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ENERGY AND ECONOMIC PERFORMANCE OF DISTRIBUTED ENERGY SYSTEM INTEGRATED WITH THERMAL STORAGE SYSTEM

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ABSTRACT

The distributed energy system becomes increasing popular in recent years because it can realize the cascade utilization of primary energy and integrate with renewable energy, which is energy efficient and environment-friendly. Thermal energy storage system can supplement the absorption chillers or boilers to utilize the surplus cooling and heating energy so that the primary energy efficiency of the system can be improved. This study investigates the feasibility of distributed energy system integrated with thermal storage systems in hot summer and cold winter areas. The energy and economic performance of the integrated system is evaluated and compared with that without thermal storage system. The impacts of climates and building mix are analyzed. Results show that the improvement of the energy and economic performance by using the thermal storage system is limited. The primary energy efficiency of the distributed energy system is improved by around 2%. The payback period is more than 20 years.

Keywords: distributed energy system, thermal energy storage, energy saving; primary energy efficiency

1 INTRODUCTION

Distributed energy system (DES) can make full use of primary energy and integrate with local renewable energy to provide users cooling, heating and electricity with high energy efficiency and low greenhouse/pollution emissions [1]. It can work independently or be integrated with the grid, operated by following the electric load or following the thermal load. In the areas where the surplus electricity generated by the DES is not allowed to be sent to the grid, FEL method is usually preferred. When the DES works under FEL, the heat and cold energy recovered from the waste heat cannot always meet the cooling or heating load and surplus thermal energy may be wasted. Thermal energy storage (TES) system can be used to supplement the DES to make full use of the primary energy.

Many studies have been done on the DES integrated with TES (DES&TES) The DES&TES can serve different types of buildings. The energy, economic, environment or exergy performance of the DES & TES is evaluated and compared that without TES, considering different climate conditions or building types[2, 3]. The control strategy of the DES&TES is important to achieve high performance. Therefore, different control strategies are developed and studied to optimize system performance considering electric demand, thermal demand or state of storage tank[4]. In the design of the DES&TES, both static and dynamic models of the TES can be used and the impacts of different modeling methods are concerned[5].

Currently, the DES&TES is often used in a single buildings such as a restaurant[2], office building[6] or hospital[4] rather than at the community level. In addition, in the hot summer and cold winter areas, ground source heat pump systems can be an efficient alternative to supplement the DES. The DES integrates with TES and GSHP should be energy efficient (as shown in Fig. 1).

However, the performance is still needed to be investigated.

This paper therefore attempts to study the performance of the distributed energy system integrated with GSHP and TES based on a campus in hot summer and cold winter area of China, comparing with that without TES. The performance of the DES with and without TES is compared. The impacts of different climates and building mix are considered. The organization of this paper is as follows. The method and steps are presented in Section 2. In Section 3, a DES&TES serving the campus is introduced and designed. In Section 4, the energy and economic performance of the DES&TES is analyzed under the different climates and building mix. Conclusions are presented in Section 5.

