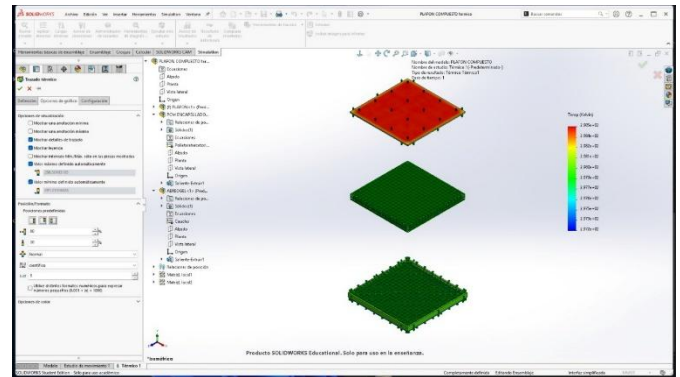


Illustration 13: SIMULATION 3 (own source)

## CONCLUSION

To evaluate the integral performance of the hybrid system, an analysis was carried out combining numerical simulation (SolidWorks FEM) and analytical heat transfer calculations. Table 1 summarizes the main indicators of thermal performance, energy efficiency, and economic viability obtained for the proposed system. The results allow quantifying the system's impact on thermal comfort, energy savings, and return on investment, facilitating comparison with conventional construction systems.

Tabla 6: Summary of Results of the Hybrid Thermal Conditioning System. (own source)

| Parameter Evaluated                 | Symbol/Unit                                                         | Value    | Observation                                                                  |
|-------------------------------------|---------------------------------------------------------------------|----------|------------------------------------------------------------------------------|
| Thermal Performance                 |                                                                     |          |                                                                              |
| Heat Transfer Coefficient (Ceiling) | $U \left( \frac{\text{W}}{\text{m}^2 \cdot ^\circ\text{K}} \right)$ | 0.832    | Highly efficient vs. concrete (14.17)                                        |
| Heat Gain Reduction (Summer)        | %                                                                   | 94.1%    | Relative to a concrete roof.                                                 |
| Thermal Lag                         | $\tau$ (hours)                                                      | 19.16    | Delay in heat transmission.                                                  |
| Storage Capacity per Dwelling       | $\text{kWh}$                                                        | 15.07    | Total energy stored in a daily cycle.                                        |
| Numerical Simulation                |                                                                     |          |                                                                              |
| Indoor Temperature Reduction        | $^\circ\text{C}$                                                    | $\sim 7$ | From $27^\circ\text{C}$ to $20^\circ\text{C}$ under $45 \text{ W/m}^2$ load. |
| Energy and Economic                 |                                                                     |          |                                                                              |
| Annual Energy Savings               | $\text{kWh/year}$                                                   | 625      | Conservative estimate (25%).                                                 |

|                                         |                               |          |                                      |
|-----------------------------------------|-------------------------------|----------|--------------------------------------|
| Annual Economic Savings                 | <i>USD/year</i>               | 175.00   | Based on \$0.28 USD/kWh.             |
| Initial Investment (10 m <sup>2</sup> ) | <i>USD</i>                    | 1,709.20 | Total CapEx.                         |
| Payback Period                          | <i>years</i>                  | 9.77     | Financially viable.                  |
| CO <sub>2</sub> Reduction               | <i>kg CO<sub>2</sub>/year</i> | 281.25   | Mexican electricity emission factor. |

The results obtained through numerical simulation (SolidWorks) and analytical calculations demonstrate that the hybrid passive thermal conditioning system is technically and financially viable. The combination of the high thermal inertia of the PCM (with a lag of 19 h) and the excellent insulation of the aerogel ( $U=0.832 \text{ W/m}^2 \cdot ^\circ\text{K}$ ) achieve a thermal load reduction of over 94% compared to traditional construction systems. The economic analysis, with a payback of 9.77 years and an IRR of 12.7%, positions this technology as an attractive and sustainable alternative for social interest housing in climates such as Atotonilco el Grande, Hidalgo.

The simulations conducted demonstrate that the model is capable of representing the thermal behavior of the system when the input conditions are adjusted proportionally to the actual operating conditions at the pilot site. The simulation results show a reduction in both the indoor air temperature and the heat transferred by convection through the gypsum ceiling, achieving a temperature reduction of 7 K. This reduction confirms that the proposed system significantly decreases heat accumulation within the indoor environment, thereby improving thermal comfort while reducing the energy demand of the occupants.

The validity of these results is supported by the calculation report, which yielded a temperature difference of 8 K. The close agreement between the analytical calculations and the simulation results confirms the consistency of the developed model and demonstrates that the simulations reliably represent the thermal behavior of the proposed system. Furthermore, comparison with previous studies in the research area shows that the values obtained are consistent with those reported in the scientific literature, strengthening the reliability of both the methodology employed and the results achieved.

It is concluded that the proposed system represents an effective solution for improving thermal comfort in social housing. The integration of phase change material (PCM) and aerogel enhances the system's capacity for heat storage and thermal regulation, reduces indoor air temperature, and decreases the energy demand required for space conditioning. The results demonstrate that the system functions effectively as a passive heat exchanger, capable of absorbing, storing, and releasing thermal energy in a controlled manner while maintaining stable and comfortable indoor temperatures. Therefore, this innovative technology represents a viable, energy-efficient solution with strong potential for application in sustainable housing.

### Proposed Innovation

#### What makes the project different?

The project distinguishes itself by employing a hybrid system that combines phase change materials and aerogel in a modular ceiling configuration. This combination is not common in the state of Hidalgo, with a specific focus on social interest housing.

#### What does it improve?

The system considerably improves the thermal performance of housing units and reduces the energy demand for air conditioning. The system reduces heat transfer by more than 90 % compared to a traditional roof.

#### What does it contribute?

The design contributes a numerically validated design confirming a temperature reduction of 7 °C. The documented integration of aerogel and PCM in social interest housing was achieved, along with the materialization of specific materials. The project is financially viable since the NPV is positive and the IRR exceeds the 10 % discount rate. Additionally, a modular and manufacturable system is implemented.

#### What competitive advantage does it have?

It possesses superior thermal performance, surpassing expanded polystyrene in both insulation and storage capacity. It does not require electricity to operate. It generates annual savings of \$175.00 USD for the user. It focuses on vulnerable populations and has complete technical validation, combining numerical simulation with analytical calculations and concrete performance data under real conditions.

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