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A Review of Carnot Battery Technology

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Abstract: As a key energy storage technology for addressing renewable energy integration and supporting the "dual-carbon" goals, Carnot Battery (Pumped Thermal Energy Storage, PTES) relies fundamentally on its heat and mass transfer efficiency for overall system performance and economic viability. This paper systematically reviews recent research progress in heat and mass transfer within Carnot Batteries, focusing on core areas such as system configuration optimization, selection of working fluids and thermal storage media, multi-scenario integration, and parameter optimization. Studies indicate that system performance can be significantly enhanced by introducing heat regeneration devices and optimizing cycle processes. For instance, a transcritical CO_2 cycle with regeneration achieved a comprehensive efficiency of 75.28%, while an integrated Heat Pump-ORC-Thermal Storage configuration exceeded 100% round-trip efficiency. Transcritical CO_2, R245fa, and mixed working fluids are preferred due to their superior thermodynamic properties. Rapeseed oil and phase change materials stand out for their cost-effectiveness and potential for increasing power density, respectively. Finally, current technical challenges are summarized, and future development prospects in integrated demonstration, material innovation, and multi-energy flow synergy are discussed, providing theoretical reference for the engineering application of this technology.

Keywords: Carnot Battery; Brayton Cycle; Rankine Cycle; High Temperature.

1. Introduction

As the threat of global climate change to human society and ecosystems intensifies, promoting a green, low-carbon transition has become a widespread consensus and urgent task. Against this backdrop, China, as the world's largest energy consumer and carbon emitter, has announced more effective policy measures to enhance its nationally determined contributions, aiming to peak carbon emissions before 2030 and achieve carbon neutrality by 2060 [1]. This national strategy not only demonstrates major-country responsibility but also necessitates comprehensive transformation across socio-economic development. The core pathway to achieving the carbon peak lies in vigorously advancing energy structure adjustment and building a new power system dominated by renewable energy. Energy storage technology can effectively mitigate the volatility introduced by large-scale integration of renewables, serving as a crucial means to address the intermittency and instability of renewable energy sources [2-3]. However, renewable electricity generation, represented by wind and solar power, is characterized by intermittency, volatility, and randomness [4]. Its large-scale grid integration poses significant challenges to grid stability. Therefore, developing efficient, large-scale, long-duration energy storage technology is considered vital for solving renewable energy integration challenges, ensuring energy security, and ultimately achieving carbon neutrality.

Among various energy storage technologies, the Carnot Battery, also known as Pumped Thermal Energy Storage (PTES), is a large-scale physical energy storage technology that stores electricity via thermal means. It offers advantages such as independence from geographical constraints, high energy storage density, and low investment costs, making it a promising technology for electricity storage and low-grade heat recovery [5-6]. The historical development of Carnot Batteries can be traced back to the 19th and early 20th centuries. In 1833, Ericsson first explored this concept [7], followed by Fritz Marguerre who patented a thermal energy storage scheme in 1924 [8]. The Carnot Battery (CB), as an emerging energy storage technology, primarily consists of a heatpump (HP), thermal storage tanks (ST), and a heat engine (HE) [9]. Its principle involves converting electrical energy into thermal energy during charging and then converting it back into electricity via components like compressors, pumps, expanders, and heat exchangers during discharging [10]. Compared to other energy storage technologies, it offers advantages such as geographical flexibility[11], high energy density [12], and low capital cost [13]. Carnot Batteries mainly include systems based on Brayton cycles and Rankine cycles [14].

This paper aims to systematically review recent research progress in heat and mass transfer related to Carnot Battery technology, covering key breakthroughs from material scale to system scale, providing researchers in related fields with a clear overview of technological development.

