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Identifications of key thermodynamic parameters for Carnot battery based on SHAP model#

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ABSTRACT

Carnot battery is an emerging long-term energy storage technology with lower cost, larger capacity, and no geography restrictions, which is expected for large-scale applications, promoting renewable energy consumption. However, the Carnot battery contains a HP unit, a heat storage unit, and an Organic Rankine Cycle unit, involving amounts of thermodynamic parameters that are coupled to each other. The importance and influence of thermodynamic parameters on power-to-power efficiency are still unclear. Therefore, in this paper, the SHAP model is used to establish the analysis framework for the power-to-power efficiency of the Carnot battery. Firstly, heat pump evaporation temperature and Organic Rankine Cycle evaporation temperature are the two most important parameters. Their maximum importance is 0.80 and 0.58, respectively. Then, the most important thermodynamic parameter in different scenarios is analyzed. Finally, the influence rules of HP evaporation temperature and ORC evaporation temperature on power-to-power efficiency are studied. The results are of guiding significance for the parameter optimization and engineering application of the Carnot battery.

Keywords: Carnot battery, Organic Rankine cycle, Energy storage, SHAP model, Key parameter

1. INTRODUCTION

A high proportion of renewable energy consumption is an important way to achieve the carbon peak and carbon neutrality. However, renewable energy, such as wind power and solar energy, is intermittent and volatile, and its large-scale grid connection will have an impact on the power grid, leading to a mismatch between supply and demand [1]. Carnot battery is a new long-term energy storage technology, which uses a heat pump (HP) to store abandoned electricity and valley electricity in the form of heat, and then uses a power cycle to convert the stored heat into electricity as needed. Carnot battery has the advantages of low cost, larger capacity, and no geographical restrictions. It is expected to be applied in large-scale scenarios, promoting deep decarbonization of the energy system [2]. According to the power cycle, Carnot battery can be divided into Brayton cycle and Rankine cycle Carnot battery, among which Organic Rankine Cycle (ORC) based Carnot battery have more application potential and promotion value because it can use low-grade heat to improve the power-to-power efficiency.

Carnot battery contains many thermodynamic parameters and complex energy-flow coupling relations, which are significant for parameter optimization and system design of Carnot battery. Existing research has been carried out on the factors influencing the power-to-power efficiency of the Carnot battery. Hu et al. [3] constructed the thermodynamic model of thermally integrated PTES (TI-PTES) and explored the effects of key system parameters and heat source conditions. Results indicated that a higher heat source flow rate/temperature leads to higher component efficiency. Yu et al. [4] evaluated the influence of key parameters in the HP-ORC system. In their work, the system performance is closely related to the working fluid, evaporation, and condensation temperatures. Frate et al. [5] proposed a novel thermally integrated Carnot battery, finding that a maximum power-to-power efficiency of 1.3 was achieved, when the heat source temperature reached 110°C. However, the existing research generally carries out analysis based on specific scenarios, such as fixed environment temperature and heat source temperature, so the importance degree and influence rule of each thermodynamic parameter in different scenarios are not clear. In addition, the analysis generally stays at the level of qualitative analysis, but lacks the quantitative analysis of the importance degree

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of various thermodynamic parameters on power-to-power efficiency. Moreover, the thermodynamic parameters in the Carnot battery are coupled with each other, and the independent contribution and influence rule of each parameter are rarely analyzed in the existing research. It is, therefore, difficult to guide which design parameters to optimize for the Carnot battery.

Therefore, based on the SHAP model, the key thermodynamic parameters of Carnot battery's electro-to-electric efficiency are identified, the importance degree of each thermodynamic parameter in 54 scenarios is analyzed, and the influence rules of key thermodynamic parameters on the power-to-power efficiency of Carnot battery is explored. The results can provide guidance for the optimal parameter selection and system design of Carnot battery.

