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Enhancing Energy Efficiency in Mediterranean Large-Scale Buildings: A Study on Mobilized Thermal-Energy-Storage Systems

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Abstract: This study investigates the use of Mobilized Thermal Energy Storage (MTES) systems to enhance energy efficiency in large-scale Mediterranean buildings, focusing on a university campus in Tripoli, Lebanon. The research question addresses whether MTES can effectively utilize waste heat from a power plant to meet heating, cooling, and water heating needs. We hypothesize that MTES, using Erythritol as the phase change material (PCM) and Therminol55 as the heat transfer fluid (HTF), will improve energy efficiency and reduce costs compared to conventional systems. The methodology involves simulating the MTES system's performance, including charge, self-discharge, and discharge phases, using Simulink-MATLAB. Key findings reveal that increasing the HTF flow reduces the charging time by 29% and enhances the efficiency by 8%, while larger project scales decrease heat costs. Economic analysis shows a payback period (PBP) of 2 years 11 months for heating only and 2 years 1 month for heating and cooling, with annual maintenance costs considered at 5%. These results demonstrate MTES as a sustainable and cost-effective solution for thermal energy storage, with potential applications in the energy sector.

Keywords: phase change materials; mobilized thermal energy storage; economic analysis; efficiency improvement

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1. Introduction

In parallel with the exponential growth of the world's population, global energy consumption has dramatically increased. A recent study conducted by British Petroleum projects the global consumption of oil to rise by approximately 30% from 2007 to 2035, whereas natural gas and coal consumption are expected to increase by more than 50% [1]. This increasing energy demand places pressure on fossil fuel resources and amplifies concerns about greenhouse gas emissions. Within this global context, the building sector emerges as a principal factor for carbon emissions and energy consumption, accounting for as much as 40% of global energy usage in certain industrialized nations and emitting a parallel 40% of global greenhouse gas emissions [2,3]. About 33% of the consumed energy by various sectors is dissipated as waste heat, remaining largely unused and wasted [4,5].

In response to this energy challenge and the consequential heat waste, the technology of Thermal Energy Storage (TES) has been implemented within a mobile concept known as MTES. This system stores the waste heat generated by industries, such as power plants, cement and steel mills, and sewage sludge incinerators [6–8]. The stored heat is retained within specially designed containers and then transferred to provide end-users with space and water heating [9,10]. The MTES is enhanced by the utilization of PCMs, which have a high potential to release or store thermal energy as latent heat, differentiating them from the materials used in conventional sensible heat-storage systems [11–14].

The adoption of MTES in providing heat has several benefits, such as a decrease in primary energy consumption, the minimization of exergy losses, and a reduction in CO_2 emissions by as much as 95% relative to traditional fossil fuel-based heating systems [15,16]. While research has been conducted on MTES technology over the years, the focus of these studies has been on the selection of storage materials, container design, and economic studies. Prominent PCM options in MTES projects include organic sugar alcohols, like Erythritol and Mannitol, as well as inorganic hydrated salts, like sodium acetate trihydrate and magnesium chloride hexahydrate [17–24].

Various designs of MTES containers have been developed and evaluated to optimize performance during both charging and discharging phases, with different configurations, such as detachable, sorptive, direct-contact, encapsulated, and shell-and-tube containers [25]. Economic evaluations of the MTES system have shown that crucial factors governing cost include both the distance between the heat source and the end-user, with findings highlighting that the heating cost is directly related to the transport distance, while inversely related to the heat demand [25]. Furthermore, sensitivity analyses show that the pricing of phase change materials affects the overall cost of heating [26].

While MTES technology has found successful applications in industrialized nations, such as Japan, Germany, and China [6,26,27], it holds considerable promise for third-world countries, like Lebanon. These countries import fuel to meet their energy requirements; thus, the implementation of MTES will contribute to lowering fuel usage to cover heating and cooling demands, as well as valorize waste heat, contributing to a sustainable and energy-efficient future. Recent studies have highlighted the critical role of energy efficiency in achieving net-zero emissions and combating climate change. For instance, the World Renewable Energy Congress Med Green Forum 2024 emphasized the importance of integrating renewable energy applications in the Mediterranean region to create carbon-neutral cities [28]. Additionally, a comprehensive review published in 2024 discussed innovative technologies and strategic measures for advancing energy efficiency, underscoring the need for tailored policies and greater consumer engagement [29]. These findings underscore the significance of our study, which explores the potential of Mobilized Thermal Energy Storage (MTES) systems to enhance energy efficiency in Mediterranean buildings. By leveraging waste heat from power plants, our research aims to contribute to the broader goal of sustainable energy solutions in the region.

