The Application of Thermal Energy Storage in Electricity System

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Abstract: Against the backdrop of the "dual-carbon" goals, China is actively advancing energy structure transformation and the rational application of energy. As an important energy storage technology, thermal storage technology holds broad application prospects in addressing the contradictions between the fluctuation of renewable energy and power grid peak regulation, as well as issues such as its spatial and temporal imbalance. This paper will introduce the relevant principles of thermal storage technology and elaborate on its applications in the electricity system, including grid power peak shaving, thermal storage materials for Concentrated Solar Power, and other fields such as renewable energy consumption and waste heat recovery. Among these, emphasis will be placed on its application in power peak regulation and the application of hybrid energy storage technology coupled with thermal storage during peak regulation. Finally, summaries and prospects will be provided to contribute to the early realization of the "dual-carbon" goals.

Keywords: Thermal Energy Storage; Peak Shaving; Energy Storage

1. Introduction

As the world's largest developing country, China is also the country with the highest carbon emissions[1]. China has put forward the goals of achieving carbon neutrality by 2030 and carbon peaking by 2060. Currently, the proportion of renewable energy in China is continuously rising with an accelerating trend[2]. By the end of December 2024, statistics show that the cumulative installed power generation capacity across China reached approximately 3.35 billion kilowatts, a year-on-year increase of 14.6%. Among this, the installed capacity of solar power generation stood at about 890 million kilowatts, up by 45.2% year-on-year; the installed capacity of wind power reached around 520 million kilowatts, with a year-on-year growth of 18.0%. Figure 1 summarizes the overall composition of China's power installation in 2024, while Table 1 presents the year-on-year growth percentages of various power generation types in China[3].

Table 1. Year-on-Year Growth of Power Generation Types in China

Type	Increase
Hydropower	3.2%
Thermal	3.8%
Nuclear	6.9%
Wind	18.0%
Solar	45.2%

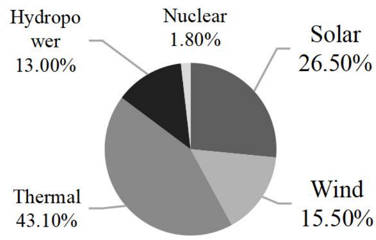

Figure 1. Composition of China's Power Installation in 2024[3]

Not only is renewable energy developing rapidly in China, but the whole world is also actively promoting energy structure transformation. Nowadays, the world is in a phase of "three transitions." From 1981 to 2023, the consumption volume and proportion of renewable energy have increased by 18.5%[5]. However, due to inherent issues such as the volatility and intermittency of renewable energy, its rapid growth has posed significant challenges to the control and operation of power systems[6]. Furthermore, although the total installed capacity of renewable energy has now exceeded that of non-renewable energy, the uneven spatial and temporal distribution of renewable energy has led to substantial curtailment of wind and solar power, resulting in electricity waste. This has caused the actual power generation from renewable energy to account for only 33% of the total electricity generation, while traditional fossil energy still constitutes 67%[2].

Energy storage technologies have attracted significant attention due to the aforementioned reasons. Among them, thermal storage technology, as an important type of energy storage technology, can balance energy supply and demand and improve energy utilization efficiency[7]. It is expected to be deployed on a large scale in the future to address the challenges encountered in the process of energy transition. In the following sections, starting from an overview of thermal storage technology, this paper will summarize the main current applications of thermal storage technology in power systems.

2. Thermal Energy Storage Technology

Thermal storage technology (TES) refers to the use of thermal storage materials as the medium for energy storage, where energy is stored in the form of heat during the energy storage and released process. According to the storage principles, thermal storage technology can be divided into three main categories: sensible heat storage, latent heat storage, and thermo-chemical heat storage[7-9].

2.1 Sensible Heat Storage

Sensible heat storage (SHS) technology refers to a technology in which the heat energy stored and released is manifested as a temperature change of the material, without phase transitions or chemical reactions occurring in the thermal storage material. Its thermal storage materials can be classified into solid materials and liquid materials[7-8]. SHS has been widely applied, with involvement in fields such as solar power, space cooling and heating, and industrial waste heat recovery.

Current solid-state thermal storage materials include concrete, rocks, ceramics, and other materials with high specific heat capacity and high thermal conductivity. Solid-state thermal storage generally features low costs but relatively low energy density and thermal conductivity. In contrast, liquid thermal storage materials typically exhibit higher energy density and specific heat capacity compared to solid-state counterparts, though their costs are relatively higher. Currently, common liquid thermal storage materials include, such as, water, oils, molten salts. Overall, sensible heat storage is widely applied with mature technologies and relatively low costs; however, it suffers from short storage duration, relatively low storage density, and significant heat loss.

