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Configuration and Efficiency Mechanism Analysis of Ultra-High Temperature Heat Pump Energy Storage Systems for New Power Systems

Zibo Xu[1*], Yinsheng Ma[2]

[1] Faculty of Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, Hong Kong
[2] CHN Energy Jinjie Energy Co. Ltd., Yulin 719000, China

Corresponding Author Email: boyi1312712497@163.com

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ABSTRACT

Starting from the demands of new power systems, this paper explores the role of heat pump energy storage in novel power systems. First, the principles of ultra-high temperature heat pump energy storage system technology are introduced. Next, a simulation analysis model of the ultra-high temperature heat pump system is built using Aspen Plus, and simulation calculations are conducted for key parameters such as outlet temperature, pressure loss, end temperature difference, cold-end heat storage medium temperature, and other design factors. Finally, an economic analysis model is developed to study the sensitivity of system efficiency, thermal storage power, annual operating hours, electricity purchase prices, and other factors on the economic performance of the heat pump energy storage system. The results show that parameters like pressure and temperature have a significant impact on the energy efficiency of the heat pump energy storage system. Notably, the turbine inlet temperature is linearly related to the outlet temperature. Increasing the turbine inlet temperature, reducing system pressure losses, lowering the cold-end heat storage medium temperature, and minimizing the end temperature difference can improve system efficiency. Many factors affect the economic performance of the system, with the top three influencing net profitability being system efficiency, thermal storage power, and annual operating hours. These three factors should be prioritized in system design and optimization. This study provides theoretical guidance for the design and analysis of ultra-high temperature heat pump energy storage systems in new power systems.

1. INTRODUCTION

With the large-scale integration of renewable energy into the power grid, the power system needs to achieve energy supply and demand balance between the randomly fluctuating load demand and the power sources. This leads to fundamental changes in its structural form, operation control methods, as well as planning, construction, and management, forming a new generation power system dominated by renewable energy production, transmission, and consumption, i.e., the renewable energy power system [1-3]. Although the prospects of new power systems are promising, their development still faces many technical challenges, which mainly manifest in the three dimensions of sufficiency, safety, and economy [4, 5]. Sufficiency is one of the challenges for the development of new power systems, which comes from the sufficiency of wind and solar power generation relative to system load, i.e., how to reserve sufficient flexibility resources in different time and space to ensure the power balance on both the generation and load sides. Safety is the second challenge for the development of new power systems, arising from the "dual-high" characteristics of high renewable energy proportion and high-power electronics devices, and the safety challenges induced by these. Economy is the third challenge for the development of new power systems, which comes from the economic factors, i.e., the resource optimization allocation efficiency determined by the power market mechanism.

2. THE ROLE OF HEAT PUMP ENERGY STORAGE IN THE CONSTRUCTION OF NEW POWER SYSTEMS

The large-scale integration of renewable energy generation into the grid has become a bottleneck restricting its further development [6]. The matching of large-scale energy storage devices can solve the time difference problem between generation and consumption, as well as the impact of intermittent renewable energy generation on grid security and stability [7, 8]. Energy storage technology, as an important means to enhance the capacity of smart grids to accommodate renewable energy generation and as the central link enabling bidirectional energy interaction in smart grids, is one of the key technologies in the construction of smart grids [9].

The application of thermal energy storage technology to large-scale energy storage in power systems has unique advantages [10-13]. First, thermal storage technology is a physical process, which has higher technical maturity and lower cost compared to chemical and electromagnetic energy storage, making it suitable for large-capacity, long-duration energy storage. More importantly, the vast majority of power generation processes in the current power system are achieved through thermal power conversion (except for hydroelectric power), where thermal energy itself is an essential part of the generation process. Therefore, when thermal storage technology is used as a large-scale energy storage method in power systems, its energy release process can take advantage of the power system’s own thermal power conversion equipment, which greatly improves the equipment utilization rate and overall energy efficiency, thus further reducing storage costs. Finally, in certain special cases, such as in distributed energy systems, thermal energy (including both heat and cold) is one of the energy forms needed by end users, so using thermal storage technology can achieve multiple benefits.

3. HIGH-TEMPERATURE HEAT PUMP ENERGY STORAGE SYSTEM CONFIGURATION

Energy storage technology is rapidly developing, and research on heat pump energy storage systems has also received widespread attention [14]. At present, there are two main technical routes for heat pump energy storage systems: one is based on the Brayton cycle, and the other is based on the Rankine cycle. The specific details of each technical route are as follows:

(1) Heat pump energy storage system based on the Brayton cycle.

A typical Brayton cycle system consists of a cold storage unit, a heat storage unit, a compressor, an expander, and a heat exchanger. The energy storage/release process of the Brayton cycle-based heat pump energy storage system is shown in Figure 1, where the power generation process is reversed. Scholars in France have studied the Brayton cycle-based heat pump energy storage system and conducted thermodynamic analysis to examine the effects of various irreversible losses on system efficiency and energy density [15]. In a heat pump energy storage system, the cycle efficiency is a function of the storage temperature. For the Brayton system, high storage temperatures are beneficial for achieving high round-trip efficiency and high storage density, but in the system, a high temperature ratio is achieved through a high-pressure ratio [16-19]. To increase the pressure ratio, higher performance requirements are needed for the compressor and expander, and this also increases the construction costs of the thermal storage/cooling units.

Some scholars have proposed a combined heat and power (CHP) system based on the Brayton cycle, suggesting three operating modes: energy storage, CHP, and combined cooling, heating, and power. The results show that when the system operates only in energy storage mode, the cycle efficiency is 63.5%; in the CHP mode, the maximum COP can reach 137.9%; in the combined cooling, heating, and power mode, the maximum COP achieved is 188.1%, and the maximum thermal efficiency is 63.9%, which is 1.4% higher than in energy storage mode, effectively recovering the system's irreversible losses [20].

(2) Heat pump energy storage system based on the Rankine cycle.