This study presents a novel approach to enhancing energy efficiency in large-scale Mediterranean buildings through the use of Mobilized Thermal Energy Storage (MTES) systems. Unlike previous research, which primarily focused on small-scale applications or single aspects of thermal energy storage, our study comprehensively evaluates the integration of waste heat from power plants with MTES to meet diverse energy needs, including heating, cooling, and water heating. By employing Erythritol as the phase change material (PCM) and Therminol55 as the heat transfer fluid (HTF), we demonstrate significant improvements in system efficiency and cost-effectiveness. Our findings provide valuable insights into the practical implementation of MTES in large-scale projects, contributing to the broader goal of sustainable energy solutions in the Mediterranean region. Our case study will investigate the modeling, simulation, and economic evaluation of the MTES project. The findings will provide valuable results that can be compared with existing studies on an economic basis.

2. Case Study Description

In this study, we utilize waste heat from a Lebanese power plant (PP) to cover heating, cooling, and domestic hot water needs in a university campus located in Tripoli. The PP comprises three fired boilers. The largest Lebanese university campus, which consists of 32 buildings covering 500,000 m^2, is the recipient of this waste heat. Previously, the campus used chiller units for cooling and oil boilers for heating. For the MTES cycle, it involves heat exchange between the industrial waste heat (IWH) and a heat transfer fluid (HTF) as a first phase. The HTF, in turn, transfers heat to Phase Change Material (PCM) within a container until it is fully charged. The container is then transported to the campus, where the PCM releases heat to the circulating water for space heating, absorption chillers for cooling, and water heating. After full container heat discharge, the container returns to the heat source to initiate a new cycle. The M-TES cycle is presented in Figure 1.

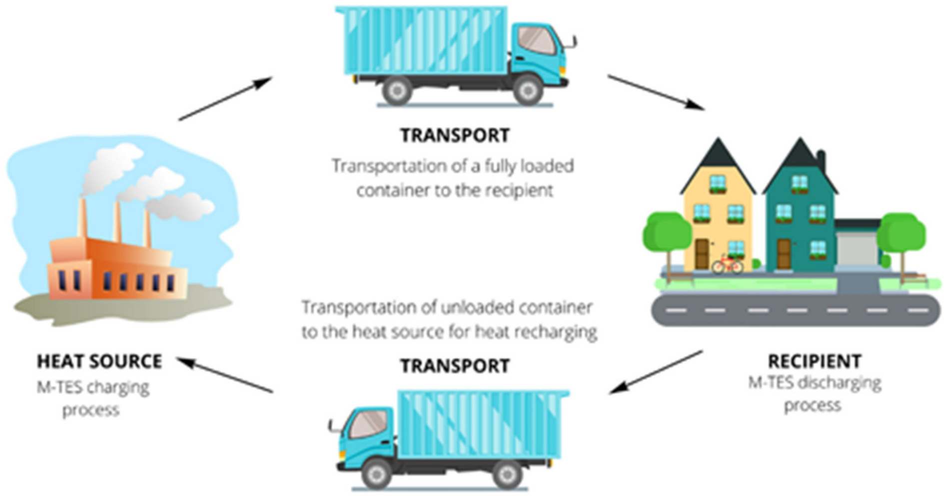

Figure 1. M-TES cycle [30].

Over the course of a year, PP's exhaust gas temperatures range from 134 °C to 176 °C, with an average of 149 °C, and the PP remains off for around 45 h annually. The IWH's annual potential and flow characteristics based on Lebanese thermal power plant data are detailed in Table 1.

Table 1. IWH potential, flow rates, and annual energy losses.

Industrial Waste Heat	Minimum	Maximum	Average Value	Energy Loss (MWh/Year)
Capacity (MW)	0.798	21.35	10.385	90,778.75
Flow rate (kg/s)	19.11	158.54	100.72	

Simultaneously, the university campus load (MW) varies annually. The energy requirements for the considered reference year are stated in Table 2. Specific operating temperature criteria are adhered to, where the radiator water should exceed 65 °C for winter heating [31] and chiller water should surpass 70 °C for summer cooling [32].

Table 2. University yearly energy requirements.

	Space Cooling	Space Heating	Water Heating	Total
Yearly used Energy (MWh)	11,794	10,833	1273	23,900

To achieve effective heat transfer from the industrial waste heat to the PCM and subsequently release it at the university to cover the energy loads, we employ Erythritol as the PCM due to its melting point temperature (118 °C) falling within the required temperature range (between 90 °C and 125 °C), in addition to its high latent heat of 339 kJ/kg and favorable cost-effectiveness. Compared to other PCMs, such as sodium acetate trihydrate (melting point of 58 °C, which is outside the required temperature range for our application), quinone (melting point of 115 °C, but lower latent heat compared to Erythritol, making it less efficient for thermal storage), and mannitol (melting point of 166 °C, which is higher than the required range, and having a lower latent heat compared to Erythritol), Erythritol provides an optimal balance of the melting point, latent heat, and cost-effectiveness [33–37]. Different candidates for the recovery of industrial waste heat (IWH) were evaluated based on their phase transition temperatures and latent heats. Benzamide has a phase transition temperature of 127 °C and a latent heat of 170 kJ/kg, while Stibene transitions at 124 °C with a latent heat of 167 kJ/kg. Benzoic acid transitions at 122 °C with a latent heat of 143 kJ/kg. Succinic anhydride and acetanilide both transition at 119 °C, with latent heats of 204 kJ/kg and 222 kJ/kg, respectively. $MgCl{\cdot}6H_2O$ transitions at 117 °C with a latent heat of 168 kJ/kg. Quinone transitions at 115 °C with a latent heat of 171 kJ/kg. Catechol transitions at 104 °C with a latent heat of 207 kJ/kg [15]. Among these, Erythritol is identified as the optimal PCM for this study due to its high latent heat and suitable phase transition temperature.

