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Simulation and Economic Analysis of a Mobilized Thermal Energy Storage System for Mediterranean Climate Buildings: Case Study

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Abstract. The mobilized thermal energy storage system (M-TES) has been investigated for decades, demonstrating its competitiveness compared to conventional heating systems like oil, gas, and biomass boilers. This paper presents a case study where waste heat from a power plant is utilized in M-TES to cover heating, cooling, and water heating needs in a university campus. Erythritol is used as the phase change material (PCM) and Therminol55 as the heat transfer fluid (HTF). The study simulates the charge, self-discharge, and discharge phases of the PCM, revealing that increased HTF flow reduces charging time and enhances efficiency, while increased waste heat potential decreases charging efficiency slightly. Economic evaluation shows that heat costs decrease with larger project scales and more PCM containers. This research highlights M-TES as a sustainable thermal energy storage solution with broad applications in the energy sector.

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 that the demand for oil will rise by approximately 30% from 2007 to 2035, while coal and natural gas 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 contributor to energy consumption and carbon emissions, accounting for up to 40% of total energy usage in some developed nations and emitting a parallel 40% of total greenhouse gas emissions [2,3]. Approximately 33% of the energy consumed 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 M-TES. This system stores the waste heat generated by industries such as steel and cement mills, power plants, and sewage sludge incinerators [6-8]. The stored heat is retained within specially designed containers and then transported to end-users to cover space and water heating loads [9,10]. The M-TES is enhanced by the utilization of Phase Change Materials (PCMs), which have a high capacity to absorb or release thermal energy in the form of latent heat, differentiating them from materials used in conventional sensible heat storage systems [11-14].

The adoption of M-TES in providing heat has several benefits, such as a decrease in primary energy consumption, minimization of exergy losses, and a reduction of CO_2 emissions by up to 95% compared to conventional heating systems that use fossil fuels [15,16]. While M-TES technology has been investigated 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 M-TES projects

include organic sugar alcohols like Erythritol and Mannitol, as well as inorganic hydrated salts like Sodium acetate trihydrate and Magnesium chloride hexahydrate [17-25].
Various types of M-TES containers have been designed and tested to optimize performance in both charging and discharging processes, with different configurations such as shell-and-tube, encapsulated, direct-contact, detachable, and sorptive containers [26]. Economic evaluations of the M-TES system have shown that crucial factors governing cost include the transport distance from the waste heat source to the end-user and the heat demand, with findings highlighting that the cost of heating is proportional to the transport distance but inversely proportional to the heat demand [27]. Furthermore, sensitivity analyses show that the pricing of phase change materials affects the overall cost of heating [28].
While M-TES technology has found successful application in developed countries such as Germany, Japan, and Sweden [6,23,29], it holds considerable promise for third-world countries like Lebanon. These countries import oil to cover their energy needs; thus, the implementation of M-TES will help reduce oil consumption to cover heating and cooling demands as well as valorize waste heat, contributing to a sustainable and energy-efficient future. In this paper, the waste heat from a typical power plant is reused and stored using M-TES technology to cover the heating and cooling loads of a university campus. Our case study will investigate the modeling, simulation, and economic and environmental evaluation of the M-TES project. The findings will provide valuable results that can be compared with existing studies on an economic basis.

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 m², is the recipient of this waste heat. Previously, the campus used oil boilers for heating and chiller units for cooling. For the Mobile Thermal Energy Storage (M-TES) 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, water heating, and absorption chillers for cooling. After full PCM heat discharge, the container returns to the PP to initiate a new cycle. The M-TES cycle is presented in figure 1.