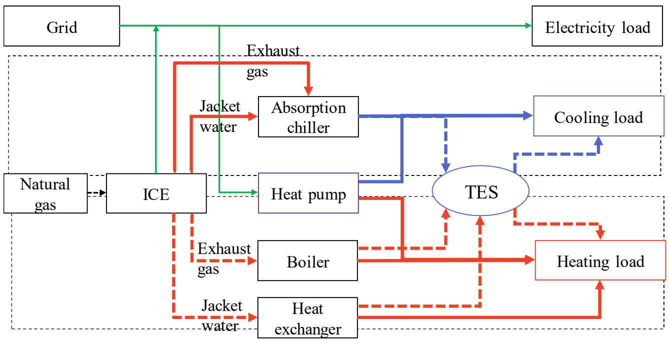

Fig. 1 The structure of DES&TES system

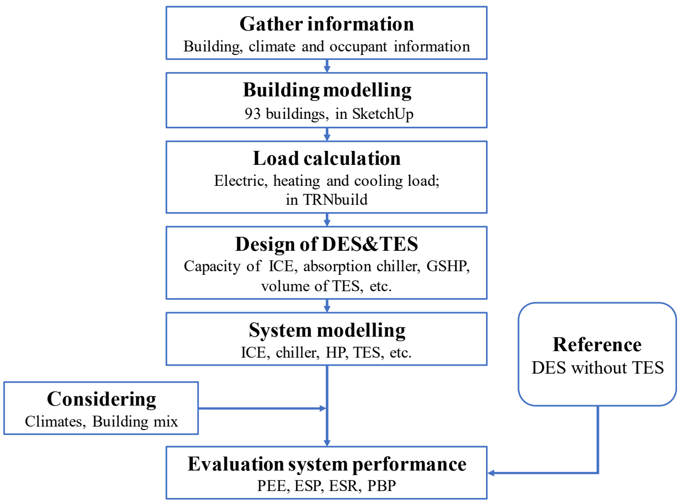

Fig. 2 Method of this study

2 METHOD

The method of this study is shown in Fig. 2. Detailed steps are explained as follows. Information about buildings, climate data and occupant schedule are gathered to establish building models and calculate electric, heating and cooling load. The capacity of equipment is designed by load results. The system and their equipment are established in TRNSYS18. Primary energy efficiency (PEE), Energy storage potential (ESP), Energy storage ratio (ESR) and Payback period (PBP) are used to energy and economic performance. When considering the influence of different climates, load coefficient k is used to change heating ang cooling load, where heat load is multiplied by coefficient k and cooling load is divided by coefficient k. Coefficient k in this study varies from 0.5 to 1.5. When considering the influence of different building mix, area ratio R of residential building to non-residential building is used.

2.1 System modeling

(1) Internal combustion engine

The mathematical model of ICE is based on Type 907 in TRNSYS 18. The electricity power output of the ICE is expressed in Eq. 1 and Eq. 2. Where P_{out} is electricity power output of the ICE; PLR_{ac} is actual part load ratio of the ICE, which influenced by T_{ab} ambient temperature and P_w electricity power wanted and P_{ca} the power capacity of the ICE. Exhaust heat from the ICE is expressed in Eq. 3 and Eq. 4. Where Q_{jw} and Q_{exh} is exhaust heat in exhaust gas and in jacket water; f_{jw} and f_{exh} is the function of exhaust heat in exhaust gas and in jacket water; Q_{re} is required heat input; P_{sh} is shaft power.

$$P_{out} = PLR_{ac} \times P_{ca} \tag{1}$$

$$PLR_{ac} = f(T_{ab}, MIN(1, P_w/P_{ca})) \tag{2}$$

$$Q_{jw} = f_{jw} \times (Q_{re} - P_{sh}) \tag{3}$$

$$Q_{exh} = f_{exh} \times (Q_{re} - P_{sh}) \tag{4}$$

(2) Absorption chiller

Flue gas hot water type lithium bromide absorption chillers are used to make the utilization of waste heat in jacket water and exhaust gas. The coefficient of performance (COP) of the absorption chiller is expressed in Eqs. 5-8. Where plr_s is part load ratio of inlet smoke gas; m_s is mass flowrate of inlet smoke; $m_{s,rate}$ is rated mass flowrate of inlet smoke; a_1, a_2, a_3, a_4, b_1, b_2 and b_3 are fitting coefficients; α is a correction factor of COP. The energy of the absorption chiller is expressed in Eq. 9 and Eq. 10. Where Q_{chw} is chiller water energy; Q_{jw} is the energy of jacket water; Q_S is the energy of smoke gas; Q_{cw} is cooling water energy.

$$plr_s = m_s/m_{s,rate} \quad (5)$$
$$plr = a_1 * plr_s^3 + a_2 * plr_s^2 + a_3 * plr_s + a_4 \quad (6)$$
$$\alpha = b_1 * T_{cw,in}^2 + b_2 * T_{cw,in} + b_3 \quad (7)$$
$$COP = COP_R * \alpha \quad (8)$$
$$Q_{chw} = (CAP_R + Q_{jw} * COP) * plr \quad (9)$$
$$Q_{cw} = Q_{chw} + Q_S + Q_{jw} \quad (10)$$