The selected HTF is Therminol55, characterized by a high flash point of 117 °C and a boiling temperature of 351 °C, ensuring safety and efficiency in heat transfer. Compared to other HTFs like Dowtherm A (similar properties but higher cost) and Syltherm 800 (lower boiling point, which could limit its effectiveness in high-temperature applications), Therminol55 offers superior thermal stability and cost-effectiveness [38,39]. Future work will include further comparative studies with other PCMs and HTFs to continuously optimize the system's performance. The key physical properties of Erythritol and Therminol55 are presented in Table 3.

Table 3. Thermo-physical properties of selected PCM and HTF at different operating temperatures [33–35,38,39].

Item	T (°C)	Density (kg/m³)	Cp (kJ/kg·K)	Thermal Conductivity (W/m·K)	Latent Heat (kJ/kg)	Melting Point (°C)	Flash Point (°C)	Boiling Temperature (°C)	Viscosity (kg/m·s)	Dynamic Viscosity (MPa·s)
Erythritol	20	1480	1.35	0.732	339	118	-	-	0.02895	-
(PCM)	140	1300	2.74	0.326			-	-	0.01602	-
Therminol55	33	865	1.94	0.1273	-	-	177	351	-	25.2
(HTF)	130	797	2.3	0.1156	-	-			-	1.71

3. Modeling and Simulation

The university's energy requirements are met by valorizing IWH. A series of heat exchangers is positioned between the waste heat source and the load that must be used to transfer the heat from the PP to the university:

- Exhaust Heat Recovery Exchanger: The exhaust gas energy is transferred to the HTF, where three counter-flow heat exchangers are used with exhaust gases for a mean power of 10.38 MW.
- Thermal Storage Exchanger: The HTF energy is transferred to the PCM, designed as a 20-foot ISO shell-and-tube container featuring encapsulated phase change material within the tubes, while the heat transfer fluid circulates around the shell side. This configuration enhances the heat exchange efficiency by providing a larger surface area for heat transfer. In addition, aluminum is known for its high thermal conductivity, which enhances the heat transfer efficiency between the heat transfer fluid (HTF) and

the phase change material (PCM). The staggered arrangement of the tubes increases the surface area for heat exchange, allowing for more effective and uniform heat distribution. This configuration minimizes thermal resistance and maximizes the rate of heat transfer, leading to faster charging and discharging cycles. Additionally, aluminum is lightweight and relatively low-cost compared to other high-conductivity materials, making it an economically viable choice. The combination of these factors results in improved system performance and reduced operational costs, thereby enhancing the overall cost-effectiveness of the MTES system. Therefore, staggered aluminum tubes are chosen due to their high conductivity, light weight, and low cost [40,41].

- Heat Distribution Exchangers: The phase change material (PCM) transfers its energy to the water circulating throughout the university. To facilitate this process, two counter-flow tubular heat exchangers, one for heating and one for cooling, are used.

Once the heat exchangers are designed, simulations involve three stages: charging, self-discharging, and discharging of the PCM, carried out on Simulink-MATLAB R2024-b. The simulation tracked the changes in the temperature of the PCM, the temperature of the oil tank, and the flow rate of the oil. First, the PCM temperature increases exponentially as it stores sensible heat, gradually reaching its melting temperature. After this, the PCM starts accumulating latent heat until it transitions to the liquid state and reaches the saturation phase. Following this saturation phase, the PCM resumes absorbing sensible heat until it reaches a temperature of 130 °C, marking the completion of the charging process. As the temperature of the oil tank rises, the flow of oil increases to recover heat more effectively from the Exhaust Heat Recovery Exchanger up to the peak flow setpoint, and the temperature of the oil tank rises as the temperature of the oil exiting the container increases, which is caused by the rise in PCM temperature.

In this simulation, the initial PCM temperature is set at 20 °C, with HTF flow rates ranging from 100 kg/s to 201.4 kg/s. The IWH potential was varied between 0.798 MW and 21.354 MW. The thermal properties of Erythritol and Therminol55, such as the thermal conductivity and specific heat capacity, were sourced from the relevant literature [33–39]. We assumed steady-state conditions and a uniform temperature distribution within the PCM and HTF. These assumptions were made to simplify the model while maintaining relevance to real-world applications. Sensitivity analyses showed that increasing the HTF flow rate decreased the charging duration by 29% and increased the efficiency by 8%.

