NOVA SCHOOL OF
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DEPARTMENT OF ELECTRICAL AND
COMPUTER ENGINEERING

DIOGO NUNO MENDONÇA SERRANO
Bachelor in Electrical and Computer Engineering

IMPROVING ENERGY EFFICIENCY IN THE WINE SECTOR BY THERMAL ENERGY STORAGE

ANALYSIS OF THE TECHNICAL AND ECONOMIC FEASIBILITY OF INTEGRATING PHASE CHANGE MATERIALS IN WINERIES

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This document was created with the (pdf/Xe/Lua)LaTeX processor and the NOVAthesis template (v6.10.10) (Lourenço 2021).

I dedicate this work to those who dare to dream and go beyond
regardless of difficulties and uncertainty.

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"I find out what the world needs. Then I go ahead and try to invent it." (Thomas A. Edison)

ABSTRACT

The maturation of wine entails a meticulous control of temperature and humidity. Many cellars employ air conditioning units throughout the year to facilitate optimal conditions for the creation of an excellent wine, as is the practice at HSLB. Thus, this study aims to assess and propose a potential solution to reduce the energy consumption incurred during the wine maturation process.

Previous studies substantiate that the implementation of PCM for latent heat storage can be advantageous and contribute to the reduction of energy consumption, by reducing heating and cooling energy loads for the most diverse applications in the industry. The agricultural sector lacks scientific innovation and energy-saving solutions, and PCM can emerge as a practical and economical solution for space climate control. In the specific context of this study, the reduction of costs and utilization of electricity from the Portuguese electrical grid can significantly impact HSLB. While numerous studies delve into the technical aspects of PCM, there is a substantial lack of research demonstrating the real-world performance of these materials in practical applications.

In order to assess the impact that PCM can have at HSLB, the study presented in this thesis is comprised of three phases: the presentation of practical experimental results, the utilization of computer simulations for energy performance, and an economic evaluation of the installation of PCM in the wine maturation cellar of HSLB. The practical study involves installing a structure containing PCM and three humidity and temperature sensors. The obtained values will be compared with results from a sensor measuring the temperature and humidity of the area without PCM. This approach will yield distinct graphs, allowing for the observation of direct differences arising from the use of PCM.

The computational simulations will be conducted considering the installation site. A computational model has been developed, taking into account the specifications required for the thermal comfort of wine maturation, as well as the exact dimensions of the location where the structure was installed. The results will precisely indicate the energy consumption required to climate-control the room both with and without PCM.

Finally, an economic evaluation will be conducted to obtain an estimate of the payback period for the investment at HSLB. Respecting certain economic indicators, but always subject to assumptions that will be carefully considered and chosen in light of the specific context of this problem, they may not align precisely with what would occur in reality.

Regarding the obtained results at the end of this study, the following conclusions can be drawn concerning the experimental results. Due to an error on the part of the HSLB staff, the sensors did not function throughout the entire period of their installation. Nevertheless, it is possible to observe certain differences when temperature and humidity values are read in proximity to the PCM. This may indicate that a well-insulated space with PCM can be more easily climate-controlled with reduced expenditures on air conditioning.

The simulations conducted using *EnergyPlus* were also deemed satisfactory, despite the results not aligning with the initially anticipated outcomes, particularly during colder months. Nonetheless, clear and concise findings regarding thermal variations and energy consumption were achieved. It was also possible to infer that the model required additional variables and internal gains to better approximate real-world conditions.

The financial analysis served primarily to understand the most significant factors to consider when conducting a detailed economic and financial study for a specific PCM application. Factors such as the price paid for PCM, the anticipated utilization of each one of them, its energy density, and the potential time for return on investment are the key considerations when contemplating investments in PCM for these types of applications.

After this study, it can be inferred that PCM materials will indeed have an impact on reducing costs associated with climate control, by computer simulations was possible to obtain a 20% reduction in total energy consumption for a year. Economic returns are anticipated to be realized given an investment payback period of approximately 15 to 20 years, contingent upon the effective planning of the project. It is evident that this solution does not eliminate the need for air conditioning; however, the utilization of these materials in cellars situated in locations experiencing significant thermal variation throughout the day will notably affect the reduction of costs linked to climate control.

Key words: Maturation of wine, temperature and humidity control, air conditioning units, energy consumption, PCM (Phase Change Materials), latent heat storage, energy-saving solutions, climate control, thermal variation.

RESUMO

A maturação do vinho implica um controlo meticuloso da temperatura e humidade. Muitas adegas empregam unidades de ar condicionado ao longo do ano para facilitar condições ótimas para a criação de um excelente vinho, conforme é prática na HSLB. Assim, este estudo tem como objetivo avaliar e propor uma solução para reduzir o consumo de energia durante o processo de maturação do vinho.

Estudos anteriores corroboram que a implementação de PCM para armazenamento de calor latente pode ser vantajosa e contribuir para a redução do consumo de energia, diminuindo as cargas de energia para aquecimento e arrefecimento para as mais diversas aplicações na indústria. O setor agrícola carece de inovação científica e soluções de poupança de energia, e os PCM podem surgir como uma solução prática e econômica para o controle climático de espaços. No contexto específico deste estudo, a redução de custos e a utilização de eletricidade da rede elétrica portuguesa podem impactar significativamente a HSLB. Embora numerosos estudos abordem os aspectos técnicos do PCM, há uma falta substancial de pesquisa demonstrando o desempenho real desses materiais em aplicações práticas.

Para avaliar o impacto que o PCM pode ter na HSLB, o estudo apresentado nesta tese é composto por três fases: a apresentação de resultados experimentais práticos, a utilização de simulações computacionais para desempenho energético e uma avaliação económica da instalação de PCM na cave de maturação de vinho da HSLB. O estudo prático envolve a instalação de uma estrutura contendo PCM e três sensores de humidade e temperatura. Os valores obtidos serão comparados com resultados de um sensor medindo a temperatura e humidade da área sem PCM. Esta abordagem resultará em gráficos distintos, permitindo a observação de diferenças diretas decorrentes do uso de PCM.

As simulações computacionais serão conduzidas considerando o local de instalação. Um modelo computacional foi desenvolvido, levando em consideração as especificações necessárias para o conforto térmico da maturação do vinho, bem como as dimensões exatas do local onde a estrutura foi instalada. Os resultados indicarão precisamente o consumo de energia necessário para controlar o clima da sala com e sem PCM.

Finalmente, uma avaliação econômica será realizada para obter uma estimativa do período de retorno do investimento na HSLB. Respeitando certos indicadores económicos, mas sempre sujeitos a suposições que serão cuidadosamente consideradas e escolhidas à luz do contexto específico deste problema, eles podem não se alinhar precisamente com o que ocorreria na realidade.

Relativamente aos resultados obtidos no final deste estudo, as seguintes conclusões podem ser tiradas. Devido a um erro por parte da equipa da HSLB, os sensores não funcionaram durante todo o período de sua instalação. No entanto, é possível observar certas diferenças quando os valores de temperatura e humidade são lidos próximos ao PCM. Isso pode indicar que um espaço bem isolado com PCM pode ser mais facilmente climatizado reduzindo consumos de ar condicionado.

As simulações realizadas com o uso do *EnergyPlus* também foram consideradas satisfatórias, apesar de os resultados não se alinharem com os resultados inicialmente esperados, particularmente durante os meses mais frios. No entanto, descobertas claras e concisas sobre variações térmicas e consumo de energia foram alcançadas. Também foi possível inferir que o modelo necessitava de variáveis adicionais e ganhos internos para se aproximar melhor das condições do mundo real.

A análise financeira serviu principalmente para entender os fatores mais significativos a serem considerados ao conduzir um estudo económico e financeiro detalhado para uma aplicação de PCM. Fatores como o preço pago pelo PCM, a utilização antecipada de cada um deles, sua densidade de energia e o tempo de retorno do investimento são considerações chave ao contemplar investimentos em PCM.

Após este estudo, pode-se inferir que os PCM terão, de facto, impacto na redução dos custos associados ao controle climático; por meio de simulações computacionais, foi possível obter uma redução de cerca de 20% no consumo total de energia por ano. Os retornos económicos são previstos serem alcançados num período de retorno do investimento de aproximadamente 15 a 20 anos, dependendo do planeamento efetivo do projeto. É evidente que esta solução não elimina a necessidade de ar condicionado; no entanto, a utilização desses materiais em adegas situadas em locais com variação térmica significativa ao longo do dia afetará consideravelmente a redução dos custos ligados ao controlo climático.

Palavras-chave: Maturação de vinho, controlo de temperatura e humidade, unidades de ar condicionado, consumo de energia, PCM (Materiais de Mudança de Fase), armazenamento de calor latente, soluções de poupança de energia, controlo climático, variação térmica.

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ACRONYMS

PCM	Phase Change Materials
LHS	Latent Heat Storage
HSLB	Herdade de São Lourenço do Barrocal
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
HVAC	Heating, Ventilating and Air Conditioning
AC	Air Conditioning
RTC	Real Time Clock
NPV	Net Present Value
IRR	Internal Rate of Return
T&H	Temperature and Humidity

1

INTRODUCTION

This chapter is subdivided into five parts: explaining the context and motivations of this study, clarifying the research objectives, outlining the challenges resulting from the approach defined at the beginning of the study, addressing the main conclusions and results expected to be achieved at the end of the work, and finally, explaining the structure of the document.

1.1 Context

Controlling the temperature is essential for the creation of high-quality wines. This implies that the local where the wine is stored for maturation greatly affects the quality of the final product, for a fine quality wine, the process of maturation requires a steady and constant temperature over several months or even years.

One of the key locations where the storage of wine takes place is in cellars, where temperature regulation is accomplished using year-round energy-intensive air conditioning facilities, especially on the ones above-ground, due to the ease with which the temperature can vary.

In addition to the monetary burden that such operation places on businesses' energy bills, it also significantly affects each company's carbon footprint.

The storage of thermal energy in the form of latent heat, using phase change materials to accomplish that, is a possible solution to keep the temperature variations inside the cellars very low, using lesser energy and consequently promoting the reduction of companies' carbon footprint.

The principle of operation of phase change materials is directly related to the desired temperature inside a particular building. These materials allow you to choose a temperature at which the phase changes, for example, at 15 °C the material will transition from solid to liquid state.

These phase transitions allow heat to be stored or released. In this way, regardless of whether the temperature inside the cellar rises or falls, the material will help maintain the desired temperature for which it is programmed. For this reason, it is expected that this type of insulation will help in terms of energy consumption used in air conditioning.

1.2 Objectives

The goal of the current work is to assess the technical and financial viability of using phase change materials for temperature stabilization, with the hope that this will reduce the energy requirements for air conditioning and, as a result, increase the sustainability of wine production processes.

Another objective will also be to assist HSLB. During a technical visit to the site, the estate staff revealed the technical difficulties they face daily due to the isolated location of their premises. Energy efficiency solutions are extremely important, as power outages are frequent. This study aims to present the estate with a possible solution to reduce air conditioning usage costs.

To achieve this objective, the work developed in this dissertation will include tests in the Herdade de São Lourenço do Barrocal in Reguengos de Mosaraz. The purpose will be to choose a space inside the cellar where to place the phase change materials and some sensors. The data will be further processed and conclusions will be drawn about their technical and economic viability.

Computational simulations and financial analysis will also be conducted. Considering that this work is in partnership with HSLB, it will be important to conclude the potential investment in these materials at the estate.

1.3 Challenges

The first challenge involves constructing a structure that will accommodate the PCM and sensors on the walls of the estate. Considering that HSLB is a luxury estate, aesthetics are important, so the walls cannot be left dirty or drilled.

One of the objectives of this work is to evaluate the savings in climate control, and understand the differences in terms of energy expenditure solely on air conditioning in the wine maturation area. It is not possible to isolate the AC load for this usage because the estate encompasses a vast area of cultivation, with a significant spatial dispersion of its loads, which ultimately complicates the analysis, measurement, and execution of the energy audit.

Understanding this, computational simulations were employed using a simple model, where the loads considered are solely for climate control of the space.

1.4 Expected results

It is expected that at the end of the work, conclusions can be drawn regarding the advantages of using PCM in wineries, understanding whether this application is reliable and makes sense, as well as comprehending the inherent obstacles and challenges associated with this application.

Regarding specific results, observing some differences among sensors, especially the sensor measuring the environment without PCM compared to the others measuring alongside the PCM. The computational simulations are expected to demonstrate differences in energy loads between the wine cellar coated with PCM and without PCM, with the application of PCM showing lower energy consumption.

Understanding and concluding about the economic feasibility of this application, determining whether investing in materials for HSLB is justified.

1.5 Document structure

This dissertation is divided into seven chapters. The first chapter serves as an introduction, with its content already explained previously.

The second chapter is the literature review, which contains the necessary concepts to support the research conducted in this work. It is subdivided into sections where the main themes addressed are the need for implementing PCM in the wine industry, the theoretical concepts behind phase change materials, and its potential for cost reduction and electricity demand.

The next chapter covers the methodology used to gather and process data needed for the technical and economic evaluation of PCM applications in wineries. This chapter, explains step by step what needs to be done and how the data will be handled afterwards.

The case study is the fourth chapter and mainly discusses the characteristics of the São Lourenço do Barrocal estate, as well as the location where PCM will be installed within the estate.

The simulation and analysis of results, as well as the economic evaluation, constitute the fifth and sixth chapters, both practical results and computer-simulated outcomes are presented and discussed. Additionally, the financial assessment is thoroughly conducted and described.

2

BIBLIOGRAPHIC REVISION

In this chapter, the state of the art will be presented, including explanations about the most relevant topics for the scope of the problem addressed.

Considering the proposed problem, this dissertation focuses on a specific problem and it is difficult to find authors in the literature who dealt with similar challenges. In this manner, the necessary topics will be addressed to support this very specific theme of PCM implementation in wineries.

2.1 Energy consumption in the worldwide agri-food industry

Approximately 30% of the energy available worldwide is used for agricultural and food systems, which are significant contributors to global energy consumption and the production of greenhouse gas emissions. Those are consequences of several operations, mainly after the goods leave the farms, such as transportation, processing, packaging or shipping (FAO 2021).

Figure 2.1, shows the EU's energy consumption and greenhouse gas emissions per capita during 2013. Analyzing the graphic helps to understand what was said before, as it is possible to recognize that, in terms of the production of polluting gases, agriculture is by far the most polluting phase of the process, even though it consumes less energy. It is also possible to observe that all the post-farm phases combined produce less greenhouse gas emissions but higher energy consumption.

It is expected that by 2050, the world population will reach 9.7 billion people, which translates into a 60% increase in the food needed to sustain all these people, compared to 2016 (FAO n.d.). This forecast speaks for itself and it is possible to understand the impact that such an increase in population could bring to the numbers shown in the graph.

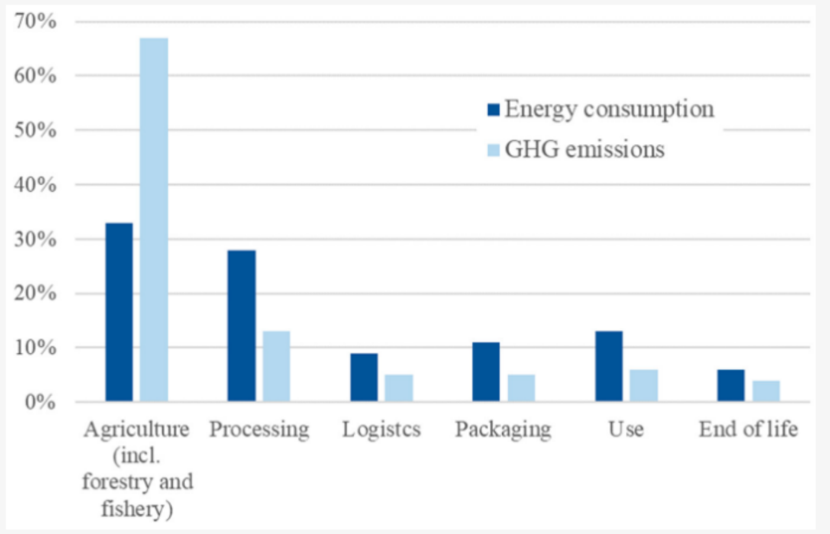


Figure 2.1: Energy and greenhouse emissions in the agr-food system, per capita, during 2013 in the EU. Adapted from Simão et al. 2022.

The agriculture industry uses diverse amounts of resources, depending on the development of the country. Developed countries consume more energy due to their more industrialized and mechanized farming methods, whereas developing nations consume less energy since they rely on traditional and labour-intensive farming techniques.

The systems for growing, transporting and distributing agricultural products lean heavily on fossil fuels to operate, however, as a result of their impact on the production of greenhouse gases and climate change, these types of fuels will be gradually less used. Since businesses are still very dependent on nonrenewable energy sources, their unsustainability will result in a possible increase in their prices.

Through the adoption of more effective procedures, there is great potential to cut energy use. This covers the application of precision agricultural methods, which employ sensors and other technology to enhance fertilization and irrigation, as well as the utilization of renewable energy sources for other farm tasks. This underlines the interdependencies that exist between different areas of the industry, which at the outset seem to be very different, but, by working together, can find solutions that allow mutual benefit. Technological innovation in agriculture is a vital step to take in order to produce food in a sustainable way, and for that, engineering solutions are needed.

The switch to renewable energy sources in agriculture can assist to reduce greenhouse gas emissions in addition to increasing energy efficiency. This is crucial since livestock methane and the use of synthetic fertilizers are the main causes of the sector's significant contribution to global greenhouse gas emissions (FAO n.d.).

2.1.1 The case of the wine sector

The wine business is a significant economic sector for the EU. Electricity accounts for 92% of the energy required in the production of wine, with gas, diesel, and fuel oil making up the remaining 8% and totaling about 1.750 million kWh yearly (Malvoni, Congedo, and Laforgia 2017).

As a result of some points described in the previous chapter, as well as an increase in wine consumption worldwide, the wine production has expanded, wine quality has improved, and the demand for wine has increased.

These conditions have, however, also made conventional manufacturing methods less sustainable. The quantity of water and plant treatments used in vineyards, the volume of wine packaged in non-recyclable bottles, the widespread use of industrial cooling equipment, and the rise in exports that have raised transport costs have all significantly increased the amount of energy and materials required for wine production (Ignacio Zabalza 2001).

Consequently, the wine business is paying more and more attention to how it contributes to sustainable development. Several legal papers from domestic and foreign wine industry organizations were published to help with the transition to more sustainable farming methods (Matos and Pirra 2022). In Portugal, the Alentejo Regional Wine Growing Commission developed the "Wines of Alentejo Sustainability Programme" to make Alentejo a sustainable wine-growing region and alert local producers to more sustainable wine production practices. These kinds of initiatives are increasingly common in wine-producing countries and are extremely necessary.

The requirements for a modern wine-making facility include a wide range of systems, each of these systems requires energy, which when added together refers to the energy input required to create the complete product. Numerous factors, including geography, winery age, wine quality, facility size and production volume, affect how this energy input is calculated and can differ from winery to winery (Smyth and Nesbitt 2014).

Energy input includes a diversity of resources, like diesel, coal, natural gas and wood, these raw materials are associated with fuel consumption and the electricity generation required to power all the machinery. However, these materials are increasingly scarce, so new production and energy-efficiency solutions are needed.

2.1.2 Solutions for energetic efficiency and sustainability of wine production

As explained in the previous chapter, sustainability in the agri-food industry is the step to follow. Being one of the goals of this dissertation, it is important to analyse the efficiency of the current wine-making facilities, and how they can be improved. This improvement mainly involves incorporating energy efficiency, renewable energy solutions and changing the mindset of producers.

Some studies carried out by researchers in the area show, in most cases, the still lack of confidence and incorporation of renewable energies in viticulture. The findings of research conducted in Spain by Nieves Garcia-Casarejos, Pilar Gargallo, and Javier Carroquino, which included 87 Spanish wineries, demonstrate that the claimed usage of renewable energy did not account for more than 10% of winery consumption. Solar thermal power (9.3%), photovoltaic electricity (11%) and biomass (11%) are the three most often used renewable energy sources. With the exception of the vineyard operations, very little renewable energy was used (Garcia-Casarejos, Gargallo, and Carroquino 2018).

Another study, this one conducted in Brazil, demonstrates that leftovers from wine manufacturing, including grape, must, may be used for the creation of biogas. The findings in the study demonstrate that the wine industry's biomass leftovers have the potential to produce biogas through anaerobic digestion, demonstrating the viability of utilising this type of sustainable energy on a wide scale. With up to 2% of the natural gas demand for the production of energy in Rio Grande do Sul being suppressed by this form of biogas (Guerini Filho et al. 2018).

These two examples, of the many that can be found in the literature, serve to show the possibilities to improve the sustainability of wine production.

Considering what was previously presented, it is obvious that sustainability in wine production is still not a priority, being the priority of many producers to satisfy demand, regardless of the costs. The following categories should be looked into in order to take action and make the wine production process more sustainable:

- Better water resources management;
- Decrease the energy consumption for industrial heating or cooling in the winery;
- Improving the efficiency of bottling and transport of the final product;
- Reducing the contamination of aquatic and terrestrial systems Ignacio Zabalza 2001.

According to research done in England, the standard benchmark of energy needed for wine production is about 0.557 kWh/l. This analysis shows that heating, cooling, and ventilation have the highest energy needs and the greatest potential for energy reductions as they represent about 0.25 kWh/l, or about 50% of the total energy consumption (Smyth and Nesbitt 2014).

Electrical energy has the advantage of being easily converted into thermal energy (Simão et al. 2022), so when this form of energy is associated with cooling or heating during the ageing of the wine, the dependence on fossil fuels lowers. By placing the materials studied during this dissertation as an extra coating layer for cellar walls, and integrating renewable energy to obtain the remaining energy needed, we can simultaneously decrease energy consumption and substantially improve the sustainability of wine production.

2.2 Wine Processes

Wine production is a complex and vast procedure, with companies and even common people contributing with new techniques of their own. For this matter, winemaking cannot be described as a single recipe, with pre-defined steps for everyone to follow, but rather as an art that wine experts from around the world will continue to develop.

Nevertheless, leaving aside the infinity of flavours and combinations that are possible to create in a wine bottle, the machinery and processes in a winemaking facility are relatively identical anywhere in the world. They can be grouped into three fundamental steps: pre-fermentation, fermentation and post-fermentation operations (Swami and Sawant 2014).

As shown in figure 2.2, a simplified diagram of the winemaking processes, the operations described above can easily be identified by the numbers in the figure, which will be described in more detail later.

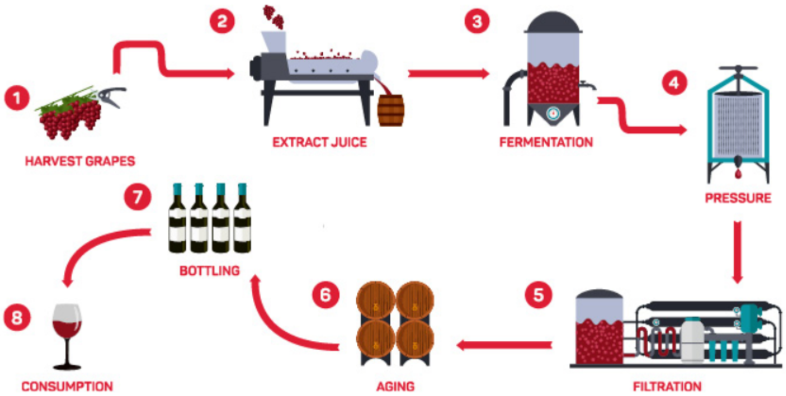


Figure 2.2: Wine-making processes.

It is important to remind that these processes may vary from company to company, and from the type of wine. For example, in the making of red wine the skin of the grape is added to the juice, in the case of white wine, the grapes are peeled and the juice separated from the skin (Swami and Sawant 2014).

The purpose of this subchapter is to present and give an inside on a daily operation on a regular wine facility, to better understand the motivation behind the case study developed during this dissertation. Considering this, the operations described are merely a simplified version of actual wine production.

2.2.1 Pre-fermentation

The pre-fermentation operations, represented with the numbers one and two in figure 1, consist of the harvesting and juice extraction of the grapes, generally this phase is associated with the intense use of mechanical machinery, with high demands of fuel and electricity.