2. Working Fluid Selection for Carnot Battery

The thermal storage technology used in Carnot Battery systems relies on their ability to effectively store and release thermal energy. Thermal storage technologies can be broadly classified into sensible heat storage (using materials like water, sand, rocks, and molten salts [15-16]), latent heat storage (using organic substances, inorganic salts, metals, or metal alloys[17-18]), and thermochemical storage

.In the selection of circulating working fluids for Carnot batteries, inert gases such as argon and helium exhibit superior comprehensive system technical indicators compared with conventional working fluids including air and nitrogen. The operating temperature range of argon spans from -173 °C to 1000 °C, which enables it to adapt to both extremely low-temperature and high-temperature operating conditions. Relevant studies have verified that argon possesses the greatest application potential in high-temperature Carnot battery systems.Nitrogen is applicable to medium and low-temperature energy storage systems with an operating temperature range of -93 °C to 505 °C, and it delivers an outstanding performance in medium-temperature Carnot batteries. As a circulating working fluid, carbon dioxide works stably within the temperature interval of -32 °C to 560 °C, presenting broad application prospects in medium-to-high temperature Carnot batteries.Hydrogen has an operating temperature range of -150 °C to 480 °C, suitable for low-temperature to medium-high temperature energy storage scenarios, and it can be adopted in low-temperature and medium-temperature Carnot battery systems. Air, as the most widely used working fluid, is matched with medium-to-high temperature energy storage systems with an operating temperature from ambient temperature to 468 °C. Benefiting from its easy accessibility, air achieves excellent operational performance in medium-to-high temperature Carnot batteries.

3. Current Research Status of Carnot Battery Technology

Current domestic and international research on PTES primarily focuses on four system types: systems based on the Brayton cycle (B-PTES), systems based on the Organic Rankine Cycle (R-PTES)[19], transcritical CO₂ Carnot Batteries, and Carnot Batteries coupled with LNG cold energy. Among these, B-PTES working fluids do not undergo phase change, typically operating over wider temperature (-170 to 1000°C) and pressure (1-300 bar) ranges, unrestricted by saturation lines. R-PTES relies on phase change of the working fluid to create isothermal processes with significant latent heat absorption/release. Due to saturation pressure limits, its operating range is typically -30 to400°C and 1-200 bar[20].

3.1. Brayton Cycle

The Brayton cycle primarily includes heat pump, charging, and heat engine sub-cycles. The internal structure of a Brayton-based Carnot Battery energy storage system is shown in Figure 1.