In this study, we investigated the impact of oil flow and the impact of the potential of IWH on the duration and efficiency of the charging process through simulations. By increasing the max oil flow setpoint and varying the IWH potential, we observed changes in these parameters. The results, summarized in Table 4, show that doubling the max oil flow setpoint led to a 29% decrease in the charging duration and an 8% rise in the charging efficiency. Furthermore, adjustments in the IWH potential showed varying effects: maximizing it resulted in a slight 3.65% decrease in the charging time but a substantial drop in efficiency from 20% to 9.9%. Conversely, minimizing the IWH potential increased the efficiency by 63% but at the expense of a 212.5% increase in the charging time. These findings show the importance of oil flow regulation, particularly when adjusting the IWH potential, for managing charging efficiency effectively. Furthermore, these trade-offs highlight the importance of balancing the IWH potential to achieve an optimal combination of the charging time and efficiency for the MTES system. This balance ensures that the system operates effectively while maintaining cost-effectiveness and energy efficiency. Also, variations in the IWH potential had a significant impact on the charging efficiency, highlighting the importance of optimizing these parameters for practical implementation.

Table 4. Simulation outcomes for charge phase with varying oil flows and IWH potentials.

Industrial Waste Heat (MW)	Maximum Oil Flow (kg/s)	IWH Energy (MWh)	Oil Recovered Energy (MWh)	Recovery Efficiency (%)	Storage Efficiency (%)	Charging Efficiency (%)	Charging Duration (s)	Saturation Duartion (s)
10.38	100	35.11	7.942	22.58	88.79	20.05	12,193	5582
10.38	201.4	24.9	7.95	31.79	88.78	28.22	8664	3122
21.354	100	71.097	7.945	11.18	88.8	9.92	11,985	5378
0.798	100	8.45	7.94	94.04	88.8	83.5	38,110	27,050

Finally, the simulation was conducted by setting the mean potential power and maximum oil flow rate at 10.385 MW and 100 kg/s respectively, with the PCM temperature set initially at 20 °C.

During normal system operation, after discharge during the previous cycle, the PCM temperature settles between 80 °C and 95 °C, depending on the load demands. At the beginning of a new cycle, the charging phase begins at these temperatures. This initial temperature influences the subsequent charging phase, impacting the efficiency, PCM charging time, and capacity of the container. Table 5 outlines all the results.

Table 5. Charge phase simulation: mean IWH potential, 100 kg/s oil flow, and initial PCM temperature variations.

Initial PCM Temperature (°C)	Max Oil Flow (kg/s)	IWH Energy (MWh)	Energy Recovered by Oil (MWh)	Storage Efficiency (%)	Charging Efficiency (%)	Charging Duration (s)	Saturation Duration (s)
80	100	34.296	7.402	85.8	18.52	11,889	5371
95	100	34.057	7.252	84.89	18.08	11,806	5303

Following the charging phase, the capacity of the PCM undergoes self-discharging, and its capacity decreases due to heat conduction through the storage tank and container shells, as well as through convection with surrounding air. During transportation, forced convection accelerates this process, while during waiting periods before the discharge phase, natural convection takes over.

The container shell is constructed from steel [42], while fiber-reinforced plastic (FRP) is selected for the shell of the storage tank. To insulate the storage tank, it was surrounded by rockwool, with a 4 cm thickness. Table 6 states these materials' physical properties.

Table 6. Characteristics of rockwool, FRP, and carbon steel [43–45].

Material Type	Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Material Thickness (mm)	Material Density($kg \cdot m^{-3}$)
Carbon Steel	45	4	7500
Fiber Reinforced Plastic	0.57	4	1550
Rockwool	0.043	40	60

The simulation results illustrated in Figure 2, demonstrate a nearly linear decrease in the self-discharge phase in the temperature of the charged PCM from 130 °C to 129.59 °C over around 2.5 h. The simulation was conducted multiple times, each with varying rockwool thicknesses and with a duration of 1.5 and 2.5 h, as summarized in Table 7. The results show that 4 cm of rockwool is a good choice since it improves the insulation significantly as the energy losses decrease from 0.017 MWh to 0.0109 MWh, while by using a 5 cm thickness, it decreases only to 0.009 MWh, and PCM final temperatures are very close. Additionally, it is shown that each one-hour delay results in a 0.11% reduction in the PCM capacity as shown in Table 6 (0.15% loss for 1.5 h of self-discharge compared to 0.26% loss for 2.5 h of self-discharge for a rockwool thickness of 40 mm).

