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Techno-economic assessment of mobilized thermal energy storage for distributed users: A case study in China

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HIGHLIGHTS

- Analyzing the matching method of the M-TES with existing heating system.
- Discussing the operating strategies of the M-TES.
- Assessing the economy of the M-TES in China.

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ABSTRACT

The mobilized thermal energy storage (M-TES) system is a promising alternative to conventional heating systems to meet the heat demand for distributed users. This paper provided a techno-economic assessment of the M-TES system based on a case study in China. According to the analysis of the design specifications of the heating system, the suitability of matching the M-TES with existing heating systems was analyzed. The results show that the M-TES is appropriate for use with heating systems with a fan-coil unit and under-floor pipe. Containers and operating strategies for the M-TES with different transportation schemes were also designed. The maximum allowed load of the M-TES container is 39 t according to the discussion of transportation regulations on the road. The cost and income of the M-TES in the study case were estimated, and the net present value (NPV) and payback period (PBP) were also calculated. The best operating strategy is the use of 2 containers and 4 cycles of container transportation per day, with a PBP of approximately 10 years. The M-TES is applicable for middle and small-scale heat users in China.

1. Introduction

Energy savings and environmental protection are two key issues of common concern. Innovative solutions of reducing energy consumption and cuttings emission of greenhouse gases (GHG) are of great importance. As the second largest energy consumption category in China, residential energy consumption accounted for 11% of the total in 2014 [1]. As most of the energy consumed by residential buildings is used for space heating or domestic hot water, how to supply heat efficiently plays an important role in realizing environmental and energy targets.

In China, approximately half of the people live in rural communities [1]. However, due to the huge initial investment required, it is not economical to expand district heating (DH) networks to rural areas. Instead, small-scale heating systems based on fossil fuels are commonly used. Therefore, other alternatives that can supply heat efficiently and in an environmentally friendly fashion are needed. As a promising option for distributed users, mobilized thermal energy storage (M-TES) technology has been taken into consideration in recent years [2–5]. Without the limitation of networks, the heat can be conveniently obtained from various heat sources and flexibly transported to distributed users. This system can support the utilization of renewable energy such as geothermal, bio-energy, and solar energy.

To promote the utilization of the M-TES, investigations have been carried out in recent years. As the main component, materials have been selected and tested based on experiments. The polyhydric alcohol erythritol ($C_4H_{10}O_4$, melting point 118 °C, latent heat 339 kJ/kg) was suggested due to its good material thermostability

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and ability to use for medium and low-temperature thermal energy storage [6]. Studies on the M-TES with erythritol as a material have been widely conducted. The thermal and flow behaviors of erythritol in the M-TES container have been studied [5], as have the thermal energy storage and release performance [2,3,7]. Other types of materials, e.g., inorganic salts and composites, were also analyzed [8–11]. To optimize the structure of the M-TES container, experimental and numerical studies were carried out. Lab-scale test facilities were designed to compare the performance of the M-TES with a direct/indirect contact thermal energy storage container [12]. Methods of container optimization by increasing the flow rate of the thermal oil, creating channels before charging and adding wall heating were discussed [3,13]. To evaluate the charging of the M-TES at the heat source site, the integration of a combined heat and power (CHP) plant with the M-TES was analyzed [4]. As shown by the above literature, many studies on the characteristics and performances of the M-TES on the lab scale have been performed. However, more work on the technological and economic feasibility of the M-TES is necessary to promote its application. Our previous study presents work on the system economic assessment in Sweden [14] and provides guidelines for the system improvement and identification of the key issues. Nevertheless, it is not applicable to the M-TES projects in China due to the different energy market and national policies. Additionally, the design codes for heating systems in China and Sweden are different. The purpose of this paper is to evaluate the prospect of harnessing the M-TES in China.

The paper is structured as follows. First, the study case and the concept of the M-TES were described. Second, the matching of the M-TES with existing heating systems was studied. Third, operating strategies (OS) with different transportation schemes were analyzed. The M-TES container was designed based on an experimental study. Fourth, the cost and income of the M-TES in the study case were estimated. The analysis of two capital budgeting indexes, i.e., net present value (NPV) and payback period (PBP), were undertaken. Finally, conclusions were drawn in the end.