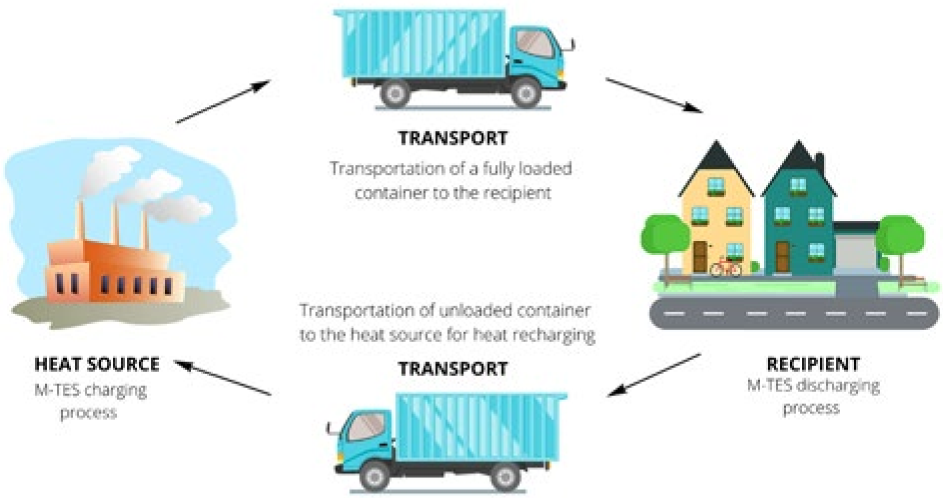

Fig. 1. M-TES cycle [49]

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 hours annually. The IWH's annual potential and flow characteristics are detailed in Table 1.

Table 1. IWH potential, flow and annual energy wasted. [30]

IWH	Minimum	Maximum	Mean value	Annual energy (MWh)
Potential (MW)	0.798	21.35	10.385	90,778.75
Flow (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 summarized 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 annual energy needs.

	Water heating	Space heating	Space cooling	Total
Energy consumed/year (MWh)	1,273	10,833	11,794	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, in addition to its high latent heat of 339 kJ/kg and favorable cost-effectiveness [33-37]. The selected HTF is Therminol55, characterized by a high flash point of 117°C and a boiling temperature of 351°C [38,39]. Key physical properties of Erythritol and Therminol55 are summarized in Table 3.

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

Item	T (ºC)	Density (kg/m^3)	Cp (kJ/kg. K)	Thermal Conductivity (W/m. K)	Latent Heat (kJ/kg)	Melting point (ºC)	Flash point (ºC)	Boiling Temperature (ºC)	Viscosity (kg/m. s)	Dynamic viscosity (MPa.s)
Erythritol (PCM)	20	1480	1.35	0.732	339	118	-	-	0.02895	-
	140	1300	2.74	0.326			-	-	0.01602	-
Therminol55 (HTF)	33	865	1.94	0.1273	-	-	177	351	-	25.2
	130	797	2.3	0.1156	-	-			-	1.71

Modelling and Simulation

IWH is valorized to cover the university energy requirements. Between the waste heat and the load, there is a series of heat exchangers that must be used to transfer the heat from the PP to the university:

- **Exhaust Heat Recovery Exchanger:** The energy of the exhaust gas 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 energy of the HTF is transferred to the PCM, designed as a 20-foot ISO shell-and-tube container with encapsulated PCM inside the tubes and HTF flowing in the shell side. This design improves the heat exchange due to a larger exchange area. Staggered aluminum tubes are chosen due to their high conductivity, light weight, and low cost [40,41].
- **Heat Distribution Exchangers:** The energy of the PCM is transferred to circulating water in the campus. Two counter-flow tubular heat exchangers are selected, one for heating and one for cooling.

Once the heat exchangers are designed, simulations are conducted for three phases: charging, self-discharging, and discharging of the PCM, carried out on Simulink-MATLAB. The simulation tracked the evolution of PCM temperature, oil tank temperature, and oil flow. First, the PCM temperature increases exponentially as it stores sensible heat, gradually reaching its melting temperature. After this, the PCM starts storing latent heat until reaching the liquid state and 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. Oil flow increases with the increase of oil tank temperature to recuperate heat through the Exhaust Heat Recovery Exchanger until reaching the maximal flow setpoint, and the oil tank temperature increases with the increase of oil temperature exiting the container due to the increase of PCM temperature.
In our study, we investigated the impact of oil flow and IWH potential on charging time and efficiency 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% reduction in charging time and an 8% increase in charging efficiency. Furthermore, adjustments in the IWH potential showed varying effects: maximizing it resulted in a slight 3.65% decrease in charging time but a substantial drop in efficiency from 20% to 9.9%. Conversely, minimizing the IWH potential increased efficiency by 63% but at the expense of a 212.5% increase in charging time. These findings show the importance of oil flow regulation, particularly when adjusting IWH potential, for managing charging efficiency effectively. Therefore, the simulation was conducted by setting the mean potential power at 10.385 MW and a maximum oil flow of 100 kg/s, with the initial PCM temperature set at 20°C.
During normal system operation, after discharge during the previous cycle, PCM temperature settles between 80°C and 95°C, depending on the load requirements. When starting a new cycle, the charging phase begins from these temperatures. This initial temperature influences the subsequent charging phase, impacting charging time, efficiency, and container capacity. All results are summarized in Table 5.
After the charging phase, PCM capacity self-discharges and its capacity decreases due to heat conduction through the storage tank and container shells, and by convection with surrounding air. During transportation, forced convection accelerates this process, while during waiting periods before the discharge phase, natural convection takes over.