The first thing to do is harvest the grapes, harvesting period usually starts 30-70 days after the fruit set, and can be done manually or mechanically. Due to the delicate handling required to pick the grapes, it is necessary to use specialized machines that handle the fruit with extra care.

These machines evolved throughout the times, the first machine to be field tested operated on the cutter-bar principle, and other methods were tried, like a vacuum principle, but, in the end, the actual machines operate using rods to shake the vines, the grapes fall into a moving conveyor belt that is posteriorly collected (Johnson 1977).

The next step is to extract the juice. Beforehand, the destemming is necessary, as the high levels of tannins present in the stems of the fruit may give an "earthy" flavour to the juice (Johnson 1977), so the same machine responsible for the crushing and juice extraction can execute the destemming and crushing consecutively, these machines are usually electric. After the extraction of the juice, is then added yeast to initiate the fermentation phase.

2.2.2 Fermentation

The wine fermentation process has been done without human intervention for thousands of years, we rely on the chemistry behind the fermentation to produce the best quality wine (Maicas 2021). Fermentation involves a reaction to convert the sugars present in the juice of the grapes into alcohol, by cutting off the oxygen supply, the yeast will consume the glucose and turn it into alcohol and CO2, the same process is used in the production of beer.

Clarification of the wine can be achieved by racking, filtration and/or centrifugation (Swami and Sawant 2014). This process is necessary to remove the suspended particles or residues of the previous mush or other products that may appear during the previous steps. The final product should be a clear and particles-free liquid.

2.2.3 Post- fermentation

During this stage, the treatment given to the wine can differentiate the palate and taste, depending on the techniques used by a specialist to produce a certain flavour, for example, some products can be added to the mixture to enhance a certain tonality.

The final stage of the winemaking process, after the fermentation, is the filtering and storage of the wine, this procedure is called maturation.

The maturation or ageing consists of the storage of the wine in wooden barrels. This technique is used to preserve the wine but also to enhance its properties and flavour (Carpena et al. 2020). During this phase, the wine is kept inside wooden barrels, primarily the ones made with oak. Depending on the treatment required for a specific type of wine, the liquid can be stored for a large amount of time and it is necessary to assure optimal conditions of temperature and humidity to promote the chemical reactions inside the barrels.

Wine maturation is mainly influenced by oxidation reactions, which can include a change of colour, loss of character and the development of different aromas and tonalites (Carpena et al. 2020).

2.3 Climate control in cellars

As explained in the previous section, maturation of the wine requires specific time and optimal conditions of temperature and humidity, which implies that the local where the wine is going to be stored can affect greatly the final product, even spoil it.

Depending on the type of cellar construction or materials used, the energy consumption on the refrigeration of the space can be a huge expense for the producers, because the air conditioning must work 24 hours per day during the whole year, this, in addition to being a very unsustainable practice in terms of energy consumption, can end up with the sustainability of the business due to fluctuations in the electricity market price.

The wine cellars can present many different typologies, the main ones being underground, above-ground and basement. The cellar's design directly impacts wine comfort, this being maintaining ideal temperature and humidity conditions during wine ageing (Arredondo-Ruiz et al. 2020).

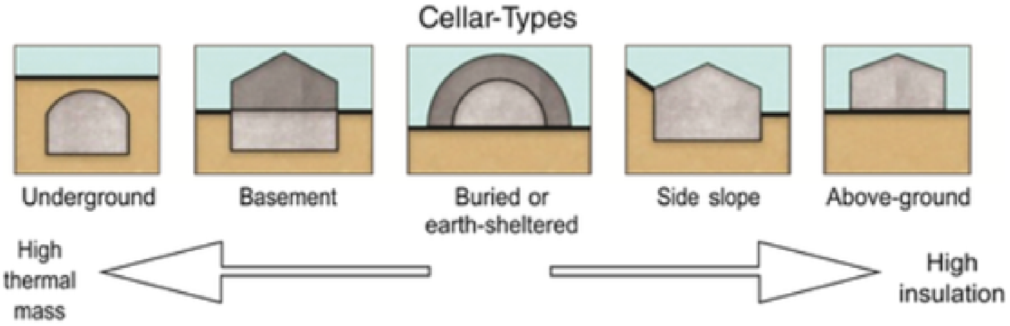


Figure 2.3: Typologies of cellars. Adapted from Arredondo-Ruiz et al. 2020.

Wine maturation is a process that involves chemical reactions, which occur at different rates and are usually associated with energy interactions with the exterior, exothermic and endothermic reactions will be another factor to consider for fluctuations in temperature inside the cellar. The Arrhenius equation allows calculating the variation of the rate constant of a chemical reaction with the temperature.

$$\ln k = \ln ko - \frac{Ea}{RT} \tag{2.1}$$

or, equivalently:

$$k = koe^{-\frac{Ea}{RT}} \tag{2.2}$$

k0 is the pre-exponential factor (constant for minor temperature fluctuations), Ea is the activation energy of the chemical reaction, R is the constant of universal gas, and K is the rate constant of a chemical process (Cadeddu and Cauli 2018).

According to Arrhenius as the temperature rises, the number of chemical reactions will also rise. Wine can age well at temperatures of around 10°C to 20°C and the ageing process can be finished in a few years. Following the reasoning, at 30°C, the wine ages in a matter of months due to the increase of chemical reactions (Cadeddu and Cauli 2018).

Nonetheless, the objective is not to accelerate the wine maturation but to keep it at a gradual pace. It is important to maintain a steady and slow maturation process, and for that, the value of the ideal temperature must be constant. The wine comfort zone can be seen as a measure that gives us the ideal temperature and humidity values to be achieved in the ageing room in order to produce the best quality wine. Figure 2.4 summarizes the ideal constants that should be achieved in the ageing rooms.

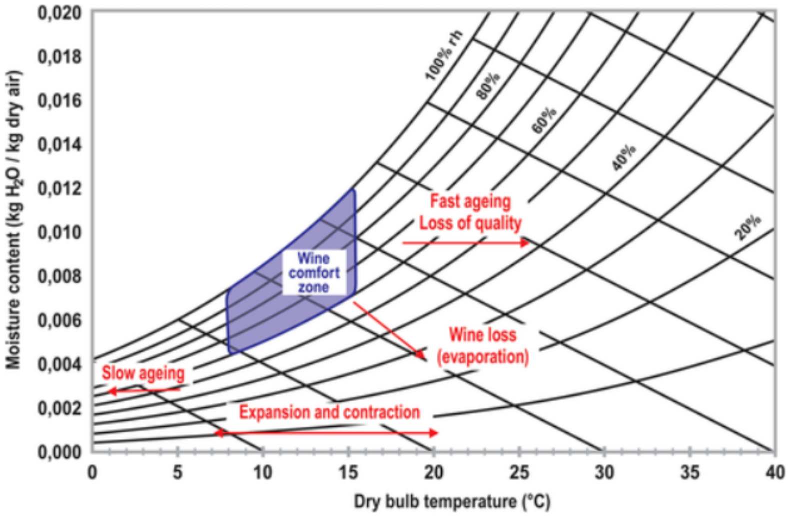


Figure 2.4: Wine comfort zone and harmful effects. Adapted from Arredondo-Ruiz et al. 2020.

As it can be seen in figure 2.4, the temperature variation should be minimal, not vary more than 5ºC and remain between 10ºC and 15ºC. To achieve low-temperature changes, air conditioning systems, which use power, are often needed for buildings above ground. Wine has historically been aged in underground cellars as a result (Mazarrón and Cañas 2009).

A study made in Spain by Mazarrón and Cañas reported that wine producers often choose between different typologies of cellars to assure optimal conditions of maturation for various types of wine (Mazarron and Canas 2008). It will be important to analyse these types of cellars to better understand where the materials used during the case-study will be best used, and where they could, due to their characteristics, provide a better use in energy consumption and efficiency. The two main types of cellars will be studied.

2.3.1 Underground cellars

These types of cellars are underground spaces that are excavated into sufficiently firm terrain. They are very popular in areas where the temperature changes many times throughout the year, and due to the thermal inertia of the soil, underground spaces maintain temperature stability during the year.

The first ones to appear were just man-made tunnels with a small entrance and a ventilation chimney, as shown in figure 2.5. These types of rudimentary cellars were isolated by the ground and some stone for structural support and are mostly found in Spain, in the region of Ribera de Duero. It is also one of the oldest typologies of wine cellars as there are records of Egyptians and Romans already using them to preserve wine.

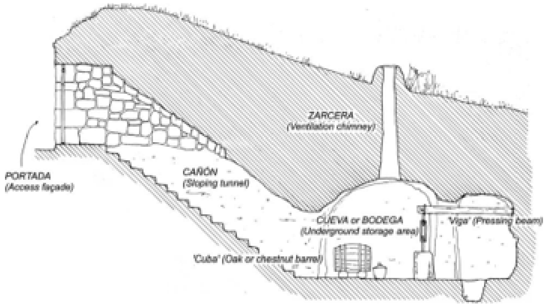


Figure 2.5: Example of underground cellar.

In modern times, undergrounds cellars suffered dramatic changes. It is possible to conjugate modern technology to better equip the space with high-precision sensors that permit constant monitoring of the conditions of temperature, and humidity and in response to these variations, adjust the air conditioning flow or dehumidifier or humidifier operations. Although, this type of control is mostly used in other types of cellars.

The main advantage of underground cellars, considering the natural isolation provided by the soil, is to limit or even suppress the need to use electric energy to fuel the air conditioning, as these types of constructions already exhibit very low-temperature variation by themselves, however, in terms of relative humidity, these cellars present high values. Which, when not treated, can promote the growth of mould, which give a bad taste or even spoil the wine.

2.3.2 Above-ground cellars

When the other forms of cellars are not possible to construct, above ground are usually used since their construction is similar to other types of wine facilities, consisting of a large storage unit equipped with air conditioning systems, that regulate temperature and relative humidity. This form of cellar typology is the least effective since it needs complete insulation and the acclimatization of the space consumes electrical energy, not benefiting from the thermal inertia of the soil, that underground cellars have.

The subterranean and buried versions appear to be the most ideal since cellars must be able to keep their temperature steady for extended periods. According to a study carried out in Spain, the average temperature changes in above-ground cellars can exceed 10°C, buried buildings do not exceed 5°C, and subterranean 3°C when the temperature swings more than 10°C during the day (Arredondo-Ruiz et al. 2020). This shows the temperature differences that the air conditioning infrastructure has to fill to maintain temperature stability within the wine storage space.

Figure 2.6: Above-ground cellar in the site where the materials will be installed.

A study that compared the thermal and humidity performance of two not climatized above-ground cellars got the following conclusions:

- The yearly temperature variance was 9.7°C and 11.6°C for the two wineries, which does not promote a gradual wine maturation and the creation of high-quality wines;
- The summer months have a larger danger of ageing processes accelerating since those months are when the biggest variations were seen.
- The highest temperature exceeded the recommended temperature (15°C) for wine maturing;
- In terms of relative humidity, above-ground presents low values, which translates into evaporative wine losses, raising the cost of production Martin and Canas 2006.

In conclusion, subterranean construction provides certain benefits for the hygrothermal regulation (related to temperature and relative humidity inside the cellar that is necessary to produce fine wine) of wine ageing, in addition to benefits in terms of cost and the environment, while not consuming energy (Martin and Canas 2006).

Above-ground cellars require acclimatization, however, the atmosphere produced in this type of structure is suited for producing high-quality wines but at the cost of higher electricity needs. When this type of cellar is not acclimatized, the results are very poor.

2.4 Phase Change Materials

Phase change materials (PCM) are characterized by their ability to change phases. By undergoing these changes they can store thermal energy, and they be distinguished from each other by the way they change phases or by the material that constitutes them. Thermal energy can be released as sensible or latent heat and can be used in numerous home and industrial applications.

The fundamental idea of PCMs is straightforward but efficient. A PCM material releases heat energy when the environment's temperature exceeds its melting point, causing it to change from a solid to a liquid state. The substance freezes when the temperature drops below its melting point, soaking up the heat. PCMs can be an excellent choice for temperature management in buildings because they are highly efficient in maintaining temperature stability. They can store and release heat energy over a wide temperature range, helping to maintain the temperature around its melting point without the consumption of electric energy.

Considering that there are many types of PCM, this study will primarily delve into the concepts related to the PCM used in this dissertation. However, a brief explanation of other types will also be provided.

2.4.1 Storage of latent heat

Thermal energy storage involves capturing and retaining heat for later use. One of the methods of storing heat energy is known as latent heat storage (LHS), PCM absorb or release heat during a phase transition, such as changing it from gas to liquid or from liquid to solid.

The latent heat of fusion (property of every material related to its molecular structure) as well as its mass, determine how much energy is stored. Because LHS materials undergo phase transitions, they are also called PCMs (Podara, Kartsonakis, and Charitidis 2021).

The PCMs utilized in the study absorb heat energy when the material transition from its solid to a liquid state, in the reverse transition, it releases heat energy when transitioning from liquid to solid. The PCM-based LHS systems are regarded as auspicious thermal storage technology and have been extensively researched. For the current study, it is expected that the incorporation of PCMs can help to improve the efficiency of the energy systems.

2.4.2 Types of Phase Change Materials

In figure 2.7 it is possible to observe existing thermal energy storage solutions. Taking a look at the PCMs, it is possible to observe that they can be classified by their phase transitions, Solid-Liquid (S-L), Liquid-Gas (L-G) and Solid-Solid (S-S). Within the S-L category, which the materials used in this dissertation fall into, they can be composed of organic, inorganic or eutectic substances.

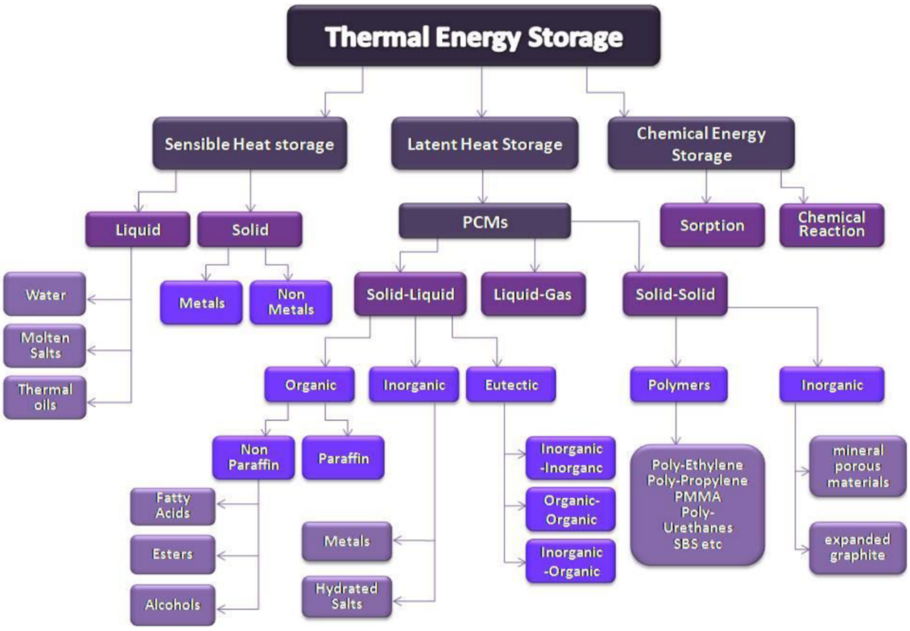


Figure 2.7: Solutions for thermal energy storage. Adapted from Podara, Kartsonakis, and Charitidis 2021.

Paraffin wax PCMs are one of the most common types, and are considered to be the most promising ones, due to the fact that they have a high latent heat capacity and suitable thermal properties, including a wide range of phase change temperatures, low melt pressure and good thermal and chemical stability (Kousksou et al. 2010).

The paraffin wax is derived from petroleum and consists of a mixture of straight chain n-alkanes CH3–(CH2)–CH3. With the increase of the chain length, the melting point and latent heat of fusion will also increase (Kousksou et al. 2010).

Table 2.1 presents some paraffinic PCMs and helps to understand how the chain of n-alkanes affects the melting point, latent heat capacity and thermal conductivity. Usually, the melting ranges of paraffin rise as the chain length grows. While the latent heat capacity of melting is independent of any particular order.

Materials	Melting point (ºC)	Latent heat (kJ/kg)	Thermal conductivity (w/mK)
n-Tetradecane (C14)	6	228-230	0.14
n-Pentadecane (C15)	10	205	0.2
n-Hexadecane (C16)	18	237	0.2
n-Heptadecane (C17)	22	213	0.145
n-Octadecane (C18)	28	245	0.148

Table 2.1: Comparison of n-alkanes that constitute the paraffinic PCMs. Adapted from Vakhshouri 2019.

The n-Hexadecane with a melting point of 18 °C corresponds to the type used in this study, they are characterised by low melting points, which makes them well-suited for low-temperature heat energy storage applications.

Organic PCM will be used in the application studied in this thesis, so it will be interesting to understand its benefits, which include:

- Available throughout a wide variety of temperatures;
- Very little supercooling;
- High chemical stability;
- High heat of fusion;
- Congruent melting. All the substance inside the container melts at a single, well-defined temperature.
- Reduced volume change during phase transition. During phase changes, a material can increase its volume. If this volume increase in a PCM were substantial, its container would explode;
- Thermal stability and reliability;
- Non toxicity, and better compatibility with traditional building materials.

However, organic PCM also has several disadvantages, including mild flammability, weak thermal conductivity, and low volumetric latent heat storage. Research is being done to address these issues and improve the suitability of organic PCM for thermal energy storage in buildings (Singh Rathore, Shukla, and Gupta 2020).

2.5 Paraffin PCMs for LHS

Due to their high latent heat, and suitable thermal properties, such as little to no supercooling, low vapour pressure, strong thermal and chemical stability, and self-nucleating behaviour, paraffins have been widely used for LHS applications (Sarı and Karaipekli 2007).

To better understand how these materials can be useful for the passive application studied in this thesis, the concept of thermal conductivity is important. A material's capacity to conduct heat is determined by its thermal conductivity. It is described as how much heat moves across a given area in a given amount of time when there is a temperature gradient perpendicular to the area. Watt per meter-Kelvin (W/mK) is the unit for thermal conductivity in the SI system.

Generally speaking, a material with better thermal conductivity will be able to transport heat more effectively, which can be advantageous for applications involving the storage of thermal energy. The amount of energy that a material can hold in the form of latent heat and its thermal conductivity, however, do not directly correlate. Among other things, a material's specific heat capacity, melting temperature, and latent heat of fusion all affect how much energy it can store as latent heat. Thermal conductivity has no bearing on these characteristics. Therefore, even while thermal conductivity can be a key component in determining how well a material stores thermal energy, it is not the only element that affects how much energy a material can store as latent heat (Sarı and Karaipekli 2007).

Studying the amount of energy in the form of LHS that a material can store, melting time and high thermal conductivity are the most important factors to study for the present application, as well as understanding the heat transfer that occurs, for example, at phase change temperatures.

2.5.1 Importance of melting time in PCM performance

A shorter melting time and high thermal conductivity are desirable for LHS applications because they can increase the efficiency and efficacy of the energy storage system.

For situations where a quick thermal reaction is required, a low melting time indicates that the PCM can absorb or release thermal energy quickly. For instance, the PCM should be able to melt fast during the day to collect solar energy and slowly release it at night to maintain building temperature stable. A shorter melting time can also reduce the size and cost of the energy storage system, as less PCM is needed to store the same amount of energy (Sarı and Karaipekli 2007).

Three distinct materials' melting temperature curves are shown in figure 2.8, pure paraffin as a phase change material (PCM), paraffin mixed with 4% of ethylene glycol (EG) as a composite PCM, and paraffin mixed with 10% of EG as a form-stable composite PCM.

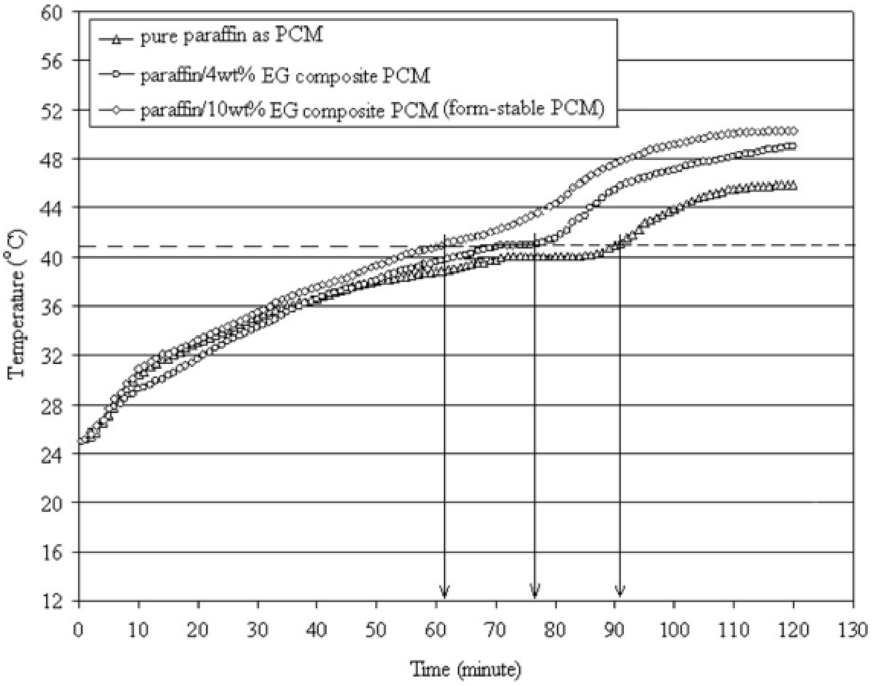


Figure 2.8: Temperature curves of paraffinic PCMs. Adapted from Sarı and Karaipekli 2007

The figure shows that the melting times of the three materials are different. The pure paraffin takes the longest time to melt, with a melting time of 91 minutes. The composite PCM with 4 % EG has a shorter melting time of 76 minutes, while the form-stable composite PCM with 10 % EG has the shortest melting time of 62 minutes.

This graph illustrates that during the heating process of paraffin, materials composed of pure paraffin take a longer time to melt. As observed in the image, pure paraffin takes approximately 90 minutes for its temperature to exceed 40°C, maintaining this temperature for about 30 minutes. This indicates that materials without impurities exhibit better performance.

This can be advantageous in applications where it is desirable to stabilize the temperature near the melting point of paraffin. This property allows for the maintenance of the desired temperature within the installation area of the materials, even if the external temperature increases.

2.6 Potencial of PCM for energy savings

Through the storage and release of thermal energy during the melting and solidification processes, PCM can aid in energy efficiency. The surplus heat produced during the day may be absorbed by PCM when it is incorporated into building materials like walls or ceilings and released at night when it is cooler. This contributes to more consistent interior temperature control, lowering the need for heating and cooling equipment and, eventually, lowering energy usage. Additionally, PCM can shift peak energy demands to off-peak hours, lowering energy expenditures even further (Singh Rathore, Shukla, and Gupta 2020).

Variations in energy demand for heating and cooling occur on a daily, weekly, and even monthly basis, resulting in load peaks that are too large to be satisfied by traditional heating or cooling systems. By storing thermal energy during off-peak hours and releasing it during peak hours, PCM can assist to even out these load surges.

When compared to a building without PCM, the energy-saving potential of PCM may be quantified mathematically in terms of percentages of energy savings. The following relation may be used to determine the energy savings:

$$\% Energy\, savings\; = \frac{Consumption\, without\, PCM\; -\; Consumption\, with\, PCM}{Consumption\, without\, PCM} \times 100 \tag{2.3}$$

There are several HVAC systems inside buildings that can be optimized when integrated with PCM. The use of PCMs in air cooling, heating, and ventilation systems to improve indoor thermal comfort and optimize building energy performance is a case study for several research articles. Some examples of studies that have investigated the use of PCMs in different building equipment and HVAC systems include (Song et al. 2018):

- Air cooling systems;
- Air heating systems;
- Ventilation systems;
- Heat pump units;
- A/C;

The majority of the results conclude that integrating PCMs with building equipment can improve indoor thermal comfort and increase the energy efficiency of air cooling, heating, and ventilation systems (Song et al. 2018).

However, for PCM-based systems to work at their best, adequate design and execution are essential. To optimize the advantages of employing PCMs in buildings, factors including system design and control techniques should be carefully studied. For this matter, the selection of PCM should include an analysis of the price of electricity and the prices of PCM that a certain application demands, because the payback cycle of the system using PCMs is strongly affected by the price of the materials used and the price of energy charged (Zhu, Ma, and S. Wang 2009).

