David Tomás Sánchez Martínez
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(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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Thermodynamic analysis of a novel pumped thermal energy storage system with waste heat integration

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ABSTRACT

Pumped thermal energy storage (PTES) system is a large-scale electricity storage technique, and the thermally integrated PTES system has been brought forward to raise the energy storage efficiency and extend feasible ways to utilize the low-grade waste heat (<100 °C). The solutions to raise the power-to-power efficiency of the thermally integrated PTES system have aroused much attention worldwide. This paper presents an innovative thermally integrated PTES system, in which the two-stage heat pump with an economizer is incorporated into the PTES system. Despite utilizing the waste heat at charge time, the low-grade waste heat is also poured into the discharging process innovatively. The simulation model of the thermally integrated PTES system is established in the software MATLAB, and the physical properties of the substances are acquired from the software Refprop 10. The parameters of the PTES system are displayed and the power-to-power efficiency of the PTES system is investigated under various thermal storage temperatures. The results indicate that the power-to-power efficiency increases first and then declines as the low heat storage temperature rises when the high heat storage temperature is deemed. However, the energy storage density of the system dwindles with the increment of low heat storage temperature. The rise of the component efficiency contributes to the improvement of the power-to-power efficiency obviously, which can reach 87.3% as the isentropic efficiencies are 90%. The exergy destruction in the heat exchangers and mechanical components occupy a large proportion of the overall exergy destruction, which infers that the modification of the heat transferring and expansion/ compression processes are viable for performance enhancement. 294

1 INTRODUCTION

Carbon dioxide (CO_2) emissions pose a great threat to the global environment as a culprit of global warming (Deng et al., 2023). United Nations Framework Convention on Climate Change (UNFCCC) established an international environmental treaty to limit the increase in global mean temperature relative to pre-industrial times to less than 2 °C (JebabliLahiani & Mefteh-Wali, 2023). As the world's largest CO_2 emitter, China has actively undertaken the responsibility for net-zero emission, pledging to peak carbon dioxide by 2030 and achieve carbon neutrality by 2060 (Jiang & Xia, 2023). With the continuous rising of the market share of renewable energy, especially solar energy, and wind energy, the mismatches between renewable energy supplies and load demands result in challenges for integrating renewable resources into the existing power grids (Liu et al., 2020). In consequence, the energy storage system should be implemented for peak shaving, load balancing, and improving the flexibility and resiliency of the power grid (KazemiTabatabaei & Moslemi, 2023; Yong, Wu, Zhou, Tao, & Chen, 2023).

The energy storage technique has aroused much attention in recent years, which can be classified into physical energy storage, electrochemical energy storage, and so on. Pumped thermal energy storage (PTES) is a branch of the physical energy storage technology (Dumont et al., 2020) and has been recognized as a promising energy storage technique with large potential, owing to the advantages of unlimited by geographical locations, high energy storage density (up to 16.86 kWh/m^3) (FrateFerrari & Desideri, 2020) and small installation footprint (Vecchi et al., 2022). The conventional low-temperature

PTES system faces the problem of relatively low round-trip efficiency as compared to other large-scale storage technologies (Zhang, Shi, Hu, Pei, & Shu, 2023). Therefore, the thermally integrated PTES system has been brought forward to improve the power-to-power efficiency, in which the low-grade waste heat from many fields (for instance, industrial waste heat, solar energy) is delivered to the charging process of the PTES system and works as the low-temperature heat source of the heat pump (HP). Many scholars have devoted much work to investigating the performances of the PTES system with heat integration from the views of selecting and matching superior working fluids in different processes (Hassan et al., 2020), evaluating thermal storage medium (Eppinger, Zigan, Karl, & Will, 2020) and searching efficient system configurations.

As the charging process and the discharging process of the thermally integrated PTES system lie in a different range of working temperatures, the configurations should be designed separately to attain high energy utilization efficiency. As can be discovered from the published literature, most studies carried out the research based on the basic structure of the charging and discharging process (Fan & Xi, 2022; FrateFerrari & Desideri, 2020; Kurşun & Ökten, 2022), namely the recuperated/ non-recuperated HP and the recuperated/ non-recuperated ORC. Weitzer et al. compared the performances of various PTES systems that based on ORC and organic flash cycle (OFC) (Weitzer et al., 2022), the results indicate that the OFC with two-phase expander outperforms the ORC for large thermal storage temperature spreads and the off-design performance of the two-phase expansion has also been evaluated (WeitzerMüller & Karl, 2022). What's more, the PTES system with OFC as the discharging process was also evaluated by (Tian & Xi, 2022) and (Wang et al., 2022), and the analyses show that the PTES system with the OFC is worse than that of the PTES system caused by the large exergy destruction in the pressure reducing valve. Apart from utilizing the low-grade waste heat in the charging process, (Zhang et al., 2023) presented an advanced thermally integrated PTES system, in which the waste heat is also conveyed to the discharging process to warm the working fluid. The evaluation results explain that the power-to-power efficiency can be promoted by 18.4% in contrast to the conventional PTES system as the thermal storage temperature is 130 °C.