(3) Water thermal energy storage

The dynamic water thermal energy storage tank used in this study is Type 158 in TRNSYS, which has two flow paths allow fluid to change heat with tank. The tank was divided into several isothermal layers and heat transfer between layers was calculated. Heat loss between working fluid and surrounding environment are also considered. The relation between temperature of the tank and inlet or outlet energy of fluid is expressed in Eq. 11. Where T_{tank} is the temperature of tank; $Q_{in,tank}$ and $Q_{out,tank}$ is the inlet or outlet energy of fluid in the flow paths. The heat transfer between temperature nodes are expressed in Eq. 12. Where k is thermal conductivity; A is area of heat transfer; T is temperature of nodes; L is distance between nodes.

$$dT_{tank}/dt = (Q_{in,tank} - Q_{out,tank})/C_{tank} \quad (11)$$
$$Q_{cond,j} = k_j A_j \frac{T_j - T_{j+1}}{L_{cond,j}} + k_{j-1} A_{j-1} \frac{T_j - T_{j-1}}{L_{cond,j-1}} \quad (12)$$

2.2 *Evaluation criterion*

Primary energy efficiency (PEE) is used to assess the performance of the DES as expressed in Eq. 13. Where Q_{power}, $Q_{cooling}$ *and* $Q_{heating}$ is electricity power, cooling power, heating power generated by DES respectively(kWh); B is nature gas consumption of DES (Nm^3); Q_{gas} is low heat value of nature gas (MJ/m^3). Energy storage potential (ESP) is used to evaluate the thermal energy storage potential (Eq. 14). Where $Q_{surplus}$ is surplus cooling or heating; Q_{total} is total cooling/heating recovered from the waste heat. Energy storage ratio (ESR) is used to evaluate the actual supplied energy of thermal energy storage. Where $Q_{TESsuply}$ is energy supplied by TES to meet cooling/heating load (Eq. 15). Payback period (PBP) is used to evaluate the economy of the DES, which is expressed in Eq. 16. Where $I_{DES\&TES}$ is initial cost of DES&TES; I_{DES} is initial cost of DES; $O_{DES\&TES}$ is annual operation cost of DES&TES; O_{DES} is annual operation cost of DES.

$$PEE_{DES} = \frac{Q_{power} + Q_{cooling} + Q_{heating}}{B \times Q_{gas}/3.6} \quad (13)$$
$$\mathrm{ESP} = \frac{Q_{surplus}}{Q_{total}} \quad (14)$$
$$\mathrm{ESR} = \frac{Q_{TESsuply}}{Q_{total}} \quad (15)$$
$$\mathrm{PBP}_{DES\&TES} = \frac{I_{DES\&TES} - I_{DES}}{O_{DES} - O_{DES\&TES}} \quad (16)$$

3 CASE STUDY

A campus in hot summer and cold winter area was selected to study the performance of DES&TES. The system design and operation mode are introduced in this section.

3.1 *System description*

The area is about 93 buildings, including dormitory, office building, residential building, classroom, canteen, supermarket, gymnasium, hotel and exhibition hall. The 3D building models were built in SketchUp and the hourly annual load of each building was calculated in TRNSYS 18 using TRNBuild.

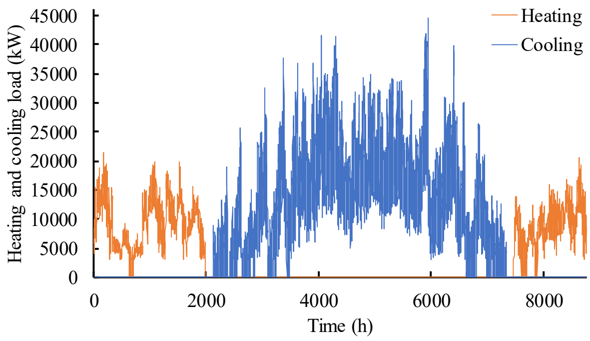

Fig. 3 Building hourly annual heating and cooling load

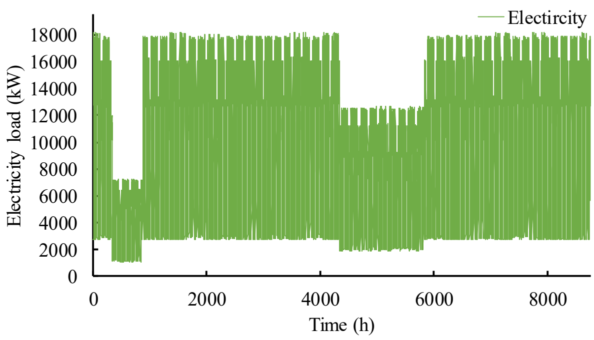

Fig. 4 Building hourly annual electricity load

The annual hourly cooling, heating and electricity loads are shown in Fig. 3 and Fig. 4. The peak cooling, heating and electricity load are 44617kW, 21394kW and