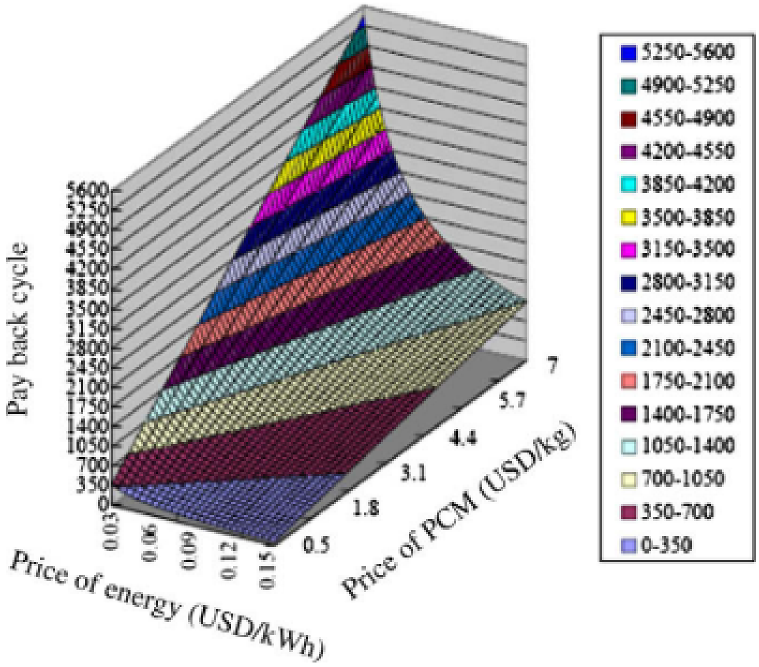


Figure 2.9: Relationship between payback cycle (days), price of energy and price of PCM. Adapted from Hauer et al. 2005

The relationship between the payback cycle, energy price, and PCM pricing for a PCM-based thermal energy storage system is depicted in figure 2.9. The payback cycle is the amount of time it takes for the system to recoup its original investment through energy savings.

The chart shows how the cost of the PCMs used and the cost of the energy have a significant impact on the payback cycle of the system utilizing PCMs. The payback period grows along with the cost of the PCM.

The image also demonstrates how the particular application and system design has a significant impact on the payback period. To get the best performance and cost-effectiveness, it is important to carefully analyze the PCM price,as well as understanding the expected use of each plate.

2.6.1 Peak load shifting using PCM

One of the main applications currently being studied for PCM is its use for peak load shifting. The research in this particular application is mostly concerned with the active usage of PCMs in buildings, where the PCM is employed as a thermal storage medium to transfer peak energy demands from on-peak to off-peak times.

The evaluated research shows that peak load shifting using PCMs may considerably cut energy use and peak demand costs while enhancing interior thermal comfort. One research, for instance, found that the use of a PCM ceiling board for peak shaving management of air-conditioning systems might lower peak demand by as much as 30%. The study was carried out in an office building in Tokyo, Japan.

2.6.2 Reduce cooling energy loads

To help understand how PCMs can help reduce cooling energy load, a study made by Seyed Masoud Sajjadian, John Lewis and Stephen Sharples will be explained and analyzed.

The concept of discomfort hours is important to better understand the study. The term "discomfort hours" describes the number of hours when the interior temperature of a building or house is over a specific limit and the occupants are uncomfortable. In the course of the study, discomfort hours during the summer months were computed.

The study simulated a detached house in London under both present and future climatic conditions. According to the modelling results, climate change will significantly impact discomfort hours. From 2020 forward, there will be a dramatic rise in discomfort hours for July and August compared to 2011. It is quite likely that temperature discomfort would worsen in homes without the use of adaptive techniques like PCM panels. The study found that PCM is an excellent passive design solution to reduce overheating risk issues when used as a building material. PCM may enhance the thermal properties of building materials and lower interior temperatures during hot weather months (Sajjadian, Lewis, and Sharples 2015).

Figures 2.10 and 2.11 present the cooling loads in kWh to remove the discomfort hours in the summer months for the house studied.

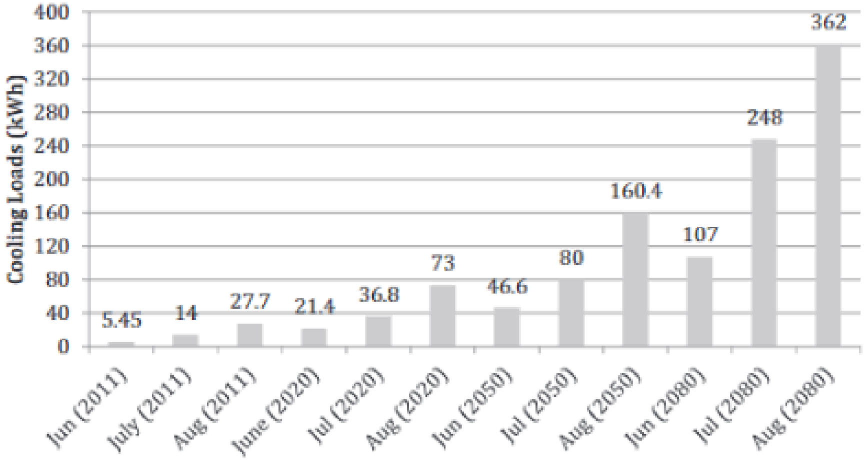


Figure 2.10: Energy load required to remove discomfort hours without PCM. Adapted from Sajjadian, Lewis, and Sharples 2015.

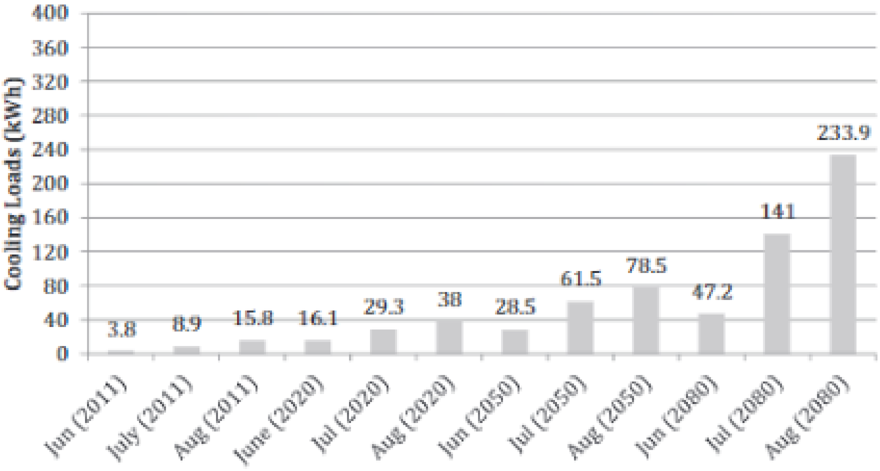


Figure 2.11: Energy load required to remove discomfort hours with PCM. Adapted from Sajjadian, Lewis, and Sharples 2015.

The difference in terms of absolute values of energy consumed with and without PCM is notorious, these graphs allow us to conclude that PCM can be an excellent investment in the long term, considering that the perspectives for climate change are that the global temperature will continue to increase, the PCMs can help in reducing the cooling energy loads in summer.

However, it is always important to carry out an economic study to understand whether the money invested in PCM will have a return, because although the technology works, it may not be viable in monetary terms depending on the application.

2.6.3 Reduce heating energy loads

The study made by Qian Wang, Runqi Wu, Yu Wu and C.Y. Zhao finds that the average inner surface temperature and heat transfer rate may be greatly reduced in walls made of PCMs during working hours. The study used a parametric analysis to look at how varied PCM thicknesses, locations, and melting temperatures affected the lowering of heating loads. The findings demonstrate that employing PCM in walls greatly lowers the rate of heat transfer and average inner surface temperature during working hours. The study also discovered that different kinds, thicknesses, and placements of PCM had an impact on the heat load reduction ratio (Q. Wang et al. 2018).

The following table helps to understand the main results of the study, as well as the benefits in terms of heat reduction using PCMs for wall coating.

PCM thickness	Heat gain (kJ)	Heat gain reduction (kJ)	Heat gain reduction ratio (%)
No PCM	4238	-	-
31 mm	3200	1038	24.5
35 mm	3111	1127	26.6
42 mm	3039	1199	28.3
47 mm	3097	1141	26.9
50 mm	3143	1095	25.8
55 mm	3197	1041	24.6

Table 2.2: Heat gain reduction from a wall with different PCM thickness. Adapted from Q. Wang et al. 2018.

It is possible to observe from the table that not always a greater thickness is advantageous for a certain application, this may be due to PCM melting time, its properties or even characteristics from the local where they are installed. This conclusion reinforces what was previously said, it is always necessary to study the characteristics of the application in order to select the most effective PCM for it.

When this thermal energy is converted to electrical energy, energy savings are also observed when the purpose of savings is to reduce heating loads.

PCM have a wide range of applications and are extremely versatile when used for LHS and passive forms of temperature conservation, however, they should always be complemented with HVAC systems, because by themselves they cannot guarantee a stable temperature, they can help to reduce consumption, as well as facilitate the acclimatization of the space.

3

METHODOLOGY

As explained in previous chapters, it is very important to maintain temperature stability within wine maturation sites. The use of PCMs is the solution presented in this thesis to try to solve this problem, as it is expected to reduce or suppress the necessity of AC systems.

Recalling the final objective of this research, which consists of the technical and economic study of the placement of PCMs in cellars, it will be interesting to understand at the end of the work, whether the placement of PCMs can help in regulating the temperature in cellars, and ultimately, help companies with practical solutions and promising results in terms of energetic efficiency and money savings.

Collecting practical data in a pilot site will be necessary, as these data will allow reaching conclusions about this possibility. These data will have to be representative and collected in a practical environment, as they will serve as a basis for technical and economic analysis.

To obtain real-life and practical data, paraffin PCMs will cover a cellar wall, where a temperature and humidity sensor will collect the daily variations and save the data on a microSD card, this simple approach will allow understanding if the materials contribute positively to the stability of temperature at that specific location. A conclusion about the effect of humidity on the site will also be conducted.

With this data will be possible to obtain clear and objective interpretations of the performance of the PCMs in this specific application.

However, the objectives do not end here, as an economic study will also be carried out. This presents a greater challenge, because its necessary to obtain values of energy consumption of the AC system on the pilot site, and it’s not possible to isolate the consumption of this particular device from the others in the facility.

With these factors in mind, computer simulations will be utilized to determine the numbers for estimated energy usage. Due to these simulations, it will be possible to isolate that particular load for the sole goal of preserving temperature stability at the location where the PCMs will be installed. Only in this way will it be possible to obtain energy consumption values close to reality, without assuming values obtained directly from the electrical switchboards of the pilot site.

3.1 Available PCM plates

Figure 3.1 shows a plate of the available materials that will be used to cover the room. As can be seen in the image by its serial number, the first two numbers represent the temperature at which the material will change phase. In this case, if the temperature rises above 15°C, the material inside the plate will be in its liquid state, on the contrary, below 15°C in the solid state.

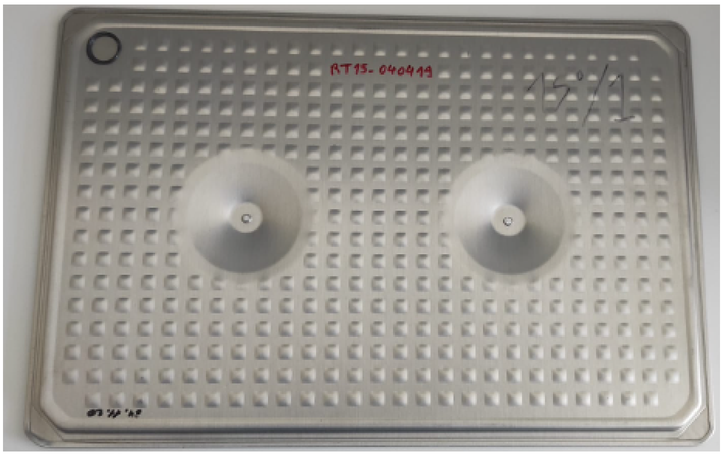


Figure 3.1: PCM to be used in the cellar.

The wine produced by the estate must be matured at 18°C, so, as explained in the bibliographic review chapter, a PCM with a phase change point a little below this value must be used, so that the results are better, in this way the materials with serial number that contain the 15 will be used.

This plate is composed of an organic paraffin, which corresponds to latent heat storage PCMS. Heat energy will be stored when the material transits from liquid to solid, that is, when the room temperature is below 15°C, helping to preserve the temperature inside the room at this value, as the energy will not be dissipated to the outside.

On the contrary, energy will be released when the phase change occurs from solid to liquid, by releasing energy the heat will be dissipated to the outside, helping the room not to exceed 15°C.

3.2 Collection of experimental data

The collection of temperature and humidity data will be carried out with a meter built from modules connected to a microcontroller. Next, these components and the Arduino connection diagram will be explained in some detail.

3.2.1 ESP32

The ESP32 is a series of low-cost and low-energy consumption microcontrollers, which allows the connection of modules that have sensors, in this way, it can be used for the most diverse applications. One of the main advantages of using this microcontroller is the fact that it has a Wi-Fi and Bluetooth connection, so it allows remote monitoring, as long as there is an internet connection.

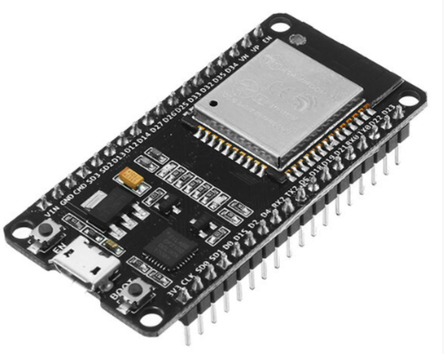


Figure 3.2: ESP32 used in the data collection.

This device is programmable through IDE applications, it will serve to control the circuit and collect the data obtained, where it will write on a MicroSD card.

3.2.2 DHT22 sensor

The DHT22 temperature humidity sensor, is used to measure temperature in the ranges from -40 to +80° degrees Celsius and air humidity in the ranges from 0 to 100%, with an accuracy that varies from 2 to 5%.

It measures the surrounding air using a thermistor and a capacitive humidity sensor, and it outputs a digital signal on the data pin (no analog input pins needed). Although reasonably easy to operate, data collection needs precise timing, therefore, it will be necessary to use a module that allows monitoring the time, to work simultaneously with the sensor.

Figure 3.3: Sensor for humidity and temperature.

It is widely used in the development of electronic projects using microcontroller boards, as it has only 1 pin with digital output, it detects humidity and temperature variations and sends this information to the microcontroller board, which must be programmed to take some action with this data.

3.2.3 Modules for time and power management

An **RTC** module will be used to keep accurate time control, as it has an individual power supply, this module allows keeping time monitoring even in case of failures or malfunctions of the power supply, it will be used with the sensor.

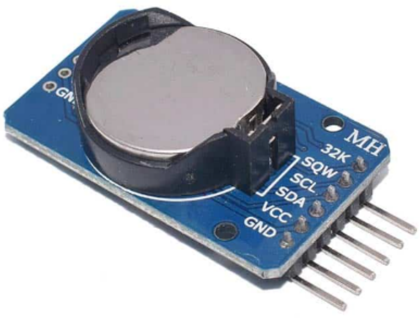


Figure 3.4: RTC module.

To complete the meter, two more modules will be used, one to write the data on the MicroSD card and used to suppress the low storage capacity of the microcontroller, and the other to recharge the lithium batteries that served as a power supply and provide greater autonomy to the circuit

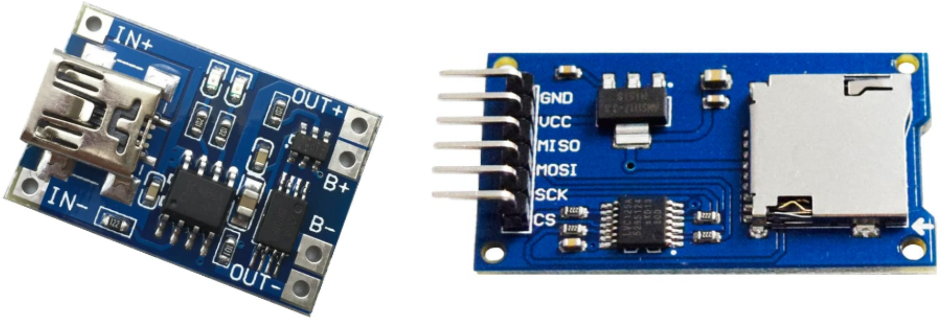


Figure 3.5: Module to recharge the batteries (left) and to write to MicroSD card (right).

After understanding how to use the modules presented above, three "boxes" were assembled, figure 3.6 show one of them, which contain all the electronics and necessary connections, with the help of a breadboard.

The code written for this application will be included in annex, since one of the boxes contains a different microprocessor from the other two, the code written for this one will also be included in annex, as it presents some differences, although the result is the same.

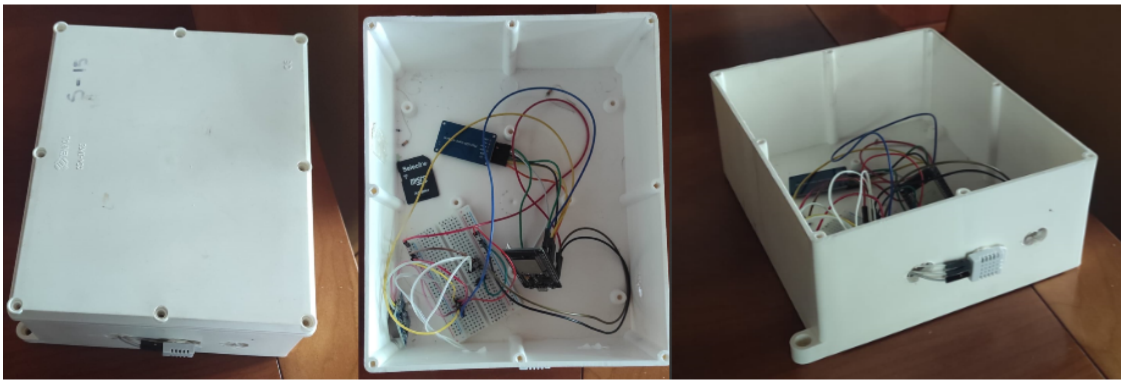


Figure 3.6: Example of one of the boxes produced.

The idea of producing three boxes arises from the fact that it will be necessary to measure the variations in humidity and temperature in three different places, in this way, it will also serve to understand the direct impact of the PCMs, since one of the meters will be placed far from the assembled structure.

In order to facilitate the reading of the electrical circuit mounted inside the boxes, the electrical connections were designed with the help of *Tinkercad* software. One of the boxes contain an Arduino Uno and the other two contain an ESP-32, despite this fact, the connections are similar inside the three boxes.

Figure 3.7 show three of the previously explained modules, since it's possible to connect the microprocessors directly to a power source, the modules for batteries are not necessary, since the circuit will not use any type of external battery to function.

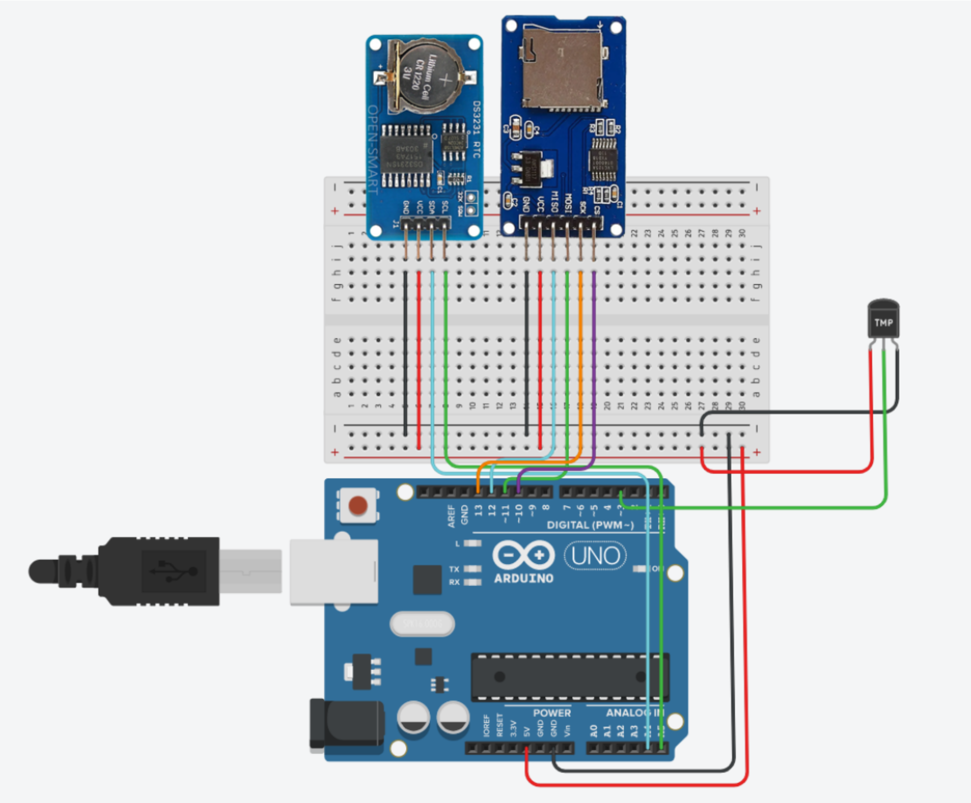


Figure 3.7: Connection diagram of the circuit produced for data collection.

This finalizes the electronics necessary for data collection, later, it will be explained where these boxes will be placed, so that the temperature and humidity sensors can effectively collect temperature variations with and without PCMs.

The structure that will support the PCMs will be explained in detail later, in this structure, two sensors will be placed in two different positions.

3.3 Structure to hold the PCMs

This section will explain the structure that was made to place the PCMs on the estate. The reason for building this structure is that the estate would not allow the direct placement of materials on the walls, which could damage it.

The assembly consists of a series of hand-cut parts, mostly made of metal, with an acrylic plate screwed in front of the PCMs, in this way, it is possible to create a division between the materials and the outside, which allows the placement of the sensors. Figures 3.8 and 3.9 shows the structure drawn with the help of *SolidWorks* software, this file was used as a guide for later assembly of the actual structure.

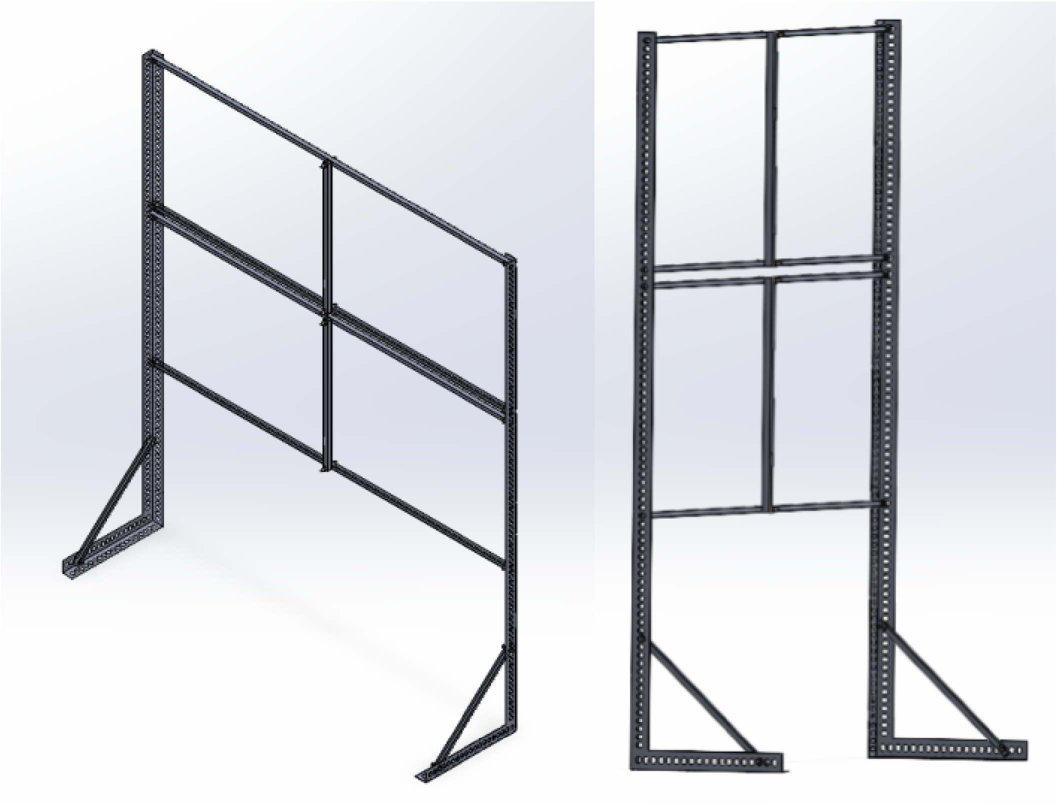


Figure 3.8: PC model of the structure.