Although a volume of research has focused on searching various kinds of PTES system configurations to improve power-to-power efficiency, the concerning study should also be carried out deeply to dig out new effective configurations for the thermally integrated system. Against this backdrop, this paper proposed a novel thermally PTES system, in which both the charging process and the discharging process are updated with new configurations. To be specific, the charging process includes parallel compression and an economizer with the intent of reducing the energy destruction in the pressure-reducing valve. In the discharging process, the waste heat is applied to assist the heating process of the working fluid into the expander. Furthermore, the proposed thermally integrated PTES system is evaluated under various internal parameters. In section 2, the proposed thermally integrated PTES system is put forward. In section 3, the basic assumptions for model construction and thermodynamic indicators are presented. In section 4, the parameters analysis and exergy evaluation results are shown. In section 5, the main conclusions of the paper are drawn. **295**

2 SYSTEM DESCRIPTION

To improve the energy storage efficiency of the thermally integrated PTES system, a novel PTES system with heat integration has been proposed to exploit the energy utilization potential of the low-grade waste heat, as displayed in Figure 1. Moreover, the T-S diagram of the proposed PTES system is also depicted in Figure 1. As can be discovered from the figure, the PTES system can be divided into three subsystems, namely the charging process (HP), the heat storage system, and the discharging process (ORC). Different from the traditional thermally integrated PTES system, the advanced PTES system adopts the parallel compression HP at the charge time. Apart from working as the low-temperature heat source of the HP, the low-grade waste heat has been also delivered to the ORC to preheat the working fluid at the inlet of the evaporator at the discharge time. In the charging process, the compressed working fluid from the two compressors is mixed and heat the heat storage medium in the condenser. Moreover, the working fluid out of the condenser splits into two streams, one of them is decompressed by valve 1, and the other stream flows into the economizer to release its heat energy. The liquid working fluid from the economizer goes into the recuperator for further temperature reduction and then reduces its pressure through valve 2 to absorb the waste heat in the evaporator. When there is an electricity demand for the local area, the high-temperature heat storage medium heats the working fluid at the inlet of the expander, and the stream expands and drives the expander for power production. Furthermore, the working fluid condensed by the cooling water is warmed in the recuperator and the additional heater successively before entering the evaporator.