18000kW, respectively. Winter and summer vacation are considered with lower electric and thermal loads.

3.2 System configuration and operation strategy

Device capacity of the DES&TES is selected to meet the load under FEL operation strategy. ICEs are selected to meet the sum of electricity load and heat pumps. Insufficient electricity load is meet by electricity grid. The capacity and number of selected devices are list in Table 1.

Table 1 System design information

Devices	Capacity
ICE	9500kW*2
Absorption chiller	9304kW*2
Waste heat boiler	7.5t/h*2
Heat exchanger	3600kW*2
Water storage tank	15000m^3*2
Heat pump	5977kW(cooling) 6528kW(heating)*4

The main strategies of the DES&TES are as follows. In cooling condition, electricity is produced by ICE. The waste gas (about 500℃) and jacket water (about 98℃) are used to produce chilled water with 7℃ in absorption chiller. When produced energy is larger than cooling load, surplus energy is stored in water thermal tank. When load is larger than produced energy, insufficient load is meeting firstly by energy in water thermal tank and secondly meet by heat pump. In heating condition, operation strategy is almost the same except that waste gas is used in waste boiler and jacket water is used in heat exchanger to produce hot water (45℃).

4 RESULTS AND DISCUSSION

The results of basic case are shown in this section. Also, the influence of different climates and building mix are discussed respectively in this section.

4.1 Performance of basic case study

The energy performance of the DES& TES is shown in Fig. 5. The PEE of the two systems are 78.38% and 76.78%. That means the TES can storage the surplus energy and improve the PEE about 1.6%. From the annual performance of TES, nearly 21% of produced heat energy and 18% of produced cold energy need to be storage, which can be stored theoretically. But the results show large differences between ESP and ESR. Only 7.3% of produced heat energy and 2.2% of produced cold energy are used to meet the thermal load actually. Although TES is installed to store the surplus energy, but 88% of the surplus cold energy and 65% of the surplus heat energy are still wasted. The reason of low ESR, on the one hand, comes from the energy loss of the TES, on the other hand, is contributed by monthly load characteristics.

The economic analysis shows that initial cost of DES &TES increases 1.2 million yuan because of the water storage tank. Annual operation cost reduces 209.1 thousand yuan because of the reduces cost of nature gas and electricity cost. The payback period is about 57years, which mean TES is not economy. In this study, the gas price is 2.5 yuan/m^3, and the electricity price is based on time of use tariff in Shanghai.