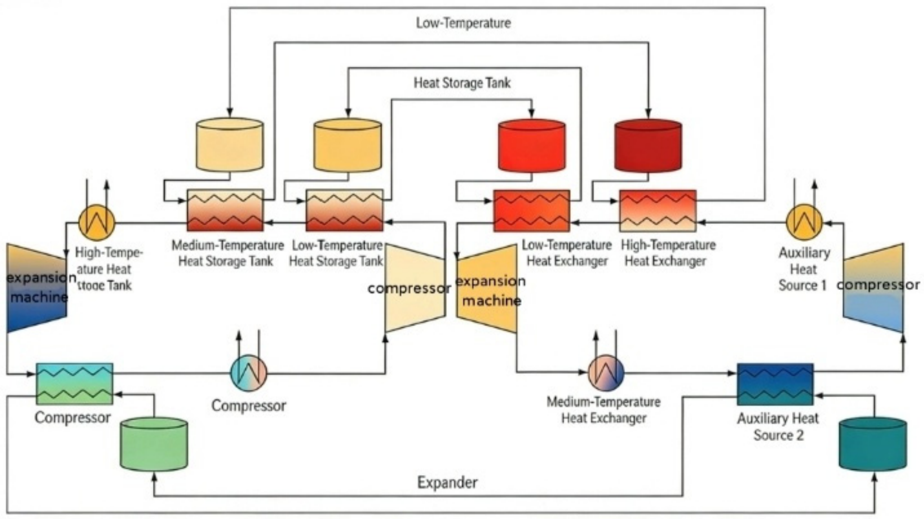


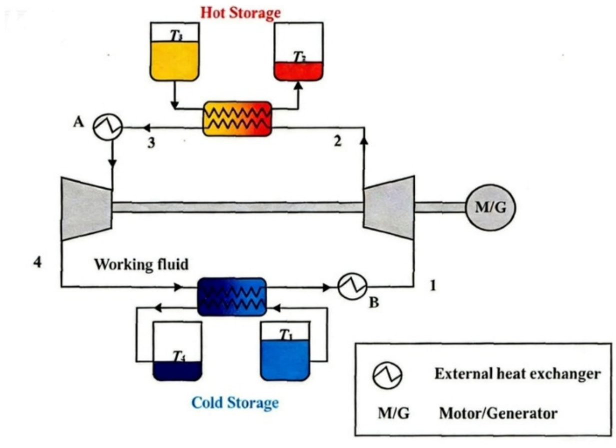
Figure 1. Structure of a Brayton-based Carnot Battery Energy Storage System [21]

Table 1. Five Basic Cycle Configurations

Configuration	Auxiliary Heat Exchanger 1	Auxiliary Heat Exchanger 2	Medium-Temperature Heat Storage Tank
1	Yes	Yes	Yes
2	No	Yes	Yes
3	Yes	No	No
4	No	No	Yes
5	Yes	Yes	No

Zhang et al. [21] established a thermoeconomic model to analyze the impact of different cycle configurations and working fluids on system performance. The study classified Brayton-based Carnot Battery systems into five basic configurations based on the presence of auxiliary heat exchangers 1 & 2 and a medium-temperature storage tank, as shown in Table 1.

The study found that auxiliary heat exchangers can enhance system performance. Configuration 1 (with specific auxiliary heat exchangers and a medium-temperature tank) achieved the maximum round-trip efficiency (54.23%), along with the lowest working fluid mass flow rate and levelized cost of storage (LCOS). Configuration 5 (with auxiliary heat exchangers but no medium-temperature tank) achieved the maximum energy storage density. Yang et al. [22]conducted a thermodynamic analysis, deriving analytical expressions for round-trip efficiency, energy density, and power density along with their influencing factors. They optimized and obtained system performance results under different operating schemes. For a PTES system using a liquid storage medium, the flow diagram is shown in Figure 2.



a) System Layout

Figure 2. System Layout Diagram [22]

Based on the above discussion, it can be concluded that auxiliary heat exchangers are crucial for improving PTES system performance, especially the one at the expander outlet during discharge, which can further optimize energy utilization efficiency through heat recovery or regulation. Among different configurations, Configuration 1 (with specific auxiliary heat exchangers and a medium-temperature tank) shows the best comprehensive performance, achieving the highest round-trip efficiency (54.23%) along with the lowest working fluid flow and LCOS, balancing efficiency and economy. Configuration 5 (with auxiliary heat exchangers but no medium-temperature tank) offers the highest energy density, advantageous for scenarios prioritizing storage capacity.