Table 4. Charge phase simulation results for different oil flows and different IWH potentials.

IWH	Maximum oil flow (kg/s)	IWH energy (MWh)	Recovered energy by oil (MWh)	Recovery efficiency (%)	Storage efficiency (%)	Charging Efficiency (%)	Charging time (s)	Saturation time (s)
10.38	100	35.11	7.942	22.58	88.79	20.05	12,193	5,582
10.38	201.4	24.9	7.95	31.79	88.78	28.22	8,664	3,122
21.354	100	71.097	7.945	11.18	88.8	9.92	11,985	5,378
0.798	100	8.45	7.94	94.04	88.8	83.5	38,110	27,050

Table 5. Charge simulation results for a mean IWH potential, a maximum oil flow of 100 kg/s and different PCM initial temperatures.

PCM initial Temperature (ºC)	Maximum oil flow (kg/s)	IWH energy (MWh)	Recovered energy by oil (MWh)	Recovery efficiency (%)	Storage efficiency (%)	Charging efficiency (%)	Charging time (s)	Saturation time (s)
80	100	34.296	7.402	21.58	85.8	18.52	11,889	5,371
95	100	34.057	7.252	21.29	84.89	18.08	11,806	5,303

The container shell is constructed from steel [42], while we choose fiber-reinforced plastic (FRP) for the storage tank shell. To insulate the storage tank, it was surrounded by 4 cm of rockwool. Physical properties of these materials are summarized in table 6.
The simulation results illustrated in fig.2, demonstrate a nearly linear decline in PCM temperature from 130°C to 129.59°C over around 2.5 hours. This simulation was repeated for different rockwool thicknesses and with a duration of 1.5 and 2.5 hours, as summarized in table 7. The results show that 4 cm of rockwool is a good choice since it improves significantly the insulation as the energy losses decreases from 0.017Mwh to 0.0109Mwh while by using 5cm thickness it decreases to 0.009MWh and PCM final temperatures are very close. Additionally, it is shown that each one-hour delay causes the loss of 0.11% of PCM capacity as shown in table 7 (0.15% loss for 1.5 hours of self-discharge compared to 0.26% loss for 2.5 hours of self-discharge for a rockwool thickness of 40mm).

Table 6. Physical properties of carbon steel, FRP and rockwool. [43,44]

Material	Thermal conductivity (W/m. K)	Thickness (mm)	Density (kg/m^3)
Carbon Steel	45	4	7500
Fiber Reinforced Plastic	0.57	4	1550
Rockwool	0.043	40	60

Table 7. Self-discharge simulation results for different rockwool thicknesses.

	Self-Discharge duration = 1.5 hours			Self-Discharge duration = 2.5 hours		
Rockwool thickness (mm)	Energy lost (MWh)	Percentage	PCM final temperature (°C)	Energy lost (MWh)	Percentage	PCM final 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

After 2.5 hours of PCM self-discharge, the discharge phase begins from a PCM Temperature of 129.59°C. For each load, PCM discharge power is calculated resulting in a power of 7 MW. The simulation in fig. 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 seconds. Following solidification, the PCM releases sensible heat until it reaches 95°C, marking the end of the discharge phase. With an efficiency of 66%.