2. METHODS

2.1 System modeling

The Carnot battery selected in this paper consists of three parts: a HP unit, an ORC unit, and a heat storage unit, and its system structure is shown in Fig. 1(a). The HP unit uses the steam compression HP with R1234ze(Z) as the working fluid, the ORC unit uses the subcritical ORC with R601 as the working fluid, and the hot tank uses high-pressure water to store the heat. The *T-s* diagrams of the HP unit and the ORC unit are shown in Figs. 1(b) and (c), respectively. In the charging process, the input power (such as valley electricity and abandoned renewable electricity) drives the compressor of the HP unit, compressing the working fluid to the state of high temperature and high pressure (1→2). The working fluid transfers the heat to the hot tank through the heat storage fluid in the condenser (2→5), then the working fluid lowers the temperature and pressure through the throttle valve (5→6). In the evaporator, working fluid absorb the heat from the low-grade thermal energy (6→1) and then into the compressor. In the discharging process, the working fluid absorbs the heat stored by the heat storage fluid from the evaporator and evaporates (8-11), then enters the turbine to do work to generate electricity (11-12). The working fluid after work enters the condenser to cool down (12-14), and finally enters the evaporator (14-8) again by the working fluid pump to complete the cycle.

In this paper, the system is assumed to be in a steady state, ignoring the heat loss and pressure loss in the pipeline and heat exchanger [6]. The thermophysical properties of the working fluid are called by the REFPROP 10.0 software. The heat source of the Carnot battery is selected as industrial waste heat at 50-95°C, which is relatively common in industrial processes [7]. The environment temperature is selected as 5-30°C. The interval of the heat source temperature and the environment temperature is 5°C, thus there are 54 scenarios in total. Other settings for the Carnot battery are shown in Table 1. In order to ensure that the heat storage fluid is liquid, its pressure is set to 0.5 MPa. Considering that the HP cycle is to obtain higher grade heat, the heat storage temperature is limited to at least 10°C higher than the heat source temperature.

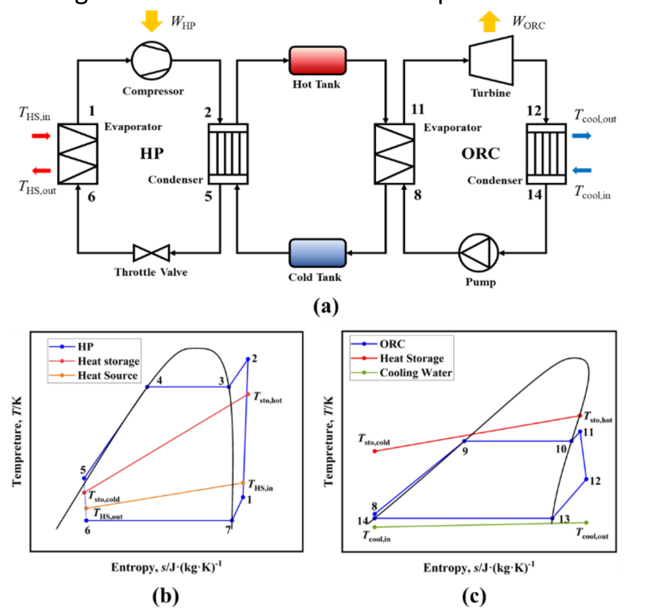

Fig. 1 The system structure and T-s diagrams of Carnot battery

Table 1 Working conditions of Carnot battery

Parameter	Symbol	Unit	Range
Heat source temperature	$T_{HS,in}$	°C	50-95
Heat source flow	$\dot{m}_{HS}$	kg·s^{-1}	30
Heat source pressure	p_{HS}	kPa	101.325
Cooling water inlet temperature	$T_{cool,in}$	°C	5-30
Cooling water temperature rise	$T_{cool,pp}$-$T_{cool,in}$	°C	5
Cooling water pressure	p_{cool}	kPa	101.325
Working fluid pump head	H	m	10
Environment temperature	T_{env}	°C	5-30
Pinch point temperature difference	ΔT_{pp}	°C	5

The power-to-power efficiency (η_{PTP}) is used as the evaluation index of the thermodynamic performance of Carnot battery. The calculation is defined as follows:

$$\eta_{\mathrm{PTP}}=\frac{W_{\mathrm{ORC}}}{W_{\mathrm{HP}}}=\frac{Q_{\mathrm{ORC,in}}\times\eta_{\mathrm{ORC}}}{Q_{\mathrm{HP,out}}/\mathrm{COP}}=\mathrm{COP}\times\eta_{\mathrm{ORC}}\times\eta_{\mathrm{sto}} \quad (1)$$

where, W_{ORC} and W_{HP} are the net power generation of ORC unit and the power consumption of HP unit, respectively; $Q_{ORC,in}$ is the heat absorption of the ORC unit; $Q_{HP,out}$ is the heat production of the HP unit; COP is the performance coefficient of the HP unit; η_{ORC} is power generation efficiency of the ORC unit.

