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Techno-Economic Design and Social Integration of Mobile Thermal Energy Storage (M-TES) within the Tourism Industry

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ABSTRACT

Industrial facilities including power plants are potential sources of cheap and low-carbon waste heat, which is often not utilized due to lack of techno-economically viable options. The present paper is based on a case study focussing at Albena tourist resort in Bulgaria to design and develop a potential Mobile Thermal Energy Storage (M-TES) system for waste heat utilization from an existing biogas-based combined heat and power (CHP) plant. Besides techno-economics, integration of the system within existing premises, freight weight, space constraint and hotel occupancy are crucial factors. Scheduling, along with the frequency of container change determines both the economic and social viability of such a project. A conceptual system design tailored to maximize energy utilization within the given constraints has been made. Core of the system is 5 containers of 15.9 tons each, with one pulling truck for minimal visibility of the transportation and a two-day container discharge cycle. A net reduction of 558 to 885 MWh per year of electricity consumption from existing electric boilers was calculated with a payback period of 7 years for yearlong operations and 14 years for summer operations. The corresponding CO_2 savings was 96.7%. Hybridization with solar thermal systems can provide a complete substitution of the use of traditional energy sources for domestic hot water.

Keywords

Mobile Thermal Energy Storage (M-TES), Waste Heat, Phase Change Material (PCM), Tourism Industry, Techno-economic Assessment

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1. Introduction

Industrial activities, including power generation, have significant potential of supplying waste heat, often released unused due to lack of technologically viable options [1, 2]. Recovery and re-use of waste heat, besides increasing the efficiency of industrial systems, provides an attractive low-carbon and low-cost energy source [3, 4], together with the reduction of primary energy need [5] for end-users. On-site waste heat utilization is an established technology due to ease of integration and operation with existing systems. However, the technical viability of waste heat utilization in district heating networks is limited by the requirement of a supply temperature of 70°C in district heating networks [4]. Furthermore, the economic viability of development of a district heating network for off-site heat utilization depends on the appropriate relation between the amount of heat available and that transported from the source to sink [2, 5, 6]

Mobile Thermal Energy Storage (M-TES) systems employing latent heat have been studied as an alternative

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Nomenclature

Variables/ Parameters	Abbreviation
Capital Expenditure	CAPEX
Combined Heat and Power	CHP
Domestic Hot Water	DHW
Mobile Thermal Energy Storage	M-TES
Net Present Value	NPV
Operation Expenditure	OPEX
Organic Rankine Cycle	ORC
Payback Period	PBP
Phase Change Material	PCM
Photovoltaic	PV

to district heating, where the source and use locations are at considerable distances [7, 8]. The capability of latent heat storage to store large amount of heat within the limited space of container is of considerable advantage. The distance of the source and demand, the temperature of the source and the type of end-use plays a crucial role in the design and viability of such systems [1, 9]. Ability of integration with new and existing bio-based combined heat and power (CHP) plants allows M-TES systems to support the development of such technologies as well.

Hotels are usually energy intensive in operations due to the need to maintain higher comfort levels with greater thermal treatment of space and requirement of additional facilities like swimming pools. Moreover, the compliance with standards and customer satisfaction often forces the hotel management to operate the services at their maximum potential. These result in considerably high energy consumption and subsequent high energy costs of operations. In this paper, an M-TES system was studied to provide heat to a resort city comprising multiple hotels. Techno-economic system design and operation strategy has been developed to ensure sustainable operations and integration of the chosen technology into the tourism industry.

2. Mobile Thermal Energy Storage (M-TES)

The heart of the M-TES system is the Phase Change Material (PCM), where the waste heat is stored as latent heat in a container. To recover the heat stored, plant equipment like heat exchanger, pump, valve and other fittings are necessary.

The system is initiated from the M-TES container being charged by the waste heat at the heat source. The container is then transported to the users by vehicles, usually trailer trucks, and the heat is released. After discharging, the container is transported back to the heat source to start a new cycle. The conceptual layout of the M-TES system with a Biogas CHP plant is shown in Figure 1.

3. Case study

The present study is based on the resort city of Albena, situated on the Black Sea Coast of Bulgaria, 30 km north of Varna, with the coordinates of 43.368°N and 28.08°E. Primarily a summer resort with over 34 hotels in operation in summer, a few hotels operate during winter. The peak hosting capacity is 20,000 including staff. The average hotel capacity is 400 visitors, with an occupancy of 80% during peak season operations.

The energy consumption analysis of Albena is complex. The operation peak, based on the tourist activity, typically occur in the months of July and August. The average summer day temperature being around 30°C [10], the energy need for space cooling is considerable. However, domestic hot water demands the highest share of consumed final energy with above 40% of the annual energy consumption of Albena. Electricity is the primary energy source for generating hot water with an average electric boiler efficiency of 95%.

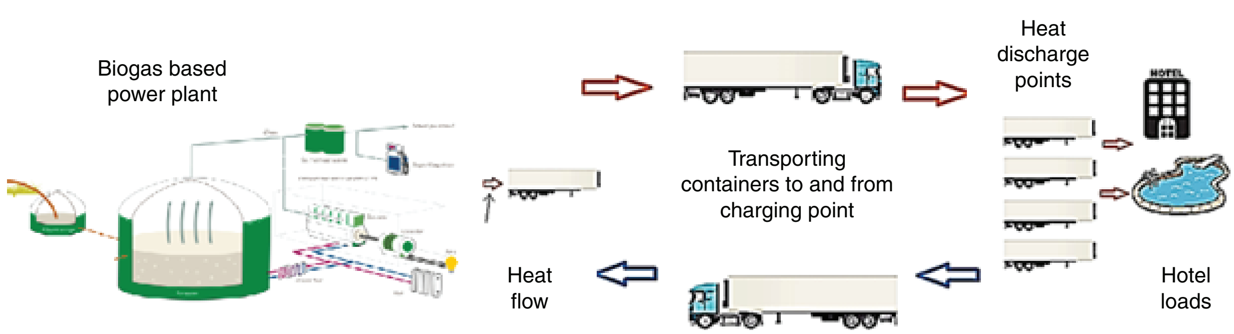

Figure 1: Conceptual Layout of the M-TES system

District heating network are an efficient and well-established option for transporting heat when the distance between source and end user is limited to 1-2 km [11]. For places without nearby district heating networks, establishing such a system is subject to several limitations and complexities unless otherwise subsidized or financed by the government. The initial investment cost being high, as well as the requirement of multiple permissions and clearance for the civil construction, makes development of such facilities extremely difficult for small scale purposes. In addition, for operation hours lower than 4000 hours per year, the fixed energy costs for the users is higher than alternatives [11]. Indeed, an inspection of the present location revealed the complicacies of crossing of highways and agricultural lands of the underground pipelines, that would be limiting to constructing a district heating network. On the other hand, using the available highway and road facilities, and the minimum land requirements for the charging and discharging units on-road transportation of waste heat would be much advantageous. Both the project cost and complicacies would be thus reduced. Furthermore, the possibility to transfer heat to other locations based on the demand makes the M-TES system attractive for waste heat utilization in the present case study.