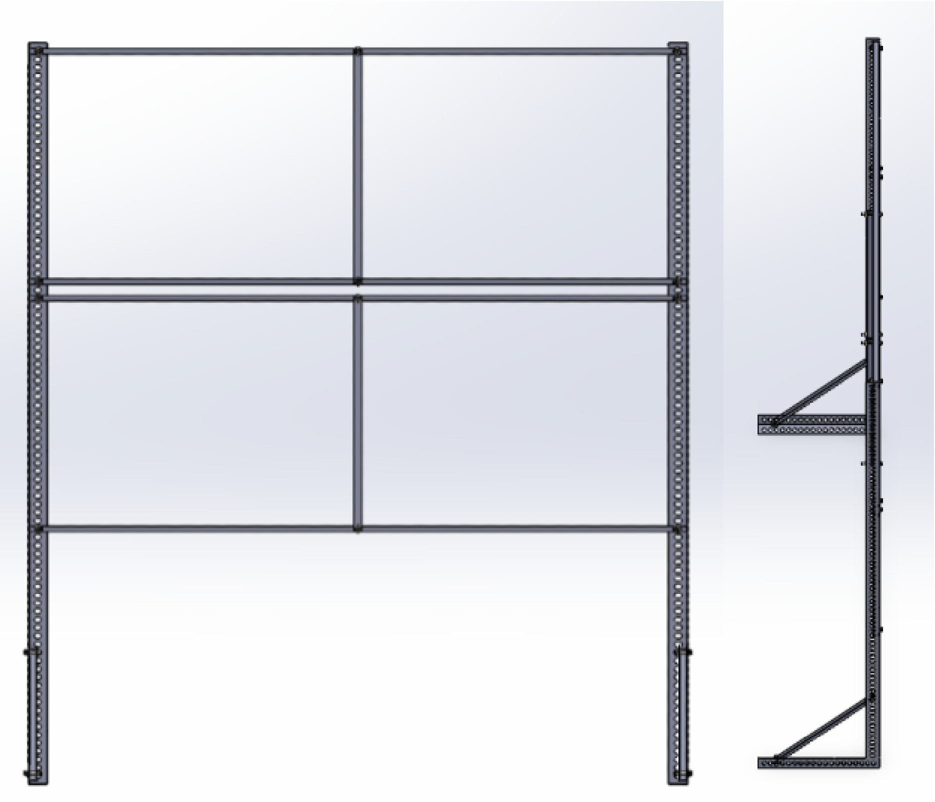


Figure 3.9: PC model of the structure (front and above view).

This file was created with the correct dimensions (0.9 m x 0.20 m x 1.60 m) so that the structure to be used is properly assembled. The design was conceived with consideration for the installation location, so as not to obstruct the work that may be necessary in the wine analysis laboratory. Therefore, the structure has a raised bottom part with the materials to be fixed higher up, allowing the workbench to be used while the sensors collect data.

This design requirement also posed a challenge in choosing the appearance and dimensions of the "feet" of the structure. The weight of the materials and their placement on the top part of the structure made it prone to easily tipping forward. Large "feet" were not an option either, as they would occupy a significant portion of the workbench. Therefore, it was decided to construct narrow and longer "feet," ensuring that the workbench would not be significantly affected.

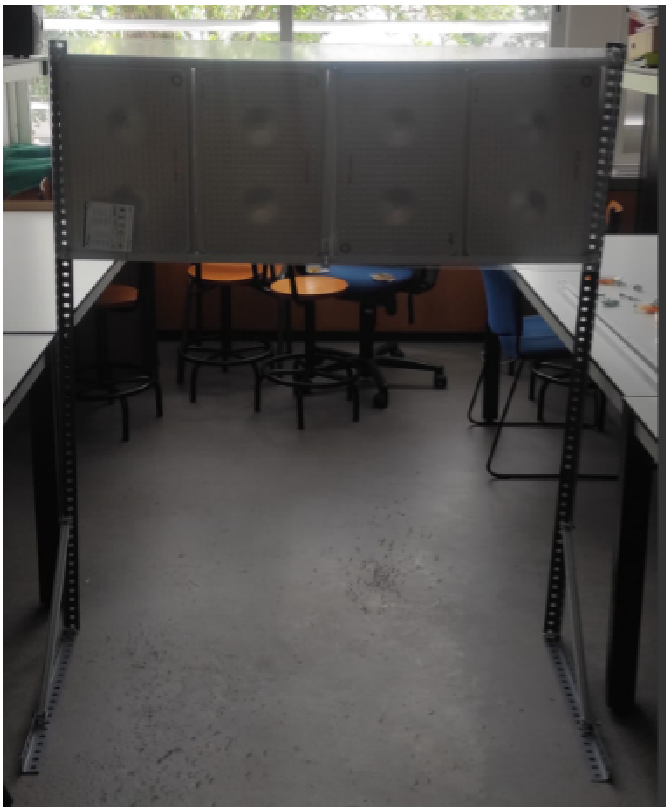


Figure 3.10: Hand-made structure to hold the PCMs.

The first hand-made structure is presented in figure 3.10, this first attempt was made of just one layer of PCM, with an acrylic plate in front of the top row, this acrylic plate was intended to create a separation between the surroundings and the plates.

It was later decided that was better to have two layers of PCM, to evaluate if the separation created by the acrylic plate has some influence on the results. The complete structure is presented, already installed in the location of testing, in figure 3.11, this is the complete structure and the lower PCM layer doesn't have an acrylic plate in front of them.

3.3.0.1 Placement of the sensors on the structure

The placement of the sensors on the structure is important for the three measurements that will be carried out. One sensor will be placed at the end of the structure to obtain more data on ambient temperature, while the other two will be positioned inside the structure, between the acrylic and the plates.

This is done to simulate the introduction of materials into the laboratory wall, although it may not be the most viable option for obtaining more precise results. It was, however, the best achievable given the limitations in terms of materials and space utilization.

Figure 3.11: Positions of the three sensors in the structure.

- A - Sensor placed between the acrylic plate and PCM;
- B - Sensor placed is placed on the bottom PCMs without acrylic plate cover;
- The third sensor is placed outside the structure to measure the room temperature.

Figure 3.12: Structure with the sensors in place.

The on-site assembly proved challenging because the structure turned out to be too large for the space initially intended for its placement. However, it was possible to install it in an alternative position within the same laboratory without compromising the workbench.

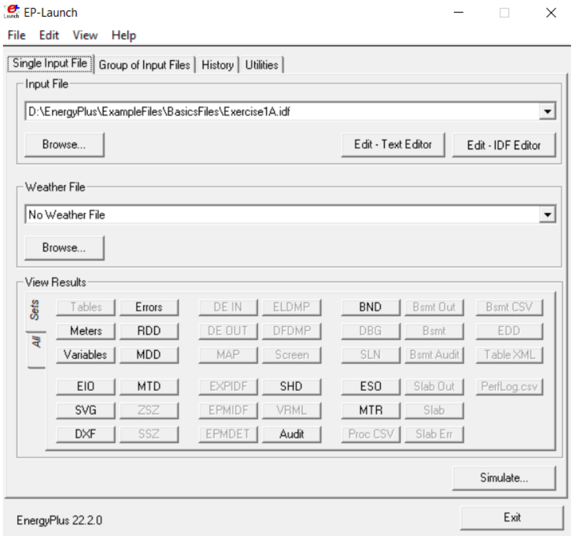
The sensors were successfully placed in the desired locations without major issues. The engineer in charge of the HSLB also ensured that the sensors would not be tampered with by anyone. Additionally, it was arranged, to the extent possible, to keep the laboratory closed to minimize contamination of the data with sudden temperature variations. This involved avoiding frequent opening and closing of doors by workers and preventing an increase in the room's relative temperature due to the body heat introduced by them.

3.4 Performance simulations

In this section, the methodology used for the simulations of the energy performance will be presented. *EnergyPlus* software will be used to obtain; Those simulations, so it's important to briefly explain how this program works and how can be used for the work.

3.4.1 EnergyPlus

EnergyPlus is a software designed for engineers, that allow modelling energy consumption for heating, cooling, ventilation and specific loads of buildings. It can also be used to model the thermal comfort of buildings.


Input File: D:\EnergyPlus\ExampleFiles\BasicsFiles\Exercise1A.idf

Weather File: No Weather File

Figure 3.13: EnergyPlus launch panel.

This program is console-based and reads input and output to text files. It is used to forecast the energy consumption of a building under various circumstances and to improve the design of the building's HVAC systems, lighting, and other energy-related factors.

Some of the key features of this software include:

- Integrated solutions of thermal zones and their corresponding HVAC system response;
- Settings that can be modified by the user, including building sizing, construction materials, interactions between the thermal zone and the environment, etc;
- Air movement and heat transfers between zones;
- It is possible to create models of the space in AutoCAD and introduce weather data to make the calculations.

With the help of computer design software, the room where the sensors will be placed will be modelled, always trying to include as much detail as possible, in this way, it will be possible to obtain good simulations. These details include materials used in construction, site and wall dimensions, air flows and, if possible, the inclusion of the PCMs themselves, this way it will be possible to compare the two configurations with and without PCMs.

For the purpose of the current work, this software allows us to estimate the approximate energy consumption that would be required to maintain the temperature inside the location where the materials will be used, this will be useful to compare the economic advantages that the use of the panels would create. As well as the difference in terms of energy consumption for the only purpose of heating or cooling the space.

The idea behind the use of simulation software will be to overcome the lack of equipment and time needed, as well as the unavailability of the estate to provide an entire room for this experience.

The computer model of the room will be introduced together with temperature data in Reguengos de Monsaraz in the *EnergyPlus* software, which is expected to be obtained an estimate of the thermal behavior inside this room, very close to reality.

3.4.2 Computer modelling

As explained before, it will be necessary to model the laboratory where the materials will be placed on a computer, in this way, it will be possible to predict the thermal behaviour and energetic performance of the wine analysis room with and without PCMs, which would correspond to the ideal experiment, which will not be possible due to the limited amount of PCMs available.

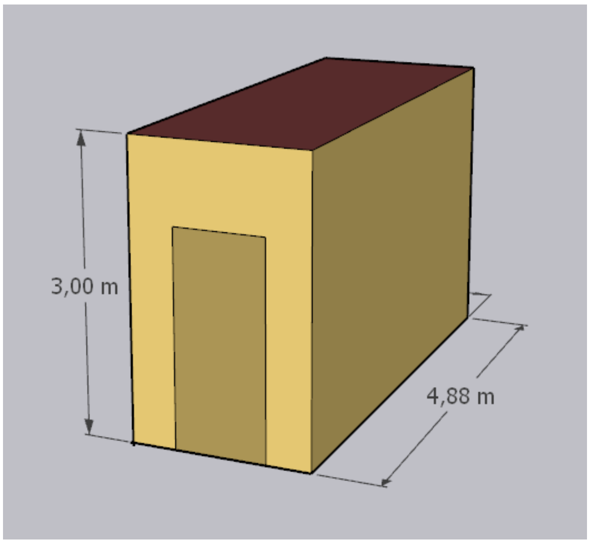


Figure 3.14: Computer model of the wine testing laboratory (front view).

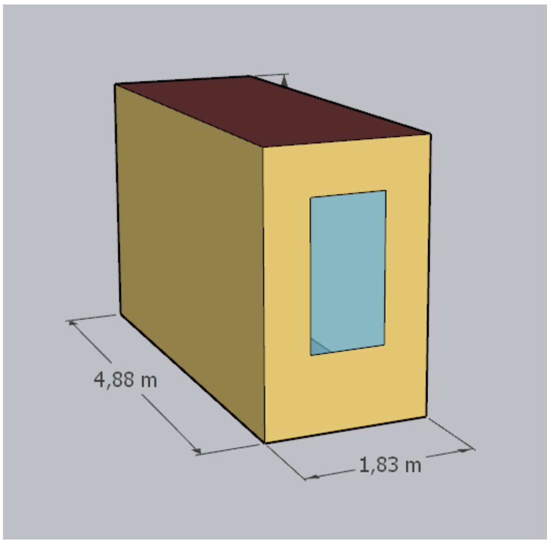


Figure 3.15: Computer model of the wine testing laboratory (back view).

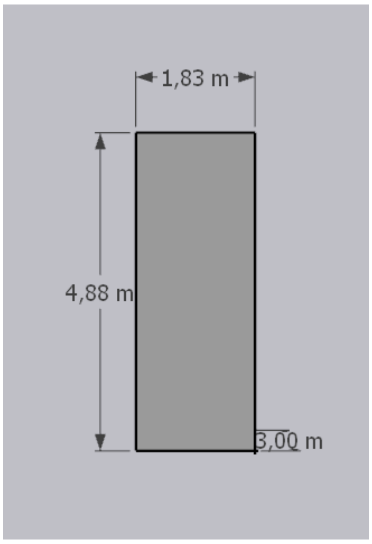


Figure 3.16: Computer model of the wine testing laboratory (bottom view).

Figures 3.14, 3.15 and 3.16 were computed using the software *SketchUp*. This software works with an add-on (*OpenStudio*) that allows to create buildings with different thermal zones and automatically add the door and window present in the actual laboratory.

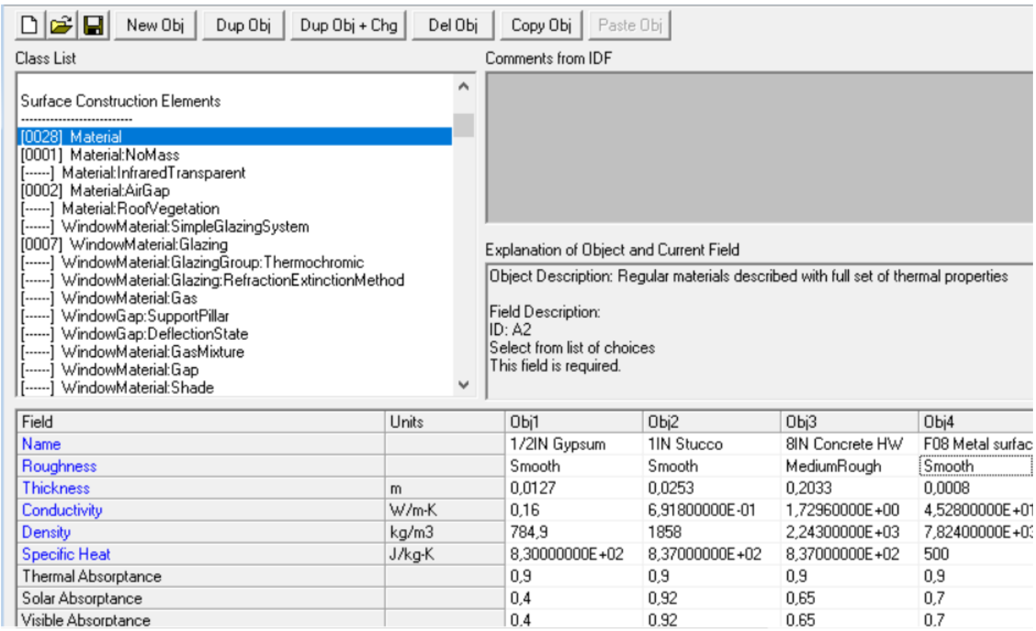
This add-on also allows to convert the 3D model into a .idf file, a .idf file is necessary to compute the simulations on the *EnergyPlus* software.

The .idf file describes in great detail the model that is going to be simulated, *EnergyPlus* allows to edit this type of file, to give more details about the model, among many others, the most important aspects that are possible to edit are the following:

- Building aspects like air zones, heat balance and shadows;
- Surface construction elements;
- Heat transfers;
- Internal gains;
- Energy consumption.

Taking into account the purpose of the work, simulations will be carried out with and without materials to cover the walls of the laboratory. According to the plan provided by the engineer responsible for maintaining the São Lourenço do Barrocal estate, the northernmost wall is made up of hollow brick and the southmost of mud bricks.

The .idf editor allows the materials that make up the laboratory to be changed, in this way, it will be possible to simulate and conclude the differences in terms of energy consumption to acclimatise the room. Internal energy and another result present in the *EnergyPlus* report will also be discussed.



Surface Construction Elements
[0028] Material
[0001] Material:NoMass
[------] Material:InfraredTransparent
[0002] Material:AirGap
[------] Material:RoofVegetation
[------] WindowMaterial:SimpleGlazingSystem
[0007] WindowMaterial:Glazing
[------] WindowMaterial:GlazingGroup:Thermochromic
[------] WindowMaterial:Glazing:RefractionExtinctionMethod
[------] WindowMaterial:Gas
[------] WindowGap:SupportPillar
[------] WindowGap:DeflectionState
[------] WindowMaterial:GasMixture
[------] WindowMaterial:Gap
[------] WindowMaterial:Shade

Object Description: Regular materials described with full set of thermal properties

Field Description:
ID: A2
Select from list of choices
This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4
Name		1/2IN Gypsum	1IN Stucco	8IN Concrete HW	F08 Metal surfac
Roughness		Smooth	Smooth	MediumRough	Smooth
Thickness	m	0,0127	0,0253	0,2033	0,0008
Conductivity	W/m-K	0,16	6,91800000E-01	1,72960000E+00	4,52800000E+01
Density	kg/m3	784,9	1858	2,24300000E+03	7,82400000E+0
Specific Heat	J/kg-K	8,30000000E+02	8,37000000E+02	8,37000000E+02	500
Thermal Absorptance		0,9	0,9	0,9	0,9
Solar Absorptance		0,4	0,92	0,65	0,7
Visible Absorptance		0,4	0,92	0,65	0,7

Figure 3.17: Example of materials selection on idf editor.

Figure 3.17 shows just an example of the various characteristics that can be changed in the editor, in this case, the materials that make up the walls of the model are shown, it is in this option that the PCM will be introduced, as well as the hollow and mud tiles.

The models of the materials are not predefined, so it's necessary to research the correct characteristics of each material, like its specific heat, conductivity, etc. That way, it's possible to guarantee a computer simulation close to real values.

3.5 Financial and economic methodology

Economic viability will be evaluated based on a series of indicators, which will be presented below, in later chapters, the data will be analysed taking these indicators into account.

In addition to economic indicators, a series of factors will be assumed that go against the particular case of this study, and the very characteristics of HSLB, these assumptions will allow the construction of a more accurate economic evaluation.

This assumptions are described below:

- The PCM's operation and maintenance (O&M) expenses were zero during the periods under study, the price of the structure is not accounted for, since the ideal would be to install the materials directly on the walls, but it was not possible;
- In the investigated time periods, the PCM does not require replenishment;
- The necessary energy applied in AC systems to bridge temperature differences does not come from renewable sources, as this model is applied to the study at HSLB;
- The price to install AC units in the location of the study is not accounted, because portable AC units are already in use, as explained previously;
- The only costs considered besides the price of the PCM are the installation costs;
- This is a passive solution to acclimatization, it is not necessary to have any kind of technical support or management costs.

For the financial aspects, the assumptions below are based on the current electricity costs, and PCM general costs, it will also be necessary to consider the following equation:

$$Energy\ storage\ density\ (kJ/L) = \frac{Specific\ heat\ capacity\ (J/Kg.K) \times Density\ (kg/L)}{1000} \tag{3.1}$$

- Adobe brick has an specific heat capacity of 840 J/Kg.K when employed as a sensible heat storage;
- Let's assume the adobe brick density is 1.7 Kg/L
  Energy storage density = $\frac{840 \times 1.7}{1000} = 1.428\ kJ/L$
- From the table 2.1 where the 18 °C PCM has a latent heat storage of 237kJ/kg, the conversion to kJ/L is described below:
  $Parrafin\ density \rightarrow 0.9g/mL = 0.9kg/L$
  $237 \times 0.9 = 213.3kJ/L;$
- The average tariff of electrical energy in peak periods is TE = 0.19 €/kWh **ERSE**.

3.5.1 Economic indicators

For the purpose of this study is gonna be used two economic indicators, which are briefly explained below.

3.5.1.1 Net Present Value (NPV)

Net present value (NPV) is a financial concept that compares the present value of anticipated future cash flows to the initial investment cost to determine the profitability of a project or investment. It is a crucial instrument in capital planning and financial judgment for both enterprises and people.

The fundamental principle underlying NPV is that owing to variables like inflation, risk, and the possibility of investing that money and earning returns, the value of money now is worth more than the same amount of money in the future. In order to assess if an investment is beneficial in terms of producing positive value, NPV considers the time value of money.

- If the NPV is positive, the investment is anticipated to yield more value than its initial cost and is therefore typically seen as a good investment;
- If NPV is negative, it indicates that there may not be sufficient returns from the investment to cover the initial outlay;
- If the NPV is zero, the investment will exactly break even and yield returns that are only sufficient to offset the initial investment.

This indicator can be computed using the following equation:

$$NPV = \sum_{t=1}^{H} \frac{CF_t}{(1+r)^t} - I_0, \tag{3.2}$$

where I_0 is the initial amount invested, H is the contemplated investment horizon, CF_t is the cash flow (balance of income and cost) in year t and r is the discount rate.

3.5.1.2 Internal Rate of Return (IRR)

An investment or project's prospective profitability is assessed using the financial statistic known as the Internal Rate of Return (IRR). The NPV of upcoming cash flows becomes zero with this discount rate. In other words, the IRR is the rate at which an investment generates precisely enough returns to offset the initial investment or break even.

In capital planning and investment decision-making, the IRR is a useful tool since it compares projected returns to the cost of capital and takes the time value of money into account when determining how appealing an investment is. IRR essentially sheds light on the anticipated effective annual rate of return on investment. The investment may be appealing if the computed IRR is higher than the needed rate of return (i.e., the cost of capital).

- A greater IRR means that the project is producing returns that outweigh the cost of funding, making it a more advantageous investment;
- The investment could not be profitable if the IRR is smaller than the cost of capital.

This indicator can be computed using the following equation:

$$\sum_{t=1}^{H} \frac{CF_t}{(1+IRR)^t} - I_0 = 0, \tag{3.3}$$

where the letters in the equation correspond to the ones previously explained.

4

CASE STUDY

This chapter examines the primary characteristics of the São Lourenço do Barrocal as well as the local climate. Understanding the normal temperature swings at this location is crucial because it will provide a way to compare the outcomes of coating the data-gathering site with PCMs. There is also a description of the many PCMs installation locations across the estate, where temperature and humidity fluctuation measurements will be made.

4.1 Characteristics of São Lourenço do Barrocal

Located in Reguengos de Monsaraz, district of Évora in Portugal, São Lourenço do Barrocal is a 7.8 million m2 estate, which has been in the same family for more than 200 years, is centred at the *Monte*, a former modest agricultural community, that has been restored as a luxurious hotel.

During the first technical visit, it was possible to observe the variety of operations and challenges that the location of the estate causes the workers responsible for maintaining the site. The estate and the hotel operate quite autonomously, due to the location of the place, which is far from the main city in the vicinity, and taking into account that the Alentejo region has a low population density, where vast plains of cork oaks predominate, the estate cannot depend on third parties to function normally.

Being located in the extreme east of Portugal, very close to the border with Spain, the site is the last to be powered by the electricity grid. Being a luxury hotel and estate, it is not possible to afford the lack of electricity, we were informed of the difficulty that this entails, as power cuts are very frequent. For this matter, new solutions to improve energy efficiency are very welcomed by the São Lourenço do Barrocal team.

Figure 4.1: Sattelite view of São Lourenço do Barrocal location.

The site also has a variety of equipment to support the management of the space, this equipment will allow the property great independence in daily processes and external service providers.

Some of this equipment includes a water treatment station, several laundry stations, a wine cellar, a warehouse and a grape treatment plant.