The COP of HP unit is calculated as:

$$\mathrm{COP}=\frac{Q_{\mathrm{HP,out}}}{W_{\mathrm{HP}}} \quad (2)$$

The power generation efficiency of the ORC unit is calculated as:

$$\eta_{\mathrm{ORC}}=\frac{W_{\mathrm{ORC}}}{Q_{\mathrm{ORC,in}}} \quad (3)$$

The net power generation of the ORC unit is calculated as:

$$W_{\mathrm{ORC}}=W_{\mathrm{T}}-W_{\mathrm{P}}-W_{\mathrm{cool}} \quad (4)$$

where, W_T is the turbine output power, W_P is the power consumption of the working fluid pump, and W_{cool} is the power consumption of the cooling system.

2.2 Dataset generation

Six thermodynamic parameters are investigated, which are HP evaporation temperature, HP condensation temperature, superheat degree of HP evaporation process, ORC evaporation temperature, superheat degree of ORC evaporation process, and heat storage temperature. The lower bound of the HP condensation temperature is the temperature corresponding to the HP evaporation pressure plus 100 kPa, and the upper bound is the temperature corresponding to the 0.9 critical pressure. The lower bound of ORC evaporation temperature is the temperature corresponding to ORC condensation pressure plus 100 kPa, and the upper bound is the temperature corresponding to 0.9 critical pressure. The heat storage temperature of the Carnot battery is selected as 60-150°C, which is common in the current market. The ranges of other thermodynamic parameters are shown in Table 2.

The Latin Hypercube Sampling method [8] is used to sample the thermodynamic parameter space. The overall sampling result is a $n \times p$ matrix, where n is the number of samples and p is the number of thermodynamic parameters. The sampling result follows uniform distribution. 30,000 samples are sampled for each scenario, which are then calculated to obtain the power-to-power efficiency. In this paper, a total of 6391 valid data satisfying constraint conditions are generated in the dataset, which is used to further analyze the importance of parameters.

Table 2 Ranges of thermodynamic parameters

Parameter	Symbol	Lower bound(°C)	Upper bound(°C)
HP evaporation temperature	$T_{HP,eva}$	5	90
HP condensation temperature	$T_{HP,con}$	$f_T(p_{HP,eva}$ +100 kPa)	$f_T(0.9p_c)$
Superheat degree of HP evaporation process	$T_{HP,sup}$	0	15
ORC evaporation temperature	$T_{ORC,eva}$	$f_T(p_{ORC,con}$ +100 kPa)	$f_T(0.9p_c)$
Superheat degree of ORC evaporation process	$T_{ORC,sup}$	0	15
Heat storage temperature	$T_{sto,hot}$	60	150

2.3 Parameter identification

SHapley Additive exPlanations (SHAP) is an additive explanation model inspired by cooperative game theory [9]. In cooperative game theory, the Shapley value is used to quantify the contribution of each member to the team so as to fairly distribute the benefits of the team. The calculation of Shapley value is defined as follow:

$$\phi_j=\sum_{S\subseteq F\setminus\{j\}}\frac{|S|!\left(|F|-|S|-1\right)!}{|F|!}\left[f_{S\cup\{j\}}\left(x_{S\cup\{j\}}\right)-f_S\left(x_S\right)\right] \quad (5)$$

where, ϕ_j is the Shapley value of the member j, representing its contribution; $F\setminus\{j\}$ is the set of all members that do not contain member j; S is the member subset; f is the mapping function; x_S is the input to subset S.

In this paper, the SHAP model is applied to the quantitative importance analysis for the thermodynamic parameters of the Carnot battery. The specific steps are as follows:

1)Determine the baseline value: Select the mean value of the power-to-power efficiency in each scenario as the baseline value y_{base} of each scenario.

2)Establish a mapping model: A data-driven random forest model is used to build a mapping model from thermodynamic parameters X to power-to-power efficiency y.

3)Calculate the contribution: For each thermodynamic parameter x_i, calculate its contribution to the power-to-power efficiency. Contribution degree is calculated by Shapley value equation.