3.1 Heat source

In the case study, waste heat is available from an energy crop anaerobic digestion CHP plant, located approximately 10 km away from Albena resort area. The CHP unit has a rated electricity output of 1 MW, operating at an electrical efficiency of 31%. It employs a turbocharged system, resulting in exhaust gas temperature of 340°C, pressure 1.09 bar and mass flow rate of 5.6 tonnes/hr. Being a base load power plant, and for a minimum temperature of exhaust of 150°C, a steady availability of 400 kW of waste heat is ensured, based on plant data.

Heat requirement of the digester is presently met by burning a fraction of the produced biogas. Nearby buildings, mostly office spaces and green houses are supplied by the waste heat from the CHP only for a few months in winter. However, this accounts for a minimal usage of the total heat generated. As for the operation during other seasons, the waste heat from the exhaust of the CHP is completely wasted. Being in an agricultural zone, the local use of waste heat is limited. On the other hand, use of waste heat in Organic Rankine Cycles (ORC) suffers from economies of scale, specifically, below 100 kW [12]. With a thermal efficiency of current high temperature ORC of 24% [13], a 96 kW-electric system can be conceptualized. With a low feed-in tariff and complicacies of grid integration of small scale power generators in Bulgaria, this would therefore constrain further electricity generation from the waste heat.

Heat pumps, solar heating as well as the use of biomass boilers, more specifically pellet boilers are commercial technologies. Of these, solar heating and heat pumps are established technologies locally. One of the main criticisms of solar heating however is the use of space which could be alternately used for generating electricity by roof mounted solar photovoltaic (PV) panels. Use of heat pumps without large storage would increase the electricity demand, leading to sharp peaks in the demand profile. This in turn would lead to the rise in the electricity purchasing price as per the local laws.

In this context, waste heat being available locally at low/no cost, assessing the techno-economic feasibility and practical of applicability waste heat utilization by M-TES system was found to be worth evaluating. This would also lead to the maximization of the use of local resources within the present case study.

3.2. Heat demand

Domestic hot water (DHW) generation, space heating and pool heating result major heat requirements in hotels. Due to higher energy requirement for DHW and easier system integration, the M-TES system was designed to provide DHW energy need in the present case study.

Average hot water consumption per day per guest is typically around 160 litres as per data collected from the case study. Distribution temperature of DHW is 55°C Assuming supply water temperature of 20°C, the net energy demand of hot water is 6.53 kWh/guest-night.

Considering peak operations with 80% occupancy, around 16,000 people were estimated to stay daily in Albena during summer. However, the distribution of the hotels within the resort city limits the complete implementation of the technology without major overhaul of the existing infrastructure for the movement of bulky and heavy containers. The present technology was analysed to be suitable to serve around 10 hotels with an average total of 4,000 tourists. Substitution of 26 MWh of heat demand for DHW generation per guest-night was therefore considered technologically feasible.

Due to absence of monitoring system in the hotels, a typical hot water load profile of a commercial European hotel was assumed based after a study by Agudelo-Vera et al [14]. Indeed, the profile varies considerably based on the day of the week, the type and location of the hotel and different tourist behaviour [15]. The hourly variation for hot water demand is crucial for both system design and to develop the operation strategies of the M-TES system and is discussed in the subsequent chapters.

4. System design

Selection of suitable phase change materials as well as the suitable container design is crucial to maximise thermal energy storage and cyclability, while minimizing heat loss at the same time. Indeed, the container sizing, in accordance with the heat demand to be met would be significant in optimizing the overall M-TES system. Accordingly, a comprehensive discussion on the selection of the PCM material, the container design and sizing have been presented in the following sections.

4.1. Selection of PCM

Multiple studies have been conducted to determine the most suitable PCM materials for mobile heat storage applications [1, 7, 8]. Temperature of both heat source and demand are crucial factors affecting the selection of the PCM, which in turn determines the storage capacity and system design [1]. Erythritol, an organic PCM with a high heat storage capacity of 339 kJ/kg, was selected for the present study. The melting point of 118°C being relatively higher than DHW temperature of 55°C, a stable hot water temperature can be generated without the need for auxiliary boilers. Besides, Erythritol being a food additive, it is nontoxic and environmentally friendly.

Erythritol is a very promising phase change material for higher temperature thermal storage having a melting point of 118°C. However, a major disadvantage is its water solubility. Waste gas from the exhaust of power generation units, especially while using biogas contains significant amounts of water vapour. This would therefore limit the direct heat exchange between the PCM and the waste gas or the hot exhaust. One of the alternatives in this regard is to use thermal oil as the heat exchanging medium. The hot gas would exchange heat with the thermal oil, which would then heat up the PCM during charging. During release of heat, i.e., discharging, the heat would be released to the point of demand via the thermal oil, thus preventing direct contact of the PCM with potentially adverse environments.

However, this would require the thermal oil to be maintained as a circulating flow between PCM and the heat source/demand. Thus, additional heat exchangers and expansion systems for oil would be necessary, increasing the design complexity and decreasing system efficiency. Furthermore, the exhaust gas temperature of 340°C necessitates the selection of thermal oil, capable of withstanding high temperature, often increasing the system cost further. The thermo-physical properties of PCM and thermal oil is shown in Table 1.

4.2. Container design

Different configurations of the Erythritol based M-TES storage systems exist [1]. Cylindrical and cubical containers are mostly studied, and implemented on pilot scale, by Kaizawa et al [17] and Guo et al [7] respectively. Nevertheless, direct contact cubical containers have been shown to provide a superior performance with respect to storage efficiency and modularity in operations. A cubical container, containing 66.3% by mass of Erythritol and 17.2% by mass of Thermal oil in direct contact was hence considered for the case study and represented conceptually in Figure 2. The remaining mass is made up of the shells, pipes and the container enclosure of the M-TES system. During charging of the container, heated thermal oil is pumped through the holes below the inlet pipeline which heats the PCM and melt them. As the heated oil melts the PCM, channels are created through which the lighter oil rises and subsequently melts more of the solidified PCM [17]. To facilitate the beginning of the heat charging, thin pipe connections between the inlet pipe and outlet pipe could enhance the melting of the solid PCM around these pipes by acting as fins. However, subsequent experiments are necessary to assess the overall benefit of the design modification.