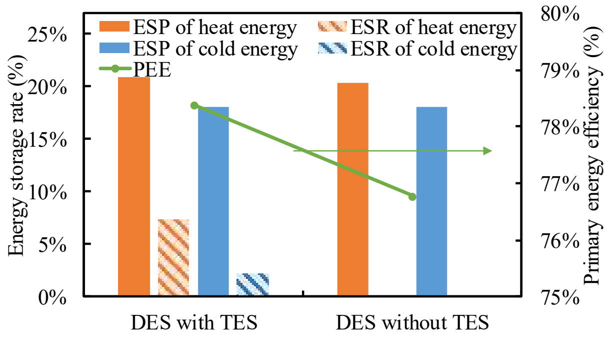

Fig. 5 Energy performance of DES&TES

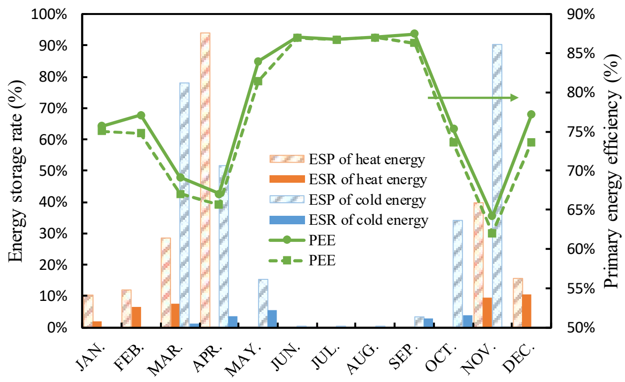

Fig. 6 Monthly performance of DES&TES

The monthly performance of TES is shown in Fig. 6. Compared with DES without TES, PEE of DES&TES improved, mostly in winter. Monthly PEE curve varies from 64.2% to 87.5%. The peak value of PEE in winter is lower than in summer because the rated COP of absorption chiller is1.4. The curve of PEE shows the lowest monthly

PEE in March April and November. The ESR columns show that over 40% of produced cold energy need to be stored but wasted in fact. In June and July, no surplus energy needs to be stored because of the large cooling demand. Although the PEE is high, low utilization rate of TES is not conducive to recover the initial cost of the energy storage system, from the economic aspect.

4.2 Performance under different climates

In this part, the influence of different climates to DES&TES is estimated by changes of thermal load. Load coefficient k is used to change heating and cooling load.

PEE and thermal to electric ratio of each case are shown in Fig. 7. The result show that compare with DES without TES, the PEE of DES&TES increases about 1-2 % at each case. And with the increase of thermal to electric ratio, PEE increases first and finally decrease. Highest PEE occurs when k equals to 0.7, at which case, thermal to electric ratio equals to 1.43 and PEE can reach to78.82%.

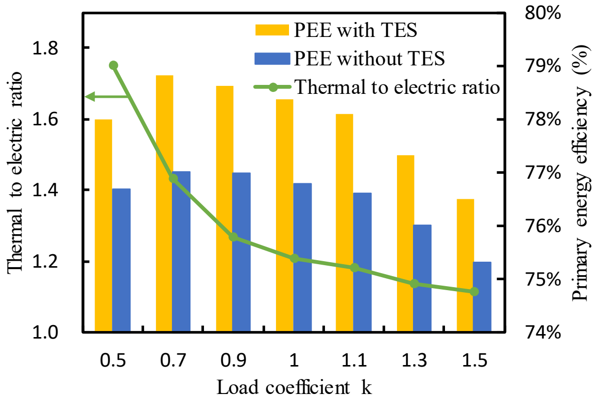

Fig. 7 Energy performance at different ratio k

The performance of TES is shown in Fig. 8. The results also show large difference between ESP and ESR. With the decrease of the cold to electric ratio, increasingly cold energy can be stored theoretically, while actual used cold energy not as fast as it grows, which causes more waste energy. The same phenomenon also occurs in heating condition, where ESP grow fast with the decrease of heat to electric ratio. But ESR even decreases when K equals to 0.5 because of the low demand of heating.

The economic performance of the DES&TES is also calculated. The initial cost of DES&TES increases 1.2 million yuan. When the load coefficient k is varying from 0.5 to 1.5, the reduction of annual operation cost is between 60.4 and 295.2 thousand yuan. The Payback period is varying from33.4 to 199 year, which means that the adoption of TES is not economic.

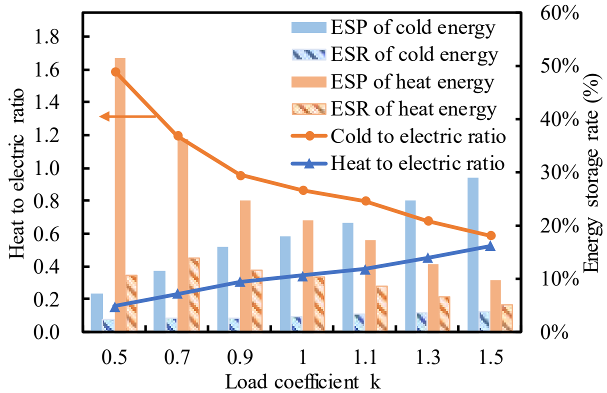

Fig. 8 TES performance at different coefficient k

4.3 Performance under different building mix

In this part, the influence of different building mix is estimated by changes of different area ratio (R) of residential building area to non-residential building area. The larger value of area ratio R, the areas of residential buildings are larger. Value of area ratio R is varying from 0 to infinity and the value of area ratio R is 0.5 in base case.