4)Construct an additive interpretation model: By taking advantage of the additivity of Shapley values, the power-to-electricity efficiency is decomposed into the sum of baseline values and Shapley values of each thermodynamic parameter, as shown in Eq. (6).

$$y_i = f(x) = y_{base} + \sum_{j=1}^{n} \phi_j \tag{6}$$

where, ϕ_j is the Shapley value of j th thermodynamic parameter; y_{base} is the baseline value; y_i is the target value (i.e. the power-to-power efficiency) of the i th sample.

The SHAP model can quantitatively analyze how each thermodynamic parameter in each sample acts on the power-to-power efficiency, and the contribution of each parameter is independent, so as to avoid the unclear contribution caused by coupling relationships between parameters. Importance is defined in this paper; its calculation is shown in Eq. (7). Importance ranges from 0 to 1. The closer it is to 1, the greater the importance. This index can show quantified results more intuitively, and eliminate the problem that Shapley values in different scenarios cannot be compared fairly due to the difference in power-to-power efficiency.

$$\text{Importance}_j^k = \frac{\bar{\phi}_j^k}{\sum_{j=1}^{n} \bar{\phi}_j^k} \tag{7}$$

where, Importance_j^k is the importance of the j th thermodynamic parameter in the k th scenario; $\bar{\phi}_j^k$ is the average Shapley value of the j th thermodynamic parameter in the k th scenario.

3. RESULTS

Fig. 2 shows the importance of each thermodynamic parameter in different scenarios. The importance of each thermodynamic parameter on the η_{PTP} can be divided into three levels. The first level is the HP evaporation temperature and ORC evaporation temperature, which has the greatest impact on the η_{PTP}, and their importance values range from 0.20 to 0.80. Therefore, the size of the power-to-power efficiency is almost determined by these two key parameters. This result is consistent with thermodynamic knowledge. This is mainly because the HP evaporation temperature is a key parameter affecting the COP, resulting in its importance to the η_{PTP}. The evaporation temperature of ORC affects the power generation efficiency of ORC directly; thus, it is also very important to the η_{PTP}. The second level is the HP condensation temperature and heat storage temperature, the importance of which is basically less than 0.15 and is significantly weakened compared with the HP evaporation temperature and ORC evaporation temperature. This is because the HP condensation temperature has less effect on the COP than the HP evaporation temperature, and the heat storage temperature does not directly affect the power cycle. The third level is the HP superheat degree and ORC superheat degree. Although they have a certain impact on the η_{PTP}, compared with other thermodynamic parameters, the importance is weak, and the importance is basically less than 0.01. SHAP model can quantitatively analyze the importance of thermodynamic parameters of Carnot battery, and can independently analyze the importance of each parameter, eliminating the parameter coupling influence.