2. Description

2.1. Study case

A six-story residential building with an area of 6500 m^2 in the north of China was chosen as the heat user. The heating load per square area is given as 65 W/m^2 [15]. The total heating load of the study case is calculated as 422.5 kW during the 180 days of the heating period. The exhaust steam generated from a local coking plant is utilized as the heat source. The parameters of the exhaust steam are a pressure of 0.361 MPa, a temperature of 140 °C and a flow of 10 t/h [16]. The distance between the coking plant and user is approximately 13 km.

2.2. M-TES system

The M-TES system consists of heat source, end user, container, vehicle, heat exchanger, pump, valve and other fittings. The M-TES container is transported to the heat source site, e.g., a power plant, steelwork or coking plant, and charged with the industrial waste heat. Using latent thermal energy storage (LTES) technology, the heat can be stored in the M-TES container. The operating process of the M-TES system is described as follows: first, the container is charged with waste heat at the source site. Then, it is conveyed to the distributed heat users by a vehicle and releases heat for space heating or domestic hot water usage. After the release, the container is transported to the heat source site for the next heat supply. The M-TES system is illustrated in Fig. 1.

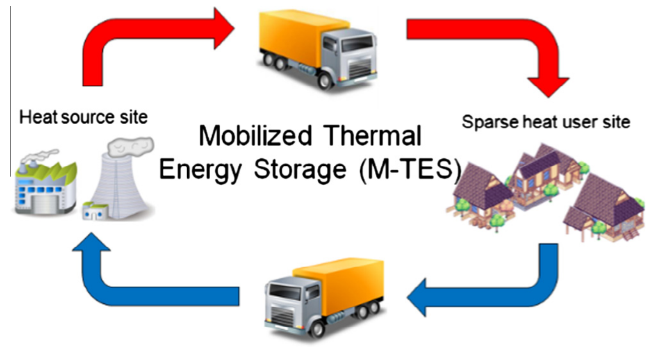

Fig. 1. Diagram of the M-TES system.

In our previous study, erythritol was chosen and studied as a promising PCM candidate for the M-TES system due to its large latent thermal energy (330 kJ/kg) and appropriate melting temperature (118 °C) for most heat sources [2–4]. Moreover, as it is used as a food additive, it is nontoxic and environmentally friendly. Therefore, erythritol is used as the PCM for the M-TES system in this study. Because erythritol is soluble in water, the steam cannot be used to heat the erythritol directly. Instead, a thermal oil is employed for the heat transfer. The thermo-physical properties of erythritol and the thermal oil are listed in Table 1.

3. Matching with existing heating system

At the user site, the M-TES container is used to heat the return water of the existing heating system. However, because of the solubility of the PCM solution, the return water cannot be heated directly by the M-TES system, but an oil-water heat exchanger is instead installed. An oil tank is set in the circulating loop in case of oil expansion.

The radiator, fan-coil unit and under-floor pipe are the common endpoints of heating systems. According to the relevant design specification of China, GB50736-2012, the temperatures of the supply water at the above three ends must be 75 °C, 50 °C and 45 °C, respectively [17]. However, it is hard to maintain the water temperature during the whole discharge process because of the instability of the heat release. Thus, for a heating system with a radiator, the return water shall be heated first by the M-TES system, and then a boiler is needed to heat the return water up to the required temperature. Due to the extra cost and GHG emissions of the boiler, this matching method is not recommended or studied in this paper.

For the system with a fan-coil unit or under-floor pipe, the return water can be heated easily to the required temperature and pumped to the heating system directly. To stabilize the water temperature, a mixing valve is employed to mix the return and

Table 1
Thermo-physical properties of the PCM and the thermal oil [3].

Parameters	PCM	Thermal oil
Density (kg/m^3)	1480 (at 20 °C) 1300 (at 140 °C)	778 (at 140 °C)
Specific heat (kJ/kg °C)	1.35 (at 20 °C) 2.74 (at 140 °C)	2.36 (at 140 °C)
Latent heat (kJ/kg)	339	–
Melting point (°C)	118	–
Viscosity (kg/m s)	0.02895 (at 20 °C) 0.01602 (at 140 °C)	0.003 (at 140 °C)
Thermal conductivity (W/m K)	0.732 (at 20 °C) 0.326 (at 140 °C)	0.125 (at 140 °C)