In order to better understand how HSLB is organized, the general plant is presented in figure 4.2. This plan does not include the hotel and room areas, only the maintenance, wine production and laboratory areas. It will be interesting to study the plant in order to understand the ideal place for the PCMs, as well as to understand in which areas the solution studied in this research can be applied later, if the results are positive.

Represented by numbers from one to three are the three zones represented in the general plant, these will be briefly presented below.

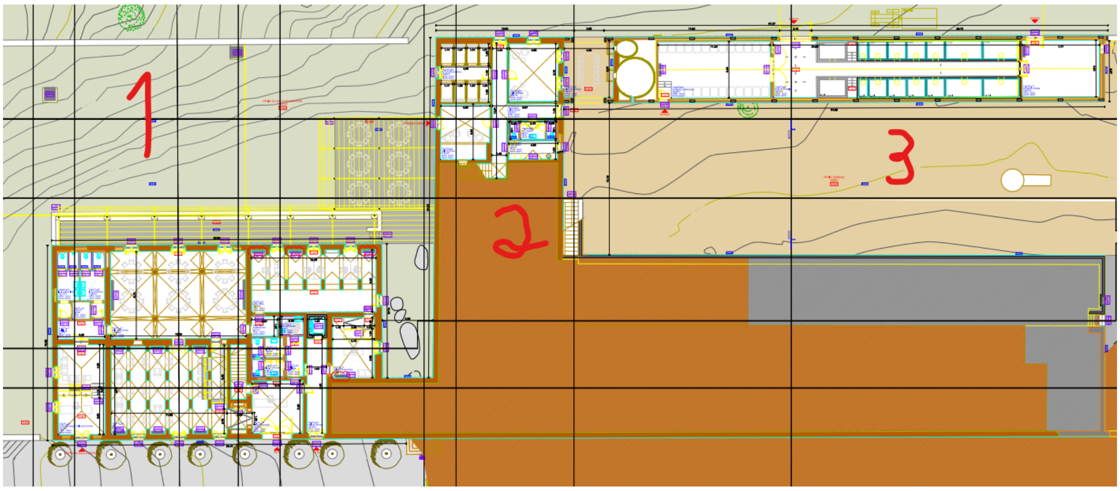


Figure 4.2: General plant of HSLB.

- **Zone 1:** Reception with rest area for guests, includes two lounges for outdoor events and management offices, as well as the security office;
- **Zone 2:** Includes wine production support rooms, a laboratory and wine tasting spaces;
- **Zone 3:** Wine production area, includes a cellar for wine maturation, machines for treating the grapes and a series of barrels for storing the wine.

4.2 Typical year in Reguengos de Monsaraz

Reguengos de Monsaraz is located in the Alentejo region of Portugal, which has a Mediterranean climate with hot, dry summers and mild, wet winters. The average temperature during the summer months (June to August) is around 30°C, while during the winter months (December to February), the average temperature is around 10°C. The humidity levels are generally low throughout the year, with an average relative humidity of around 60-70%.

To obtain more concrete and precise data, the database of the *Portal do clima* website was used, which allowed the construction of the table that follows, where the average temperature and humidity can be observed during a typical year in Reguengos de Monsaraz. The data consists of a monthly average for 30 years, between 1971 and 2001.

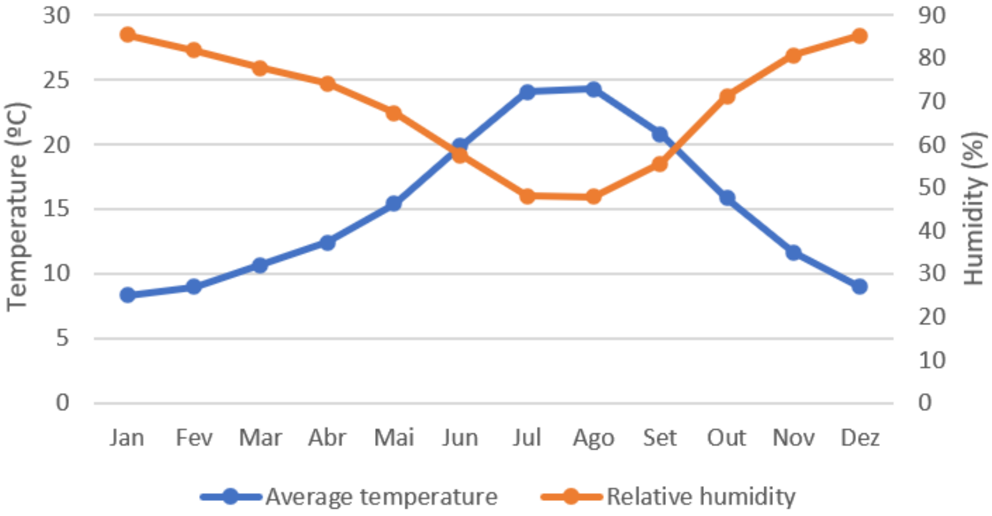


Figure 4.3: Typical values of temperature and humidity in Reguengos de Monsaraz.

As can be seen by figure 4.3, average temperature values vary greatly throughout the year, which is not optimal for wine maturation processes, only during October and May the average temperature reaches values that are close to the desired temperature for maturation. This leads us to conclude that during these months, the acclimatization costs of the wine maturation space should not be as pronounced as in the rest, however, acclimatization systems will always be necessary throughout the year.

Figure 4.3 also tells us about the relative humidity, as expected, in months when the temperature is higher, the humidity will be lower and in months with lower temperatures, the humidity will increase. What can be drawn from this graph is the same as can be concluded previously, the values vary a lot throughout the year, which is not optimal for maturation, this means that it is also necessary to regulate the humidity values, which represents an increase in the electricity bill.

4.3 Placement of the materials

With the help of the people responsible for making wine, an optimal location has been selected for the placement of the PCMs.

The place consists of a wine analysis laboratory, where there are test tubes and some more laboratory equipment. This room was considered optimal because it does not have any acclimatization system, it only has a window that is usually closed, so, it is likely that the materials will help acclimatize this space to a temperature close to the PCMs phase change value.

This laboratory is located in zone 2 of the general plant and its exact location and constructive measures are shown in the figure 4.4.

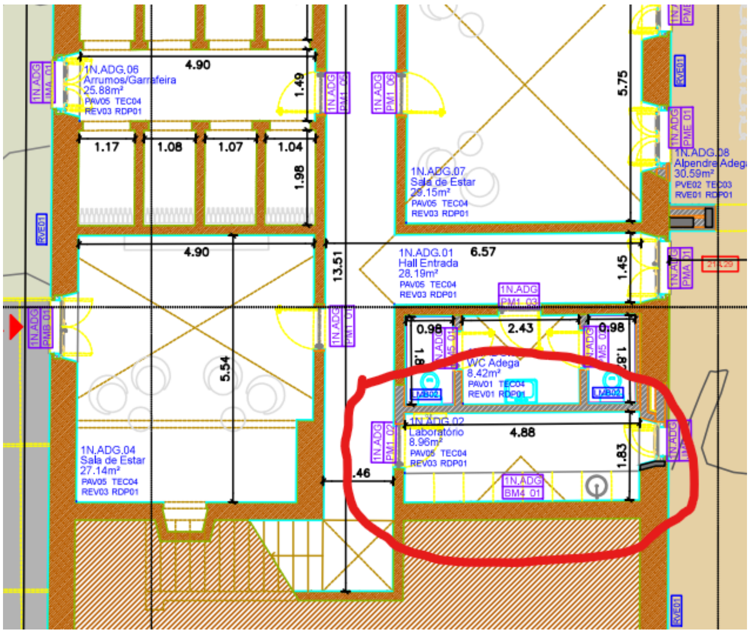


Figure 4.4: Location and measurements of the wine laboratory.

It is a relatively small and cramped laboratory, with a large bench and an area of only 8.96 m2. The height is not present in the plan, but by measurements on site, it is about 3 meters.

By analyzing the plant, it is possible to know that the walls of the room are made of two different materials, the northernmost wall being made of hollow brick, and the southernmost wall of adobe brick.

These materials will be taken into account when carrying out the computer simulations, as they will have a direct influence on the thermal behaviour inside the room, which will result in the better or worse performance of the PCMs.

Finally, the figure 4.5 shows the laboratory where the materials will be placed, it is expected that the structure is leaning against the southernmost wall, on top of the main workbench.

Figure 4.5: Wine analysis laboratory.

The temperature fluctuations, and the average temperature inside the room, will be very close to the temperature outside the building because the wall lacks proper isolation materials, this is another reason why the room is optimal, as the final objective of this study is to access if the materials contribute to the temperature stability without the need for AC systems.

The structure presented in the previous chapter serves to overcome the impossibility of placing the materials on the walls, the walls are an important part of the estate's aesthetics, as this is also a luxury accommodation, the looks are essential and every space must be appealing for the client's eye. Although this space is not for customers, it would not be possible to drill or glue materials directly to the wall, as this would damage it.

The figure 4.6 shows the structure positioned inside the analysis room.

Figure 4.6: Wine analysis room.

5

Simultions and experimental measurements

In this section, the results obtained through both simulation and experimentation will be presented. The results obtained from the experimentation conducted in the wine analysis laboratory will include the tables of temperature and relative humidity for the months during which the sensors and the structure were operational. The evaluation of these results will be analyzed in the following chapter.

Regarding the results obtained through simulation, the relevant reports and information contained therein, generated by the *EnergyPlus* software, will be discussed. This includes, for example, the total energy required to supply the laboratory and the energy necessary for its climatization, etc.

For the computational model, real construction materials and Phase Change Materials (PCMs) will be utilised. In this way, it will be possible to draw conclusions and evaluate the differences in terms of economic advantages and feasibility of using PCM to coat the walls of the wine cellar., again, this evaluation will be conducted in the following chapter.

5.1 Experimental measurements

5.1.1 Sensor for outside temperature

Due to the easier installation of this sensor, it was possible to collect data for a longer period of time. However, it will only be possible to use the data for comparison during the months when it was also possible to measure with the sensor placed on the structure.

However, these data may become important for a better understanding of temperature variations in that location, which could be crucial for a subsequent analysis of the possibilities for installing materials in the HSLB.

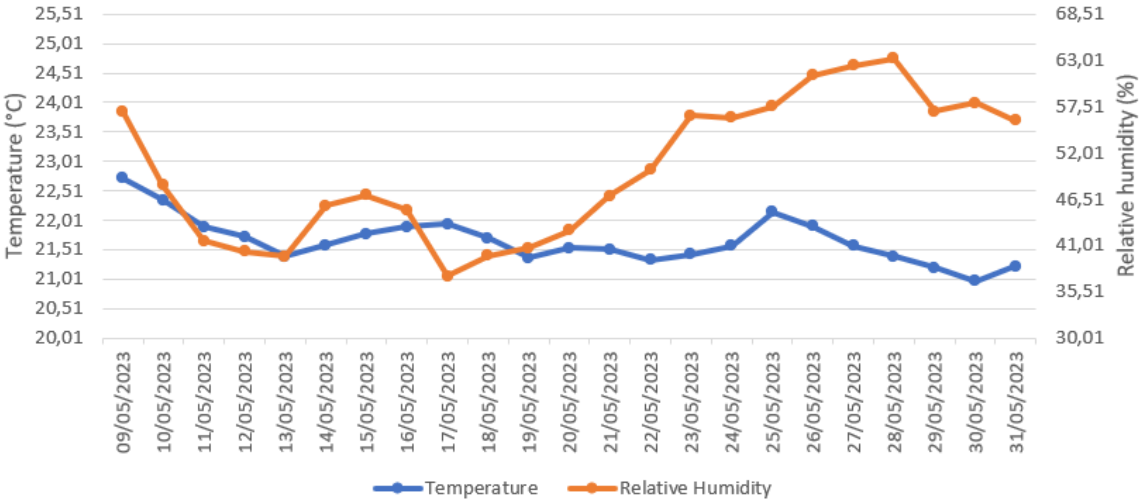


Figure 5.1: Graph T&RH for sensor placed outside the structure during May.

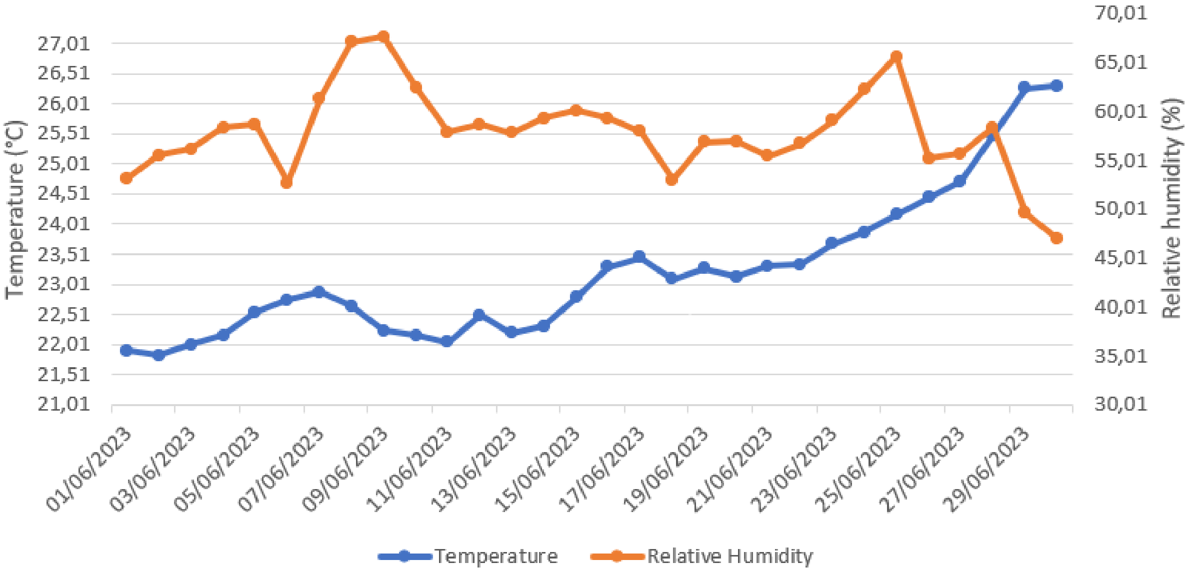


Figure 5.2: Graph T&RH for sensor placed outside the structure during June.

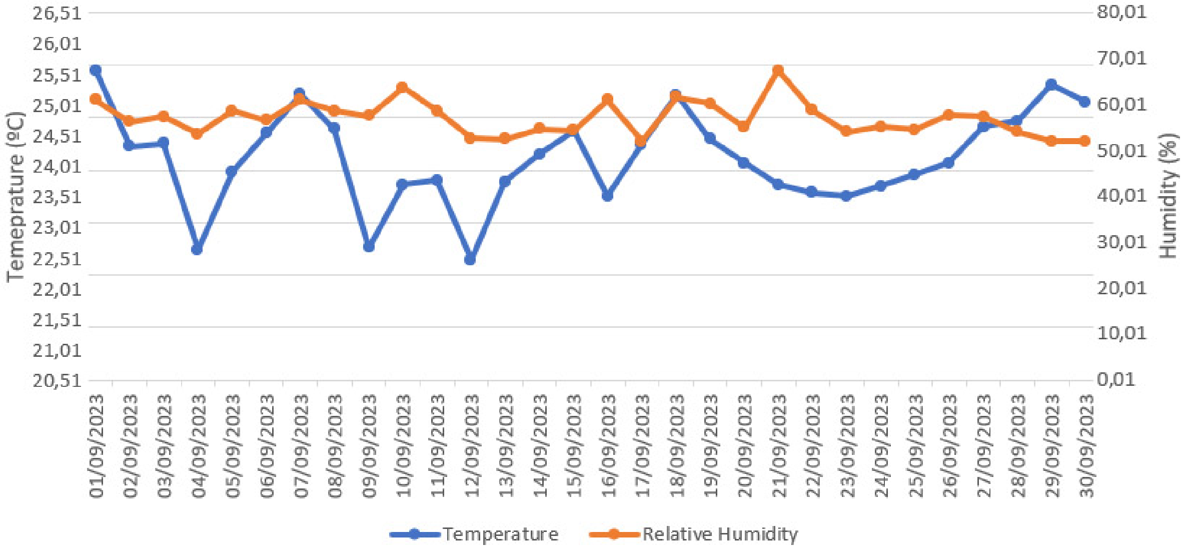


Figure 5.3: Graph T&RH for sensor placed outside the structure during September.

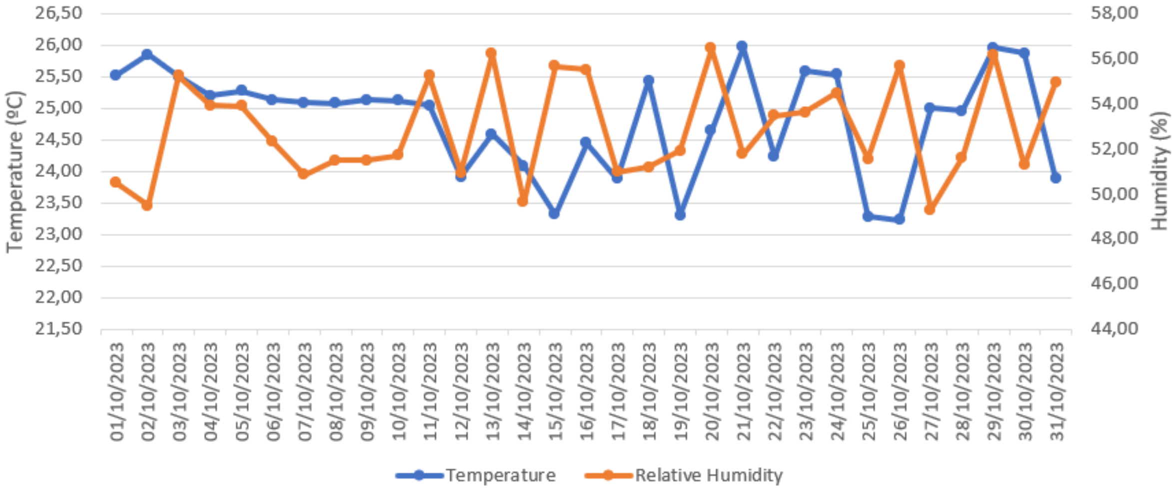


Figure 5.4: Graph T&RH for sensor placed outside the structure during October.

Due to an error during the data gathering, the ambient temperature sensor was turned off for two months. This resulted in a lack of data for July and August, it was not possible to take additional measurements. Therefore, comparisons will have to be made with the available data.

5.1.2 Sensor placed on the structure

Similar to the previously presented graphs, the following are the graphs of the sensors placed on the structure. For the period of 4 months of data gathering.

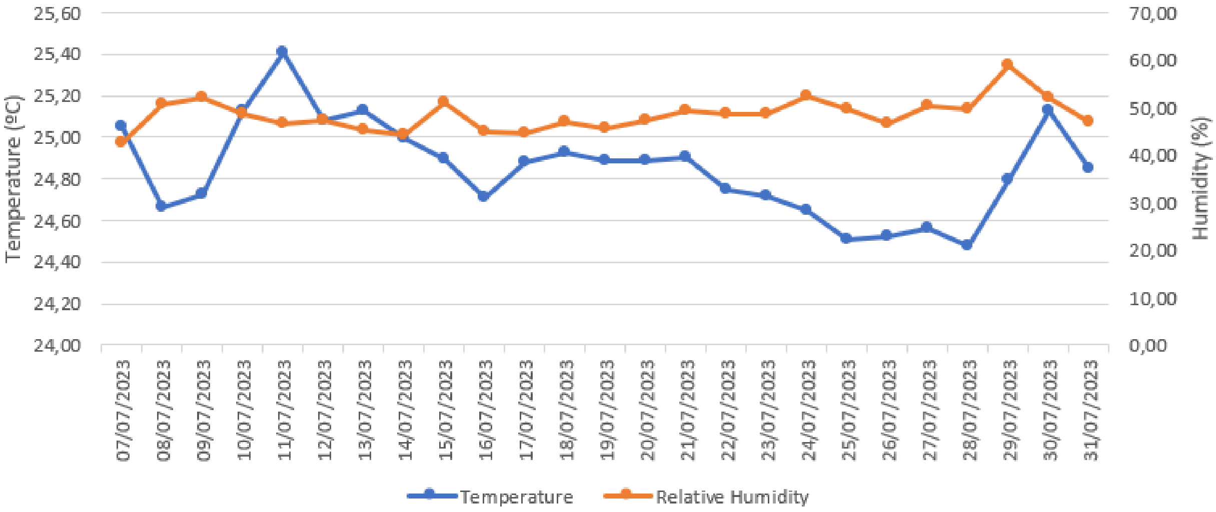


Figure 5.5: Graph T&RH for sensor placed on the structure during July.

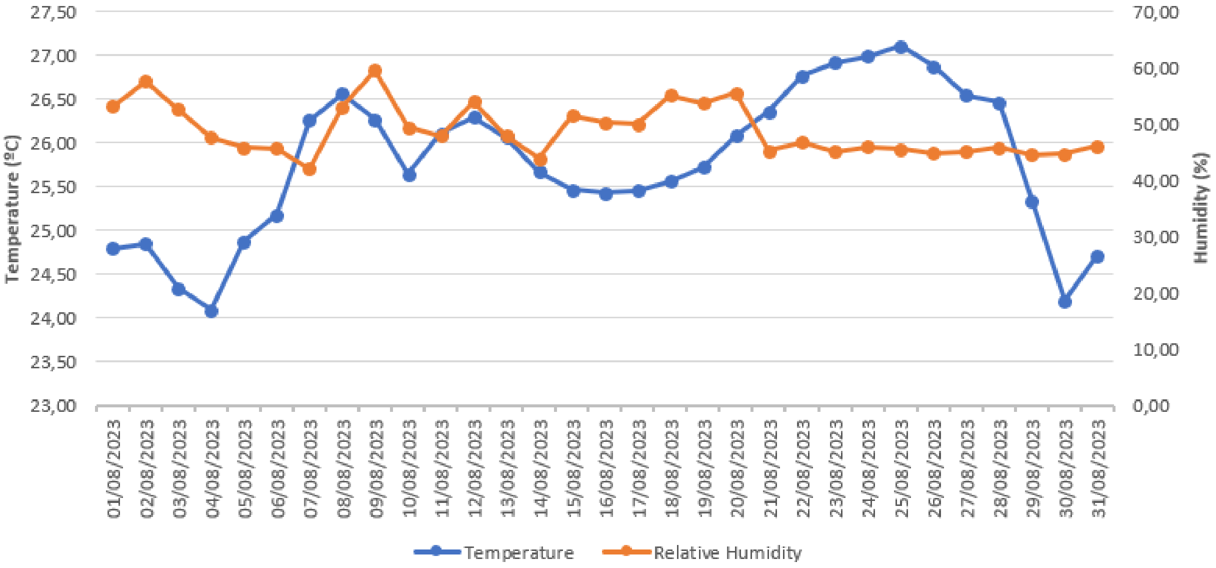


Figure 5.6: Graph T&RH for sensor placed on the structure during August.

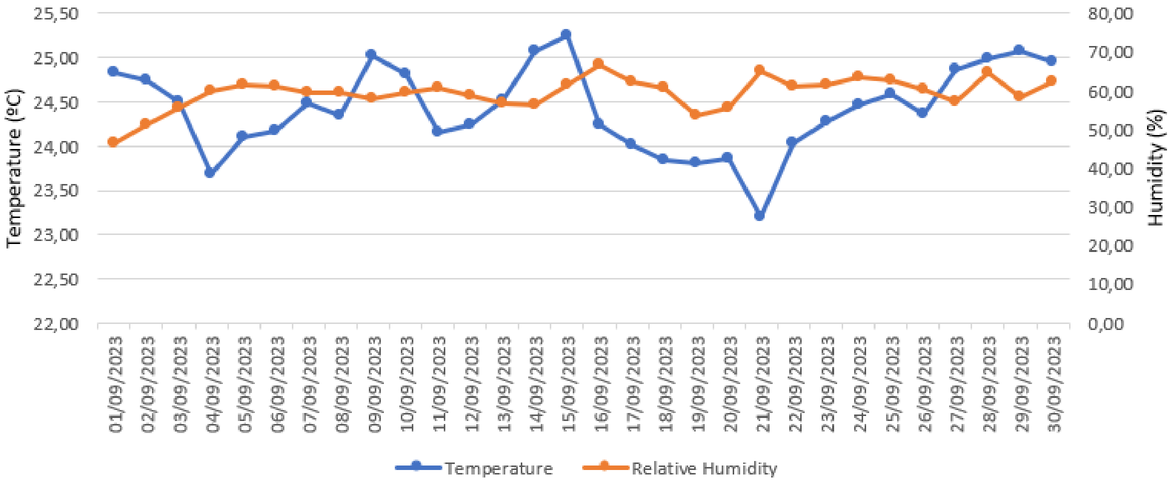


Figure 5.7: Graph T&RH for sensor placed on the structure during September.