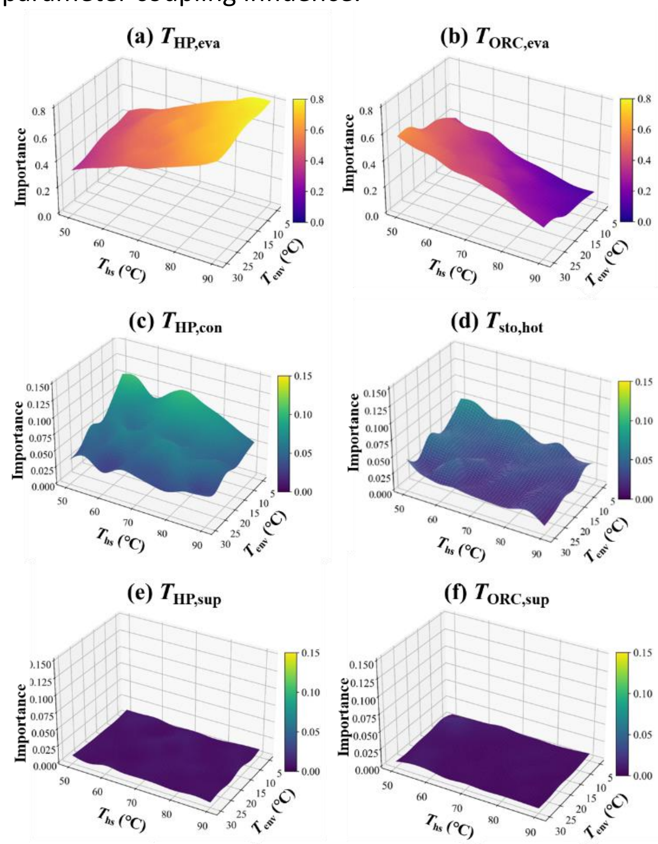

Fig. 2 Importance of thermodynamic parameters in different scenarios

Due to the high importance of the HP evaporation temperature and ORC evaporation temperature, they are further analyzed. For the HP evaporation temperature, when the environment temperature is lower and the heat source temperature is higher, its importance is greater. When the environment temperature is 5°C and the heat source temperature is 95°C, the maximum importance is 0.80. For the ORC evaporation temperature, a maximum importance of 0.58 is obtained when the environment temperature is 30°C and the heat source temperature is 50°C. This is because when the environment temperature is low, the power generation efficiency of ORC reaches the upper limit, so the HP evaporation temperature, which has a greater impact on COP, is more important. As the environment temperature decreases, the power generation efficiency of ORC deteriorates, so ensuring a higher power generation efficiency of ORC is the key to improving the η_{PTP}. Thus, the ORC evaporation temperature is dominant.

In different scenarios, the most important thermodynamic parameter is shown in the Fig. 3. When the environment temperature is higher than 10°C, ORC evaporation temperature begins to appear as the most important thermodynamic parameter. At the same time, the heat source temperature is basically below 60°C. In these scenarios, COP is not high, and ORC dominates the η_{PTP}. When the heat source temperature is greater than 60°C or the environment temperature is less than 10°C, the HP evaporation temperature is still the most important thermodynamic parameter.

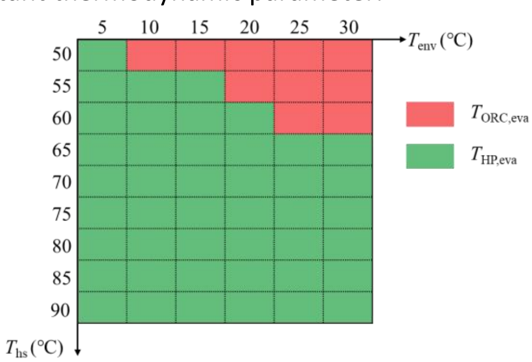

Fig. 3 The most important thermodynamic parameter in different scenarios

Fig. 4 shows the influence rules of HP evaporation temperature and ORC evaporation temperature on the η_{PTP}. For the HP evaporation temperature, the higher the HP evaporation temperature, the greater the positive contribution to the η_{PTP}. This is because the HP evaporation temperature increases, the power consumption of the HP compressor is significantly reduced, and the COP is improved, which can improve the η_{PTP} significantly. For the ORC evaporation temperature, before 300 K, with the increase of ORC evaporation temperature, it is helpful to improve the η_{PTP}. Because it can increase the output work of ORC, thereby improving the power generation efficiency of ORC and η_{PTP}. After more than 300 K, as the ORC evaporation temperature further increases, the positive contribution to the η_{PTP} gradually decreases. This is because, with the further increase in ORC evaporation temperature, higher heat storage temperature is required, resulting in an increase in the HP condensation temperature and a decrease in the COP of HP.

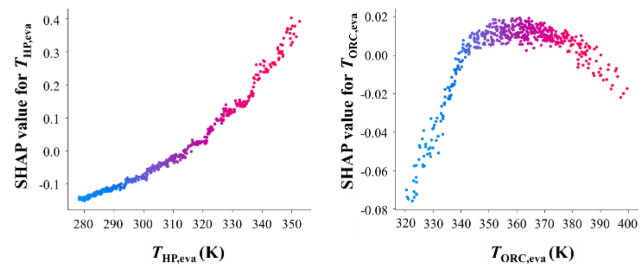

Fig. 4 Influence rules of HP evaporation temperature and ORC evaporation temperature on the η_{PTP}

4. CONCLUSION

1) The importance of six thermodynamic parameters in 54 scenarios is quantitatively presented. HP evaporation temperature and ORC evaporation temperature are the most important two parameters. Their maximum importance is 0.80 and 0.58, respectively.

2)The most important thermodynamic parameter in different scenarios is analyzed. When the environment temperature is higher than 10°C, and the heat source temperature is below 60°C, ORC evaporation temperature begins to appear as the most important thermodynamic parameter. HP evaporation temperature is still the most important in other scenarios.

3)The η_{PTP} increases with the increase of HP evaporation temperature, and first increases and then decreases with the increase of ORC evaporation temperature.

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