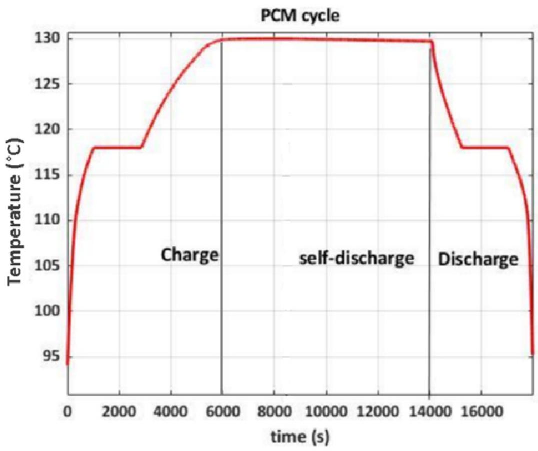

Figure 2. PCM cycle: charge, self-discharge, and discharge phases.

Table 7. Simulation results of self-discharge for various rockwool thicknesses.

	Self-Discharge Duration = 1 h 30 min			**Self-Discharge Duration = 2 h 30 min**		
Rockwool thickness (mm)	Energy loss (MWh)	Loss Percentage	Final PCM temperature (°C)	Energy loss (MWh)	Loss Percentage	Final PCM temperature (°C)
25	0.017	0.23%	129.64	0.026	0.37%	129.44
40	0.0109	0.15%	129.76	0.018	0.26%	129.59
50	0.009	0.13%	129.79	0.015	0.21%	129.67

The selection of 40 mm rockwool insulation for the MTES system is justified based on its optimal balance between the insulation efficiency and material cost. Our simulations demonstrated that 40 mm of rockwool significantly reduces energy losses and slows down the self-discharge rate of the PCM. Specifically, energy losses decrease from 0.017 MWh with a 25 mm thickness to 0.0109 MWh with a 40 mm thickness, while further increasing the thickness to 50 mm only marginally reduces the losses to 0.009 MWh. Additionally, the final PCM temperatures remain higher with 40 mm insulation, indicating better retention of thermal energy. This thickness provides substantial insulation benefits without incurring the higher costs associated with thicker insulation. Therefore, 40 mm rockwool is selected as it offers an effective and cost-efficient solution for maintaining the PCM's temperature and capacity during transportation and waiting periods, thereby enhancing the overall performance and cost-effectiveness of the MTES system.

After 2.5 h of PCM self-discharge, the discharge phase begins from a PCM temperature of 129.59 °C. For each load, the PCM discharge power is calculated resulting in a power of 7 MW. The simulation in Figure 2 shows that the PCM temperature decreases until it reaches 118 °C. At this point, the PCM undergoes a phase change, reaching a solid state after 2392 s. Following solidification, the PCM discharges sensible heat up to 95 °C, marking the end of the discharge phase.

4. Operating Strategy

Yang et al. [42] conducted a comprehensive study on mobilized thermal energy storage (MTES), focusing on three key areas: MTES design (including material selection—PCM: 99% pure erythritol and heat exchanger design—shell and tube type heat exchangers), environmental evaluation, and economic analysis. Their analysis, based on a case study in Sweden for a district heating network located 48 km from the heat source, examined three transportation alternatives: road, rail, and maritime. The authors optimized the operational strategy to maximize the project's economic viability and determined the proposed project to be feasible. Their model revealed a non-linearity in the loading and unloading process, with rapid rates up to 60% of the storage level, followed by an exponential decrease. To optimize cost-effectiveness, they recommended minimizing the number of runs and MTES units used. The study concluded that while district heating networks are more favorable for transporting large volumes of heat between fixed locations, MTES offers significant advantages in supply flexibility. One critical parameter identified was the rate of storage loading/unloading, which is particularly important for large heat loads. This insight justifies our selection of 9 and 12 containers to ensure efficient and flexible heat supply for the university campus.

Thus, to ensure a continuous strategy of operation, 9 containers are required for winter (with 3 containers discharging simultaneously) and 12 containers for summer (with 4 containers discharging simultaneously) to cover the university daily load requirements. Assuming an 80% average efficiency of the Heat Distribution Exchangers, the annual total cycles is determined by dividing the total discharged energy by the energy discharged per container, resulting in 4705 cycles.

Additionally, taking into account an additional useful energy amounting to 23,900 MWh annually for water heating, cooling, and space heating using the potential of fuel oil in the power plant, MTES improved the power plant efficiency by 0.98%, as shown in Table 8.

Table 8. Assessment of power plant Efficiency in different conditions.

Power Plant	Fuel Oil Capacity (MWh)	Annual Useful Energy (MWh)	Power Plant Efficiency
Without MTES	2,443,239	738,130	30.21%
With MTES		738,130 + 23,900	31.19%

5. Economic Analysis

In most studies involving MTES, the system typically focuses on covering water and space heating needs. To align the results of this research with other research, several economic evaluations are performed for different scenarios:

- Scenario 1: MTES solely provides water and space heating (requiring 6 or 9 containers).
- Scenario 2: MTES serving both cooling, water heating as well as space heating (requiring 9 or 12 containers).