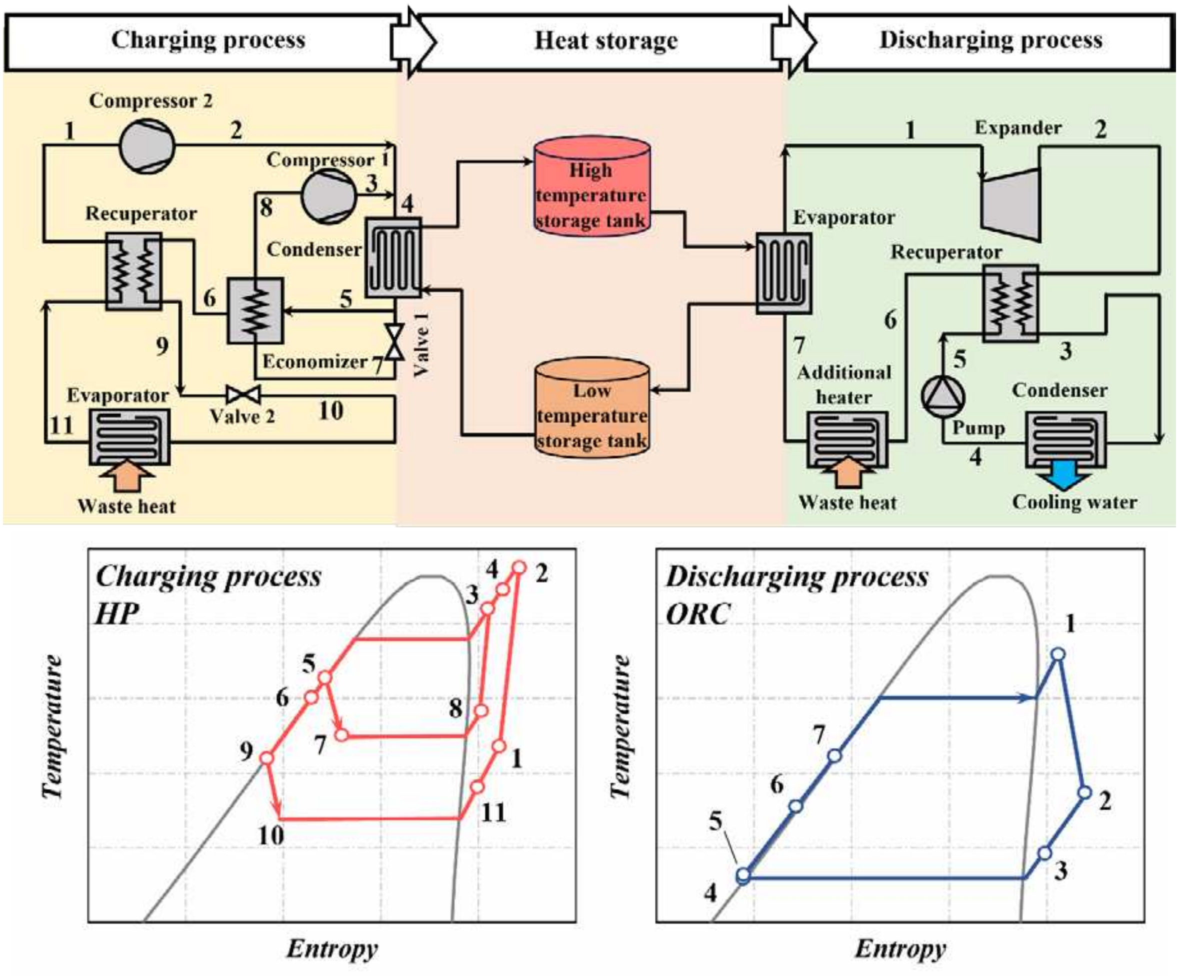

Figure 1: System configuration T-S diagram of the novel thermally integrated PTES system

3 METHODOLOGY

3.1 Basic assumptions

The software MATLAB is a mathematical calculation-based programming software widely used in many fields, which has been implemented to simulate the proposed PTES system in this work. The physical properties of the substances (organic working fluid and pressurized water) utilized in this paper is acquired from the software Refprop 10. The basic parameters of the novel PTES system are summarized in Table 1. The working fluid in the charging and discharging process affects the performance of the PTES system directly, which should be chosen carefully to achieve the best performance of the system. However, the selection of the working fluid is not in the scope of this study, and the working fluid applied in the HP and ORC is the R1233zd(E) for its advantages of safety properties and good performance. Under the consideration of the physical properties, safety, and economic feasibility, the thermal storage medium is selected as pressurized water. To compare the performance of the PTES system under different working conditions, the surplus power poured into the charging process is deemed as 1000 kW. The temperature differences of the phase change heat exchanger and the single-phase heat exchanger are chosen as 2 °C and 5 °C, respectively. Moreover, the isentropic efficiencies of the pump, the compressor, and the expander are 85%, and the efficiencies of the motor and the generator are also 98%. The thermal storage efficiency of the heat storage tank strongly depends on the construction material and the external conditions and should be determined by the real experiment. For the simplicity of the theoretical research, the heat storage efficiency is assumed as 100% in this study.

Table 1: Basic parameters of the novel PTES system

Item	Unit	Value
Surplus power poured at the charge time	kW	1000
Temperature of the cooling water	°C	20
Temperature difference of the phase change heat exchanger	°C	2
Temperature difference of the single change heat exchanger	°C	5
Waste heat inlet temperature	°C	80
Waste heat outlet temperature	°C	60
Compressor efficiency	-	85%
Pump efficiency	-	85%
Motor efficiency	-	98%
Expander efficiency	-	85%
Generator efficiency	-	98%
Thermal storage efficiency	-	100%
Working fluid of the PTES system	-	R1233zd(E)