3.2. Rankine Cycle Carnot Battery System

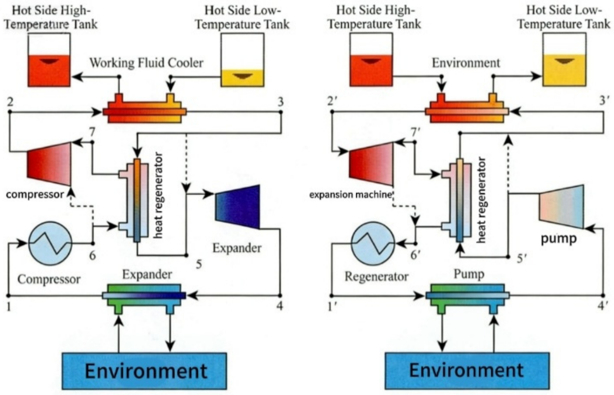
Conventional steam Rankine cycle PTE systems can reach temperatures up to 400°C with corresponding efficiencies around 38.6%[23]. ORC-PTES systems, due to working fluid limitations, are suitable for lower temperatures (below 250°C), with efficiencies ranging from 15% to 56% under different conditions[24-25]. Feng et al.[26]addressed the low utilization of low-temperature waste heat in the steel industry by proposing an integrated heat pump, thermal storage, and ORC heat pump energy storage system. A thermodynamic model was constructed to analyze the effects of HP condensation temperature, ORC evaporation temperature, and superheat on system performance. Results showed that lowering the HP condensation temperature and raising the ORC evaporation temperature can improve system COP_HP and power efficiency η_PE. Among ORC working fluids, R245fa performed best, followed by isobutane and R236ea [26]. Furthermore, the impact of increasing ORC superheat varied with the working fluid: performance decreased for R245fa and R236ea, while isobutane performed best at a 4°C superheat [26]. This study provides a theoretical basis for efficient recovery of low-temperature sintering flue gas waste heat and suggests prioritizing R245fa as the ORC working fluid in PTES systems. ORC technology is widely used for medium- to low-temperature waste heat recovery. Zhang et al. [27] demonstrated that PTES systems integrating low-temperature waste heat can achieve high energy storage efficiency. Steinmann[28-29] noted PTES systems can reach efficiencies of 15%-56% at temperatures below 250°C, suitable for industrial waste heat recovery. Additionally, Frate et al.[30]found that with a waste heat temperature of 90°C, the power efficiency of a PTES system could reach 107%, highlighting its advantage under low-temperature heat source conditions. Liu et al.[31]studied the performance of azeotropic mixtures in ORC, indicating an optimal glide temperature exists for maximizing net power output. Zhao et al.[32] and Sheng et al.[33]optimized PTES systems from the perspectives of transcritical CO_2 cycles and phase change storage media, respectively, further improving system efficiency and economy.

Based on the preceding discussion, it can be concluded that lowering the heat pump condensation temperature significantly improves the heat pump COP and power efficiency, reducing HP energy consumption and optimizing energy conversion efficiency. Raising the ORC evaporation temperature directly improves the heat engine's thermal-to-power conversion efficiency, while also enhancing the HP COP and power efficiency, making it a key direction for performance optimization. For scenarios involving low-temperature waste heat (e.g., steel industry sintering flue gas), the working fluid performance ranks as R245fa (optimal) > isobutane > R236ea. R245fa demonstrates the best comprehensive performance in efficiency and stability, making it the preferred ORC working fluid for ORC-PTES systems.

3.3. Transcritical Carnot Cycle Systems

A Carnot Battery energy storage system based on a transcritical CO_2 cycle, as shown in Figure 3, mainly consists of: a compressor, pump, two expanders, two hot-side storage tanks, and four heat exchangers operating under different conditions. These include single-phase heat exchangers (fluid cooler during charging or gas heater during discharging), a regenerator, and an auxiliary heat exchanger, as well as two-phase heat exchangers (evaporator during charging or condenser during discharging)[32].

Taking the supercritical CO_2 recompression power generation cycle based on solar thermal energy as an example, the cycle employs air cooling. When the ambient air temperature varies from –3°C to 42°C throughout the year, the cycle's output power fluctuates between 22MW and 25MW. [34] The Transcritical CO_2 Regenerative Thermal Cycle (RTRC) can effectively utilize low-temperature cold sources for waste heat power generation. However, during the regenerative process, the large thermal difference leads to increased irreversible losses. The SRC employs a flow-split and recompression cycle structure, which can reduce the irreversible losses in the regenerative process and improve cycle efficiency. Nevertheless, the cycle is constrained by the supercritical state, and the ability of the supercritical CO_2 recompression cycle (SRC) to enhance performance using low-temperature cold sources is limited. [35].Chen Pengfei[35]