Table 1: Thermo-physical properties of Erythritol and Thermal Oil [7, 16]

Parameter	Unit	Erythritol (PCM)	Thermal Oil
Specific heat	(kJ/kgK)	1.35 (at 20°C) 2.76 (at 200°C)	1.86 (at 140°C) 2.02 (at 200°C)
Latent heat	kJ/kg	339	–
Melting point	°C	118	–
Density	kg/m^3	1480 (at 20°C) 1300 (at 200°C)	915.3 (at 200°C)

Due to lighter weight, thermal oil floats on top of PCM when the container is fully charged. During discharge, heat is released by flowing the thermal oil in the same direction, and hence solidifying the PCM. However, channels are created due to the flow of the thermal oil within the PCM while solidification, which are then used in subsequent charging cycle to re-melt the PCM.

The heat of the proposed M-TES container is attributed by the latent heat of fusion of PCM; the sensible heat of PCM and the sensible heat of Thermal Oil as described in equation (1) [7].

$$Q = m_{PCM} * L_{fus_{PCM}} + m_{PCM} * C_{p_{PCM}} * \Delta T + m_{oil} * C_{p_{oil}} * \Delta T \tag{1}$$

where, m_{PCM}, is the mass of the PCM, $L_{fus_{PCM}}$ is the latent heat of fusion of the PCM, $C_{p_{PCM}}$ is the specific heat capacity of the PCM and ΔT is the temperature difference of the charged and the discharged phase of the storage. m_{oil} and $C_{p_{oil}}$ are the mass and specific heat capacity of the thermal oil respectively. The container was proposed to be charged to 200°C to utilize the high temperature of exhaust as sensible heat, even though this would result in higher temperatures of exhaust towards the end of the charging cycle. Based on the thermophysical properties of Erythritol and Thermal oil as shown in Table 1, a net heat storage capacity of 756 MJ/m^3 or 0.21 MWh/m^3 of the M-TES container was obtained.

Nevertheless, solidification of the PCM at 118°C prevents the recovery of the sensible heat stored at lower temperatures due to the blockage of holes of the inlet pipe for oil flow. Mathematically, this results in a loss of 20% of the stored heat. Experiments have revealed that the container shape, the temperature of heat use, rate of discharge, types of heat transfer are crucial factors with the maximum utilizable heat stored typically varying between 60 to 80%. [17] [7]. Considering an average overall system discharge capacity of 70%, along with 10% auxiliary losses, net system efficiency of 63% can be obtained. This would result in a usable heat storage capacity of 468 MJ per m^3. The storage efficiency can, nevertheless, be improved through innovative container design like implementing thin connecting tubes between inlet and outlet pipes of container, however, subject to experiments.

4.3. Container sizing

The number of trips (N) over a period t, can be generically represented in terms of individual container energy storage volume V_d (m^3), heat demand at user site over the period t, Q_d (MWh) and the specific usable heat capacity of the container, as per equation (2),

$$N = \frac{Q_d}{0.13 * V_d} \tag{2}$$

where 0.13 MWh or 468 MJ is the useable heat stored per m^3 within the container.

Effectiveness and time for charging and discharging, are few of the limits to the size the container. Additional constraints exist for the allowable size and volume of a container on road [7] based on available road facilities to transport heavy and bulky containers and road permit. As per local policy documents, the maximum permissible axle-load is 11.5 tonnes [18]. This would limit the maximum payload of a 12m container to 20.3 tonnes for a typical two axle tractor with a 13.6 m trailer and to 28.3 tonnes for a typical three axle tractor [19]. For a 6m long container the load decreases to 10.5 tonnes and

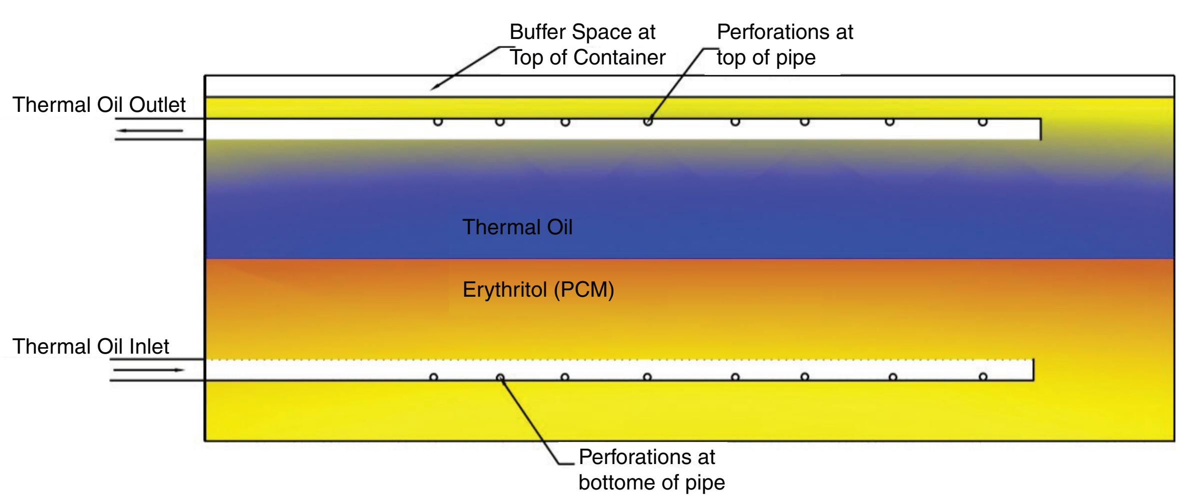

Figure 2: Simplified layout of the M-TES Container

15.9 tonnes respectively for the two types of trailer trucks respectively [19]. Accordingly, a summary of four scenarios based on truck sizes was developed as represented in Table 2.

The maximum transportable load of 28.3 tonnes, with a net stored heat of 4.06 MWh was obtained, of which around 2.56 MWh would be useable. As discussed, for a heat demand of 26 MWh per night, 11 trips per day would be necessary for OS A and 27 trips for OS D.