3.2 Thermodynamic modelling

Energy storage efficiency is a crucial performance indicator of the energy storage system. As low-grade waste heat (<100 °C) is widely distributed in various scenarios, for instance, industrial waste heat, solar energy, and geothermal energy, the waste heat utilized in the advanced PTES system is recognized as sufficient and free of charge. Therefore, the energy storage efficiency of the thermally integrated PTES system, namely the power-to-power efficiency, is defined as the ratio of the power output at the discharge time to the surplus power into the PTES system at the charge time.

$$\eta_{\mathrm{PTP}} = \frac{Power_{\mathrm{dischar}}}{Power_{\mathrm{char}}} \tag{1}$$

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where $Power_{\mathrm{dischar}}$ is the electric power output of the PTES system at discharge time, kWh; $Power_{\mathrm{char}}$ is the electric power input of the PTES system at charge time, kWh.

During the charging process of the PTES system, the heat energy released from the condenser in the HP is stored in the high-temperature storage tank, and then the energy is delivered to the evaporator in the ORC for power production. The relationship between energy storage efficiency and the charging and discharging processes can be derived as below:

$$\eta_{\mathrm{PTP}} = COP * \eta_{\mathrm{st}} * \eta_{\mathrm{ORC}} \tag{2}$$

where the COP is the coefficient of the HP, the η_{ORC} is the efficiency of the discharging process, the η_{st} is the thermal storage efficiency of the heat storage tanks.

The energy storage density (ESD, kWh/m^3) is also an important indicator for the energy storage system, which is formulated as:

$$ESD = Power_{\mathrm{dischar}} / V_{\mathrm{tank}} \tag{3}$$

where the V_{tank} is the total volume of the high-temperature and low-temperature heat storage tanks, m^3.

Furthermore, the second law of thermodynamics has been also applied to evaluate the energy transmission process of the PTES system and thereby discover the energy-saving potential of the thermally integrated system. The exergy destruction in each component (for instance, the heat exchanger, the compressor, and the expander) can be described as Equation (3), which is formulated as the difference between the total exergy inflows and total outflows. The dead state of the exergy analysis is set to be 20 °C and 101.325 kPa.

$$EX_{\mathrm{des,i}} = \sum EX_{\mathrm{inflow,i}} - \sum EX_{\mathrm{outflow,i}} \tag{4}$$

4 RESULTS AND DISCUSSION

4.1 Parameter analysis

The parameters of the proposed PTES system are demonstrated in Table 2, in which the main thermophysical properties at each state point are shown. The temperatures of the high-temperature and low-temperature storage tanks are selected as 130 °C and 90 °C. Apparently, the power-to-power efficiency of the new PTES system can achieve 78.89% when the waste heat inlet temperature is 80 °C.

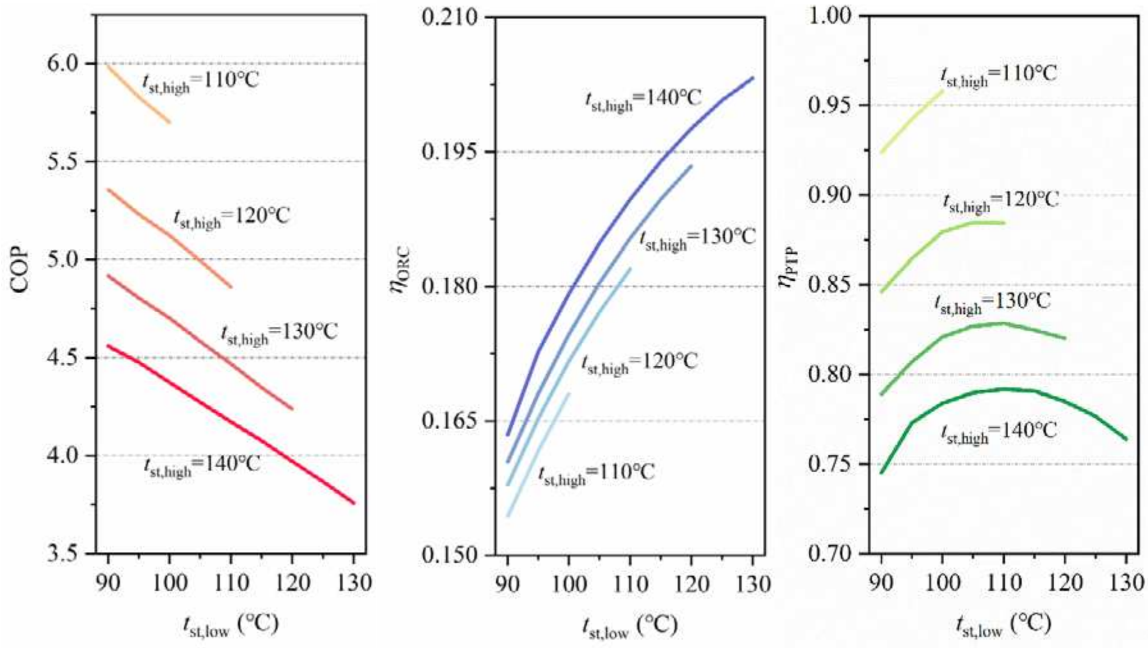
Table 2: Parameters of the novel PTES system at the high and low heat storage temperatures are 130 °C and 90 °C