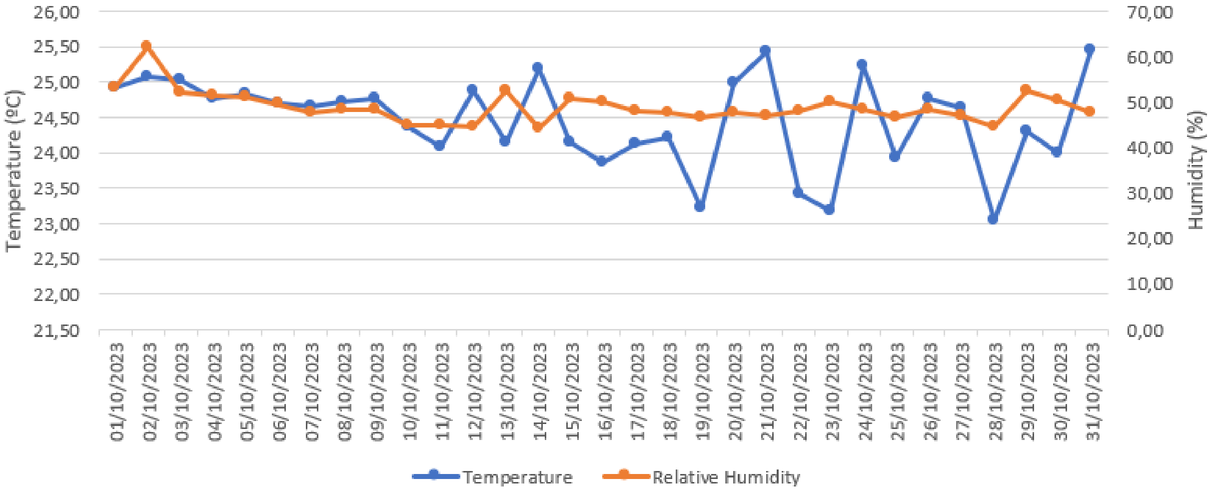


Figure 5.8: Graph T&RH for sensor placed on the structure during October.

One of the two sensors measuring values near the PCM was unintentionally contaminated with wine, rendering its data unavailable. The other sensor remained operational throughout the 4-month measurement period. The four graphs above depict the values measured by the sensor positioned between the acrylic and the PCM.

5.2 Computer simulations

In this section, the results obtained through simulation will be presented. Two models have been constructed, considering the explanations provided in the methodology chapter. The simulations will include the differences obtained for variations in temperature and energy expenditures, these computational models will also take into account the following assumptions:

- Will be considered lights, electric equipment, people and laboratory equipment for the internal gains of the model;
- The electric equipment includes HVAC systems, humidifier/dehumidifier and other laboratory equipment present in the real laboratory;
- The materials considered for the two models will be PCM and adobe brick, with specific characteristics of each material;
- The PCM will have the characteristics of a 18°C melting point PCM, this can be observed in the table 2.1;
- The thermostat will be programmed to 18°C always because this is the temperature required all year round for producing wine at HSLB.

5.2.1 Results regarding temperature variations

The following graphs were obtained through simulation using the *EnergyPlus* model. They depict the temperature differences experienced inside the room when the walls are composed of adobe brick vs PCM.

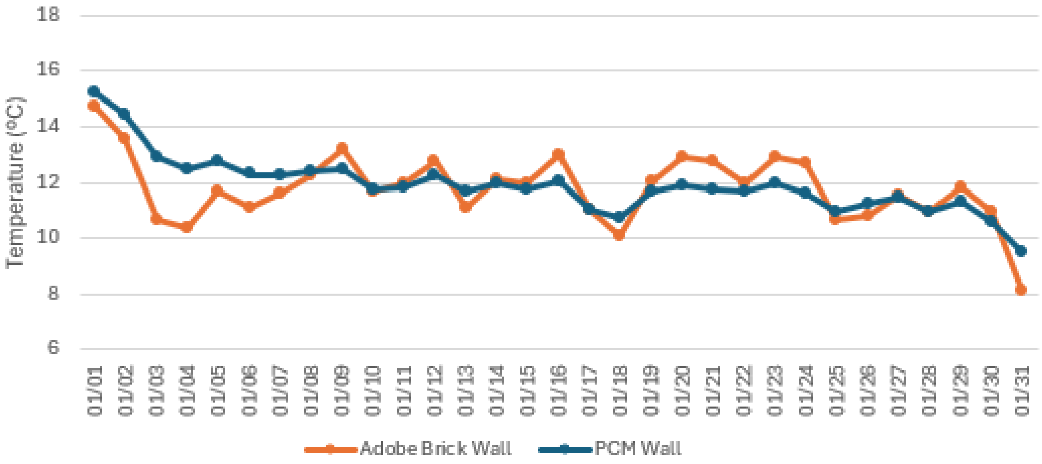


Figure 5.9: Temperature variations for the walls covered with and without PCM in January.

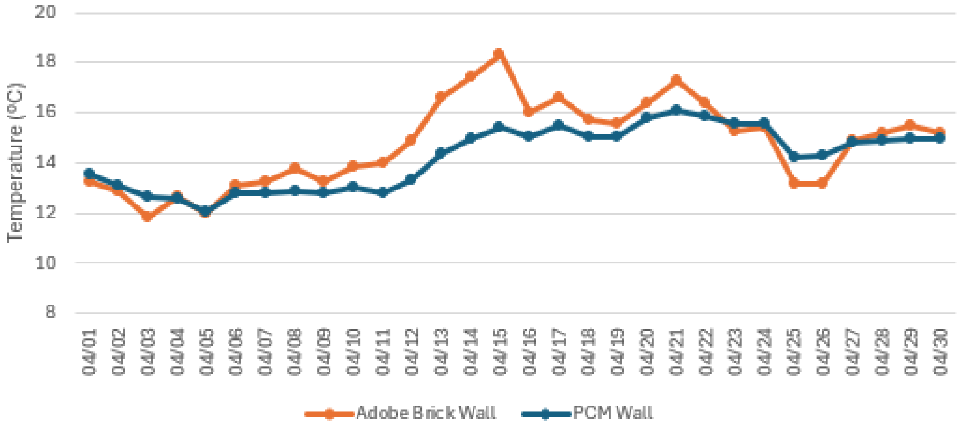


Figure 5.10: Temperature variations for the walls covered with and without PCM in April.

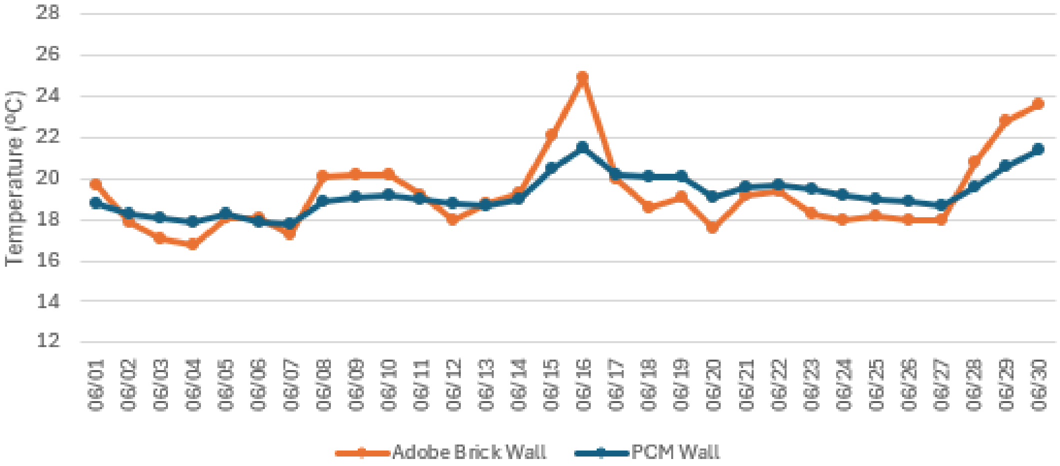


Figure 5.11: Temperature variations for the walls covered with and without PCM in June.

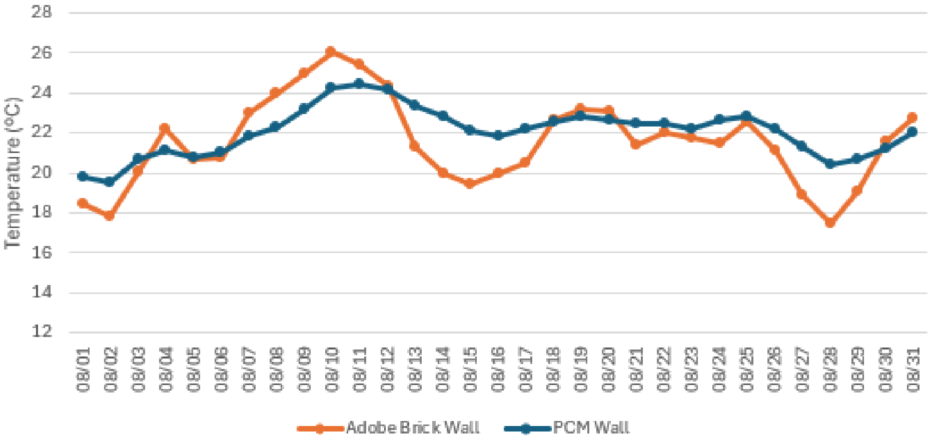


Figure 5.12: Temperature variations for the walls covered with and without PCM in August.

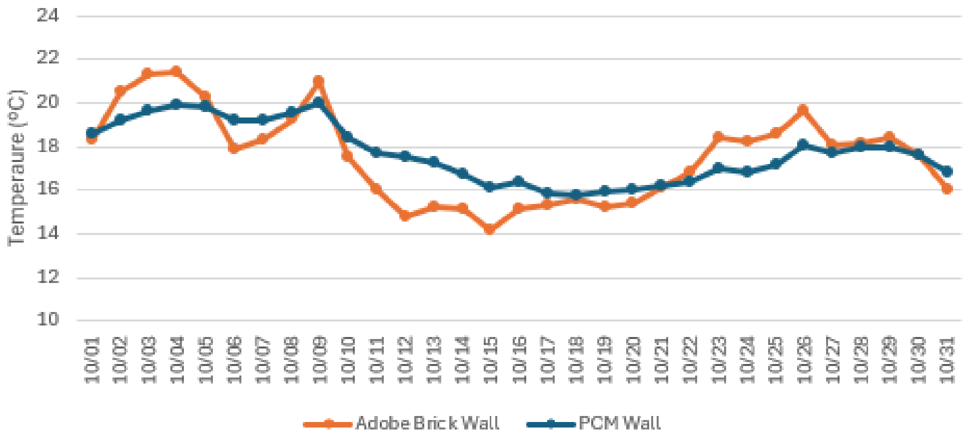


Figure 5.13: Temperature variations for the walls covered with and without PCM in October.

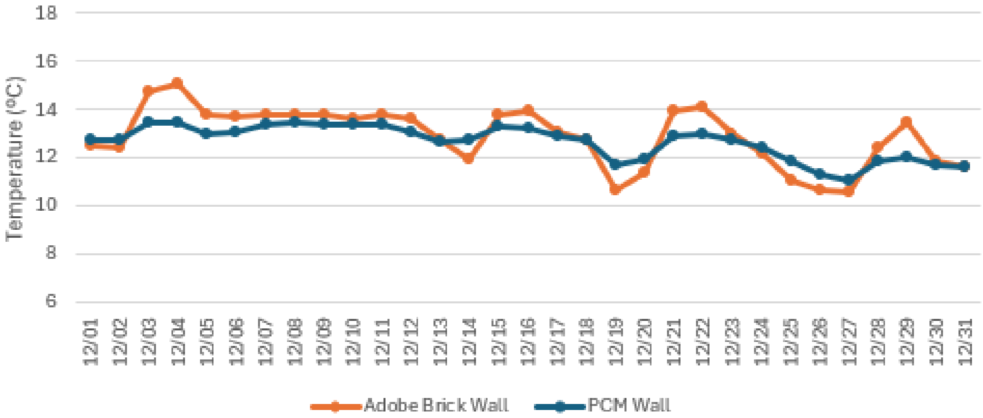


Figure 5.14: Temperature variations for the walls covered with and without PCM in December.

The rest of the graphs for the remaining months of the year can be consulted in subsection I.1.1 of the anex.

The analysis of these graphs is carried out in the following chapter, in section 6.2.

5.2.2 Results regarding energy consumption

The following graphs demonstrate the results obtained for the differences in energy consumption between the two typologies studied.

The results presented will be limited as only the wine analysis laboratory is being simulated; however, these findings will also be valuable for understanding potential energy consumption patterns in other areas of the estate.

The values of energy consumption below represent both cooling and heating loads combined.

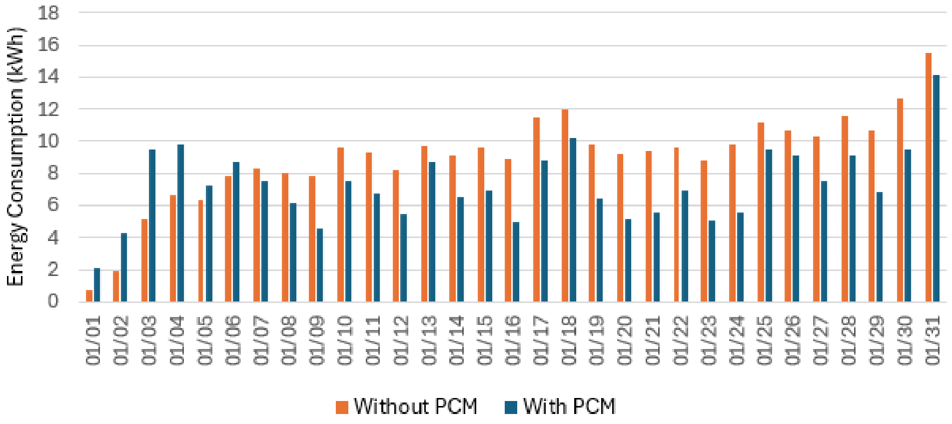


Figure 5.15: Energy consumption variations for the walls covered with and without PCM in January.

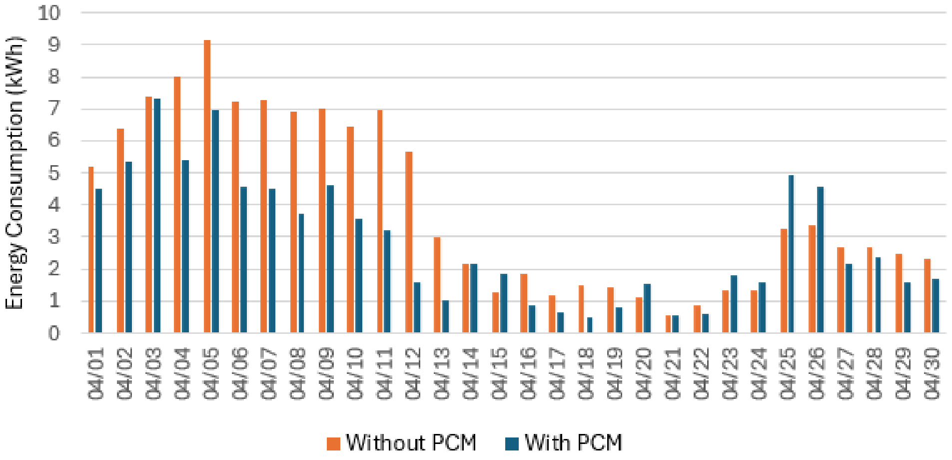


Figure 5.16: Energy consumption variations for the walls covered with and without PCM in April.

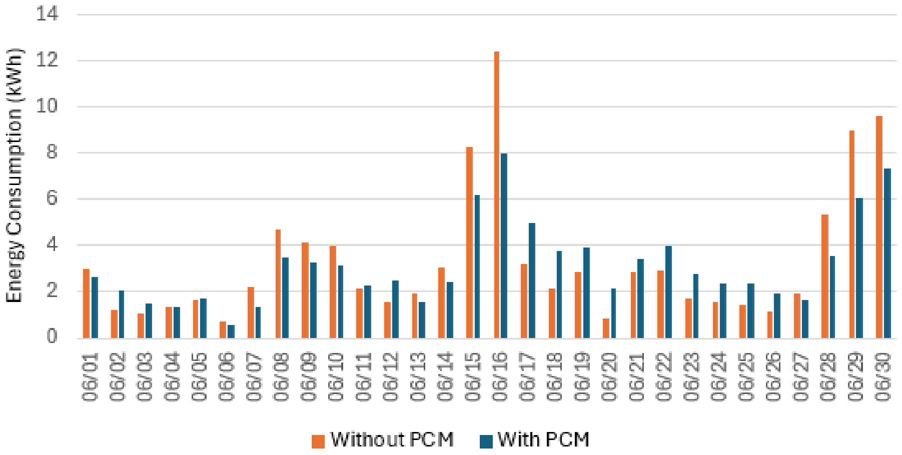


Figure 5.17: Energy consumption variations for the walls covered with and without PCM in June.

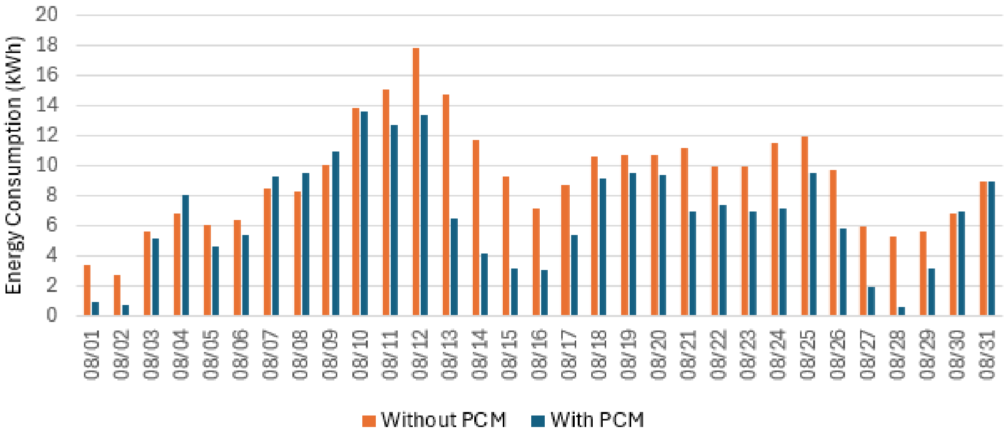


Figure 5.18: Energy consumption variations for the walls covered with and without PCM in August.

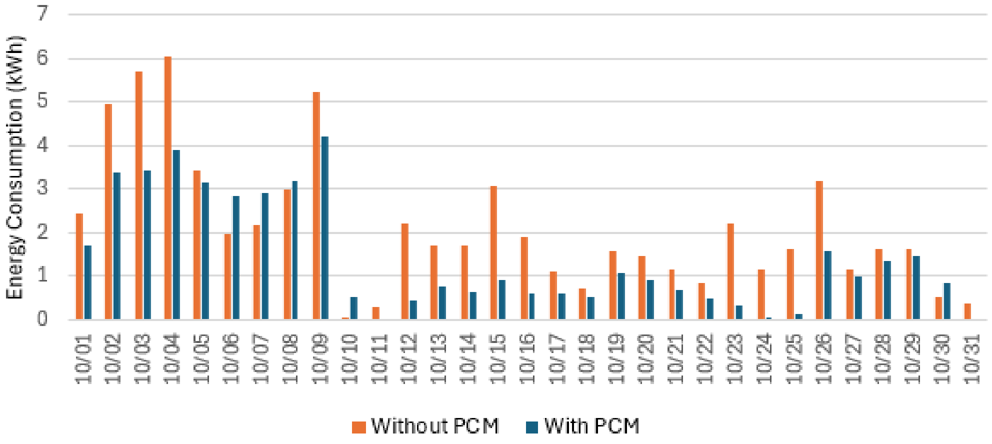


Figure 5.19: Energy consumption variations for the walls covered with and without PCM in October.

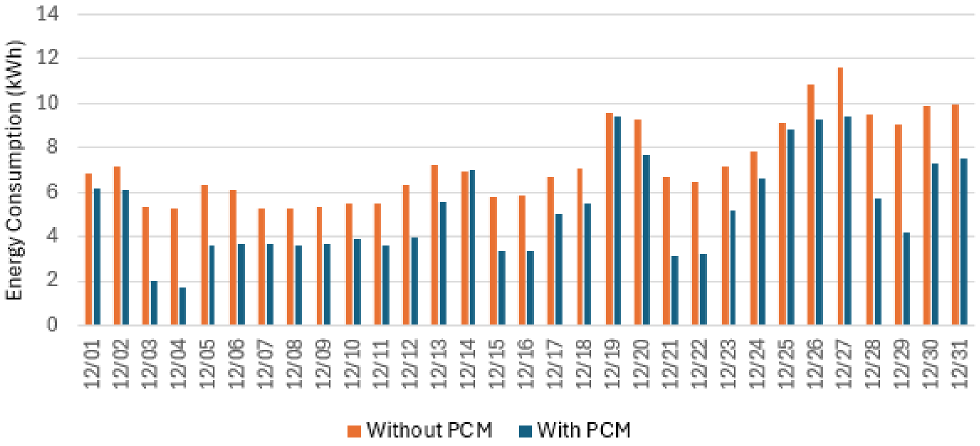


Figure 5.20: Energy consumption variations for the walls covered with and without PCM in December.

The rest of the graphs for the remaining months of the year can be consulted in subsection I.1.2 of the anex.

The analysis of these graphs is carried out in the following chapter, in section 6.2.

6

ANALYSIS OF RESULTS AND ECONOMIC VALUATION

This chapter will delve into the discussion of experimentally obtained results and simulated values using the *EnergyPlus* software. In addition to the results discourse, calculations and corresponding assumptions for the economic evaluation of the material installation project at HSLB will also be conducted.

As previously mentioned, the experimental results obtained do not exhibit the highest quality, owing to two principal factors. Firstly, the sensors and materials ought to have been more effectively isolated within the confines of the laboratory walls. Secondly, the enclosures housing the measurement circuits were disconnected. Not only were these enclosures disconnected for a certain duration, but they were also inadvertently tainted with wine, as evidenced by Figure 6.1. Consequently, one of the sensors linked to the structure was rendered incapable of measurements.

Because the experimental results do not present sufficient quality, relying solely on them is deemed inadequate. The simulated values, therefore, will be employed for the economic calculation. This approach ensures enhanced credibility in assessing economic returns and potential energy savings.

The economic assessment calculation will incorporate the economic indicators outlined in the methodology chapter. While acknowledging that certain assumptions may vary from project to project, those considered in this study are tailored to best suit the specific issues investigated in this dissertation.

Figure 6.1: Contaminated sensor box.

6.1 Experimental results

Only during the months of September and October was possible to extract values for both the sensor placed on the structure and the sensor measuring ambient temperature. Consequently, a direct comparison of results is possible during this time frame.

By analysing the graphs from figures 5.3, 5.4, 5.7 and 5.8 it possible to observe the following information:

6.1.1 Regarding temperature:

- The PCM helped stabilize the values of temperature, as it's possible to observe that a lesser variation between the maximum and minimum temperature values was observed in the months of September and October, with fluctuations of only 2 and 2.5°C, respectively, for the sensor placed near the PCM;

- The overall maximum value of temperature dropped when compared to the ambient temperature sensor;

- The graphs of the sensor placed near the PCM exhibit a lower daily variation in values. Overall, there is a reduced temperature fluctuation from day to day, although consecutive days with significant temperature variations are also observed;

- Even though a direct comparison with other months is not possible, the trend persists, as a lower variation between maximum and minimum temperatures is evident in the sensor placed near the PCM.