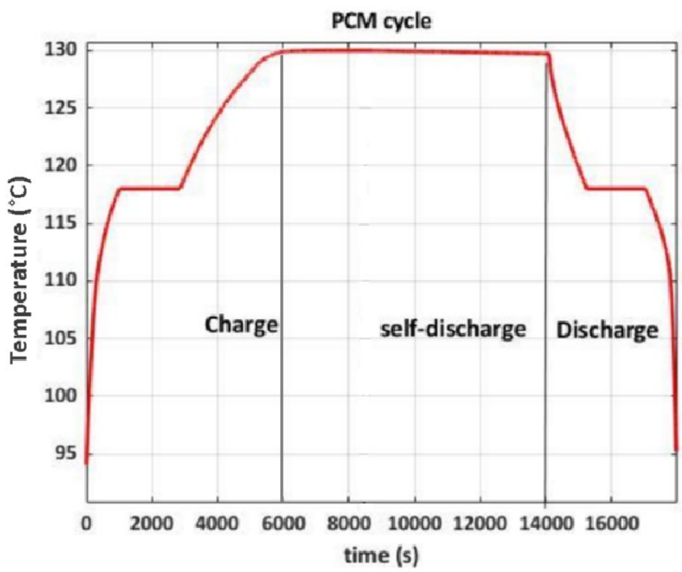

Fig. 2. PCM cycle: charge, self-discharge, and discharge phases.

To ensure a continuous operation strategy, we require 9 containers for winter (with 3 containers discharging simultaneously) and 12 containers for summer (with 4 containers discharging simultaneously) to cover the university daily loads requirements. The total number of cycles per year is calculated by dividing the total discharged energy by the energy discharged per container, resulting in 5,196 cycles:

Additionally, by considering an additional useful energy of 23,900 MWh/year for space heating/cooling and water heating using fuel oil potential in the Power Plant, the M-TES system improved the Power Plant efficiency by 0.98%, as shown in Table 8.

Table 8. PP efficiency calculation with and without M-TES.

PP	Fuel oil potential (MWh)	Useful energy/ year	PP efficiency
Without M-TES	2,443,239.15 [28]	738,130 [28]	30.21%
With M-TES		738,130+23,900	31.19%

Economic Analysis

In most studies involving M-TES, the system typically focuses on covering space and water heating needs. To align our results with other research, two economic evaluations are conducted for different scenarios:

Case 1: M-TES solely provides space and water heating (requiring 9 containers).

Case 2: M-TES serving both space heating/cooling and water heating (requiring 12 containers).

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

Operation costs vary based on the total number of cycles per year. In Case 1, there are 2,638 cycles annually, while Case 2 involves 5,196 cycles. The cost per cycle is estimated at 57.5USD, 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 9. Initial cost breakdown for cases 1 and 2.

Description	Unit price [50]	Quantity Case 1	Quantity Case 2	Cost of case 1 (USD)	Cost of case 2 (USD)
Container	2,500 USD/container	9	12	22,500	30,000
Erythritol	3.5 USD/kg	9 *30,048 kg	12*30,048 kg	946,512	1,262,016
Aluminum tubes	2 USD/kg	9*1,080*3.2m*2.5kg/m	12*1,080*3.2m*2.5kg/m	155,520	207,360
Therminol 55	3 USD/kg	20,000 kg	20,000 kg	60,000	60,000
PRF	1,510 USD/ton	9*137.7 kg	12*137.7 kg	1,865.907	2,487.89
Rockwool	1 USD/m^2	9*67.23 m^2	12*67.23 m^2	605.07	806.76
HX & Pumps	1.33 USD/kWh	14,100 kWh	14,100 kWh	18,753	18,753
Sum				1.206 million	1.58 million
Shipping				15%	15%
VAT				11%	11%
Total cost				**1.52 million USD**	**1.99 million USD**

Table 10. Annual savings for cases 1 and 2.

Description	Useful Energy (MWh/year)	System efficiency or COP	Energy saved (MWh/year)	Unit price (USD/kWh)	Total savings (USD/year)
Water heating	1,273	0.8	1,591.25	0.05	79,562
Space heating	10,833	0.8	13,541.25	0.05	677,062
Space cooling	11,794	3.8	3,104	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 cost for cases 1 and 2.