State point	Pressure (MPa)	Temperature (°C)	Mass flow rate (kg/s)	Power (kW)
Charging process of PTES system				
1	0.37	81.5	25.22	-
2	1.81	143.5	25.22	-
3	1.81	129.3	1.16	-
4	1.81	142.8	26.38	-
5	1.81	92.1	25.22	-
6	1.81	87.0	25.22	-
7	0.74	85.0	1.16	-
8	0.74	90.0	1.16	-
9	1.81	74.0	25.22	-
10	0.37	58.0	25.22	-
11	0.37	63.0	25.22	-
Power input	-	-	-	1000
Discharging process of PTES system				
1	0.93	94.7	28.38	-
2	0.15	45.1	28.38	-
3	0.15	36.1	28.38	-
4	0.15	30.0	28.38	-
5	0.93	30.4	28.38	-
6	0.93	36.6	28.38	-
7	0.93	75.0	28.38	-
Power output	-	-	-	788.9

The thermal storage system is a crucial subsystem of the PTES system, and the heat storage temperature pair of the heat storage system influences the COP and the ORC efficiency as the boundary conditions. Hence, the variations of the performance indicators of the charging and the discharging process along with the heat storage temperatures are investigated and the results are shown in Figure 2. In the performance evaluation process, the temperature difference of the heat storage tanks should be larger than 10 °C. It should be noted that the COP of the HP declines when the low heat storage temperature increases, whereas the efficiency of the ORC goes up under the condition that the high heat storage temperature is deemed.

With the rising of the low heat storage temperature, the power-to-power efficiency firstly augments and then dwindles along with the increment of the low-temperature heat storage temperature when the high heat storage temperature is higher than 110 °C. This is mainly because the presence of the power-to-power efficiency of the thermally integrated PTES system is a competition between the performances of the HP and ORC, and the importance of the charging process on the whole system performance is becoming more predominant as the low storage temperature goes up. What's more, the power-to-power efficiency declines with the increment of the high heat storage temperature, and the performance of the charging process has a huge impact on the overall efficiency. Under the condition that the heat storage temperatures are 140 and 110, the power-to-power efficiency is calculated to be 79.2%.

The power-to-power efficiency of the PTES system reaches its highest value when the temperatures of the high-temperature storage tank and low-temperature storage tank are 110 °C and 100 °C, respectively. However, the energy storage density can only attain 0.94 kWh/m^3, which is relatively low as compared to other energy storage techniques. Figure 3 depicts the energy storage 298 density of the proposed PTES system under various heat storage temperature pairs. It is obvious that the energy storage density increases along with the temperature difference of the heat storage tanks. Taking into consideration the variation trend of the power-to-power efficiency under different heat storage temperatures, the heat storage temperatures of the tanks should be selected carefully to fulfill the requirements of high power-to-power efficiency and energy storage density. When the high heat storage temperature is 140 °C, the power-to-power efficiency and energy storage density have the opposite trends as the low heat storage temperature is lower than 110 °C. The selection of the low heat storage temperature to be 110 °C seems to be a rational option considering the balances of the two indicators, and a temperature higher than 110 °C is not worth choosing for the poor performances in the two aspects.