The heat pump energy storage system based on the Rankine cycle was first proposed and analyzed by German researchers [21]. Since the Brayton cycle-based heat pump energy storage system requires large high-pressure storage tanks, leading to higher system costs, German scholars proposed a solution based on the transcritical CO_2 Rankine cycle. The system principle is shown in Figure 2 [22]. This system has a maximum heat storage temperature of 123°C, and the system cycle efficiency reaches 53%. Building on this research, other scholars have constructed a trans-critical CO_2 system with both hot water and cold-water storage. In the energy storage phase, the heat pump cycle heats the water in the storage tank, and the heated water provides power for the heat engine cycle during the energy release phase [23]. The latent heat on the cold side is stored through low-temperature brine, ultimately achieving a 60% round-trip efficiency and a heat storage temperature of 177°C. Research on Rankine cycle-based heat pump energy storage systems has focused more on optimizing the system configuration [24]. Some scholars have added two heat exchangers to the conventional system, as shown in Figure 3 [25]. The addition of heat exchangers improves the system's performance. From an economic perspective, the system configuration with heat transfer oil as the thermal storage medium and heat recovery is considered the best solution [26]. To improve the energy storage density of the heat pump energy storage system, scholars in China have proposed a heat pump energy storage system with supplementary heating, and on this basis, coupled it with an organic Rankine cycle system [27].

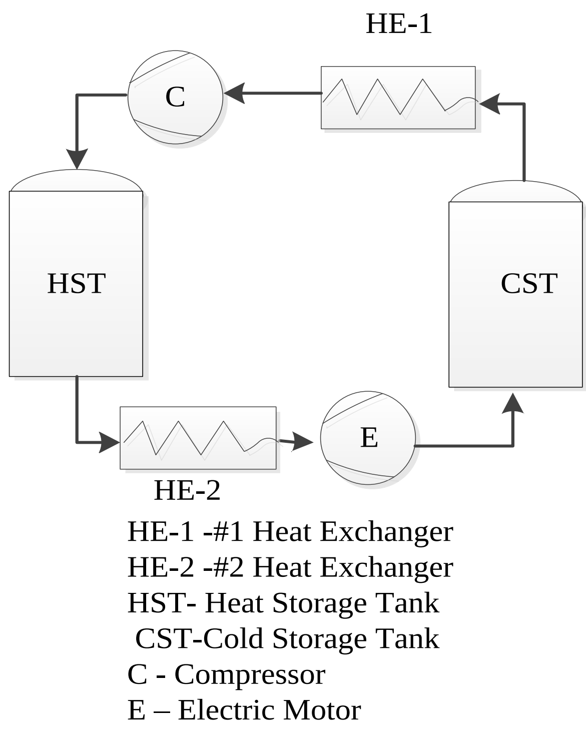


Figure 1. Schematic diagram of the Brayton cycle heat pump energy storage system process

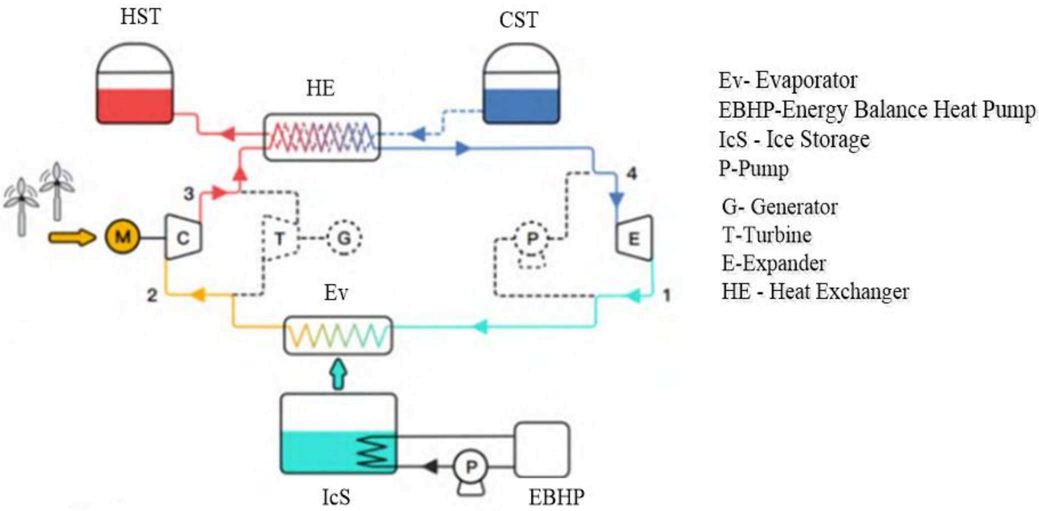
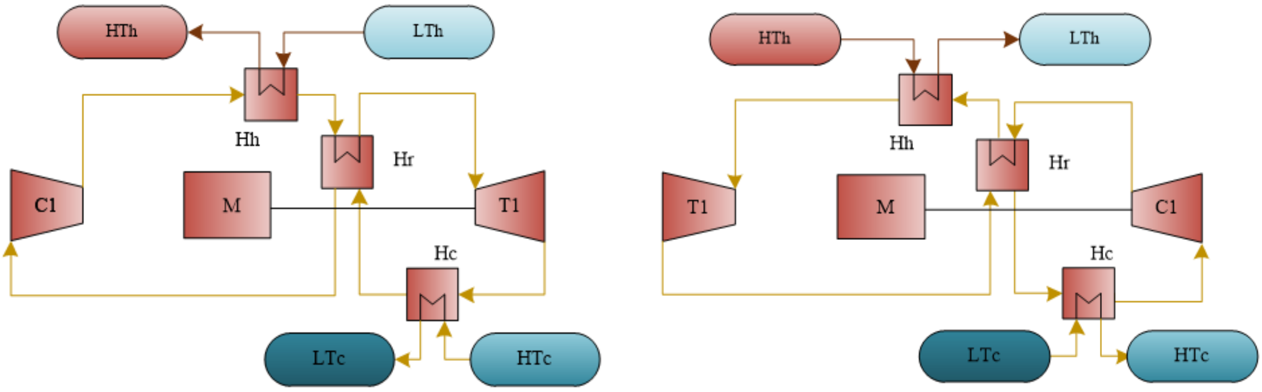


Figure 2. Schematic diagram of the Rankine cycle heat pump energy storage system



(a) Energy storage process

(b) Energy release process

Figure 3. Energy storage and release process of the high-temperature heat pump energy storage system

3.1 Comparison of different technical routes

3.1.1 Heat pump energy storage system based on the Brayton cycle

The energy storage/release process of the Brayton cycle-based heat pump energy storage system is the reverse of the power generation process. Early research on heat pump energy storage technology focused more on the Brayton cycle-based heat pump energy storage system [28-30]. This type of system uses helium, argon, CO_2, or air as the working fluid. The Brayton cycle-based heat pump energy storage system has a high heat storage temperature, typically exceeding 800 K, and even approaching 1300 K [31]. Such high storage temperatures, on one hand, increase thermal losses and pressure losses in the heat storage components, and on the other hand, pose greater challenges for the manufacturing of high-temperature, high-pressure compression components. It is generally believed that these factors are important barriers to the large-scale commercialization of Brayton cycle-based heat pump energy storage systems [32]. Scholars in France have studied the Brayton cycle-based heat pump energy storage system and conducted thermodynamic analysis, examining how various irreversible losses affect system efficiency and energy density, concluding that the system efficiency is approximately 66.7% [33]. Scholars in the UK analyzed and optimized the parameters of heat pump energy storage, and the results showed that the system efficiency mainly depends on the performance of the compressor and expander. When the variable efficiency of the compressor and expander reaches 99%, the energy storage efficiency of the system can reach 70% [34]. Both domestic and international scholars generally agree that the closed Brayton cycle heat pump energy storage system has advantages such as high energy storage density, high energy storage efficiency, and simple structure, which saves costs and is more suitable for large-scale engineering applications [35].