For the economic assessment, the cost of the project is first calculated, then the operation cost, and savings. Table 9 outlines the project cost for all scenarios. Currently, the system relies on an oil boiler for space and water heating, along with electricity for the space cooling system. Implementing MTES will lead to savings in fuel and electricity consumption, as detailed in Table 10.

Costs of operation fluctuate with the annual number of cycles. In scenario 1, there are 2384 cycles annually, while scenario 2 involves 4705 cycles. The cost per cycle is estimated at 57.5 USD, based on feedback from a local transport company and the distance separating the PP from the university. These operation costs are summarized in Table 11.

Table 12 presents the annual maintenance costs considered as a constant 5% constant cost annually for the two scenarios of this study. For the scenario involving only space and water heating, the maintenance cost is estimated at 76,000 USD per year. For the scenario that includes space heating, cooling, and water heating, the maintenance cost increases to 99,500 USD per year. These costs have been factored into the economic analysis to provide a more comprehensive evaluation of the system's financial viability.

Table 9. Initial cost breakdown of scenarios 1 and 2.

Description	Unit Price [25,26]	Quantities Scenario 1	Quantities Scenario 2	Cost of Scenario 1 (USD)	Cost of Scenario 2 (USD)
Container	2500 $/container	6 or 9	12	15,000/22,500	30,000
Erythritol	3.5 $/kg	6 or 9 × 30,048 kg	12 × 30,048 kg	631,008/946,512	1,262,016
Aluminum tubes	2 $/kg	6 or 9 × 1080 × 3.2 m × 2.5 kg/m	12 × 1080 × 3.2 m × 2.5 kg/m	103,680/155,520	207,360
Therminol 55	3 $/kg	20,000 kg	20,000 kg	60,000	60,000
PRF	1510 $/ton	6 or 9 × 137.7 kg	12 × 137.7 kg	1247.5/1865.9	2488
Rockwool	1 $/m^2	6 or 9 × 67.23 m^2	12 × 67.23 m^2	403/605	807
Pumps and Heat Exchangers	1.33 $/kWh	14,100 kWh	14,100 kWh	18,753	18,753
Subtotal				830,000/1,206,000	1,580,000
Shipping charges				0.15	0.15
Value Added Tax				0.11	0.11
Grand Total				$1,060,000/1,520,000	$ 1,990,000

Table 10. Yearly savings for scenarios 1 and 2.

Description	Useful Annual Energy (MWh)	System Efficiency or COP	Annual Energy Saved (MWh)	Unit Price ($/kWh)	Total Savings ($/Year)
Water heating	1273	0.8	1591.25	0.05	79,562
Space heating	10,833	0.8	13,541.25	0.05	677,062
Space cooling	11,794	3.8	3104	0.18	558,720
Total (water and space heating)	12,106		15,132.5		756,624
Total (water and space heating/cooling)	23,900		18,502.5		1,315,344

Table 11. Operation costs of scenarios 1 and 2.

Case	Number of PCM Cycles/Years	Unit Price (USD/Cycle)	Operation Cost (USD/Year)
Space and water heating only (6 containers)	3575	57.5	205,562
Space and water heating only (9 containers)	2383	57.5	137,023
Space heating, cooling, and water heating	4705	57.5	270,538

Table 12. Maintenance costs of scenarios 1 and 2.

Case	Maintenance Cost (USD/Year)
Space and water heating only	76,000
Space heating, space cooling, and water heating	99,500

The economic analysis was performed under the assumption that both the container and PCM have a lifespan of 15 years, with the PCM costing 3.5 USD per kilogram, to facilitate a comparison with the findings of Li et al. [24]. This study focuses on a campus area of approximately 500,000 m^2, located about 23 km from the waste heat source. The outcomes of the economic analysis for both scenarios are detailed in Table 13.

Table 13. Financial analysis outcomes for scenarios 1 and 2.

Scenario	Payback Period (PBP)	Cooling/Heating Cost ($/kWh)
Space and water heating only (6 containers)	2 y 9 m	0.019
Space and water heating only (9 containers)	2 y 11 m	0.02
Space heating, cooling, and water heating	2 y 1 m	0.01

Previous studies, such as Li et al., have shown that as the area being served increases from 500 m^2 to 30,000 m^2, the heating cost (COH) decreases significantly, ranging from 0.12 $/kWh down to 0.04 $/kWh, for the same distance of 23 km [25]. Moreover, the time required to recoup the investment (PBP) in replacing an oil system with MTES reduces from 10.5 years when only two containers are used to meet the heat demand to approximately 2 years in our case with 12 containers used.