(a) Charging Process (b) Discharging Process

Figure 3. Schematic of a Transcritical CO_2 Cycle-based Carnot Battery Energy Storage System

When the novel Partial Condensation-Recompression Cycle (PCRC) was introduced, research revealed that the PCRC cycle achieved a thermal efficiency of 33.97%. This represents a 17.5% to 50% improvement over traditional transcritical CO_2 reheating cycles (RTRC). By reducing the condensation load through partial condensation and improving the matching of the reheater through recompression, irreversible losses can be effectively minimized. The integrated PC-CB system, which utilizes residual heat, outperforms traditional CO_2 Carnot batteries in terms of return efficiency, cold source adaptability, and performance under varying operating conditions.Morandin et al. [36]A PTES system based on a transcritical CO_2 cycle was investigated for multi-objective thermal-economic optimization under different coupling conditions of liquid storage tanks. Kim et al.[37]A system based on CO2 for isothermal PTES was proposed. Tauveron et al.[38]A PTES system based on a transcritical CO_2 cycle was designed using a ground-based heat exchanger. Wang and Zhang.[39]A PTES system incorporating a coupled transcritical CO_2 and NH_3 cycle was proposed, and its thermodynamic properties were evaluated. Additionally, Salomone et al. [18] A thermodynamic analysis was conducted on this CO_2 transcritical PTES system, which concluded that irreversible losses during compression and expansion are the primary source of energy loss for this energy storage system.

3.4. Carnot Battery Coupled with LNG Cold Energy

Introducing LNG on the condenser side of the ORC in a CB system can also lower the cold-side temperature and improve system P2P efficiency[40]. Compared to a basic CB system, the LNG-CB system can significantly reduce the ORC condensation temperature, increase ORC thermal efficiency, boost system output power, and enable on-demand supply of natural gas at required pressures[41]. The schematic of an LNG-CB system is shown in Figure 4.

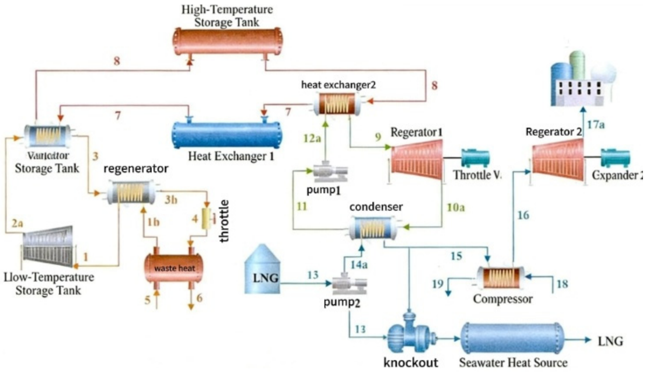


Figure 4. Schematic of an LNG-CB System

The LNG-CB system significantly outperforms the basic CB system, with a boost of 2.31 to 4.52 times, reaching a maximum of 222.47% (at 120°C storage temperature and 7 MPa LNG pressure). Heat pump COP: decreases as the storage temperature increases, but can be improved by reducing the temperature difference between waste heat and storage. Smoke efficiency: the LNG-CB system exhibits stable performance in terms of smoke efficiency, reaching a maximum of 39.44%. The LNG-CB system significantly surpasses the basic CB system in terms of thermodynamic performance, particularly in P2P efficiency. Although the equipment is more expensive, its high power output results in lower LECs. Multi-objective optimization effectively balances the conflicts between thermodynamics and economy, providing the optimal combination of operating parameters.