3.1.2 Heat pump energy storage system based on the Rankine cycle

The Rankine cycle-based heat pump energy storage system has a lower energy storage temperature and a simpler structure. Therefore, another popular research direction for Rankine cycle-based heat pump energy storage systems is using heat-integrated systems. Compared with conventional heat pump energy storage systems, heat-integrated systems offer better application prospects. They not only allow efficient energy storage by utilizing various forms of low-grade heat, but also can be connected to regional power grids and heating networks in smart energy systems. Common heat integration methods include industrial waste heat, district heating networks, solar thermal energy, and geothermal brine injection [36].

In summary, both domestic and international scholars generally believe that the Brayton cycle-based heat pump energy storage system has advantages such as high energy storage density, high energy storage efficiency, and simple structure, which saves costs and is more suitable for large-scale engineering applications. Research on Rankine cycle-based systems focuses more on optimizing the selection of working fluids and exploring system performance and economic benefits under different heat integration scenarios. In comparison, the Brayton cycle-based system is closer to actual engineering applications and is more suitable for large-scale energy storage applications [37]. Therefore, considering factors such as system simplicity, ease of operation, and low maintenance workload, the Brayton cycle technology route with air as the working fluid is preferred [38].

3.2 System model composition

The energy storage and release processes of the heat pump energy storage system are shown in Figure 4. When there is an excess of power, the system stores energy by running the reverse Brayton cycle heat pump mode [39]. The residual electricity in the grid drives an electric motor, which in turn drives the compressor. The compressor drives the working fluid to absorb heat from the low-temperature heat source and release heat to the high-temperature heat source, establishing a temperature difference between the thermal storage and cooling systems, thus converting electrical energy into thermal energy stored in the storage medium. When there is insufficient power or high electricity demand, the system releases energy by running the forward Brayton cycle heat engine mode [40]. The working fluid expands through the turbine, doing work to drive the generator and regenerate electricity. In this phase, the working fluid absorbs heat from the high-temperature heat source and releases heat to the low-temperature heat source, transferring heat from the thermal storage system to the cooling system [41].

3.2.1 Energy storage phase

The required power for the charging part can come from the abandoned electricity of renewable energy stations such as solar and wind energy or off-peak electricity from the grid. Through the heat pump cycle, composed of compressor C1, expander T1, cold-source heat exchanger Hc, regenerator Hr, and hot-source heat exchanger Hh, electrical energy is efficiently converted into thermal energy of the working fluid [42]. In the energy storage section, the low-temperature molten salt working fluid is heated into high-temperature molten salt through Hh and stored in the high-temperature molten salt tank HTh, achieving large-scale energy storage [43].

3.2.2 Energy release phase

The working fluid flows through the cooling system to complete pre-cooling. Compressor C1 compresses the low-temperature, low-pressure gaseous working fluid to a medium-low-temperature, high-pressure state. After passing through the regenerator Hr, the fluid becomes a medium-temperature, high-pressure state. The thermal storage system releases heat through the high-temperature heat exchanger, and the working fluid absorbs heat to become a high-temperature, high-pressure state. The expander expands the working fluid to a medium-temperature, low-pressure state. The fluid then passes through the regenerator and becomes a medium-low-temperature, low-pressure state. The cooling system releases cold energy through the low-temperature heat exchanger, and the working fluid, after releasing heat, reaches a low-temperature, low-pressure state, returning to the compressor inlet, completing the discharge cycle [30, 35].

3.3 System modeling

In this paper, Aspen Plus simulation software is used to build a simulation analysis model of the high-temperature heat pump energy storage system. The main components include the compressor, expander, low-temperature heat exchanger, and high-temperature heat exchanger. In the Aspen Plus V12 version modeling, both the compressor and expander use the compressor/turbine Comor model. The high-temperature and low-temperature heat exchangers use the Heater model for heat exchangers. The physical property method of the working fluid uses the PENG-ROB method. The process flow diagram of the cycle is shown in Figure 4.

Based on the operating conditions of the heat pump energy storage system, the design parameters of the compressor and expander, as well as the performance parameters of the heat exchangers, are determined. The system parameters selected are shown in the Table 1 below. The influence of each parameter on the cycle efficiency is analyzed using the control variable method [13].