Case	Number of PCM cycles/years	Unit price (USD/cycle)	Operation cost (USD/year)
Space & water heating only	2,638	57.5	151,685
Space heating, cooling and water heating	5,196	57.5	298,770

The economic study was conducted by assuming that the lifespan of the container and PCM are 15 years and the cost of PCM is 3.5 USD/kg to compare results with Li et al. [25]. In this paper, the campus area is approximately 500,000 m^2 and the distance between the waste heat source and the campus is around 23 km. The results of the economic study for both cases are summarized in table 12.

Previous studies such as Li et al. [27] have shown that as the area being served increases from 500 m^2 to 30,000 m^2, the cost of heating (COH) decreases significantly, from 0.12 USD/kWh to 0.04 USD/kWh, for the same distance of 23 km. Moreover, the payback period for replacing an oil system with M-TES reduces from 10.5 years when only two containers are used to meet the heat demand to approximately 2 years in our case.

Table 12. Economic evaluation results for cases 1 and 2.

Case	Payback period	Cost of heating/cooling (USD/kWh)
Space & water heating only	2 y 8m	0.018
Space heating, cooling and water heating	1y 10m	0.009

In our study, despite dealing with a larger area and higher initial costs due to more containers being employed, we achieved promising results. The COH for Case 1 dropped to 1.8 cents/kWh, which is encouraging for large-scale projects. Furthermore, when M-TES is utilized to fulfill both heating and cooling needs, the cost further reduces to 0.9 cent/kWh due to the increased useful energy covered. Additionally, the payback period decreased by 10 months when M-TES is applied to both heating and cooling demands. These findings align closely with those reported by Guo et al. [24]. A comparison of our results with COH of different heating systems is summarized in Table 13.

Table 13. Economic results comparison with different heating systems.

Energy resources	M-TES case 1	M-TES case 2	Electricity	Pellet	Bio-oil	Biogas	Oil
Energy price (USD/kWh)	0.018	0.009	0.1-0.12 [45]	0.013-0.04 [46]	0.04-0.07 [47]	0.07-0.1[48]	0.09-0.12 [45,48]

Conclusion

The M-TES system studied and simulated on large scale project and with high-capacity containers under the Mediterranean climate conditions and heat/cooling loads was evaluated, and the several key conclusions can be emerged:

- The M-TES system increased the efficiency of PP by 0.98% by using only 45.2% of the PP's waste heat.
- Energy costs were reduced significantly, by 50% compared to previous studies conducted to cover smaller areas energy needs. The cost also decreased 75% when using M-TES for both space heating and cooling. This leads to the conclusion that increasing the number of cycles decreases the energy cost.
- From an economical perspective, the M-TES system has a PBP of 2 years and 8 months if only used for heating and 1 year and 10 months if used for both space heating and cooling.
- As shown in Table 13, 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), & SDG 11 (Sustainable Cities and Communities).

The primary challenge associated with implementing M-TES on a large scale will be ensuring a continuous energy supply. Issues such as traffic delays, unscheduled shutdowns of Power Plants, and

the maintenance needs of mechanical systems could disrupt the process of charging and transporting the containers. 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 comparison with other configurations utilizing different Heat HTF and PCM indirect Heat Exchangers.
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.

References

[1] BP, British petroleum, statistical review of world energy, 2010.

[2] EIA, U.S. Energy Information Administration, International Energy Outlook, U.S. Department of Energy, 2014.

[3] U. Berardi, moving to sustainable buildings: paths to adopt green innovations in developed countries, Versita, London, 9788376560090, 2013.

[4] WJ. Duan, QB. Yu, ZL. Zuo, Q. Qin, P. Li and JXLiu, the technological calculation for synergistic system of BF slag waste recovery and carbon resources reduction. Energy conversion and Management, 2014. 87: p. 185-190

[5] TC. Wang, WL. Luan, W. Wang, and ST. Tu, waste heat recovery through plate heat exchanger based thermoelectric generator system. Applied energy, 2014. 136: p. 860-865.

[6] W.L. Wang, Mobilized Thermal Energy Storage for Heat Recovery for Distributed Heating, in School of Sustainable Development of Society and Technology. 2010, Mälardalen University.