5. Operation strategy and social integration

Charging time plays the technological limiting role to the frequency of the number of cycles. Available waste heat rate is 400 kW. As discussed, a container entering the charging station in steady state operations would require only the usable heat fraction to be recharged. For OS A and OS C, for example, the need to recharge 2.56 MWh and 1.44 MWh would ideally require around 7 hours and 3.6 hours respectively. However, experiments revealed that, the rate decreases considerably for indirect contact heat exchange systems, increasing charging time further [17]. Moreover, to increase the final temperature to 200°C, the exhaust gas needs to be released at higher temperature to avoid temperature cross-over in the heat exchanger, lowering the available heat rate and further increasing the charging time. This would limit the number of trips per day to maximum two and four for OS A and OS C respectively.

To integrate the M-TES system into the tourism industry, multiple considerations are necessary. Use of latest state-of-the-art heavy-duty diesel trucks in accordance to EU regulations, would ensure minimization of emissions of fine particulate matters and different oxides of nitrogen, collectively called NOx [20, 21]. System design improvements to ensure minimum noise during operation is crucial as well. These are essential for social acceptance of heavy-duty trucks within the resort premises. However, to avoid conflict with the perception of the people, mostly tourists, thereby increasing acceptability by hoteliers as well, intelligent scheduling is most crucial. essential. A minimum discharge period of a single container was considered as two days to limit the vehicle movement within the resort area

Table 2: Thermal energy storage capacity of M-TES Container as per weight

Operation System (OS)	Unit	A	B	C	D
Container mass	t	28.30	20.30	15.90	10.60
PCM mass per container	t	18.76	13.46	10.54	7.03
Oil mass per container	t	4.89	3.5	2.73	1.82
Net Stored Heat Energy	MWh	4.06	2.91	2.28	1.52
Useable Heat Stored	MWh	2.56	1.83	1.44	0.96

Table 3 shows the number of person-nights that the M-TES container can cater, based on two different durations of the operation cycle and an average demand of energy for hot water per person-night of 6.53 kWh. For a typical summer hotel in the studied region, with an operation spanning 184 days (01 May to 31 October), a 2-day cycle would thereby ensure a maximum supply of 235.5 MWh of waste heat (OS A) per container per year. However, the maximum utilizable waste heat available increases to 374 MWh per container per year (OS A) for yearlong operations. In fact, the yearlong operation is limited to the source of waste heat, with the biogas CHP typically operating for 7,000 hours, equivalent to approximately 292 days.

In comparison to a 2-day cycle, a 7-day cycle would lower the number of persons-nights served from a single container, and hence a lower utilization of the waste heat. This in turn would lower the economic returns. Thus the seven day scenario was not pursued in the following arguments in this work.

The occupancy of hotels plays a crucial role as well, in the operation of the M-TES system. Discharging schedule through various operation strategies is possible to ensure the operation period of two days. Peak load substitution is an effective strategy for energy conservation, also resulting in economic benefits. For containers unable to meet complete energy demand of DHW, operation strategy to ensure peak load substitution was suggested. Indeed, such considerations would

Table 3: Thermal energy savings for hot water per M-TES container and possible operation strategies

System	Unit	A	B	C	D
Useable Heat Stored	MWh	2.56	1.83	1.44	0.96
Days in continuous Operation		2			
Daily heat energy supplied	MWh	1.28	0.92	0.72	0.48
Person equivalent of Demand per night	No. of Guests	196	140	110	74
Days in continuous Operation		7			
Daily heat energy supplied	MWh	0.37	0.26	0.21	0.14
Person equivalent of Demand per night	No. of Guests	56	40	32	21

directly benefit the proposed M-TES systems to be coupled to Solar Thermal systems for DHW in hotels. Often electric or oil-fired boilers are employed in addition to the solar thermal collectors to maintain a stable hot water system, especially at peak load periods. However, with adequate system sizing and scheduling, the M-TES system could replace such conventional boilers, enabling a complete substitution of traditional boilers in typical hotels and summer resorts as this study proposes.

The percentage share of the full load demand met by the OSs based on the occupancies, is presented in Figure 3 for an average hotel in the present case study. A larger system, even though, would ensure higher substitution of energy demand, would result in longer running days in off-peak seasons with lower occupancy. This would reduce the potential of heat utilized and increase the complicacies in system operation and changes in operation schedules with occupancy. At 30% occupancy, typically occurring at the beginning or end of a tourist season, it would take 3.3 and 2.3 days for OS A and B respectively to discharge as per the specific case study. Smaller systems, on the other hand, would be able to cater a very high share of DHW demand at lower occupancy rates (92% by OS C at 30% occupancy) without a change in the 2-days container change schedule, even though discharging schedule would vary nonetheless.

5.1 Scheduling of container change

The daily peak of DHW, typically occurring in the morning and around evening for an average European hotel [14], constraints the container change-over period. Midnight to early morning hours or in the afternoon between 14.00 to 16.00 hours were found most suitable with minimum impact on the daily activity of the tourists and hotel operations. Therefore, to maximize the effectiveness of a two-day cycle, as discussed in the previous section, four discharge points at four hotels have been proposed, with the container movement being limited to two trips daily. With four discharge points and one charging point, a total of five containers would be put into service. A roster of the M-TES containers was developed between hotels and charging point. The rotation of the container charging and discharging was assumed to be uniform, subject to integration of the demand profile among the discharge points between hotels. Therefore, ensuring an intelligent change-over schedule, typically requiring about 30 minutes, based on the knowledge of DHW demand profile and occupancy, can potentially be performed without or minimum operation of hotel electric boiler, as shown in Figure 4.