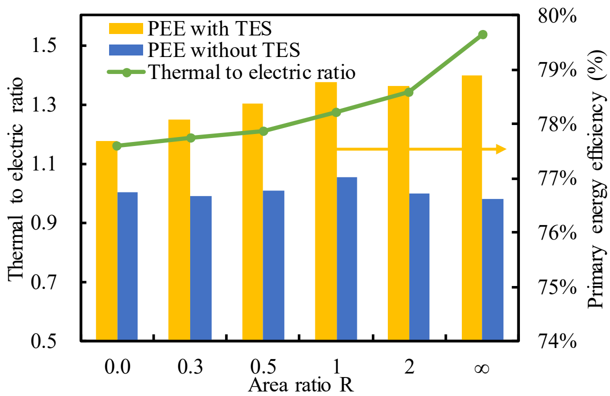

Fig. 9 Energy performance at different ratio R

Annual PEE and thermal to electric ratio of each case are shown in Fig. 9. The results show that compare with DES without TES, the PEE of DES&TES increases about 1-2 % at each case. The lager area of residential buildings, the difference between PEE with TES and PEE without TES is larger, which mean the TES is more useful. Thermal to electric ratio increase with the increase of the area ratio R. While, when area ratio R increases from 0 to 2, PEE firstly increase and decrease. PEE of DES&TES varies from 77.7% to 78.9% and the maximum value appears when R equals to infinity. If both types of buildings exist in the area, the maximum value of PEE is 78.8%, when residential building area to non-residential building area equals to 1.

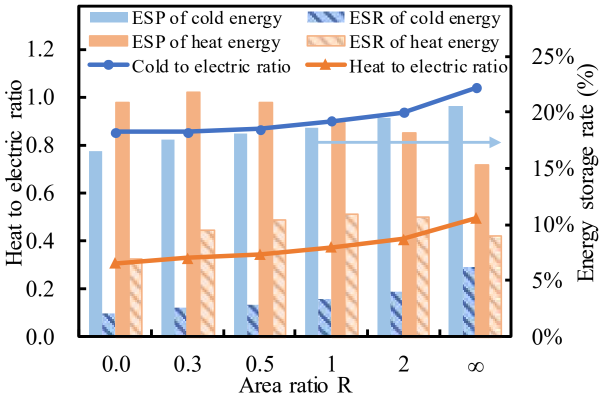

Fig. 10 TES performance at different ratio R

The annual performance of TES is shown in Fig. 10. The results show that with the increase of the area ratio R, more cold energy and less heat energy can be stored in TES. Difference between heat ESR and heat ESR is small with the increase of ratio R, which mean saving more surplus energy.

The economic analysis shows that initial cost of DES &TES increases 1.2 million yuan. Annual operation cost result from reduction in energy consumption reduces between 10.1 and 289.4 thousand yuan at each case. Payback period is all over 40 years, which mean TES is not economy.

5 CONCLUSIONS

A distributed energy system integrated with thermal storage systems is studied to serve a campus in hot summer and cold winter areas. The energy and economic performance of the DES&TES is evaluated and compared with that without TES. The impacts of different climates and different building mix of residential buildings and non-residential buildings are analyzed. Some conclusions can be obtained.

- In the hot summer cold winter area, the improvement of using DES&TES to the typical campus buildings is limited. Primary energy efficiency can improve around 2% compared with no TES.
- Due to the low utilization rate in summer and lots of energy wasted during transition season, the additional cost of TES is difficult to recover with a payback period of more than 20 years. The TES is therefore is not recommended if the DES operates under FEL.
- The variation of primary energy efficiency of DESs is between 1% to 2 % under different load profiles (different climate and building mix). It indicates that the energy saving potential of using TES is limited.
- The economic performance of the DES&TES in this paper is evaluated without considering the time-of-use tariff. The results will be different and will be concerned in future work. In addition, appropriate operation strategies need to be developed for the DES&TES to improve PEE and optimize the utilization of waste heat.

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