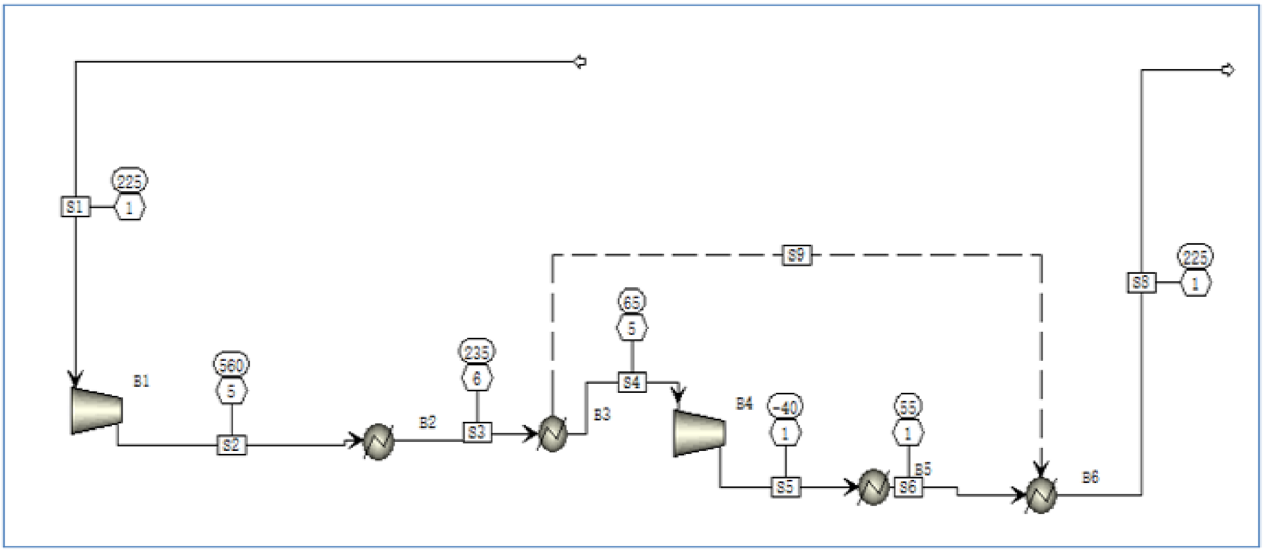


Figure 4. Simulation process flow of the high-temperature heat pump system

Table 1. Parameter values for the heat pump energy storage system design

System Parameter	Unit	Value
Compression Ratio (Energy Storage)	——	4.76
Isentropic Efficiency of Compression Process	%	78
Isentropic Efficiency of Expansion Process	%	90
Mechanical Efficiency	%	98
Heat Exchanger Temperature Difference	℃	10

3.4 Economic modeling

(1) System economic analysis model [29].

Let the net profit Y=Revenue E−Cost C

Revenue E=Peak-shaving Subsidy E1+Carbon Reduction Benefit E2+Electricity Sales Revenue E3

Cost C=Electricity Cost C1+Operation and Maintenance Cost C2

System Efficiency η_p= Power Generation Pg/Electricity Consumption Pu

Thus, it can be written as:

$$Y = E - C = \mathrm{p_u} \left(\mathrm{e_1} \times \eta_P \times \mathrm{a} + \mathrm{e_2} \times \eta_P \times \mathrm{a} + \mathrm{e_3} \times \eta_P \times \mathrm{a} - \mathrm{c_1} \times \mathrm{a} - \mathrm{c_2}\right) \tag{1}$$

where, e_1 represents the unit peak-shaving subsidy, in yuan/kWh; $e_2$represents the unit carbon reduction benefit, in yuan/kWh; e_3 represents the unit electricity sales price, in yuan/kWh; $c_1$represents the unit electricity cost, in yuan/kWh.

(2) Sensitivity concept and calculation.

The purpose of sensitivity analysis is to identify the sensitive factors, which can be determined by calculating the sensitivity coefficient and critical points.

3.4.1 Sensitivity coefficient (SAF)

The sensitivity coefficient represents the degree of sensitivity of the economic effect evaluation index of the technical solution to uncertain factors. The calculation formula is:

$$\chi_{EF} = \frac{\Delta E / E}{\Delta F / F} \tag{2}$$

where, χ_{EF} is the sensitivity coefficient; $\frac{\Delta F}{F}$is the rate of change of the uncertain factor F (%); $\frac{\Delta E}{E}$is the relative rate of change of the evaluation index *E* when the uncertain factor *F* changes (%).

The method of calculating the sensitivity coefficient to identify sensitive factors is a relative measurement approach, which determines the ranking of the sensitivity of each factor based on its relative change's effect on the economic effect index of the technical solution.

If $\chi_{EF} > 0$, it indicates that the evaluation index *E* changes in the same direction as the uncertain factor *F*. If $\chi_{EF} < 0$, it indicates that the evaluation index *E* changes in the opposite direction to the uncertain factor *F*. The larger the sensitivity coefficient $|\chi_{EF}|$, the more sensitive the evaluation index *E* is to the uncertain factor *F*; conversely, the smaller the sensitivity coefficient, the less sensitive the evaluation index *E* is to the uncertain factor *F*. Based on this, we can identify the factors that have the greatest impact on the evaluation index *E*.

3.4.2 Determination of sensitivity coefficients

By rearranging Eq. (2), we obtain:

$$\chi_{EF} = \frac{F}{E} \cdot \frac{\Delta E}{\Delta F} = \frac{F}{E} \cdot \frac{\partial E}{\partial F} \tag{3}$$

Thus, the sensitivity coefficients of heat storage power Pu, unit peak-shaving subsidy e_1, system efficiency η_p, unit carbon reduction benefit e_2, unit electricity sales price e_3, and unit electricity cost c_1 to the net profit can be obtained by calculating the above Eqs. (1)-(3).

$$\frac{\partial Y}{\partial P_\mathrm{u}} = \mathrm{e_1} \times \eta_P \times \mathbf{a} + \mathrm{e_2} \times \eta_P \times \mathbf{a} + \mathrm{e_3} \times \eta_P \times \mathbf{a} - \mathrm{c_1} \times \mathbf{a} - \mathbf{c_2} \tag{4}$$

$$\frac{\partial Y}{\partial \eta_\mathrm{p}} = \mathrm{p_u}\left(\mathrm{e_1} \times \mathrm{a} + \mathrm{e_2} \times \mathrm{a} + \mathrm{e_3} \times \mathrm{a}\right) \tag{5}$$

$$\frac{\partial Y}{\partial \mathrm{a}} = \mathrm{p_u}\left(\mathrm{e_1} \times \eta_P + \mathrm{e_2} \times \eta_P + \mathrm{e_3} \times \eta_P - \mathrm{c_1}\right) \tag{6}$$

$$\frac{\partial Y}{\partial \mathrm{c_1}} = -\mathrm{p_u} \times \mathrm{a} \tag{7}$$

$$\frac{\partial Y}{\partial \mathrm{e_1}} = \mathrm{p_u} \times \eta_P \times \mathrm{a} \tag{8}$$

$$\frac{\partial Y}{\partial \mathrm{e_2}} = \mathrm{p_u} \times \eta_P \times \mathrm{a} \tag{9}$$

$$\frac{\partial Y}{\partial \mathrm{e_3}} = \mathrm{p_u} \times \eta_P \times \mathrm{a} \tag{10}$$

$$\chi_{IP_\mathrm{u}} = \frac{P_\mathrm{u}}{Y} \cdot \frac{\partial Y}{\partial P_\mathrm{u}} \tag{11}$$

$$\chi_{\mathrm{Y}\eta_P} = \frac{\eta_P}{Y} \cdot \frac{\partial Y}{\partial \eta_P} \tag{12}$$

$$\chi_{\mathrm{Ya}} = \frac{\mathrm{a}}{Y} \cdot \frac{\partial Y}{\partial \mathrm{a}} \tag{13}$$

$$\chi_{\mathrm{Y}\eta_P} = \frac{\eta_P}{Y} \cdot \frac{\partial Y}{\partial \eta_P} \tag{14}$$

$$\chi_{\mathrm{Ye_1}} = \frac{\mathrm{e_1}}{Y} \cdot \frac{\partial Y}{\partial \mathrm{e_1}} \tag{15}$$

$$\chi_{\mathrm{Ye_2}} = \frac{\mathrm{e_2}}{Y} \cdot \frac{\partial Y}{\partial \mathrm{e_2}} \tag{16}$$

$$\chi_{\mathrm{Ye_3}} = \frac{\mathrm{e_3}}{Y} \cdot \frac{\partial Y}{\partial \mathrm{e_3}} \tag{17}$$

4. RESULTS AND DISCUSSION

4.1 Simulation results and analysis

(1) System parameter sensitivity analysis.