(a) COP of charging process (b) η_{ORC} of discharging process (c) η_{PTP}

Figure 2: Performance indicators of the charging and discharging process under different thermal storage temperatures

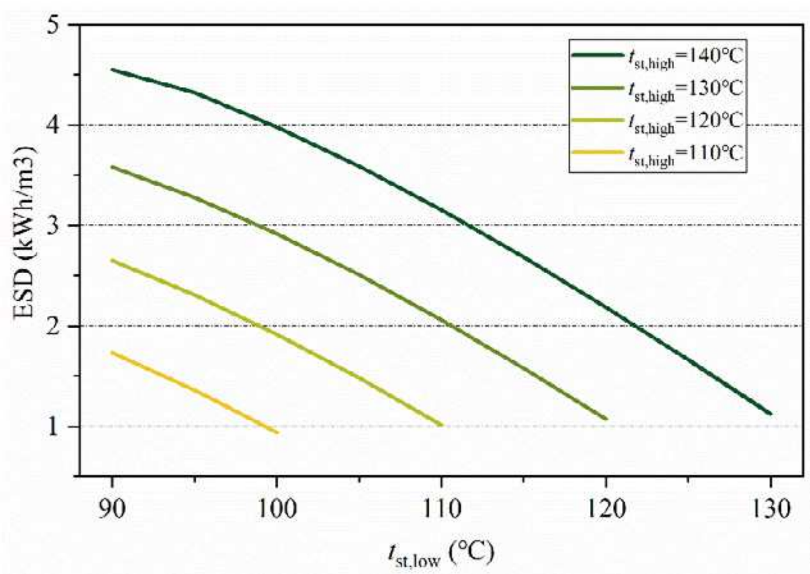


Figure 3: Energy storage density of the PTES system under different heat storage temperatures

The mechanical components, namely the compressor, the expander, and the pump, are significant equipment in the PTES system. Generally, improving the efficiencies of the mechanical components has been proven to be a viable measure to promote the power-to-power efficiency of the thermally integrated PTES system by many scholars. However, the quantitive research on the isentropic efficiencies of the compressor and the expander on the performance of the thermally integrated PTES system should be evaluated thoroughly. The variations of the power-to-power efficiency with various isentropic efficiencies are demonstrated in Figure 4, and the efficiencies vary from 60% to 90%. The performances of the PTES system are evaluated under the condition that the high and low heat storage temperatures are 140 °C and 110 °C. The power-to-power efficiency increases along with the isentropic efficiencies, and it can be discovered that the energy storage efficiency of the PTES system reaches the largest value (87.3%) when the compressor efficiency and the expander efficiency are 90%. Whereas the power-to-power efficiency can only attain 43.4% as the isentropic efficiencies are 60%. Moreover, the same amount of isentropic efficiency increment in the expander seems to be more beneficial to the performance of the proposed PTES system than that of the compressor.

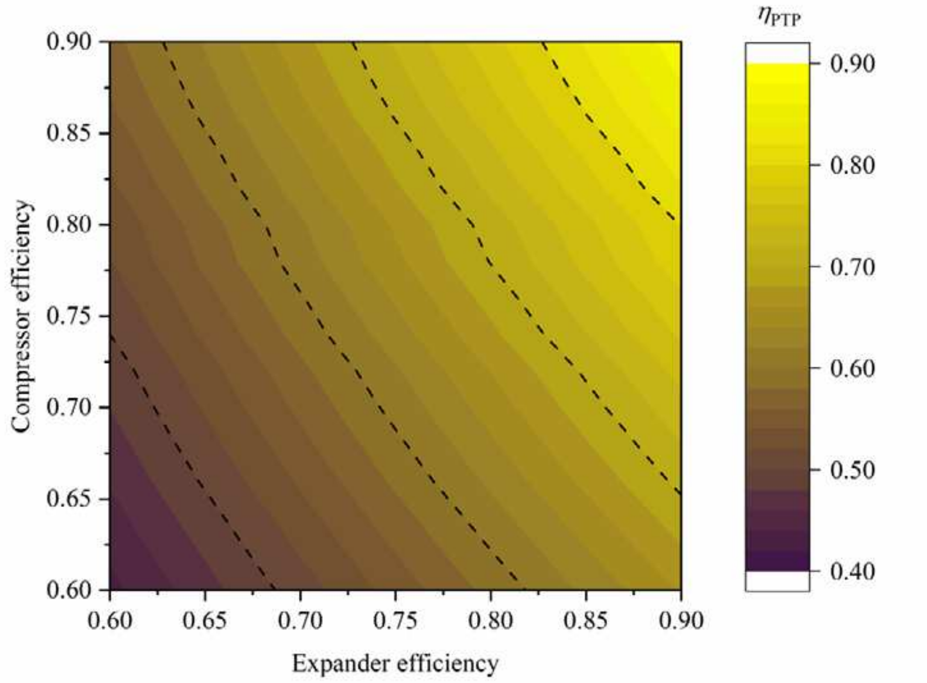


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Figure 4: Variations of power-to-power efficiency under different compressor efficiency and expander efficiency