The roster would begin by charging the containers numbered 1 and 2 on the Day 1, whereby, container 1 would be set at discharge point 1 in the afternoon. On the second day containers 3 and 4 would be charged, while containers 2 and 3 would be set at respective

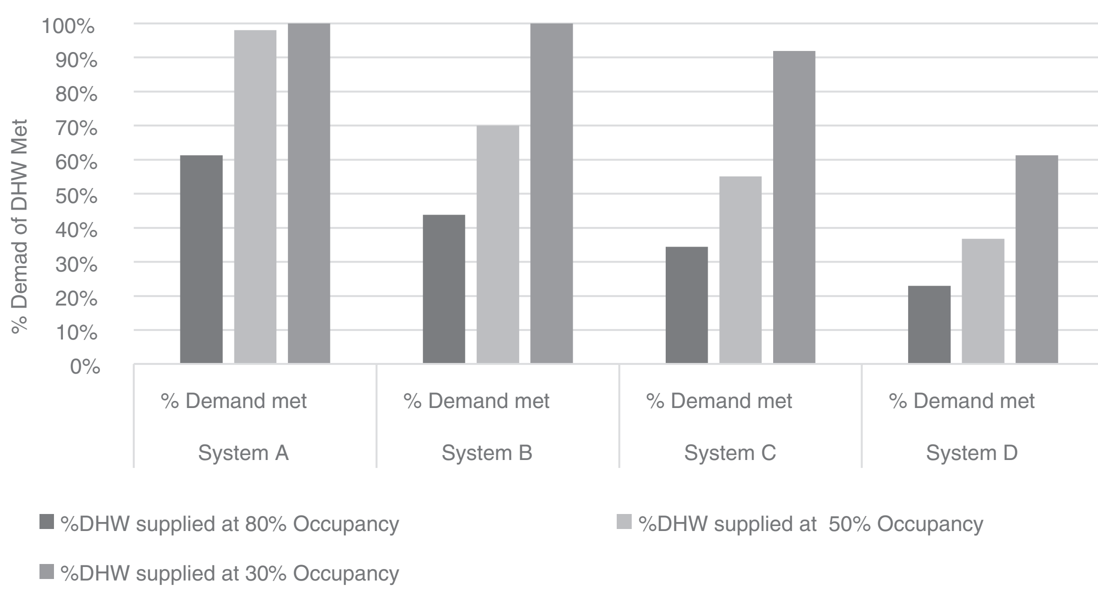

Figure 3: Percentage of demand met by the M-TES container for an average hotel of capacity 400 person, based on occupancy and proposed operation strategy

discharge points. On Day 3 morning, container 4 would be set to discharge, and therefore, all four discharging points would be occupied. On the afternoon of the third day, container 5 would replace container 1 at the first discharge station and the roster cycle will continue accordingly.

5.2. Integration with the existing system

The scheme of integration of the containers to the waste heat source (charging point) and DHW network of the hotels (discharging point) is shown in Figure 5. As mentioned above, an indirect contact heat exchanger has been considered with Thermal Oil. A buffer oil tank is necessary at both the charging and discharging points prior to the exhaust-oil and water-oil heat exchanger to compensate thermal expansion and contraction of oil. This also requires the discharge points to be adjacent to the hotels, specifically, boiler rooms to reduce heat loss and minimize construction cost of the connecting materials. Existing boiler would be required to meet the demand based on operation schedule of the containers, occupancy and during shifting of containers.

Being a replacement of electric boilers for DHW generation, operating five containers would yield considerable savings in electricity consumption, however, subject to occupancy. A summary of the net savings obtained in three different operating conditions is listed in Table 4. As discussed, for larger OS_s, and with lower occupancy, inability to discharge in two days would result in a lower electricity being saved than its true potential.

Table 4: Electricity savings for multiple operation scenarios of the five container M-TES syste

Description / Operation System	A	B	C	D
Energy Saved in seasonal operation with 80% occupancy	992	709	558	372
Energy Saved in yearlong operation with 80% occupancy	1574	1125	885	590
Energy Saved in seasonal operation with 30% occupancy	576	576	558	372

6. Carbon dioxide savings

The heating substituted was from electric boilers with an average efficiency of 95%. The specific emissions of the low voltage electricity consumed in Bulgaria is 669 grams

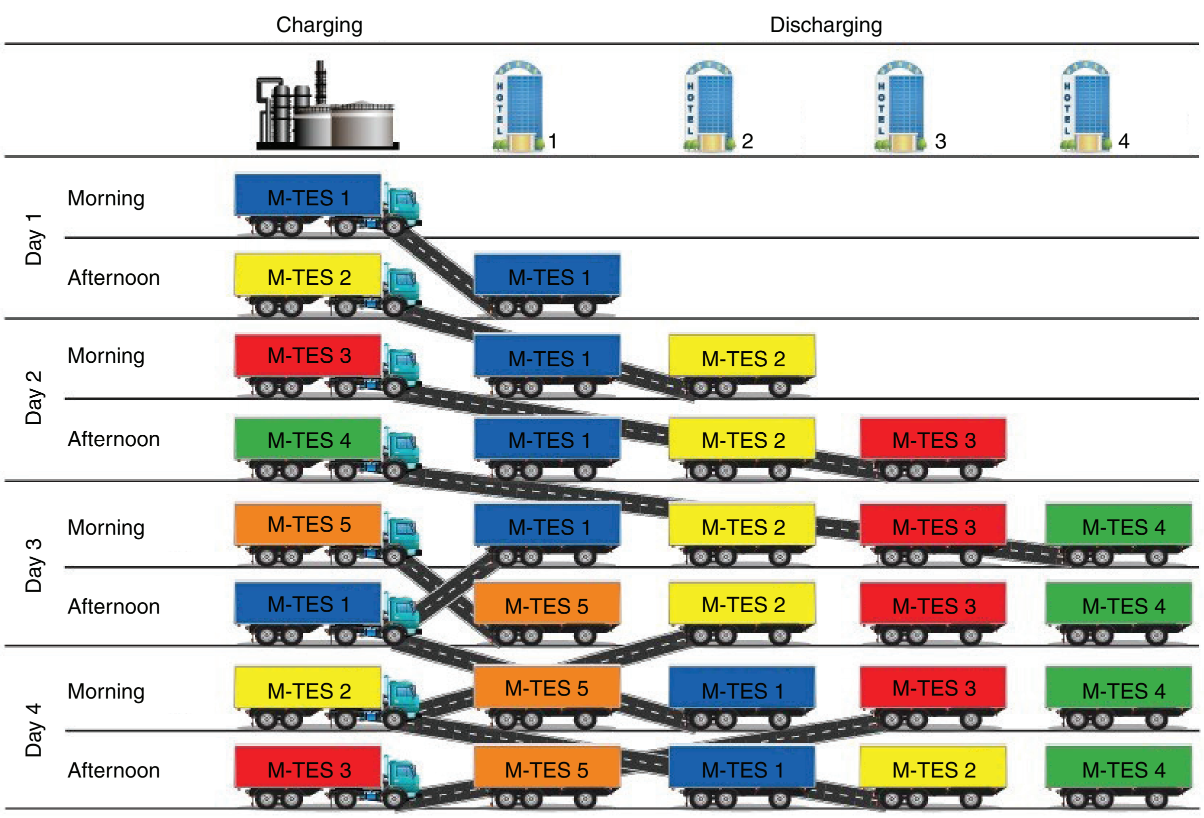

Figure 4: Roster of thermal containers and Scheduling for a 2-day cycle operation with 5 containers