As shown in Figure 5, when the turbine inlet temperature is -28.5℃, keeping other parameters constant, the outlet temperature is -100℃. As the turbine inlet temperature increases, both the outlet temperature and COP increase. As shown in Figure 6, when the low-temperature end storage temperature is 158℃ (requiring ternary salts at this point), and the turbine inlet temperature is 0℃, the outlet temperature is -100℃. As the low-temperature end storage temperature increases, the turbine outlet temperature increases, but the COP decreases.

Due to the viscosity of the working fluid and the effects of secondary flow during the flow process, pressure losses are inevitably caused near the heat exchanger and along the pipeline, which reduces the overall energy efficiency of the system. As shown in Figure 7, as the pressure loss in the heat exchanger increases, the work done by the low-temperature turbine during the energy storage process decreases, resulting in a lower system COP. When the pressure loss is 15%, the turbine inlet temperature is -30℃, and the turbine outlet temperature is close to -100℃. When the pressure loss is 5%, the turbine inlet temperature is -10℃, and the turbine outlet temperature is -100℃, with a COP of 1.1. Furthermore, as the pressure loss increases, the low-temperature refrigerant temperature increases, which in turn raises the turbine outlet temperature. Figure 8 shows that the temperature difference has little effect on the turbine outlet temperature. With other conditions unchanged, when the turbine inlet temperature is -30℃, altering the temperature difference of the heat exchanger keeps the outlet temperature at -101.5℃.

The performance parameters of the heat pump energy storage system studied in this section are assumed to be independent. In reality, the various parameters of the system interact and influence each other, which increases the difficulty of system performance analysis. Nevertheless, this chapter reveals the mechanisms affecting system performance, analyzes the sources of system losses, and evaluates the impact of each source on overall system efficiency. This provides a reliable basis for the future development and improvement of the system.

(2) Economic sensitivity analysis.

This paper considers factors affecting the economic viability of high-temperature heat pump energy storage systems at different thermal storage temperatures, such as annual operating hours, electricity costs, grid electricity prices, and peak-shaving subsidies. The price difference between peak and off-peak electricity in major provinces of China is shown in Figure 9. Cost factors mainly consider annual operating hours, system efficiency, electricity costs, and operation and maintenance (O&M) costs. Revenue factors primarily include peak-shaving subsidies, carbon emission income, and electricity sales (generation income). The net revenue formula is: Net Revenue = Peak-shaving subsidy + Carbon reduction income + Sales revenue - Electricity costs - O&M costs, which identifies the conditions under which the high-temperature thermal energy storage combined cycle power generation project can achieve profitability and good economic benefits.

The sensitivity coefficients for the main parameters are shown in Table 2. It can be seen that the top three factors affecting the system's net revenue are system efficiency, thermal storage power, and annual operating hours. These three factors should be given priority consideration when designing and optimizing the system.

There are many factors influencing the system's economic performance, but the most important ones include the grid electricity price, annual operating hours, peak-shaving subsidies, and electricity costs.

As shown in Figure 10, with the increase in the grid electricity price, the net revenue at all thermal storage temperatures shows an upward trend. Moreover, under a fixed grid electricity price, as the thermal storage temperature increases from 1200℃ to 1600℃, the rate of increase in net revenue gradually decreases.

As shown in Figure 11, with the increase in operating hours, the net revenue at all thermal storage temperatures shows a growing trend. Moreover, for a fixed number of operating hours, as the thermal storage temperature increases from 1200℃ to 1600℃, the rate of growth in net revenue gradually decreases.

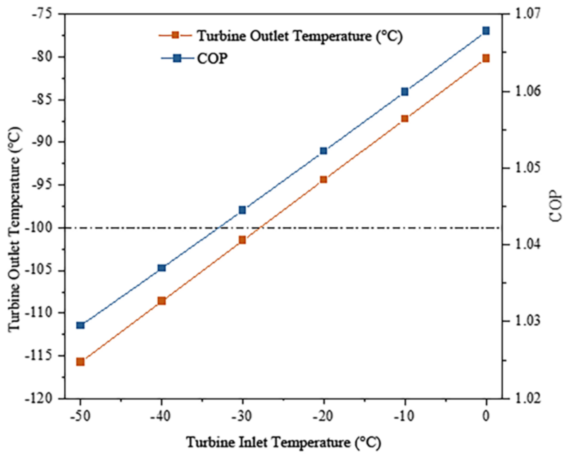


Figure 5. The relationship between the turbine inlet temperature, turbine outlet temperature, and COP

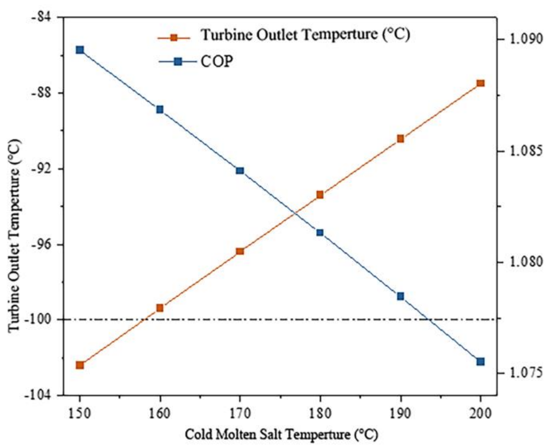


Figure 6. The relationship between the low-temperature end storage temperature, turbine inlet and outlet temperatures, and COP

