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Exergy analysis of thermal energy storage in a district energy application

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ABSTRACT

The role of thermal energy storage (TES) in district energy (DE) system is assessed. The Friedrichshafen DE system is considered as a case study and exergy analysis is utilized. The TES is designed to complement and to increase the effectiveness of the solar panels included in the district energy system. The TES stores the surplus solar energy until is needed by thermal energy users of the Friedrichshafen DE system. The results quantify the positive impact of the TES on the performance of the Friedrichshafen DE system, and demonstrate that the overall energy and exergy efficiencies of the TES are 60% and 19%, respectively. It is also shown over an annual period that the temperature, energy, exergy and energy efficiency of the TES exhibit similar trends and that the TES exergy accumulation and exergy efficiency exhibit similar trends.

1. Introduction

Environmental issues are receiving increasing attention in recent years. For instance, increasing greenhouse gas (GHG) emissions are increasing the concentrations of such gases in the atmosphere and are considered to be causing climate change [1]. Many approaches have been tried to address these environmental problems, including some that involve improved use of energy resources. Energy use patterns, from individual to societal levels, have been modified in two main ways: replacing existing sources of energy and increasing the sophistication of energy use, including increasing efficiency and reducing waste.

District energy (DE) is an energy technology that offers many advantages for society [2], and research has been ongoing to enhance DE technology and improve its efficiency. DE can utilize recycled or waste thermal energy, as well as renewable energy sources. Rezaie and Rosen [3] have recently reviewed DE technology and its potential. Andrepont [4] stated that using DE in conjunction with other energy technologies enhances overall system efficiency. Energy technologies that can be integrated with DE include combined heat and power, on-site or distributed generation, thermal energy storage, multi-fuel heating, electric and non-electric chilling, and "free" cooling using deep lake water and other such sources.

Thermal energy storage (TES) can enhance the performance of DE significantly. Much research has been reported which shows the impact of TES in DE systems [5–8]. Here, a case study is used to assess thermodynamically the role of TES in a DE system that uses solar energy and fossil fuel. The case study considered is the Friedrichshafen DE system in Germany. The TES stores the surplus solar energy until is needed by thermal energy users of the system. Using solar energy allows the DE system to use significantly less fossil fuel than would otherwise be the case. Seasonal TES, which normally requires significant thermal insulation to adequately reduce thermal losses, is used in the DE system. Large-scale and long-term thermal storage is typically more cost effective than small-scale TES [9]. Originally, the Friedrichshafen DE system used only natural gas boilers. When a second residential area was added to the user base, solar thermal flat panels were added to provide energy for the whole thermal network.

The use and role of thermal storage in a district energy system is assessed considering the Friedrichshafen DE system. A thermodynamic approach utilized is based on exergy [10], which provides a useful tool for assessing energy systems in general and TES and DE systems in particular. The objective is to quantify the thermodynamic impact of the TES on the performance of the Friedrichshafen DE system, and to identify energy and exergy behavioral trends.

TES has been investigated previously with exergy or related methods. For instance, Bejan [11] used second law of

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thermodynamics to investigate TES, so to reduce the destroyed exergy and increase the stored energy. Also, Zubair et al. [12] performed a thermodynamic analysis of a sensible TES, and exergy analysis has been applied to TES by Rosen and Dincer [10,13]. This research extends those studies.

2. Analysis

The thermodynamic analysis of the TES in Friedrichshafen DE system is described. Energy and exergy balances are described and applied to the TES in the Friedrichshafen DE system. A simplified diagram of the Friedrichshafen DE system is presented in Fig. 1.

An energy balance for a thermal system can be written according to Rosen and Dincer [10,14] as:

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \quad (1)$$

where

$$\text{Energy output} = \text{Product energy output} + \text{Waste energy output} \quad (2)$$

Rosen et al. [15] describe exergy as a tool to evaluate and improve energy systems, by presenting more meaningful and useful information than the more conventional energy analysis. In particular, exergy analysis identifies true thermodynamic losses and efficiencies. Therefore, exergy analysis can help reduce thermodynamic losses in thermal systems like district energy systems. When using exergy analysis, an exergy balance is written for the overall system and its main components. A general exergy balance can be expressed as follows [10,14]:

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \quad (3)$$

where the exergy output can be broken down as:

$$\text{Exergy output} = \text{Product exergy output} + \text{Waste exergy output} \quad (4)$$

The TES considered in this paper stores solar energy when there is no demand for it. The TES releases the stored energy to the Friedrichshafen DE system when a large demand for heat exists. The TES volume is large (12,000 m^3). The temperature of the storage medium (water) varies spatially and temporally throughout the TES, but is assumed to be uniform spatially in this study. The exergy of the fully mixed storage (Ex_m) can be written as:

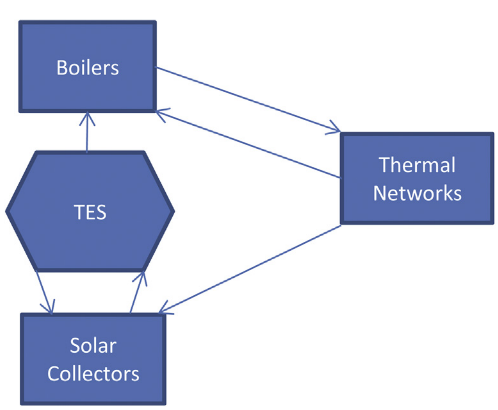

Fig. 1. Simplified illustration of the Friedrichshafen DE system, showing flows of energy.

$$Ex_m = E - m_{tot} C_p T_0 \ln(T_m / T_0) \quad (5)$$

where E denotes the energy for the fully mixed storage, m_{tot} the mass of water in the TES, C_p the specific heat at constant pressure of the storage medium, T_0 the reference environment temperature (taken to be the mean ambient temperature here), and T_m the fully mixed TES temperature, both temperatures are in absolute unit.

A TES generally has three operating stages [13]: charging, storing, and discharging. Energy and exergy analyses are now provided of the various stages for the TES in different seasons.

2.1. TES charging stage

Surplus energy from the solar collectors is input to the TES in the charging stage. A simplified illustration of the charging stage of the TES is provided in Fig. 2. The water with the lowest temperature, at the bottom of the TES, flows to the solar panels where it is heated and returns to the top of the TES where the temperature is highest.

The general energy balances in equations (1) and (2) can be expressed for the charging stage as:

$$\text{Net energy input} - \text{Heat loss} = \text{Energy accumulated in TES} \quad (6)$$

$$Q_{in-TES} - Q_{loss-TES} = \Delta U_c \quad (7)$$

Here, $Q_{in\text{-}TES}$ denotes the net energy input to the TES and $Q_{loss\text{-}TES}$ the TES energy loss. Also, ΔU_c denotes the energy accumulated in the TES during the charging, and can be written as:

$$\Delta U_c = m_{tot} C_v \Delta T_m \quad (8)$$

where ΔT_m denotes the TES average temperature difference of the TES water in a certain period of time (taken here to be a month) and C_v the specific heat at constant volume of the storage medium (4.19 kJ/kg K at 72 °C). Also, m_{tot} can be written as follows:

$$m_{tot} = \rho V \quad (9)$$

Here, T_m is the average temperature of the water in the TES, and tabulated in Table 1. With these data and equation (8), the energy accumulated in the TES can be estimated for every month.

The input energy to the TES in equation (7) can be evaluated with the monthly heat loss data in Table 1. Energy is transported to and from the TES with water. The mass of flowing water during charging can be written as follows:

$$m_c = \frac{Q_{in-TES}}{C_p (T_{in} - T_{out})} \quad (10)$$

where m_c is the mass of water transporting energy to the TES in the charging stage, T_{in} and T_{out} denote the TES inlet and outlet temperatures respectively, and other terms are as defined earlier.

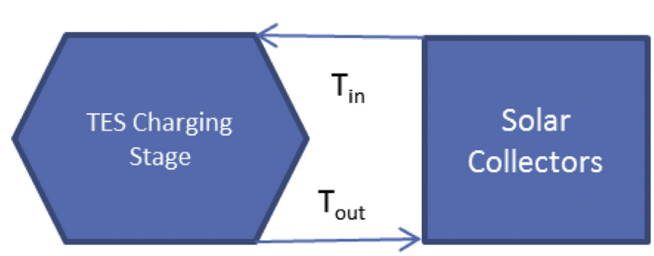

Fig. 2. Charging stage of the TES, where stored energy is provided by solar energy.