Given that the payback periods for Scenario 1 with 9 containers and 6 containers are nearly identical, we will focus on the 9 containers scenario in this study. This decision is based on the fact that the 6 containers scenario results in higher pollutant emissions. The same for scenario 2, we will focus on 12 containers scenario. The cost of providing 1 kWh of heat was determined by considering the capital cost, compound interest, and operation and maintenance (O and M) expenses [25]:

$$COH = \frac{m(C)(1+i)^n + COT}{Q \times A \times n \times 365} + COWH \text{ (USD/kWh)} \quad (1)$$

Here, m represents the number of M-TES systems, C denotes the capital cost in USD, which encompass the expenses for the container, PCM, HTF, HTF pump, and the charging station. The variable i stands for the compound interest set to 6%, and n signifies the system's lifetime in years, considering 15 years in this study; Q represents the annual heat demand per square meter of the building area (kWh/m^2·year). A is the building area that requires space heating (m^2). COT stands for the cost of transportation (USD), and $COWH$ denotes the cost of waste heat (USD/kWh) considered free of charge for this study.

Additionally, the COT is influenced by the distance and transport frequency. It can be calculated using the following formula [25]:

$$COT = \frac{Q \times A \times n \times 365}{Q_{PCM}} \times Dist \times 2 \times C_{mileage} \quad (2)$$

where Q_{PCM} is the heat provided by one container of PCM (kWh), $Dist$ is the distance between the heat source and the end-user (km), and $C_{mileage}$ is the cost to transport the M-TES system per kilometer (USD/km).

6. Discussion

In this study, despite dealing with a larger area and higher initial costs due to more containers being employed, we achieved promising results. The COH for scenario 1 dropped to 0.02 $/kWh, which proves to be encouraging for large-scale projects. Furthermore, when MTES is utilized to fulfill both heating and cooling needs, the cost further reduces to 0.01 $/kWh due to the increased valuable energy covered. Additionally, the payback period decreased by 10 months when MTES is applied to both heating and cooling demands. These findings align closely with those reported by Guo et al. [23]. A comparison of our results, including the COH of various systems of heating, is presented in Table 14 using the same cost model (Equation (1)) and same assumptions; the costs of providing 1 kWh of heat using pellet, bio-oil, biogas, and oil boiler systems, as well as an electrical air-source heat pump, were also estimated. These costs were then compared with the Cost of Heat (COH) for the M-TES system. For a newly built system, the Cost of Heat (COH) for all methods decreases as the heat demand increases. However, the COH for the M-TES system is most significantly impacted by heat demand due to its high capital cost. Additionally, unlike other methods, the COH for the M-TES system is distinctly influenced by the transport distance.

Table 14. Economic outcome comparison of various heating systems.

Energy Resources	MTES Scenario 1	MTES Scenario 2	Bio-Oil	Pellet	Electricity	Bio-Gas	Fuel Oil
Energy price ($/kWh)	0.02	0.01	0.04–0.07 [46]	0.013–0.04 [47]	0.1–0.12 [48]	0.07–0.1 [49]	0.09–0.12 [46,49]

The scale of the area served by the MTES system significantly influences the heating cost due to economies of scale. As the area served increases, the fixed costs associated with the MTES infrastructure, such as the cost of PCM containers, heat exchangers, and transportation, are distributed over a larger energy output. This distribution reduces the cost per unit of energy delivered. Additionally, larger-scale projects can benefit from the bulk purchasing of materials and more efficient utilization of resources, further driving down costs. For instance, our study shows that the cost of heating (COH) decreases from $0.02/kWh for smaller-scale applications to $0.01/kWh for larger-scale projects. This reduction is attributed to the more efficient use of the MTES system's capacity and the ability to optimize operational strategies over a larger area. Therefore, serving a larger area with the MTES system enhances its cost-effectiveness, making it a more viable solution for large-scale energy efficiency initiatives.

Given the high price of oil, the M-TES system is more appealing than the oil boiler system, particularly when the transport distance is within 30 km [25]. Compared to other methods, the M-TES system is better suited for scenarios with short transport distances and a high heat demand.

Furthermore, the economic analysis clearly demonstrates that the MTES system is a highly cost-effective solution for enhancing energy efficiency in large-scale projects. The significant savings and short payback periods make it an attractive option for reducing energy costs and improving sustainability in Mediterranean buildings. By utilizing waste heat from power plants, the MTES system not only lowers operational costs but also contributes to environmental sustainability by reducing CO_2 emissions. The study's findings are consistent with previous research, indicating that increasing the number of PCM containers and optimizing system parameters can further enhance the economic benefits. This optimization leads to greater efficiency and cost savings, making the MTES system a viable and sustainable choice for large-scale energy efficiency initiatives in the Mediterranean region.

Our results align with previous research on MTES and other thermal energy storage systems. For instance, Guo et al. (2017) conducted a techno-economic assessment of MTES for distributed users in China and found that increasing the number of PCM containers and optimizing system parameters led to significant economic benefits [22]. Similarly, Li et al. (2013) highlighted the importance of optimizing the distance between the heat source and the end-user to minimize heating costs [25]. Our study confirms these findings, demonstrating that the careful optimization of system parameters can enhance both the efficiency and cost-effectiveness. The economic analysis reveals that the MTES system is a cost-effective solution for large-scale energy efficiency projects. The payback periods for the two scenarios considered—water and space heating, and combined heating and cooling—are relatively short, at 2 years and 11 months and 2 years and 1 month, respectively. These results are consistent with the findings of Deckert et al. (2014), who reported similar payback periods for mobile latent heat storage systems [26]. The cost of heating (COH) in our study is also competitive, with scenario 1 at $0.02/kWh and scenario 2 at $0.01/kWh, which is lower than the costs associated with other heating systems, such as bio-oil, pellet, and electricity. In addition to economic benefits, the MTES system offers significant environmental advantages. By reducing the reliance on fossil fuels and utilizing waste heat, the system contributes to lower CO_2 emissions and supports sustainable energy practices. This aligns with the goals of the Sustainable Development Goals (SDG) 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities).