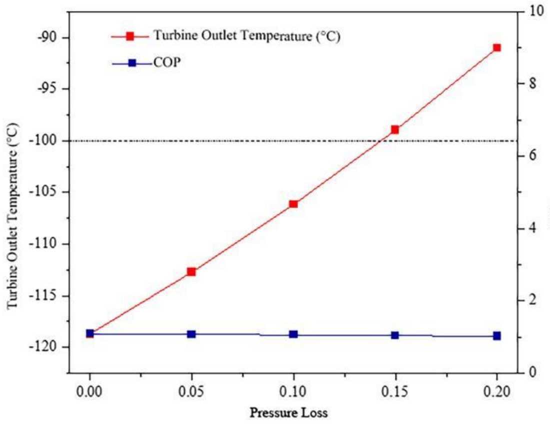


Figure 7. The relationship between pressure loss, turbine outlet temperature, and COP

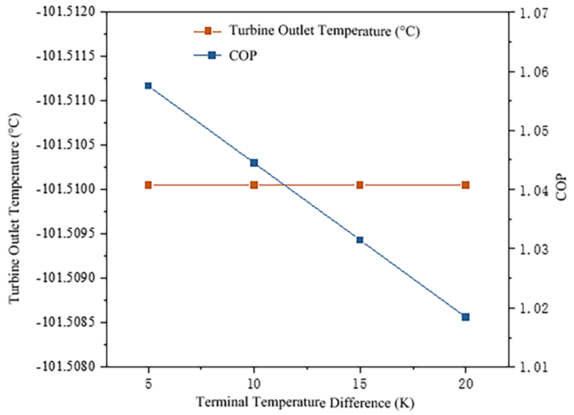


Figure 8. The relationship between end temperature difference, turbine outlet temperature, and COP

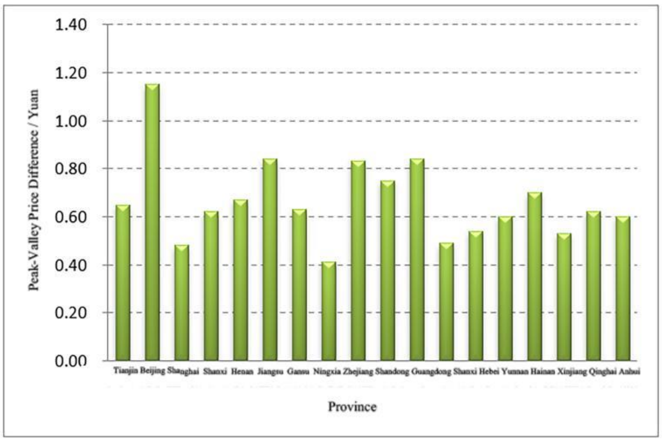


Figure 9. Peak-valley electricity price difference in major provinces of China

Table 2. Sensitivity coefficients of main parameters

Sensitivity Coefficient	System Power	1.00
	System Efficiency	1.65
	Annual Operating Hours	1.07
	Peak-shaving Subsidy	0.89
	Grid Electricity Price	0.65
	Carbon Reduction Income	0.11
	Electricity Cost	-0.57

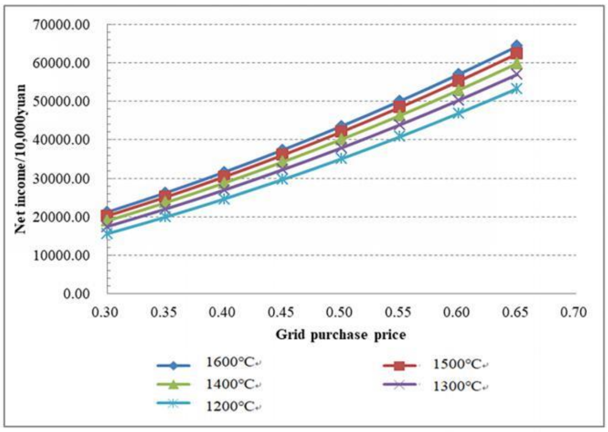


Figure 10. Impact of grid electricity price

As shown in Figure 12, when the peak-shaving subsidy approaches or exceeds 0.2 yuan/kWh, the combined cycle power generation system at all thermal storage temperatures becomes profitable. As the thermal storage temperature increases, the corresponding system's revenue critical point's peak-shaving subsidy becomes smaller. With an increase in the peak-shaving subsidy, the net revenue at all thermal storage temperatures shows an upward trend. Additionally, for a fixed peak-shaving subsidy, as the thermal storage temperature increases from 1200°C to 1600°C, the rate of increase in net revenue gradually decreases.

As shown in Figure 13, with the increase in electricity costs, the net revenue at all thermal storage temperatures decreases. Additionally, for a fixed electricity cost, as the thermal storage temperature increases from 1200°C to 1600°C, the rate of decrease in net revenue gradually slows down.

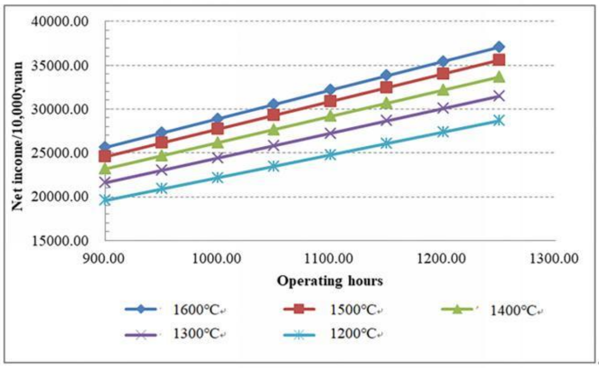


Figure 11. Impact of operating hours

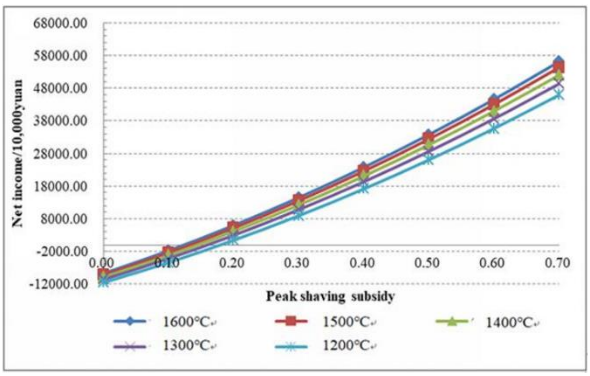


Figure 12. Impact of peak-shaving subsidy

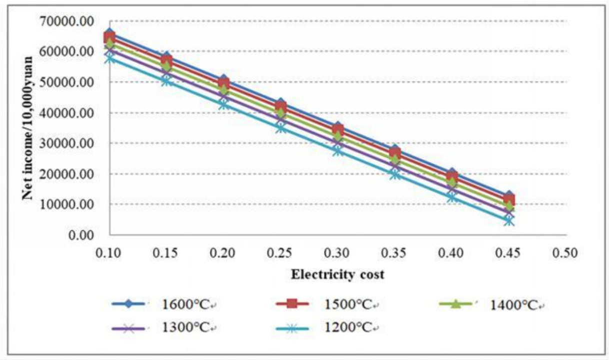


Figure 13. Impact of electricity cost

5. CONCLUSION

Heat pump energy storage, as an emerging technology that is not geographically limited and can achieve large-scale energy storage, has broad prospects in future power systems. This paper introduced the air-based heat pump energy storage system, built a mathematical simulation analysis model, and conducted a comparative analysis of different parameter configurations. The main conclusions are as follows:

The relationship between the turbine inlet temperature and outlet temperature is linear. Increasing the turbine inlet temperature of the heat pump energy storage system, reducing system pressure losses, cooling end heat transfer medium temperature, and end temperature difference can all improve system efficiency.

There are many factors influencing system economics, with the top three factors affecting net revenue being system efficiency, storage power, and annual operating hours. These three factors should be given particular attention in system design and optimization.

As the proportion of renewable energy installation continues to rise rapidly, heat pump energy storage, based on the most mature thermal power conversion technologies, will play an important role in energy network management.

REFERENCES

[1] National Energy Administration. Win the tough battle of low-carbon transformation. http://www.nea.gov.cn/2021-04/09/c_139869435.htm, accessed on Nov. 10, 2024.

[2] Yang, Z., Zhang, J., Kintner-Meyer, C.W., Lu, X., Choi, D., Lemmon, J.P., Liu, J. (2011). Electrochemical energy storage for green grid. Chemical Reviews, 111(5): 3577-3613. https://doi.org/10.1021/cr100290v

[3] Xiao, X., Zheng, Z. (2022). New power systems dominated by renewable energy towards the goal of emission peak & carbon neutrality: Contribution, key techniques, and challenges. Advanced Engineering Sciences, 54(1): 47-59. https://doi.org/10.15961/j.jsuese.202100656

[4] Hughes, L. (2010). The technical potential for off-peak electricity to serve as backup in wind-electric thermal storage systems. International Journal of Green Energy, 7(2): 181-193. https://doi.org/10.1080/15435071003673690

[5] National Energy Administration. Guiding opinions on promoting the development of energy storage technology and industry. http://www.nea.gov.cn/2017-10/11/c_136672015.htm, accessed on Nov. 10, 2024.

[6] Rong, A., Lahdelma, R., Luh, P.B. (2008). Lagrangian relaxation based algorithm for trigeneration planning with storages. European Journal of Operational Research, 188(1): 240-257. https://doi.org/10.1016%2Fj.ejor.2007.04.008

[7] Mahon, H., O'Connor, D., Friedrich, D., Hughes, B. (2022). A review of thermal energy storage technologies for seasonal loops. Energy, 239: 122207. https://doi.org/10.1016/j.energy.2021.122207

[8] Desrues, T., Ruer, J., Marty, P., Fourmigué, J.F. (2010). A thermal energy storage process for large scale electric applications. Applied Thermal Engineering, 30(5): 425-432. https://doi.org/10.1016/J.APPLTHERMALENG.2009.10.002

[9] Rodriguez, I., Pérez-Segarra, C.D., Oliva, A., Jaramillo, J.E. (2009). Numerical study of the transient cooling process of water storage tanks under heat losses to the environment. Numerical Heat Transfer, Part A: Applications, 55(12): 1051-1074. https://doi.org/10.1080/10407780903014418

[10] Suárez, C., Iranzo, A., Pino, F.J., Guerra, J. (2015). Transient analysis of the cooling process of molten salt thermal storage tanks due to standby heat loss. Applied Energy, 142: 56-65. https://doi.org/10.1016%2Fj.apenergy.2014.12.082

[11] Wang, X., Palazoglu, A., El-Farra, N.H. (2015). Operational optimization and demand response of hybrid renewable energy systems. Applied Energy, 143: 324-335. https://doi.org/10.1016/j.apenergy.2015.01.004

[12] Hall, E.W., Hausz, W., Anand, R., Lamarche, N., Oplinger, J., Katzer, M. (1979). Conceptual design of thermal energy storage systems for near term electric utility applications. Department of Energy, Office of Energy Technology, Division of Storage Systems, 2: 79-84. https://doi.org/10.2172/5777283

[13] Zhang, H., Liang, W., Liu, J., Wang, J. (2020). Modeling and energy efficiency analysis of thermal power plant with high temperature thermal energy storage (HTTES). Journal of Thermal Science, 29: 1025-1035. https://doi.org/10.1007/s11630-020-1310-6

[14] Li, D., Wang, J. (2018). Study of supercritical power plant integration with high temperature thermal energy storage for flexible operation. Journal of Energy Storage, 20: 140-152. https://doi.org/10.1016/j.est.2018.09.008

[15] Andersen, T.V. (2009). Integration of 50% wind power in a CHP-based power system: A model-based analysis of flexible power generation. Ph.D. Dissertation. Department of Electrical Engineering, Technical University of Denmark, Kongens Lyngby, Denmark. https://www.ea-energianalyse.dk/wp-content/uploads/2020/02/integration_of_50_percent_wind-power.pdf.