6.1.2 Regarding humidity:

- The PCM helped stabilize the values of humidity, as it's possible to observe that a lesser variation between the maximum and minimum values was observed in the months of September and October, with minimal fluctuations for the sensor placed near the PCM;
- The graphs of the sensor placed near the PCM exhibit a lower daily variation in values. Overall, there is a reduced humidity fluctuation from day to day, and no significant daily humidity variations are observed;
- Even though a direct comparison with other months is not possible, the trend persists, as a lower variation between maximum and minimum humidity is evident in the sensor placed near the PCM.

As anticipated, PCM alone do not have the capability to lower the temperature of a room to values near their melting point; rather, they should be utilized as insulation material and complemented with air conditioning units. However, as observed, one could expect greater stability and a slight reduction in temperature. This will enable energy consumption savings by the air conditioning units, as they do not have to counteract larger daily temperature variations.

Regarding humidity levels, it would not be expected that the materials could have a significant impact. The primary purpose of their use is related to temperature stability. However, a bigger stability of humidity values can be observed.

Although it would have been interesting to observe the graphs for colder months, considering the results obtained for warmer months, one would expect that the sensors near the PCM would exhibit greater temperature and humidity stability. However, contrary to the subsequent analysis, it might be anticipated that these sensors would show relatively higher maximum and minimum temperature values. This is because the PCM would also assist in bringing the laboratory's ambient temperature closer to its melting point (18°C). With regard to humidity values, as explained earlier, one would anticipate greater stability of values.

All these assumptions are solely based on the obtained results; true values may differ. Hence, obtaining data for colder months would have been valuable for a more comprehensive understanding.

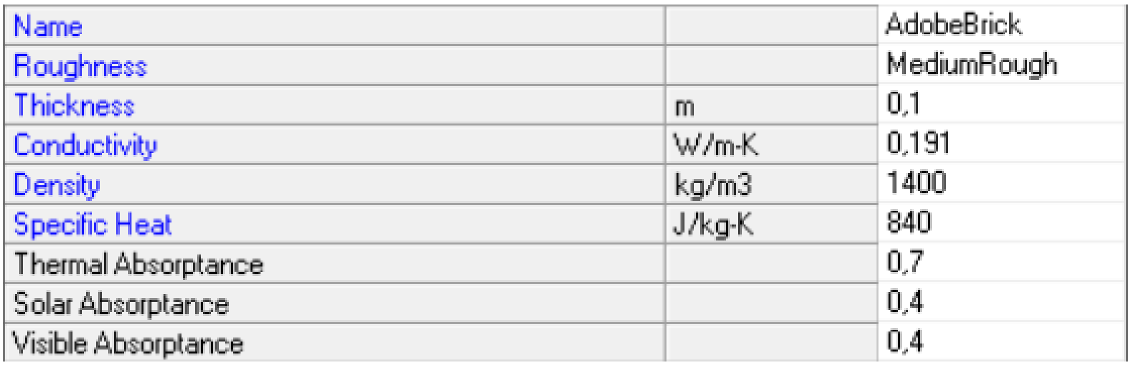
6.2 Simulation results

6.2.1 Without PCM

The primary distinction to be imposed in the model for simulations without PCM, when compared to simulations with PCM, lies in the materials utilized for coating the walls of the wine analysis laboratory.

For simulations without PCM, adobe brick was taken into account as the material for wall coating, corresponding to the presently employed in the HSLB. To define the material in *EnergyPlus*, approximate values of conductivity, density, and specific heat, as well as thermal, solar, and visible absorption, will be considered.

The figure 6.2 shows the model used in the simulations for the adobe brick,



Name		AdobeBrick
Roughness		MediumRough
Thickness	m	0,1
Conductivity	W/m-K	0,191
Density	kg/m3	1400
Specific Heat	J/kg-K	840
Thermal Absorptance		0,7
Solar Absorptance		0,4
Visible Absorptance		0,4

Figure 6.2: Model defined for Adobe Brick in EnegyPlus.

Analyzing the results obtained from the temperature variation graphs ranging from 5.9 to 5.14, it can be observed that the adobe brick exhibits a greater thermal variation throughout the months when compared to the results obtained for PCMs.

These results are to be expected because the brick has a much lower specific heat capacity than the PCMs. This will make it much easier for thermal variations to occur for the same amount of energy, in this case, heat from the exterior, equipment, or staff of the estate.

However, it was observed that the brick performed better than the PCMs during the winter, where it was possible on most of the colder days to obtain temperature values closer to the reference value of 18°C. This may be due to two reasons. Firstly, it could be attributed to the characteristics of the brick, where thermal variation occurs more easily. With less heat, this material will heat up more than the PCM, providing a warmer room in the winter. However, this is always accompanied by significant thermal variations throughout the month.

Another reason could be attributed to the minimal internal gains defined in the *EnergyPlus* model. This would imply that the only way to heat the room besides the air conditioning would be through the exterior temperature, which does not correspond to reality, as the laboratory has some equipment and staff entering and exiting the space.

It was observed that the lowest temperature recorded was 8°C in January, corresponding to the coldest month, and a maximum temperature of 26°C in July, which corresponded to the hottest month overall.

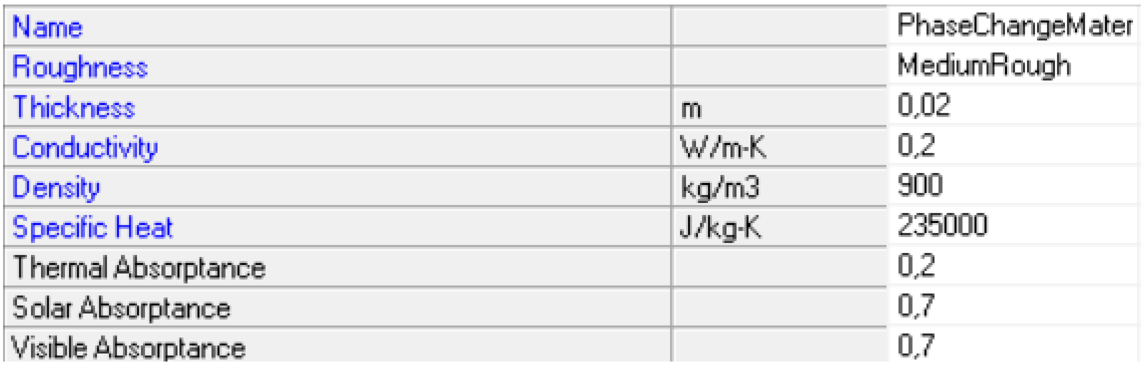
Concerning the results obtained for energy consumption, it can be observed that simulations without PCM had poorer outcomes. This would be expected, and it could be attributed to a variety of reasons.

It was noted that the adobe brick did not aid in stabilising the temperature, resulting in significant temperature variations both between and throughout the day. This will cause the air conditioning units to work harder to compensate for these differences, making it more difficult to stabilize the temperature at the reference value of 18°C.

The performance of the adobe brick was better during the colder months. There are months, such as January, when energy consumption is nearly equal. This could be attributed to the previously explained factors, namely the low specific heat capacity of the adobe brick. It would require less energy for the temperature to rise. Since in colder months in Reguengos de Monsaraz the exterior temperature is below 18°C, as observed in figure 4.3, it would be necessary to compensate for these low temperatures.

6.2.2 With PCM

As previously described, the only variation considered in the model during PCM simulated scenarios pertained to the application of PCM as the wall coating. The specific PCM utilized is detailed in table 2.1 for a temperature of 18°C.



Name		PhaseChangeMater
Roughness		MediumRough
Thickness	m	0,02
Conductivity	W/m-K	0,2
Density	kg/m3	900
Specific Heat	J/kg-K	235000
Thermal Absorptance		0,2
Solar Absorptance		0,7
Visible Absorptance		0,7

Figure 6.3: Model defined for PCM in EnegyPlus.

The results obtained for the PCM are practically the opposite of what was analyzed previously regarding the adobe brick. The thermal variation results show that PCMs help stabilize the temperature in all months, with some months closer to the reference value, but in all of them whether warmer or colder, there was greater temperature stabilization.

This can be evidenced by the fact that the greatest temperature variation within a single month was only 7°C, recorded in September. It was observed that in warmer months, PCMs perform better than in colder months, for reasons previously explained.

In colder months, it would be expected that PCMs would help raise the temperature to higher values. Overall, the adobe brick even performed better as higher temperatures were observed during the winter.

However, there may be reasons for these results, such as the limited introduction of variables in the *EnergyPlus* model, notably internal gains and other heat-generating equipment within the room. The only variable promoting temperature increase is the exterior temperature, and as explained earlier, PCMs require more energy to increase their temperature. This will result in poorer outcomes in colder months due to the lower availability of heat energy, as the adobe brick will increase its temperature more for the same energy input.

Taking this into account and considering scenarios closer to reality, where heat-generating equipment and staff are entering and exiting the room, as well as working within it, internal gains will increase along with the room temperature. This will lead to PCM having better performance than adobe brick both in winter and summer.

Analyzing the results of energy consumption and considering the limitations of the model constructed by *EnergyPlus*, it can still be observed that PCM exhibits a significantly superior performance compared to adobe brick. These results align with the findings of thermal variations, where it was observed that in colder months, the performance is similar to adobe brick, while in warmer months, there is much less energy consumption.

Even considering the limitations of the *EnergyPlus* model, an energy saving of approximately 20% was achieved when summing up the total annual consumption.

The *EnergyPlus* model constructed was based on the research done by Patrício et al. 2023.

6.3 Financial and economic analysis

In this subsection, the financial and economic analysis of the presented problem will be discussed. To ensure a comprehensive evaluation, a set of assumptions will be considered, aiming to characterise the problem effectively. Additionally, the methodology's financial indicators will be employed.

The assumptions under consideration, to best describe this particular problem, are described in the methodology chapter, taking this into account as well as the economic indicators the following valuation was created.

6.3.1 Financial analysis

The cost saved by the conclusion of the operational period, representing the expense of the energy that was not purchased from the electrical grid, measured in euros per liter:

$$Ce = \Delta Ev \cdot Te \cdot Y \cdot N \tag{6.1}$$

The subsequent factors are described as follows:

- The storage capacity of $\Delta Ev = 213.3 - 1.43 = 211.87\ kJ/L$, provided by the PCM, or 0.0588 kWh/L (this values can be found on the methodology chapter);
- N, denoting the count of annual cycles the system undergoes (namely, the cycles involving heating and cooling of the PCM);
- Y, indicating the duration of operation for the PCM, excluding any replenishment, extending to at least the specified investment horizon.

Substituting the values of ΔEv and Te on the equation 6.1 will result in

$$Ce = 0.0588 \cdot 0.19 \cdot Y \cdot N \leftrightarrow Ce = 0.0112 \cdot Y \cdot N$$

This expression will help identify the necessary conditions to make the investment feasible, by correlating the years of operation with the cycles of heating and cooling of the PCM.

In a financial assessment, for the viability of PCM, it is essential to confirm the condition $Ce < C_{PCM}$. The relationship between Ce, Y, and N is illustrated in 6.6. Values below the designated C_{PCM}, specifically 80.00 €/L, are therefore considered feasible.

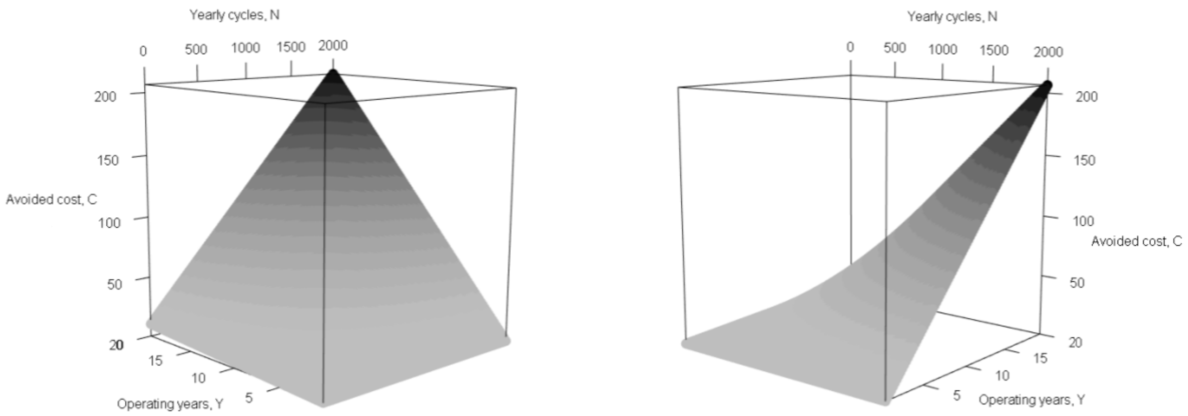


Figure 6.4: The relationship between the overall saved expenses linked to the incorporation of Phase Change Material (PCM), denoted as Ce, and the quantity of initial charge and discharge cycles, represented as N, along with the duration of operation, denoted as Y. In this particular instance, figures below 80 euros per liter are considered feasible.

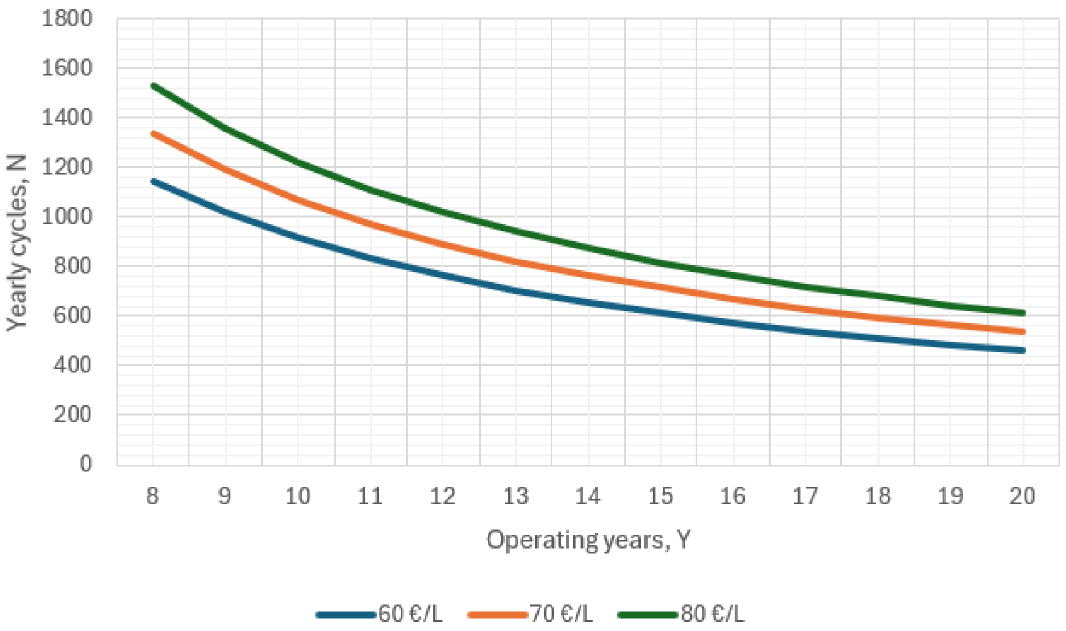


Figure 6.5: The outcomes of the sensitivity analysis for the avoided cost (Ce) concerning the cost of the PCM (C_{PCM}).

To illustrate, when evaluating 15 years of operation, the economic feasibility of the concept is established for a minimum of approximately 800, 650, and 600 annual charge and discharge cycles. These quantities correspond to PCM costs of 80, 70, and 60 euros per litre, respectively.

This analysis was based on the study conducted by Simão et al. 2022.

The main points that can be derived from this financial analysis are the aspects that need to be considered when evaluating the possibility of investing in Phase Change Materials for a specific application.

Through the examination of the graphs, an investment in which PCMs are placed under conditions where there is already temperature stability from the outset will not lead to a recovery of the investment. This is because such conditions correspond to very low yearly cycles. A well-thought-out investment must consider the intended use of the PCM, the conditions under which it will be utilized to optimise the investment, and obviously, the price that will be paid for each PCM.

Further, in the economic analysis, the importance of the energy density that a PCM can store will also be demonstrated in influencing the investment. A meticulous selection of its characteristics and price will impact the payback period of the investment.

6.3.2 Economic analysis

The indicators mentioned in the methodology chapter, namely the Net Present Value (NPV) and the Internal Rate of Return (IRR), will be utilised in the economic analysis.

Two separate investment scenarios will be assumed in this analysis. Consequently, it will be possible to observe the effects of the choice of PCM and its characteristics on the investment, which may prove to be more advantageous or ultimately result in a much swifter return on investment, when certain characteristics are taken into account in the selection of materials to be purchased.

For the first scenario the following assumptions were considered:

- C_{PCM} = 33 € per plate;
- $Y = 17$, which refers to operating years;
- Discount rate, $r = 6\%$
- $Te = 0.19$ €$/kWh$;
- PCM used for this example has an energy storage density of 288 kJ/L.

Given the results obtained from the computational simulations, it is possible to construct the accumulated cash flows graph, which facilitates the estimation of the investment payback period.

- The consumption of energy using PCM was 1691.44 kWh/year;
- The consumption of energy without using PCM was 2171.12 kWh/year;
- Each PCM has an area of 0.1723 m2;

Estimating a suitable payback period is difficult given the specific conditions of the study. The room where measurements were taken is small but has tall walls, requiring only one air conditioning unit but many PCM to insulate the walls. The use of a single portable air conditioning unit would significantly delay the return on investment. Therefore, the following assumptions were made:

- The area of the new room will be three times bigger, which will be 26.88 m2;
- Each wall has a new length of 5.18 m, but the 3-meter tall remains;
- Each wall will need $\frac{5.18\times3}{0.1723}$ = 90 plates;
- Will use three portable air conditioning units;
- It is assumed that the energy savings achieved from using one air conditioning unit apply to three units, that is, $479.68kWh \times 3$ = 1439.04 kWh.
- The new cash flow will be $1439.04kWh \times 0.19$ €/kwh = 273.42 €/year

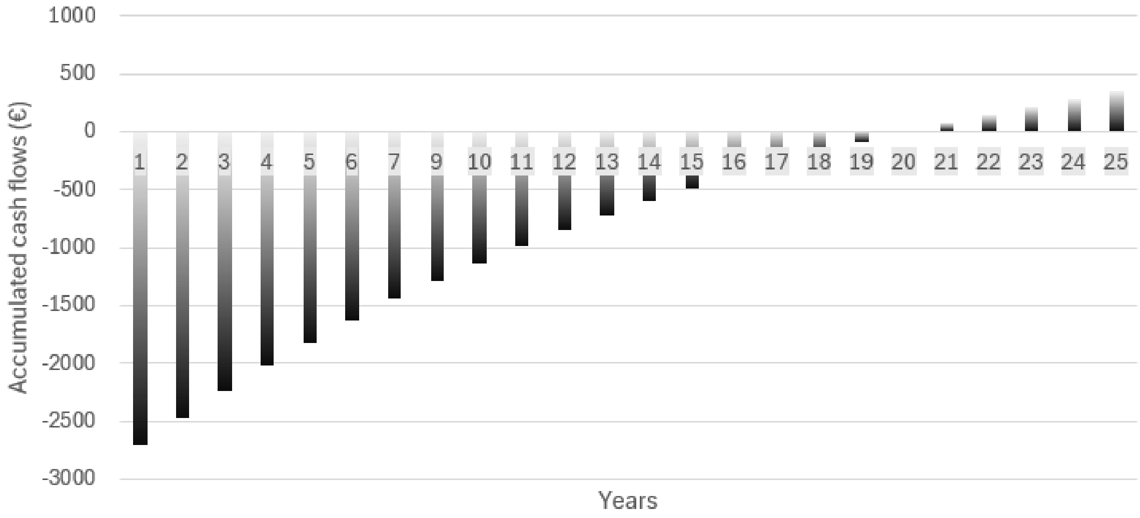


Figure 6.6: Total cash inflows, taking into account their NPV. The break-even point is reached in the 20th year when the values turn positive.

The primary conclusions drawn from this economic analysis highlight the influence of specific characteristics of the chosen PCM on the profitability of the project. In this case, it is evident that the energy density values associated with each PCM significantly impact the outcome.

As previously explained in the economic analysis, it is imperative to take into account the specific location where PCM installation will be implemented. Indeed, in a setting characterized by minimal air conditioning energy consumption, even with a reduction in energy consumption, the resultant savings may not be substantial enough to justify the cost of applying PCM to the walls. Consequently, it is crucial to assess the prevailing climate control energy demands within that particular space before any investment.

Given this understanding, the optimal course of action would be to select a PCM with a high energy density. Assuming that electricity prices will continue to rise, opting for a PCM with a high energy density is likely to result in a rapid return on investment. Additionally, when purchasing the PCM, attention should be paid to the price per litre. Buying in larger quantities may lead to a reduction in this cost, consequently translating into an even quicker return on investment.

When contemplated over the long term, any investment will eventually yield a return on the invested capital. However, for shorter operational periods, it is essential to conduct a thorough analysis and make well-considered choices based on the specific characteristics and needs of each project. This approach is crucial to avoid financial losses resulting from the improper allocation of resources. A careful consideration of relevant variables and a decision aligned with the project's objectives are fundamental to ensure efficiency and profitability during shorter operational periods.

7

CONCLUSION AND FUTURE WORK

Taking into account the results achieved in this work, it is possible to draw a series of conclusions. This chapter will address the positive and negative points of the approach developed throughout this thesis. It is also important to discuss what could be improved in future work and how this idea can be introduced into HSLB, in a practical and financially advantageous way.

Not everything went well during the data collection for this work, in addition to the human interference previously explained, due to some complications with moving and assembling the equipment, the sensors should have collected more data over at least a year. Only in this way would it be possible to understand the impact of PCM throughout all seasons of the year. This being said, the first thing that should be done in future work, is to assess the performance of the PCM for an entire year. With this data will be possible to construct more rigorous financial and economic analyses and study the differences in terms of electricity consumptions that would come from this application.

From an academic point of view, where a smaller project can be developed, a continuation of this project would be, firstly, to obtain more stable values and develop a structure in which there is more protection of the T&H sensor. This can be achieved, if possible, by introducing PCM inside the walls of the room where data will be collected. It would also be necessary to place sensors inside the walls, this way it will be possible to observe a greater discrepancy with the ambient temperature sensor, which ended up not happening in this project.

This is relatively important because it is these discrepancies in terms of temperature between sensors that made it possible to understand whether the introduction of PCM in the wine cellar will result in less energy consumption by the AC units, and consequently, financial savings.

If it is not possible to insert materials within the walls or conduct any form of practical investigation on the estate, another option would be to undertake an investigation solely based on the study of energy performance utilizing *EnergyPlus*.

Throughout this thesis, the limitations of the model created for this work have been exposed. A project encompassing all the characteristics of the estate, including additional rooms and introducing more variables into the model, would enable the development of a considerably rigorous model, facilitating the acquisition of exact data regarding the actual occurrences at HSLB. Simulating the entire estate would also allow for the identification of optimal applications for PCMs, which could prove beneficial in areas beyond the winery.

If an administrative decision is made to purchase and install PCM in the cellar where maturation takes place, it would be interesting to closely monitor the differences in terms of electricity consumption used in the acclimatisation of this space, conclusions will be easily drawn about the advantages of using PCM in the wine cellar. This can be achieved by placing an energy analyser on the electric switchboard that feeds the AC units.

Using this information would allow the evaluation of the installation of this type of materials in the other areas of the estate.

In conclusion, based on this study and considering the results obtained, it is possible to assert that PCMs would have a positive impact on HSLB. The data collected from sensors indicate that PCMs contribute to stabilizing temperature values, resulting in fewer daily fluctuations and reducing the maximum temperatures recorded during the summer.

Based on the computational results, it is possible to corroborate the findings obtained through practical experimentation. Graphs generated from the computational data illustrate that PCMs contribute to stabilizing temperature, thereby alleviating the necessity for the air conditioning system to counteract temperature fluctuations throughout the month, ultimately resulting in reduced energy consumption.

Furthermore, it was observed that PCMs exhibited superior performance during the summer months, effectively mitigating temperature towards values closer to the reference temperature of 18°C. In contrast, the performance during winter was not as optimal, potentially due to certain limitations of computer model, as discussed in Chapter 6. An approximate 20% reduction in annual energy consumption was achieved with the use of PCMs.

From the financial and economic analysis, it became apparent that the primary factors to consider when evaluating a project involving PCMs are: the price paid for PCM, the anticipated utilization of each unit, its energy density and the potential time for return on investment. Its also necessary to consider the energy usage for acclimatization in the location that will receive the PCMs, a room with little to no use of energy to acclimatize will obviously not generate savings to compensate the investment. Regardless of these factors, with a well-executed investment plan, it is feasible to achieve a return on investment within approximately 15-20 years.