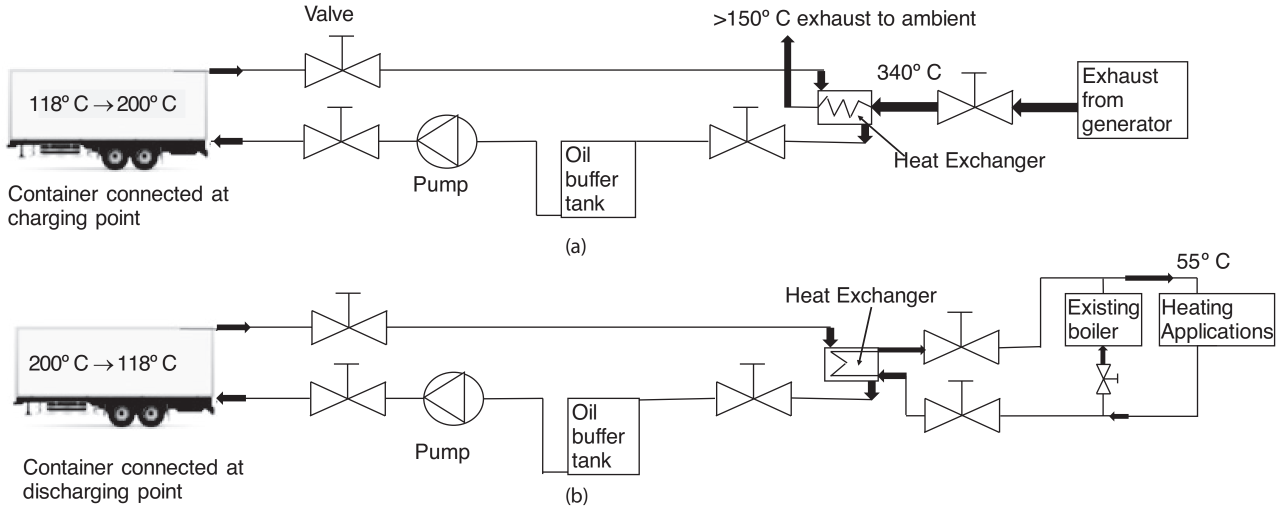

Figure 5: Integration of container (a) Charging of container at biogas power plant (b) Discharging of container at hote

CO_2/kWh [22]. The waste heat from biogas was considered carbon neutral. The primary emissions from operating the system is related to the emissions from the transport of the M-TES container. A typical truck emits 100 g CO_2 per tonne-km [21]. Neglecting emissions from auxiliary consumption of electricity, a saving of 96.7% of CO_2 emissions was obtained based on the energy mix of Bulgaria. With increase in the renewable mix as per the national and EU targets, the grid emission factor could be predicted to decrease with much confidence. Considering the EU-28 average grid emission factor of 447 grams CO_2 /kWh [22], 95.3% CO_2 emissions could be reduced still. Sweden has the lowest grid emissions at 47 grams CO_2 /kWh [22]. Such a low grid emission factor would also result in a net CO_2 saving of over 53%. On the other hand, considering an increase in the average emissions of the trucks to the 2014 EU average of 140 grams-CO_2 /tonne-km [23], the net CO_2 emission reduction would be 95.6%. Thus, a rise in the truck emissions by 40% would cause the overall CO_2 emission benefits to reduce by only around 2%. Therefore, it can be concluded with fair confidence, that comprehensive savings in the CO_2 emissions can be achieved by the M-TES system over electric boilers in the foreseeable future.

7. Economic assessment

The upfront costs of the PCM (Erythritol), thermal oil, the balance of the plant, including pipes, pumps, heat exchangers, valves, were obtained from literature [9, 17].

Table 5 Capital cost of one M-TES Container for the hypothesized systems

Description	Cost (“1000 €)			
Operation System	A	B	C	D
PCM	60	43.1	33.7	22.5
Thermal Oil	13.8	9.9	7.8	5.2
Steel Plate and Pipes	2.9	2.0	1.6	1.1
Total	76.7	55	43.1	28.7
Capital cost of balance of plant per container				
Pumps	1.6	1	1	0.8
Heat Exchangers	3	2	2	1.8
Valves and Pipe Fittings	2	2	2	2

Both PCM and Thermal oil were considered to cost 3,200 €/tonne; while the cost of steel was 589 €/tonne [7]. An additional 5% cost was accounted for the cost of insulation, material transportation and other miscellaneous charges. A summary of the cost of OS A, B, C and D have been presented in Table 5.

An average cost of 15,000€ per charging and discharging station was calculated. A significant cost of the charging station was that of the heat exchanger. 17,000€ was considered for the cost of transportation truck [24]. One truck would be sufficient to handle 5 containers while simultaneous operation of 2 trucks would be needed for 10 containers. The number of containers had been varied to provide a perspective on the total CAPEX as well as the economy of scale with increased number of containers. This is because, even though the cost containers as well as that of the discharging station would increase linearly, only one charging station would be necessary. Thus, the specific CAPEX per container would be reduced with an increased number of containers. The overall upfront costs, of OS A, B, C and D, based on the number of containers operated is shown in Figure 6.

The operation costs of the system comprise the cost of transportation, labour, waste heat and auxiliary electricity [24]. The waste heat was assumed to be available for free, since it is presently wasted. Two trips would be performed per day, each being 1.5 hours long. Thus, only three hours of employment of truck drivers would be needed each day, who would also be responsible for setting up the connections necessary for charging and discharging. In addition, no operation scenarios would require more than 292 days of operation per year. Furthermore, the monitoring activities of the charging and discharging stations could be done by existing personnel at the power plant and the hotel. Considering contractual agreement of three hours per day of employment to be made, a high end cost of labour was assumed at 8,000 €/year, including extra cost for night work as per the local labour laws [25]. Cost of diesel was considered as 1€/litre [26] with a fuel efficiency of 28 litres per 100 km for heavy duty trucks [27]. A summary of the total operation costs for seasonal operations of the four OSs with 5 containers in operation is provided in Table 6.