[16] Banos, R., Manzano-Agugliaro, F., Montoya, F.G., Gil, C., Alcayde, A., Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy: A review. Renewable and Sustainable Energy Reviews, 15(4): 1753-1766. https://doi.org/10.1016/j.rser.2010.12.008

[17] Xu, X., Jin, X., Jia, H., Yu, X., Li, K. (2015). Hierarchical management for integrated community

energy systems. Applied Energy, 160: 231-243. https://doi.org/10.1016/j.apenergy.2015.08.134

[18] Tyagi, V.V., Buddhi, D.P.C.M. (2007). PCM thermal storage in buildings: A state of art. Renewable and Sustainable Energy Reviews, 11(6): 1146-1166. https://doi.org/10.1016/j.rser.2005.10.002

[19] Soprani, S., Marongiu, F., Christensen, L., Alm, O., Petersen, K.D., Ulrich, T., Engelbrecht, K. (2019). Design and testing of a horizontal rock bed for high temperature thermal energy storage. Applied Energy, 251: 113345. https://doi.org/10.1016/j.apenergy.2019.113345

[20] Sowmy, D.S., Prado, R.T. (2008). Assessment of energy efficiency in electric storage water heaters. Energy and Buildings, 40(12): 2128-2132. https://doi.org/10.1016/j.enbuild.2008.06.007

[21] Reboussin, Y., Fourmigue, J.F., Marty, P., Citti, O. (2005). A numerical approach for the study of glass furnace regenerators. Applied Thermal Engineering, 25(14-15): 2299-2320. https://doi.org/10.1016/j.applthermaleng.2004.12.012

[22] El Qarnia, H. (2009). Numerical analysis of a coupled solar collector latent heat storage unit using various phase change materials for heating the water. Energy Conversion and Management, 50(2): 247-254. https://doi.org/10.1016/j.enconman.2008.09.038

[23] Regin, A.F., Solanki, S.C., Saini, J.S. (2006). Latent heat thermal energy storage using cylindrical capsule: Numerical and experimental investigations. Renewable Energy, 31(13): 2025-2041. https://doi.org/10.1016/j.renene.2005.10.011

[24] Kandasamy, R., Wang, X.Q., Mujumdar, A.S. (2008). Transient cooling of electronics using phase change material (PCM)-based heat sinks. Applied Thermal Engineering, 28(8-9): 1047-1057. https://doi.org/10.1016/j.applthermaleng.2007.06.010

[25] Zhang, H., Liu, J., Liang, W., Yu, D. (2020). Analysis on peak-shaving energy efficiency of thermal power plant with high temperature thermal energy storage. IOP Conference Series: Earth and Environmental Science, 474(5): 052009. https://doi.org/10.1088/1755-1315/474/5/052009

[26] Li, D., Hu, Y., He, W., Wang, J. (2017). Dynamic modelling and simulation of a combined-cycle power plant integration with thermal energy storage. In 2017 23rd International Conference on Automation and Computing (ICAC), Huddersfield, United Kingdom, Huddersfield, UK, pp. 1-6. https://doi.org/10.23919/IConAC.2017.8081972

[27] Denholm, P., Holloway, T. (2005). Improved accounting of emissions from utility energy storage system operation. Environmental Science & Technology, 39(23): 9016-9022. https://doi.org/10.1021/es0505898

[28] Denholm, P., Kulcinski, G.L. (2004). Life cycle energy requirements and greenhouse gas emissions from large scale energy storage systems. Energy Conversion and Management, 45(13-14): 2153-2172. https://doi.org/10.1016/j.enconman.2003.10.014

[29] Zhang, H., Liu, J., Liang, W., Shan, H., Wang, J. (2022). Design and simulation analysis of high-temperature heat-storage combined-circulation system. Clean Energy, 6(1): 77-88. https://doi.org/10.1093/ce/zkab047

[30] Dumont, O., Frate, G.F., Pillai, A., Lecompte, S., De paepe, M., Lemort, V. (2020). Carnot battery technology: A state-of-the-art review. Journal of Energy Storage, 32: 101756. https://doi.org/10.1016/j.est.2020.101756

[31] Carrasco, J.M., Franquelo, L.G., Bialasiewicz, J.T., Galván, E., PortilloGuisado, R.C., Prats, M.A.M., Leon, J.I., Moreno-Alfonso, N. (2006). Power-electronic systems for the grid integration of renewable energy sources: A survey. IEEE Transactions on Industrial Electronics, 53(4): 1002-1016. https://doi.org/10.1109/TIE.2006.878356

[32] Kuravi, S., Trahan, J., Goswami, D.Y., Rahman, M.M., Stefanakos, E.K. (2013). Thermal energy storage technologies and systems for concentrating solar power plants. Progress in Energy and Combustion Science, 39(4): 285-319. https://doi.org/10.1016/j.pecs.2013.02.001

[33] Bejan, A., Tsatsaronis, G., Moran, M.J. (1996). Thermal Design and Optimization. John Wiley & Sons.

[34] Bai, Z.H., Miao, C.H., Wang, W. (2019). The value of thermal storage technology in integrated energy system. Distribution & Utilization, 36(3): 20-26.

[35] Verda, V., Colella, F. (2011). Primary energy savings through thermal storage in district heating networks. Energy, 36(7): 4278-4286. https://doi.org/10.1016/j.energy.2011.04.015

[36] Morisson, V., Rady, M., Palomo, E., Arquis, E. (2008). Thermal energy storage systems for electricity production using solar energy direct steam generation technology. Chemical Engineering and Processing: Process Intensification, 47(3): 499-507. https://doi.org/10.1016/j.cep.2007.01.025

[37] Jian, Y., Falcoz, Q., Neveu, P., Bai, F., Wang, Y., Wang, Z. (2015). Design and optimization of solid thermal energy storage modules for solar thermal power plant applications. Applied Energy, 139: 30-42. https://doi.org/10.1016/j.apenergy.2014.11.019

[38] Hao, J., Chen, Q., Ge, W., Chen, L., Xu, F., Min, Y. (2019). Influence of thermal characteristics on the synthetic scheduling of an integrated heat and power supply system with thermal storage. Proceedings of the CSEE, 39(29): 5063-5072. https://doi.org/10.13334/j.0258-8013.pcsee.181157

[39] Wu, B., Shao, Z., Hu, X. (2015). Heat supply transformation for four 215 MW units using steam extraction. Thermal Power Generation, 44(5): 87-90. https://doi.org/10.3969/j.issn.1002-3364.2015.05.087

[40] Liu, J., Duan, C., Zheng, D., Liang, P., Wang, Q. (2018). Research on phase separation of mesophase pitch and its carbon fiber. New Chemical Materials, 46(10):165-169.

[41] Duan, C.T., Zheng, D.F., Liu, J.Q., Wang, Q.S., Liang, P., Gong X.Y., Song, H.H. (2018). Research progress on the characterization of mesophase pitch. New Carbon Materials, 33(3):193-202.

[42] Pasta, M., Wessells, C.D., Huggins, R.A., Cui, Y. (2012). A high-rate and long cycle life aqueous electrolyte battery for grid-scale energy storage. Nature Communications, 3(1): 1149. https://doi.org/10.1038/ncomms2139

[43] Khamlich, I., Zeng, K., Flamant, G. (2021). Technical and economic assessment of thermal energy storage in concentrated solar power plants within a spot electricity market. Renewable and Sustainable Energy Reviews, 139: 110583.