2.2 Latent Heat Storage

Latent heat storage (LHS) technology uses the phase change process of phase change materials (PCMs), converting thermal energy into the phase change enthalpy (latent heat of phase change) of substances for storage. LHS can be classified according to the phase change processes into solid-solid phase change storage, solid-liquid phase change storage, liquid-liquid phase change storage, and liquid-gas phase change storage. It can also be categorized based on operating temperatures: generally, materials operating below 100°C are referred to as low-temperature phase change materials, those working between 100°C and 250°C as medium-temperature phase change materials, and those above 250°C as high-temperature phase change materials[10-12].

PCMs possess advantages such as high energy storage density, minimal temperature variation during heat absorption and release, and stable chemical properties. These characteristics endow latent heat storage with broad application prospects, making it a technology that has attracted extensive attention from scholars. However, the relatively high cost of PCMs restricts their large-scale application. Moreover, individual latent heat storage materials each have distinct drawbacks[13]. Therefore, the main research directions in LHS technology involve developing and preparing materials with more comprehensive performance, as well as designing rational thermal storage devices tailored to address the issues of these materials.

2.3 Thermo-Chemical Storage

Thermo-chemical heat storage (TCHS) converts energy into the breaking and formation of chemical bonds through reversible thermo-chemical reactions. A common example is the thermal decomposition reaction of slaked lime: $Ca(OH)_2 \rightleftharpoons CaO + H_2O$. During the endothermic process, which is also the heat storage process, chemical bonds are broken, and slaked lime decomposes into calcium oxide and water. In the energy release process, a recombination reaction occurs to regenerate slaked lime, enabling a cyclic and repetitive operation.

TCHS features high energy storage density and is convenient for long-term storage and transportation. However, the promotion of THCS is mainly limited by issues such as low thermal conductivity, low conversion efficiency, poor cyclic stability, and high costs. Therefore, selecting appropriate material preparation methods and improving its safety and service life are the main research directions of this technology at present[14].

In conclusion, each type of thermal storage technology has its own advantages. A rational thermal storage technology should be selected based on the application scenario and investment cost. Table 2 provides a brief summary of the basic characteristics of these three thermal storage technologies.

Table 2. Characteristics of Three Types of TES[8-14]

TES	Energy density KWh/t	Cost	Storage Period	Conversion efficiency %	Application status
SHS	Low(10-50)	Low	Short	Low(50-90)	Industrial
LHS	High(50-150)	High	Short	Medium(75-90)	Lab
TCHS	High(120-250)	High	Long	High(75-100)	Lab

3. TES Applications in Electricity System

The proportion of renewable energy is rising rapidly. Renewable energy sources are characterized by intermittency and instability. Therefore, to better utilize the electricity generated by renewable energy, energy storage technologies are needed for regulation. In this section, it mainly introduces the applications of thermal storage technology in power peak shaving, Concentrating Solar Power, and other related technologies aimed at energy conservation and carbon reduction.

3.1 Power Peak Shaving

3.1.1 TES in peak shaving

To mitigate the impact of the instability of renewable energy on power grids, the demand for power peak shaving and frequency modulation technologies has become increasingly urgent. When traditional thermal power units participate in deep peak shaving, the furnace temperature may drop, leading to flameout; it may also deteriorate combustion stability and cause combustion degradation, thus failing to ensure stable combustion[15]. These issues result in extremely poor economic efficiency of traditional units during deep peak shaving and significantly limit their peak shaving capacity. Therefore, in response to the current growth trend of renewable energy, traditional units must undergo flexibility retrofits[16]. Thermal storage technology, which can directly store thermal energy, serves as a primary approach to achieve flexibility retrofits for thermal power units[17]. The following sections will introduce the main applications of thermal storage technology in power peak shaving.

(1) Molten Salt TES System

Benefiting from advantages such as large energy capacity, long storage period, molten salt energy storage has now become the world's third-largest energy storage mode and also serves as a primary application of thermal storage systems in power peak shaving. In the context of power peak shaving, it can be categorized into electric heating type and extraction heat storage type[18].

Electric heating type primarily utilizes electric heaters (electric boilers) to convert the excess electricity generated by steam turbines during off-peak periods into thermal energy, which is then stored in the molten salt thermal storage system. During peak power demand periods, the stored energy is released to expand the power range of the unit, and its system flow is illustrated in Figure 2. The electric heating type exhibits favorable thermal efficiency; however, significant exergy loss occurs during the electric-to-heat conversion process. Miao et al.[19] investigated the thermal performance of a 600 MW integrated electric-heating molten salt thermal storage system. The results showed that among multiple schemes, the highest equivalent round-trip efficiency (electricity-to-thermal-electricity) could reach 49.36%, while the exergy loss of the electric heater during the heat storage process amounted to 44.3%. Therefore, reducing exergy loss during the heat storage process is a key issue in this research direction.