Generated income was based on the savings of electricity consumption from electric boilers. The electricity tariff obtained from the bills of the hotels of Albena was 99.4 €/MWh. Other assumptions made for the necessary financial evaluations are as follows:

Corporate tax: 10% [28]; Debt Equity Ratio: 70:30; Inflation rate: 3%; Tax holiday period: 0 years; Project Lifetime: 20 years [7]; Increase of OPEX per year: 2%; Increase in Electricity price per year: 1% [29].

The discounted clash flow of the different OS_s corresponding to three different scenarios of hotel operation and occupancy rates is shown in Figure 7. The Net Present Value, calculated as the cumulative cash flow over the project life of 20 years was obtained negative to very low for OS D, rendering the system economically infeasible. With yearlong operation at high occupancy, larger systems provide a superior economic performance. However, a significant drop of system economic competence for large systems was noticed at lower occupancy rates. The payback periods of OS A, B, and C were obtained as 9, 12 and 14 years for seasonal operations and 5, 6 and 7 years for yearlong operations with average occupancy of 80%. However, for a seasonal hotel with an average occupancy of 30%, in the present case study, the payback periods of OS A, B and C would be 19, 14 and 14 years respectively. Hence, a smaller system would provide superior economic resilience to occupancy, even though the payback period is relatively longer for higher occupancy rates.

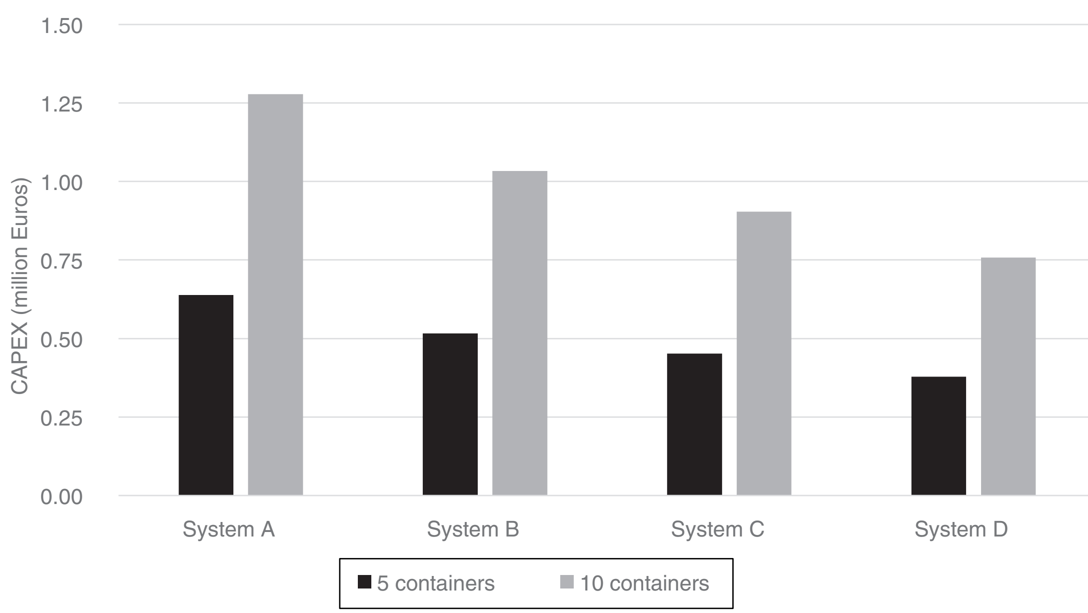

Figure 6: System CAPEX for different containers used

Table 6 OPEX Components of the different M-TES System with 5 containers for seasonal operations

Description / Operation System	A	B	C	D
Manpower costs (€/year)		8,000		
Cost of diesel for transport		2,100		
Costs auxiliary energy @ charging (€/cycle)	1,629.63	1,164.93	916.67	611.11
Costs auxiliary energy @ discharging (€/cycle)	952.86	681.14	535.98	357.32
Other aggregated Costs (€)		1,000		
Net Annual OPEX	13,629.42	12,946.07	12,552.63	12,068.43