[7] U.D.o. Energy, Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining. 2004.

[8] Y. Yabuki and T. Nagumo, Non-conduit Heat Distribution Using Waste Heat from a Sewage Sludge Incinerator. Proceedings of the Water Environment Federation, 2007. 2007(8): p. 9306-9309.

[9] W. Wang, Y. Hu, J. Yan, J. Nyström, E. Dahlquist, Combined heat and power plant integrated with mobilized thermal energy storage. (M-TES) system. Front Energy Power Eng China 2010; 4(4): 469–74.

[10] WL. Wang, J. Yan, E. Dahlquist, J. Nyström, A new mobilized energy storage system for industrial waste heat recovery for distributed heat supply. International conference of applied energy, Hong Kong; January 5–7, 2009.

[11] L.F.C. H. Mehling, Heat and cold storage with PCM. 2008, New York: Springer.

[12] K. Du, J. Calautit, Z. Wang, Y. Wu, and H. Liu, A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. Applied Energy, 2018. 220: p. 242-273.

[13] S. Eid, M. Brouche, C. Lahoud, C.Lahoud. May 2021. Phase Change MAterials Technologies Review and Future Application in Lebanon: Part II. Key Engineernig Materials 886: 256-270.

[14] S. Eid, M. Brouche, C. Lahoud, C.Lahoud. May 2021. Phase Change MAterials Technologies Review and Future Application in Lebanon: Part I. Key Engineernig Materials 886: 228-240.

[15] W. Wang, Y. Hu, J. Yan, J. Nyström, A new mobilized energy storage system for industrial waste heat recovery for distributed heat supply. International conference of applied energy, Hong Kong; January 5–7, 2009.

[16] K. Du, J. Calautit, P. Eames, Y. Wu, A-state-of-the-art review of Phase Change Materials (PCM) in Mobilized- Thermal Energy Storage (M-TES) for recovering low-temperature Industrial Waste Heat (IWH) for distributed heat supply, Renewable Energy, 2021. 168: p.1040-1057.

[17] JN. Chiu and V. Martin, Industrial surplus heat storage in smart cities. in ASME 2015 9th international conference on energy sustainability. 2015.

[18] N.M. A. Kaizawa, A Kawai, H Kamano, T Jozuka, T Senda, T Akiyama, Thermophysical and heat transfer properties of phase change material candidate for waste heat transportation system. Heat and Mass Transfer, 2008, 44:763-769.

[19] A. Kaizawa, H. Kamano, A. Kawai, T. Jozuka, T. Senda, N. Maruoka, N. Okinaka, and T. Akiyama, Technical Feasibility Study of Waste Heat Transportation System Using Phase Change Material from Industry to City. ISIJ International, 2008. 48(4): p. 540-548.

[20] G. Peiró, J. Gasia, L. Miró, and L.F. Cabeza, Experimental evaluation at pilot plant scale of multiple PCMs (cascaded) vs. single PCM configuration for thermal energy storage. Renewable Energy, 2015.83: p. 729-736.

[21] Y. Wang, K. Yu, and X. Ling, Experimental study on thermal performance of a mobilized thermal energy storage system: A case study of hydrated salt latent heat storage. Energy and Buildings, 2020. 210: p. 109744.

[22] G. Storch and A. Hauer. Cost-effectiveness of a heat energy distribution system based on mobile storage units: two case studies. In Ecostock conference. 2006.

[23] Mobile latent heat storage unit, efficient use of waste heat. 2013, Fraunhofer Umsicht.

[24] JN. Chiu, J. Castro Flores, V. Martin, and B. Lacarrière, Industrial surplus heat transportation for use in district heating. Energy, 2016. 110: p. 139-147.

[25] K. Nagano, K. Ogawa, T. Mochida, K. Hayashi, and H. Ogoshi, Thermal characteristics of magnesium nitrate hexahydrate and magnesium chloride hexahydrate mixture as a phase change material for effective utilization of urban waste heat. Applied Thermal Engineering, 2004. 24(2): p. 221-232.