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I

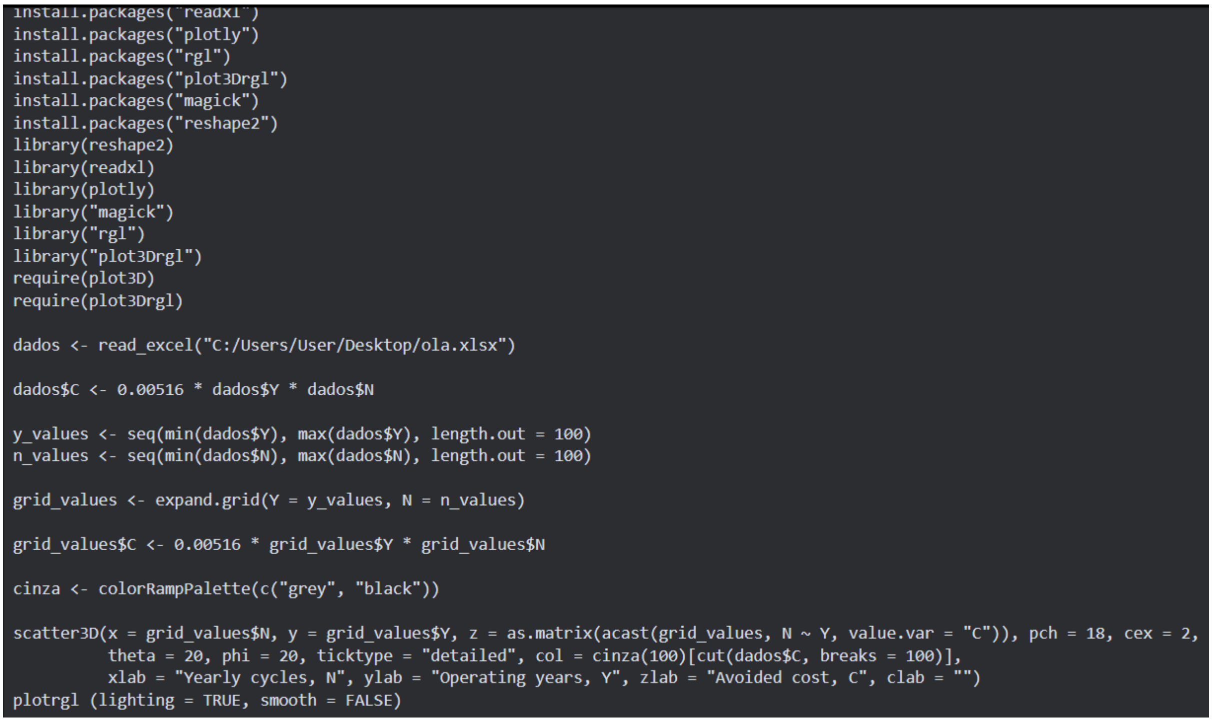
ANEX

```
#include <SD.h>
#include <Wire.h>
#include <RTClib.h>
#include <DHT.h>

#define DHTPIN 2 // DHT11 sensor connected to pin 2
#define DHTTYPE DHT11 // DHT11 sensor type
#define CS_PIN 4 // CS pin of the SD card module
#define FILENAME "data.txt" // filename for saving data

DHT dht(DHTPIN, DHTTYPE);
RTC_DS1307 rtc;

void setup() {
  Serial.begin(9600);
  while (!Serial) {}

  if (!SD.begin(CS_PIN)) {
    Serial.println("SD card initialization failed!");
    return;
  }

  if (!rtc.begin()) {
    Serial.println("RTC initialization failed!");
    return;
  }

  if (!rtc.isrunning()) {
    Serial.println("RTC is not running, set the time first!");
    //rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
    return;
  }

  dht.begin();
}
```

```
void loop() {
  float temperature = dht.readTemperature();
  float humidity = dht.readHumidity();
  DateTime now = rtc.now();

  if (isnan(temperature) || isnan(humidity)) {
    Serial.println("Failed to read from DHT sensor!");
  } else {
    // check if it's been 1 hour since the last reading
    static uint32_t lastReading = 0;
    if (millis() - lastReading >= 3600000) {
      lastReading = millis();

      File dataFile = SD.open(FILENAME, FILE_WRITE);
      if (dataFile) {
        dataFile.print(now.year(), DEC);
        dataFile.print('/');
        dataFile.print(now.month(), DEC);
        dataFile.print('/');
        dataFile.print(now.day(), DEC);
        dataFile.print(' ');
        dataFile.print(now.hour(), DEC);
        dataFile.print(':');
        dataFile.print(now.minute(), DEC);
        dataFile.print(':');
        dataFile.print(now.second(), DEC);
        dataFile.print(',');
        dataFile.print(temperature);
        dataFile.print(',');
        dataFile.println(humidity);
        dataFile.close();
        Serial.println("Data saved to SD card!");
      } else {
        Serial.println("Error opening data file!");
      }
```

```
    }
  }

  delay(1000); // wait for 1 second before reading again
}
```

Figure I.1: Code used for the sensors of temperature and humidity



```
install.packages("readxl")
install.packages("plotly")
install.packages("rgl")
install.packages("plot3Drgl")
install.packages("magick")
install.packages("reshape2")
library(reshape2)
library(readxl)
library(plotly)
library("magick")
library("rgl")
library("plot3Drgl")
require(plot3D)
require(plot3Drgl)

dados <- read_excel("C:/Users/User/Desktop/ola.xlsx")

dados$C <- 0.00516 * dados$Y * dados$N

y_values <- seq(min(dados$Y), max(dados$Y), length.out = 100)
n_values <- seq(min(dados$N), max(dados$N), length.out = 100)

grid_values <- expand.grid(Y = y_values, N = n_values)

grid_values$C <- 0.00516 * grid_values$Y * grid_values$N

cinza <- colorRampPalette(c("grey", "black"))

scatter3D(x = grid_values$N, y = grid_values$Y, z = as.matrix(acast(grid_values, N ~ Y, value.var = "C")), pch = 18, cex = 2,
          theta = 20, phi = 20, ticktype = "detailed", col = cinza(100)[cut(dados$C, breaks = 100)],
          xlab = "Yearly cycles, N", ylab = "Operating years, Y", zlab = "Avoided cost, C", clab = "")
plotrgl (lighting = TRUE, smooth = FALSE)
```

Figure I.2: Code used in R for the financial analysis

I.1 Graphs for year-round computer simulations

I.1.1 Temperature simulation

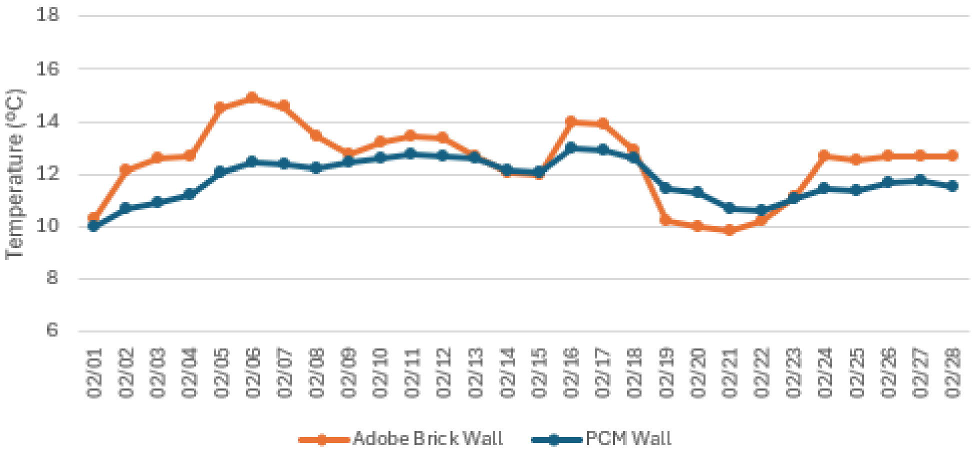


Figure I.3: Temperature variations for the walls covered with and without PCM in February.

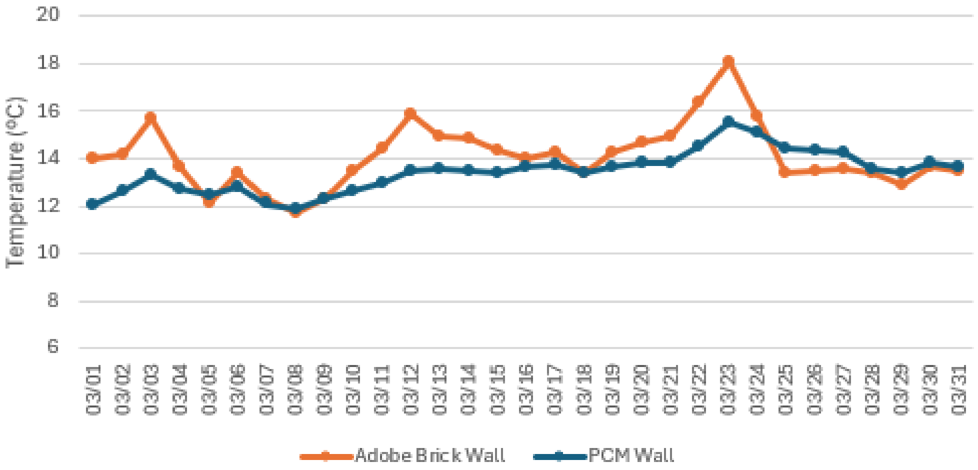


Figure I.4: Temperature variations for the walls covered with and without PCM in March.

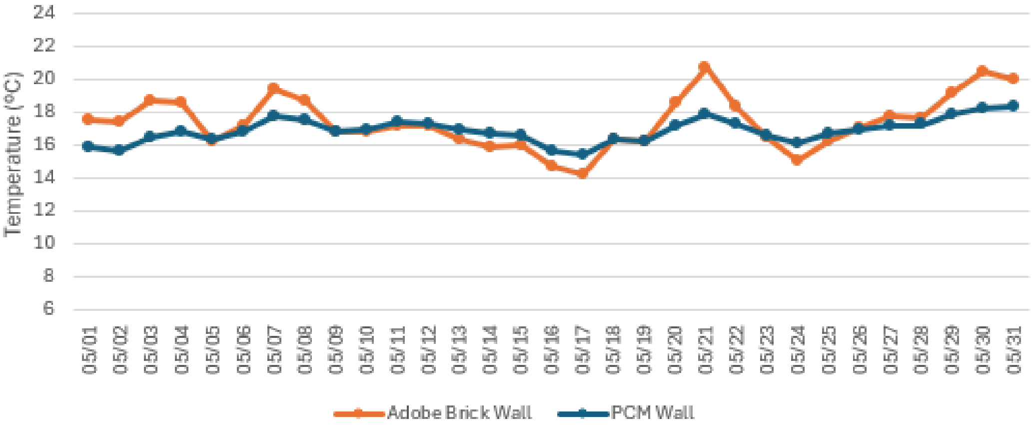


Figure I.5: Temperature variations for the walls covered with and without PCM in May.

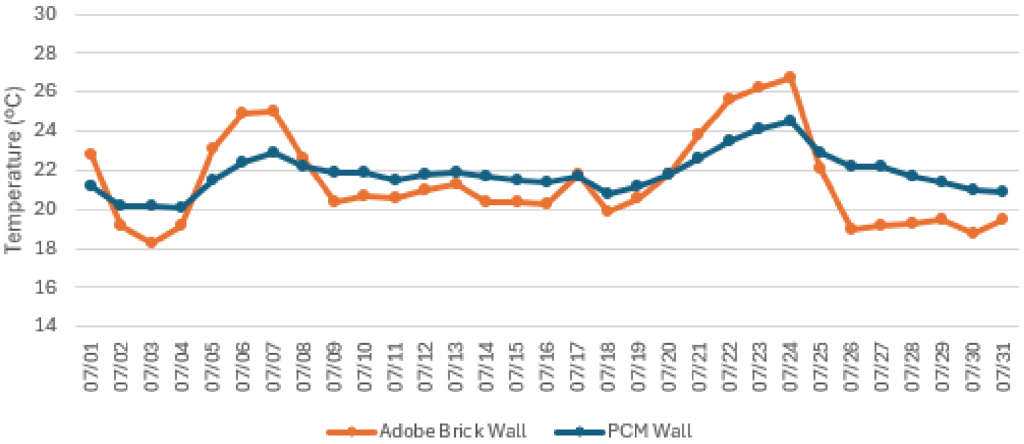


Figure I.6: Temperature variations for the walls covered with and without PCM in July.

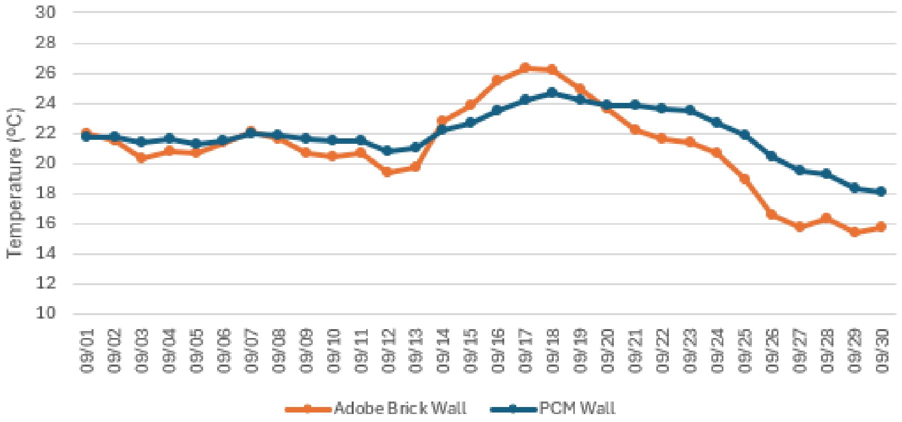


Figure I.7: Temperature variations for the walls covered with and without PCM in September.

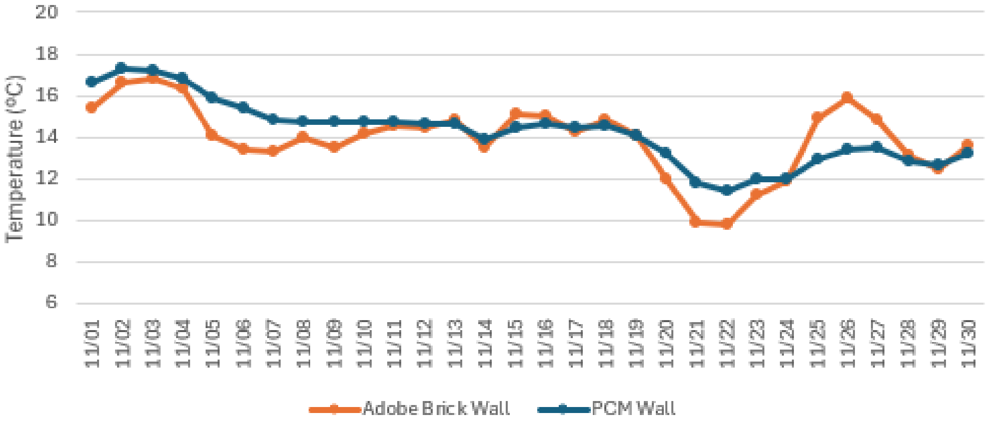


Figure I.8: Temperature variations for the walls covered with and without PCM in November.

I.1.2 Energy consumption

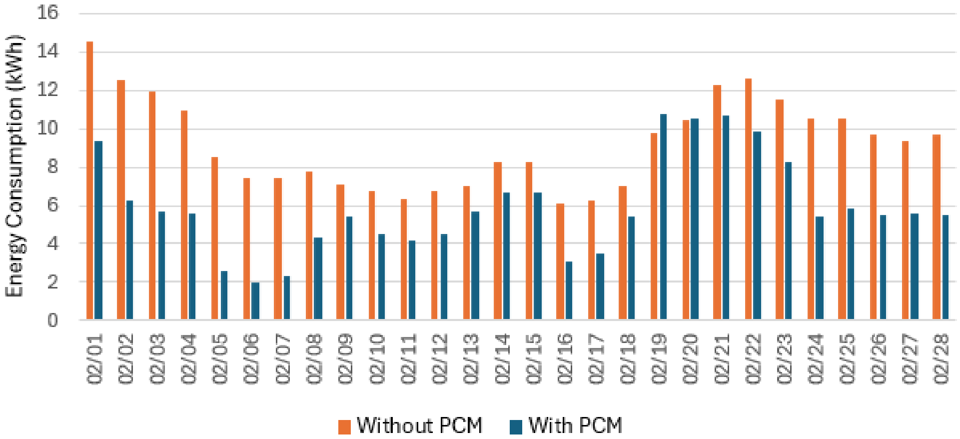


Figure I.9: Energy consumption variations for the walls covered with and without PCM in February.

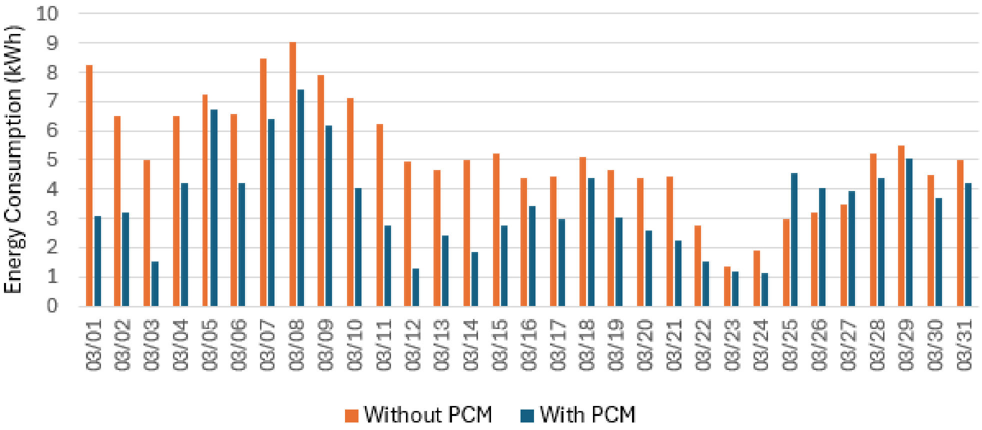


Figure I.10: Energy consumption variations for the walls covered with and without PCM in March.

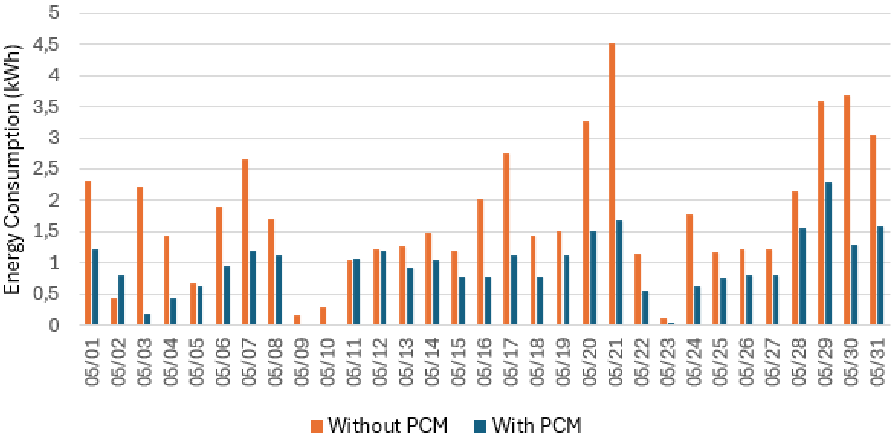


Figure I.11: Energy consumption variations for the walls covered with and without PCM in May.

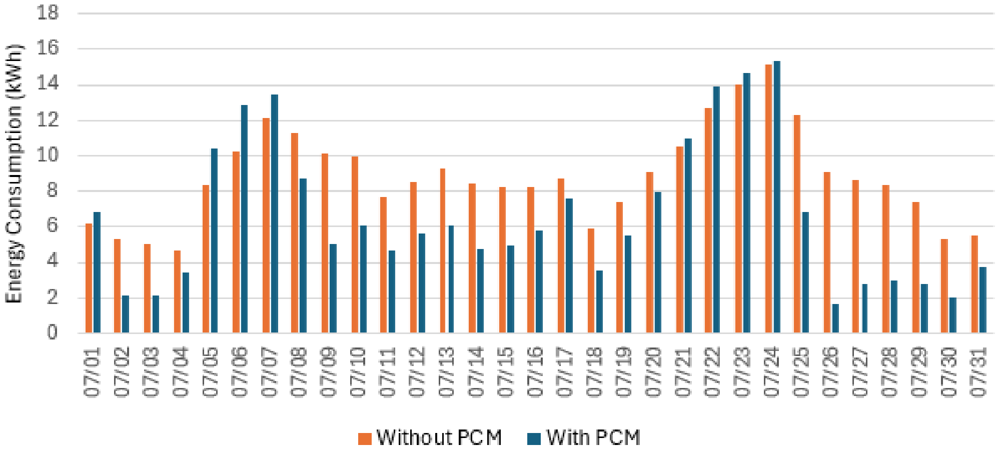


Figure I.12: Energy consumption variations for the walls covered with and without PCM in July.

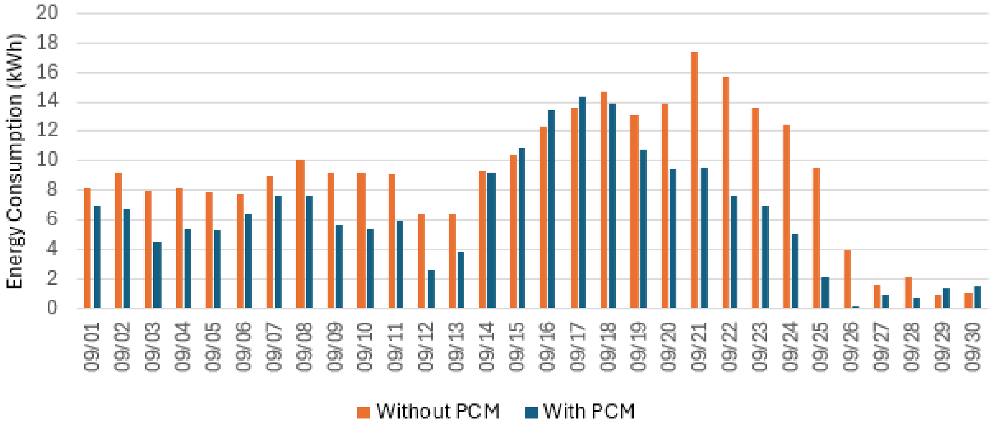


Figure I.13: Energy consumption variations for the walls covered with and without PCM in September.

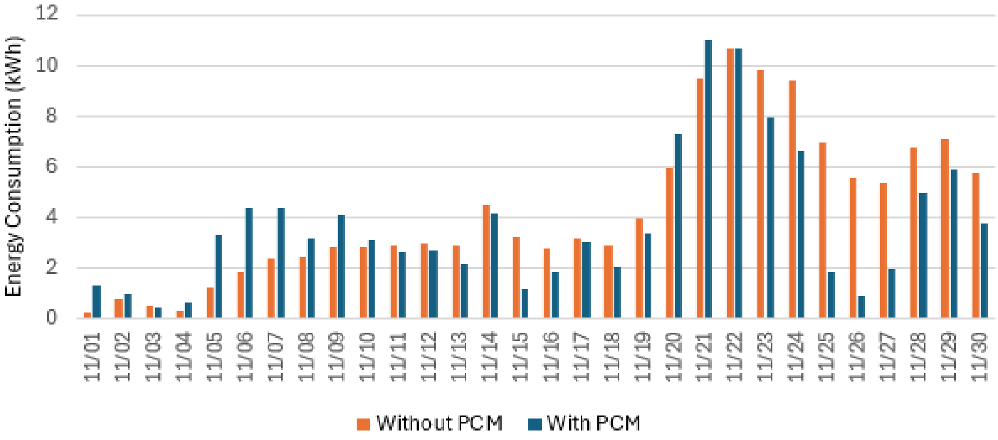


Figure I.14: Energy consumption variations for the walls covered with and without PCM in November.

2024 Improving Energy Efficiency in the Wine Sector by Thermal Energy Storage

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