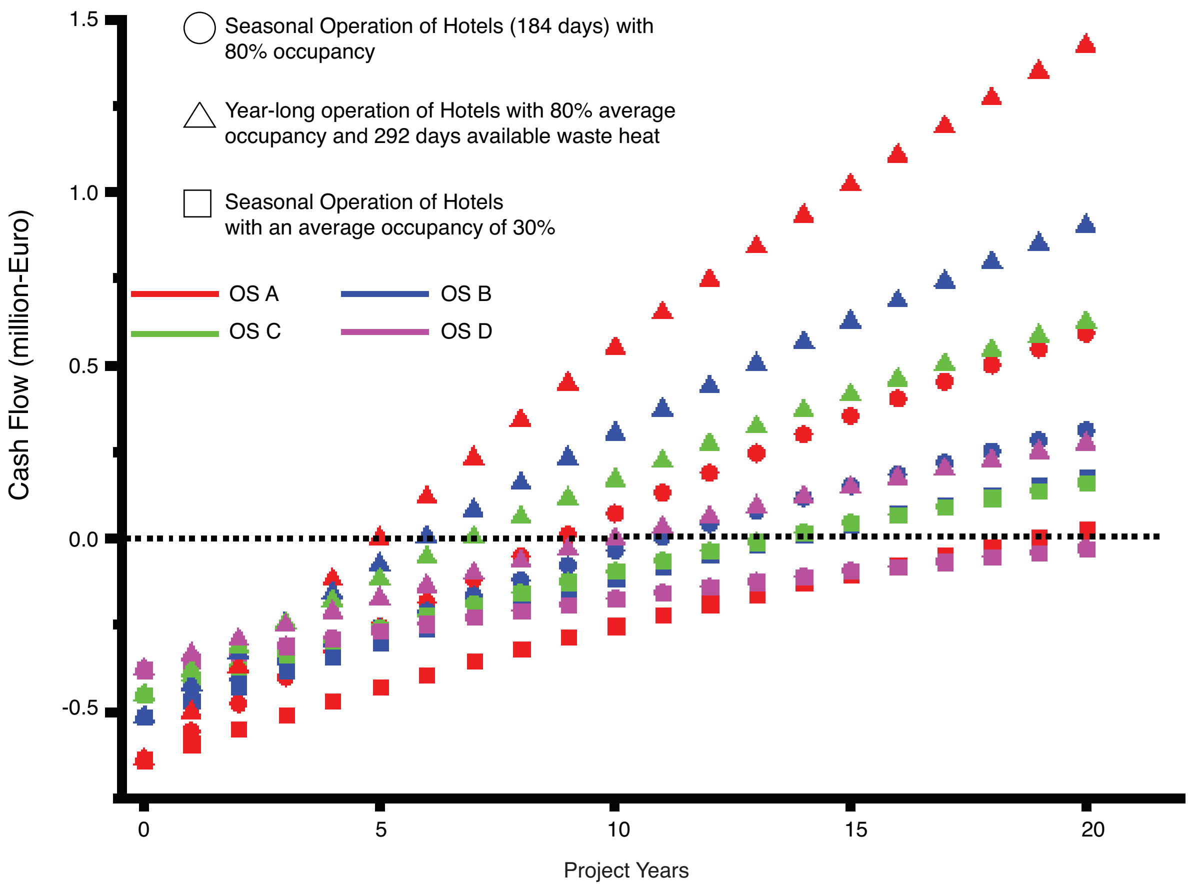

Figure 7: Project Cash Flow Diagrams for three different Scenarios: Seasonal Operation of Hotels (184 days) with 80% occupancy; Year-long operation of Hotels with 80% average occupancy and 292 days available waste heat; and Seasonal Operation of Hotels with an average occupancy of 30%

To assess the impact of the different factors, a sensitivity assessment was performed on the OS C, operating during summer with 80% occupancy. NPV, evaluated assuming a discount rate of 3% was selected as the factor for comparison. Five factors, namely, debt fraction, discount rate, fixed CAPEX and OPEX and electricity price were increased and decreased by 25% to study the percentage change in the resulting NPV. The results are indicated in the following Figure 8.

Electricity price is the most dominant factor affecting the economic viability of the proposed M-TES system. With a 25% rise in the electricity price, the NPV is found to increase by almost 800%, a 9-fold rise. Thus, with the predicted rise in the electricity costs, the M-TES system

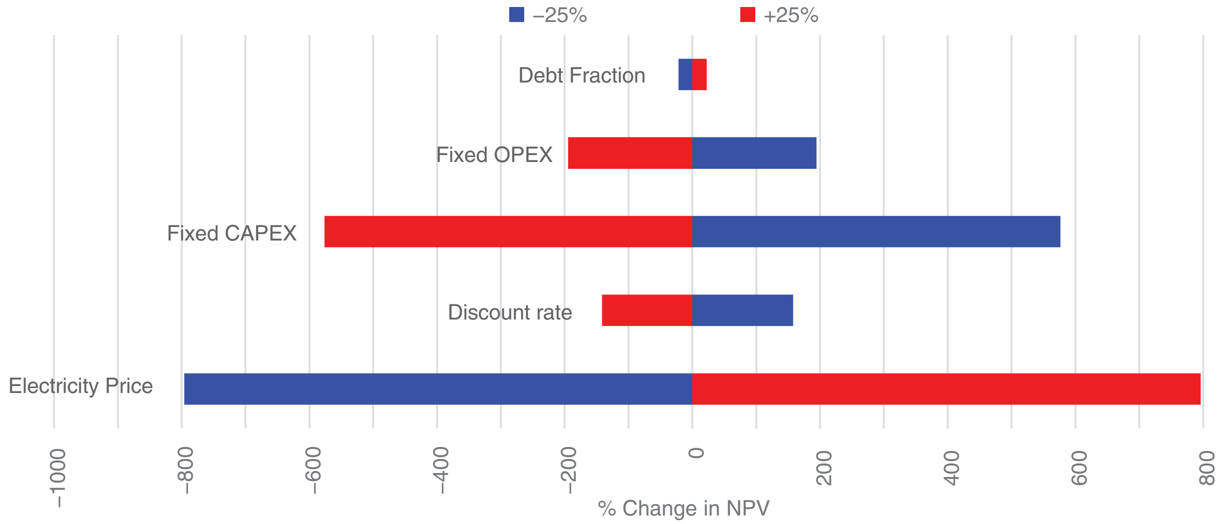

Figure 8: Sensitivity Assessment of five parameters including debt fraction, discount rate, fixed CAPEX and OPEX and electricity price on the NPV of OS C operating during summer months with 80% occupancy. The base value of the parameters are as follows: Debt fraction: 30%; Discount rate: 3%; Fixed CAPEX: –4,51,973.60 €; Fixed OPEX: 12,555.51 € for the first year; and Electricity price: 99.4 €/MWh;

would be of significant economic gain. Fixed CAPEX is the second most dominant economic factor. A change of almost 600% in the NPV was found from 25% variation of the CAPEX. The corresponding changes from OPEX and discount factor would be 200% and 150% respectively. Debt-Equity ratio however is the least effective financial parameter. Therefore, apart from the debt-equity ratio, the system economics is vulnerable to changes in most of the economic parameters, however to the highest extent by electricity price.

Acceptance of the proposed M-TES technology could be further increased by providing financial incentives to the CHP plant operators for providing high temperature waste heat. However, this would increase the OPEX and hence decrease the economic returns of the proposed system. Indeed, for summer operations at 80% occupancy for OS C, a waste heat price of 15 €/MWh and 18 €/MWh would raise the payback to 19 and 20 years respectively from that of 14 years without any cost of heat. On the other hand, for yearlong operations at 80% occupancy, a waste heat price of 45 €/MWh could be afforded for a payback period of 20 years. Increasing the number of cycles or increasing the days of operation are therefore crucial to realize improved financial benefits, as well as greater acceptance of the proposed system.

8. Conclusion

In this paper, a practical application to the M-TES system was developed using techno-economics and social integration strategies within the tourism industry. A complete scheduling with charging and a two-day discharging cycle for 5 containers was proposed. The occupancy of hotels is a key factor for system design and economic success, where, lower occupancy rates would render large systems economically incompetent. A 15.9 tonne container was found to provide considerable savings with acceptable financial returns, besides being able to maintain a constant container changeover schedule over large variation of occupancy. Net savings of 558 to 885 MWh per year of heat generation from existing electric boilers were obtained with a payback period of 7 years for yearlong operations and 14 years for summer operations. A net CO_2 savings of 96.7% from substitution of electric DHW boilers could be achieved. Economic barrier due to initial investment cost, especially for seasonal performance made the focused case challenging with a high payback period. However, authors are confident enough to find better economic performance with improved container design, increased operation days and number of trips of container truck, as well as policy instruments like carbon credits. Indeed, with the predicted rise in the electricity prices, the economic benefit from the system would be much increased.

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