[26] S. Guo, Q. Liu, J. Zhao, G. Jin, W. Wu, J. Yan, H. Li, H. Jin, Mobilized thermal energy storage: Materials, containers and economic evaluation, Energy conversion and Management 177 (2018) 315-329.

[27] Li H, Wang W, Yan J, Dahlquist E, Economic assessment of the mobilized thermal energy storage (M-TES) system for distributed heat supply, Applied energy 104 (2013) 178-186.

[28] M. Deckert, R. Scholz, S. Binder, A. Hornung, Economic efficiency of mobile latent heat storages, Energy Procedia 46 (2014) 171-177.

[29] R.E. Hester and R.M. Harrison, “Energy storage options and their environmental effect”, Royal society of chemistry 2019.

[30] Lebanese public data.

[31] H. Fang, J. Xia, K. Zhu, Y. Su, and Y. Jiang, Industrial waste heat utilization for low temperature district heating. Energy Policy, 2013. 62: p. 236-246.

[32] V. Brancato, A. Frazzica, A. Sapienza, and A. Freni, Identification and characterization of promising phase change materials for solar cooling applications. Solar Energy Materials and Solar Cells, 2017. 160: p. 225-232.

[33] M. Yuan, Y. Ren, C. Xu, F. Ye, and X. Du, Characterization and stability study of a form-stable erythritol/expanded graphite composite phase change material for thermal energy storage. Renewable Energy, 2019. 136: p. 211-222.

[34] F. Agyenim, P. Eames, and M. Smyth, Experimental study on the melting and solidification behaviour of a medium temperature phase change storage material (Erythritol) system augmented with fins to power a LiBr/H2O absorption cooling system. Renewable Energy, 2011. 36(1): p. 108-117.

[35] A. Mawire, T.M. Lefenya, C.S. Ekwomadu, K.A. Lentswe, and A.B. Shobo, Performance comparison of medium temperature domestic packed bed latent heat storage systems. Renewable Energy, 2020. 146: p. 1897-1906.

[36] G. Gan and Y. Xiang, Experimental investigation of a photovoltaic thermal collector with energy storage for power generation, building heating and natural ventilation. Renewable Energy, 2020. 150: p. 12-22.

[37] Y. Lin, G. Alva, and G. Fang, Review on thermal performances and applications of thermal energy storage systems with inorganic phase change materials. Energy, 2018. 165: p. 685-708.

[38] M. Liu, W. Saman, et F. Bruno, "Review on storage materials and thermal performance enhancement techniques for high temperature phase change thermal storage systems", Renewable and Sustainable Energy Reviews, vol. 16, no. 4, pp. 2118-2132, 2012.

[39] www.therminol.com

[40] metals.4u.co.uk/materials/aluminium/aluminium-tube/1989-p.

[41] T. L. Bergman, A. S. Lavine, P. F. Incropera, D.P. Dewitt, Fundamentals of heat and mass transfer, seventh edition, John Wiley and sons, 2011.

[42] CTX CONTAINEX, technical specification for steel dry cargo container, specification no. ‘’CTX 20 DVDR-Domestic Spec. HH, October 2013.

[43] https://www.engineeringtoolbox.com/thermal-conductivity-metals-d/

[44] https://www.totalinsulation.com.au/

[45] H. Li, B. Saršon, H. Song, E. Dalhquist, E. Thorin, J. Yan, Potentials of energy saving and efficiency improvement from lighting and space heating: a case study of SAAB workshop. In: Proceedings of international conference on applied energy, Suzhou, China; July 6–8, 2012.

[46] International Renewable Energy Agency (IREA). Biomass for power generation. Renewable energy technologies: cost analysis series, vol. 1, Power Sector; June 2012.

[47] J. Sadhukhan, Ng KS. Economic and European union environmental sustainability criteria assessment of bio-oil-based biofuel systems: refinery integration cases. Ind Eng. Chem Res 2011; 50(11):6794–808.

[48] http://pelletheat.org/pellets/compare-fuel-costs/; 2012 [accessed 28.10.12].

[49] D. Matuszewska, M. Kuta, P. Olczak, Techno-Economic Assessment of Mobilized Thermal Energy Storage System Using Geothermal Source in Polish Conditions. Energies 2020, 13, 3404.