4. Summary and Outlook

This paper systematically reviews the research progress of Carnot batteries (Pumped Thermal Energy Storage, PTES) in the field of heat and mass transfer. It delineates the core breakthroughs and current development status of the technology from the perspectives of system configuration, working fluids and thermal storage media, multi-scenario coupling, and thermo-economic optimization. The main conclusions are as follows:

In terms of system configuration optimization, innovative configurations serve as the core driver for enhancing Carnot battery performance. The incorporation of recuperators, additional heat exchangers, and optimized cycle processes significantly reduces energy losses and improves system efficiency and energy storage density. Among these, the transcritical CO_2 cycle with recuperation exhibits higher overall efficiency and significantly improved energy storage density compared to the cycle without recuperation. In Brayton cycle configurations, Configuration 1 (featuring specific auxiliary heat exchangers and a medium-temperature thermal storage tank) achieves the optimal round-trip efficiency, balancing both economy and efficiency, whereas Configuration 5 (without a medium-temperature thermal storage tank) offers advantages in energy storage density. The integrated heat pump–ORC–thermal storage configuration achieves deep coupling between low-grade industrial waste heat and energy storage, attaining a high round-trip efficiency and providing an efficient pathway for low-grade energy recovery.

Regarding the selection of working fluids and thermal storage media, the proper choice of both is critical for balancing system efficiency and cost. Among working fluids, transcritical CO_2 is preferred for medium- to high-temperature systems due to its excellent environmental properties (ODP = 0, low GWP) and superior thermodynamic performance. R245fa demonstrates optimal performance in low- to medium-temperature ORC systems. Mixed working fluids (e.g., R1233zd(E)-cyclopentane) can enhance heat exchange matching by adjusting temperature glide, yielding modest improvements in system efficiency. For thermal storage media, sensible heat media such as rapeseed oil and thermal oil achieve a favorable balance between efficiency and cost, while phase change materials (PCMs), owing to their high latent heat, show great potential for increasing power density. However, the low thermal conductivity of PCMs remains a technical bottleneck to be addressed.

In multi-scenario coupling applications, the integration of Carnot batteries with low-grade energy sources highlights unique advantages, giving rise to three typical application scenarios: industrial waste heat coupling (e.g., low-temperature sintering flue gas in steelmaking) enabling waste heat resource utilization; LNG-CB systems utilizing cold energy to reduce ORC condensation temperature, achieving a higher power-to-power (P2P) efficiency than conventional systems; and data center waste heat coupling systems that significantly reduce power usage effectiveness (PUE) and achieve synergistic benefits of “energy storage plus heat dissipation,” providing an irreplaceable energy solution for specific industrial scenarios.

In terms of thermo-economic and parameter optimization, heat exchangers and expanders constitute the major cost components of the system. After optimization, the specific energy investment cost is substantially reduced. Parameter sensitivity analysis indicates that condensation temperature has the most significant impact on system efficiency, followed by compressor/expander polytropic efficiency and heat exchanger effectiveness. Using multi-objective optimization algorithms such as NSGA-II, a global optimum balance among efficiency, energy storage density, and cost can be achieved.

Although current theoretical research on Carnot batteries has yielded fruitful results, challenges remain, including insufficient integrated demonstration projects, a shortage of novel materials, and the need for improved multi-energy flow coordinated control. Future efforts should focus on developing megawatt-scale integrated demonstration projects, advancing high-thermal-conductivity phase change materials and low-GWP working fluids, promoting deep coupling with photovoltaic and wind power systems, and constructing “electricity–heat–cooling–gas” multi-energy flow synergistic systems. These steps will facilitate the engineering application of Carnot battery technology and provide efficient, economical energy storage support for achieving the “dual carbon” goals.

In summary, Carnot battery energy storage technology, through continuous innovation in system configuration, working fluids and media, multi-scenario coupling, and system optimization, has demonstrated significant application potential and unique market competitiveness. It is not merely an energy storage device but also a key technical bridge for improving comprehensive energy utilization efficiency and enabling waste-to-energy conversion. Looking ahead, through collaborative efforts among industry, academia, research, and application, and by achieving breakthroughs in materials, integration, control, and business models, Carnot batteries are poised to play an important role in the ongoing energy revolution, offering an efficient, economical, and highly resilient technological pathway toward the “dual carbon” goals.

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