4.2 Exergy analysis

The exergy evaluation method is developed based on the second law of thermodynamics and has been widely implemented to investigate the energy-saving potential of various energy systems in many fields. The exergy flow diagram of the novel PTES system is depicted in Figure 5, in which the exergy inflows, exergy outflows, and exergy destruction in the main equipment are displayed. It should be mentioned that the exergy flows were calculated and diagrammed under the condition that the high and low heat storage temperatures are 140 °C and 110 °C, respectively. To be specific, in the charging process of the PTES system, a total power input of 1000 kW is conveyed to the compressors in the HP. What's more, the working fluid in the evaporator absorbs 464.54 kW exergy from the low-grade waste heat, and then the gas working fluid (525.51 kW) flows into the recuperator for temperature enhancement. During the charge time, the heat exchangers possess the largest part of the total exergy destruction (54.62%), and the sum of the exergy losses in the compressors is 118.77 kW (32.52%). And the exergy destructions happened in the mixer and the valves are 1.44 kW and 45.52 kW.

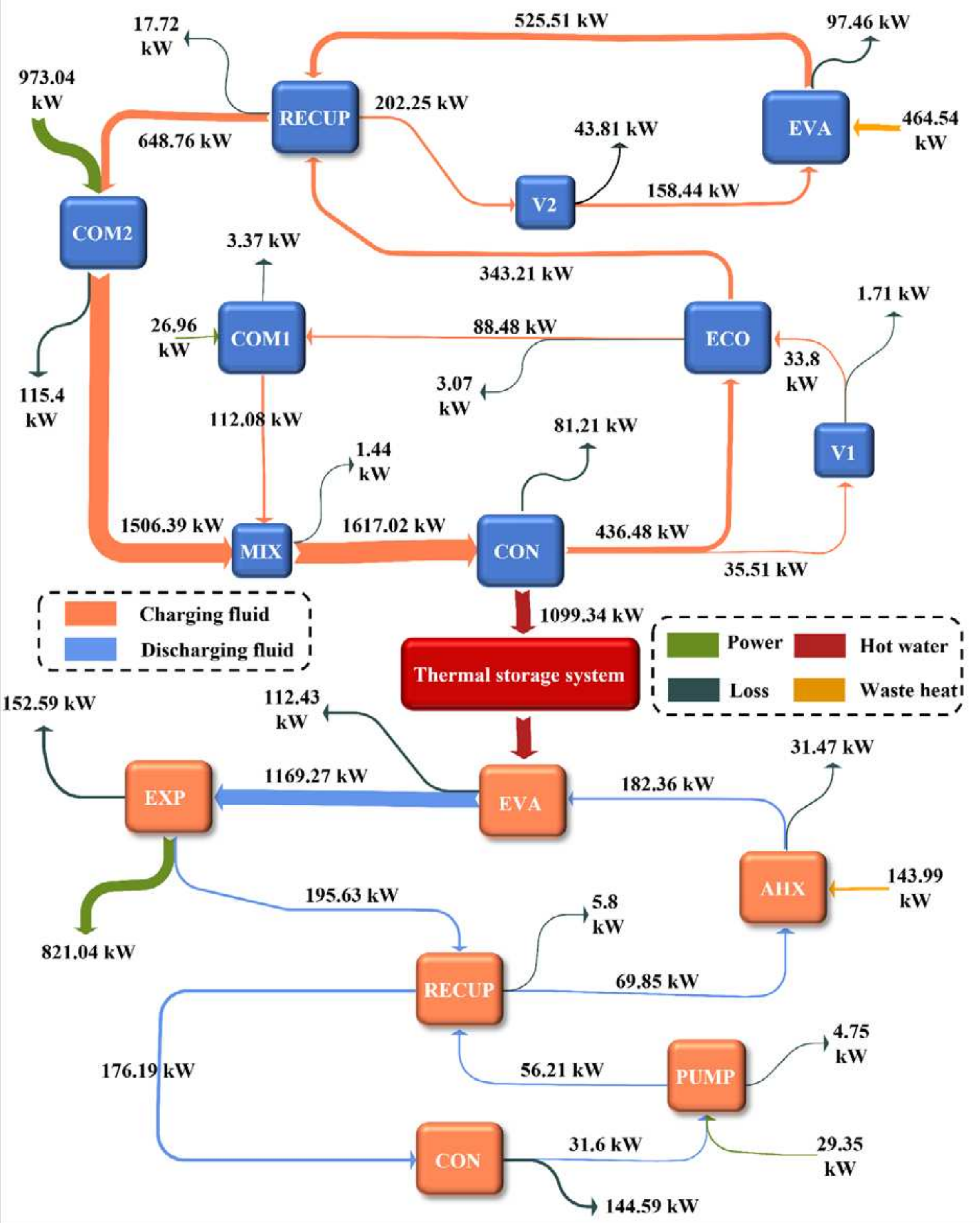

Figure 5: Exergy flow diagram of the novel PTES system (the high and low thermal storage temperatures are 140 °C and 110 °C)

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The heat storage system stored the exergy of 1099.34 kW after the charging process in the HP. The expander can produce electricity of 821.04 kW when there is a demand for power, and the power output of the ORC is 791.69 kW after deducting the power requirement of the pump. While in the discharging process of the novel PTES system, the total exergy losses in the heat exchangers (the evaporator, condenser, regenerator, and the additional heater) are 294.30 kW. Furthermore, the exergy destructed in the expander and the generator takes a proportion of 33.79% of the overall exergy loss in the ORC. To sum up, the total exergy loss of the novel PTES system is calculated to be 816.84 kW.

The heat exchangers have the largest part of the overall exergy loss, and the exergy destruction that happened in the mechanical components is second to it. The analysis results indicate that modifying the heat exchange processes of the heat exchangers and improving the efficiencies of the mechanical components should be the dominant measures for the efficiency-boosting of the PTES system. Furthermore, the reduction of the exergy destruction in the heat transferring process, namely the heat transfer area of the heat exchangers, would augment the investment cost of the PTES system. Therefore, the minimum temperature difference of the heat exchangers ought to be selected based on the PTES overall performance and the economic indicators.

1 CONCLUSIONS