It is worth mentioning that the heat charging time of the PCM is a critical factor that significantly impacts the cost of heat (COH), as it determines the maximum heat availability. To increase the transport frequency of the container, it is essential to reduce the charging time. Unfortunately, the heat charging process is typically very slow [50] because, in a direct-contact container, the solid PCM initially blocks the oil pipe, preventing the hot HTF from entering the container. The only method of heat transfer for melting a solid PCM is pure heat conduction, which has a much lower heat transfer coefficient than convection. Additionally, the heat discharging time is also a crucial parameter that determines the heating capacity. Therefore, enhancing heat transfer during the PCM heat charging and discharging process is a key issue in the development of the M-TES system [50,51].

7. Conclusions

The M-TES system studied and simulated for extensive projects and high-capacity system containers under the Mediterranean climate conditions and heat/cooling loads was evaluated, and the several key conclusions can emerge:

- The power plant efficiency increased with the use of the MTES system by 0.98% knowing that only 45.2% of its waste heat was utilized.
- Energy costs were reduced significantly, by 50% in comparison to other studies performed to cover more compact spaces energy needs. Utilizing M-TES for space heating and cooling resulted in a 75% cost reduction. This leads to the conclusion that raising the cycle number leads to a reduction in energy costs.
- From an economical perspective, the M-TES system has a PBP of 2 years and 11 months if only used for heating and 2 years and 1 month if utilized for both space heating and cooling.
- As shown in Table 14, the cost of heating (COH) using M-TES for large-scale projects is the lowest compared to other heating systems, making it a highly cost-effective solution.
- The outcomes of this research align perfectly with SDG 7 (Affordable and Clean Energy) and SDG 11 (Sustainable Cities and Communities).

The practical implementation of the MTES system in large-scale projects, such as the university campus, demonstrates its feasibility and effectiveness. The system's ability to provide consistent and efficient heating and cooling solutions makes it a viable option for other large-scale buildings in the Mediterranean region. However, challenges, such as ensuring a continuous energy supply, managing traffic delays, and maintaining mechanical systems, need to be addressed to optimize the system's performance. The MTES system presents a promising solution for enhancing energy efficiency and sustainability in large-scale Mediterranean buildings. The study's findings highlight the importance of optimizing system parameters and increasing the number of PCM containers to achieve significant economic and environmental benefits. To address the challenges associated with ensuring a continuous energy supply for large-scale M-TES systems, several strategies could be explored. Firstly, implementing a robust logistics and transportation plan can help mitigate issues, such as traffic delays and unscheduled shutdowns. This includes optimizing transportation routes, scheduling regular maintenance, and having backup transportation options. Secondly, incorporating advanced monitoring and control systems can enhance the reliability of the energy supply by providing real-time data on system performance and enabling prompt responses to any disruptions. Thirdly, diversifying the sources of waste heat and integrating renewable energy sources, such as solar or wind power, can provide additional resilience and reduce the dependency on a single energy source. Lastly, conducting regular maintenance and adopting predictive maintenance techniques can minimize mechanical failures and ensure the continuous operation of the M-TES system. By exploring and implementing these strategies, the reliability and efficiency of large-scale M-TES systems can be significantly improved. The impact of these challenges, along with others, needs more studies. By conducting such a study, we can optimize the weight of the containers, leading to more efficient operation. This optimization process also extends to improving the operation strategy and determining the ideal number of containers needed for optimal functionality. Furthermore, a Computational Fluid Dynamics (CFD) study can represent the behavior of the phase change state of the PCM, allowing for comparisons with other configurations utilizing different Heat HTF and PCM indirect Heat Exchangers.

Future research should focus on conducting field studies to validate the simulation results, optimizing the system scale through detailed simulations and sensitivity analyses, investigating long-term reliability, and expanding comparative studies to identify the most efficient and cost-effective materials for MTES applications. Furthermore, it should focus on field studies to validate simulation results, investigate long-term reliability, and explore comparative analyses with other PCMs and HTFs to continuously improve the system's performance. By addressing these research gaps, future studies can further advance the understanding and implementation of MTES systems, contributing to more sustainable and energy-efficient building solutions.

While there remain numerous challenges for further research and study on the M-TES system, our results demonstrate its promising potential as a technology capable of replacing conventional heating systems.

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