In this paper, a novel thermally integrated PTES system has been proposed to improve the power-to-power efficiency of the system and exploit the energy utilization potential of low-grade waste heat. In order to evaluate the performance of the PTES system under various working conditions, the parameter analysis has been carried out to show the variations of the power-to-power efficiency with different heat storage temperatures and the isentropic efficiencies of the compressor and the expander. Furthermore, the exergy flow diagram of the novel PTES system was also diagrammed to point out the direction of boosting the energy storage efficiency of the PTES system with heat integration.

- In the charging process of the advanced PTES system, parallel compression with an economizer is employed to increase the amount of waste heat utilization. Moreover, an additional heater is added to the ORC to boost power production at the discharge time.
- With the increment of the low heat storage temperature, the COP declines and the ORC efficiency increases under certain high storage temperatures. And the power-to-power efficiency can attain the highest value when the temperatures of the high heat storage tank and low heat storage tank are 110 °C and 100 °C. However, the energy storage density is relatively low as the temperature differences of the tanks are small.
- The isentropic efficiencies of the compressor and the expander affect the performance of the PTES system directly. The rise of the component efficiency contributes to the improvement of the power-to-power efficiency, which can reach 87.3% as the isentropic efficiencies are 90%.

- The exergy evaluation results show that the exergy destruction that happened in the heat exchangers is the mechanical components that are the most important parts of the overall system. The findings imply that modifying the heat-transferring process and improving the isentropic efficiencies of the mechanical component would be effective measures for performance enhancement.

According to the analysis results above, the heat storage temperatures of the tanks ought to be chosen carefully to sustain the requirements of high power-to-power efficiency and energy storage density. More possible measures for raising the two indicators simultaneously should be developed, for instance, optimizing the heat storage method and searching for more effective configurations. This is also a direction of future research.

NOMENCLATURE

Abbreviations			
AHX	additional heater	HP	heat pump
COM	compressor	ORC	organic Rankine cycle
CON	condenser	PTES	pumped thermal energy storage
ECO	economizer	RECUP	recuperator
ESD	Energy storage density	V	valve
EXP	expander		
Symbols			
COP	coefficient of performance	*power*	electric power (kWh)
ESD	energy storage density (kWh/m^3)	*V*	volume (m^3)
EX	exergy flow (kW)	η	efficiency
Subscripts			
char	charging process	ORC	organic Rankine cycle
dischar	discharging process	st	storage
PTP	power-to-power	tank	heat storage tank

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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