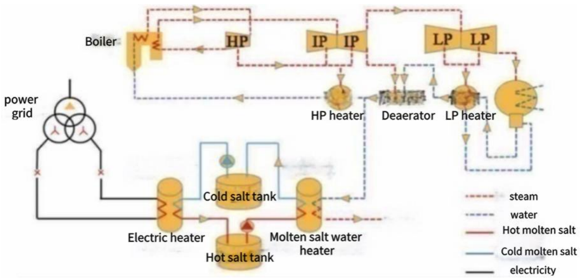

Figure 2. Electrically Heated Flexibility-Retrofit Thermal Power Units System Flow[17]

For extraction heat storage-type thermal power units, the electric heater (electric boiler) is replaced by a steam-heated molten salt system. By extracting excess steam generated by the boiler, its internal energy is directly stored in the molten salt thermal storage system. This allows the boiler to operate at a higher load during off-peak electricity periods, thereby increasing the depth of peak regulation. The system flow diagram is shown in Figure 3. The extraction heat storage type features a higher peak regulation depth and can achieve high thermal efficiency even under high steam parameters. Fang et al.[20] analyzed the peak regulation characteristics of an ultra-supercritical 1000 MW thermal power unit coupled with different thermal storage systems. The study showed that the peak regulation depth of the main steam extraction scheme could reach up to 17.49%, which is 6.64% higher than that of the electric heating type under the same load. Wang et al.[21] analyzed and simulated the performance of a 100 MW-class unit coupled with a molten salt thermal storage system for deep peak regulation. The results indicated that when the main steam pressure is 21.5 MPa and the temperature of the molten salt during heat storage is 480.1 C, the comprehensive efficiency of the system can be as high as 77.8%, exhibiting broad application prospects in the field of large-scale energy storage.

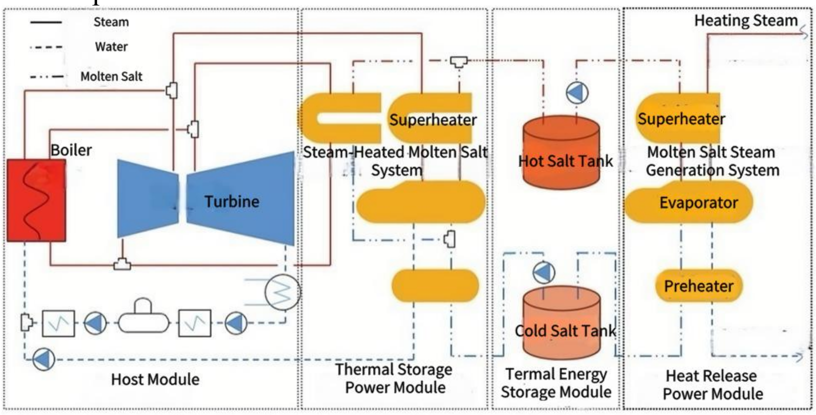

Figure 3. Extraction Heat Storage-type Thermal Power Units System Flow[20]

The application of molten salt thermal storage in power peak shaving, both the extraction-type and electric heating-type systems currently suffer from significant exergy losses, with the electric heating-type exhibiting relatively lower losses, though both are around 40%. The extraction-type system demonstrates stronger peak shaving capability, while the electric heating-type system features a faster response speed and relatively lower coal consumption[20-23].

(2) Packed-bed TES system

The packed bed thermal storage system consists of an outer thermal insulation layer, an internal support network, and thermal storage units enclosed within it. Heat exchange fluid flows through the interior of the packed bed and comes into contact with the surface of the thermal storage units to achieve heat absorption and release[24] (its structure is shown in Figure 4). The packed bed system, characterized by compact structure and strong heat exchange performance, has been widely applied in industrial fields. Unlike other thermal storage systems, the packed bed integrates thermal storage materials and heat exchange fluid within a single cavity, enabling the entire charging and discharging process to occur in one device. This reduces its floor space and thus contributes to cost savings[25].

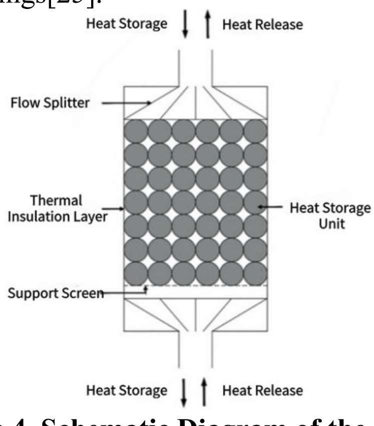

Figure 4. Schematic Diagram of the Packed Bed Structure[24]

The packed bed thermal storage system exhibits excellent performance, compatibility, and system economy, thus possessing broad application prospects in power peak shaving. Zhang et al.[26] analyzed the unit lifespan and economic performance of thermal power units coupled with phase-change packed beds for deep peak shaving through numerical simulation. The results showed that compared with the unit's own variable operating conditions of 30%~20%, the unit lifespan could be extended by 13.3%~15.3%, and the annual economic benefits could increase by 400,000 yuan and 720,000 yuan respectively. Liu et al.[27] implemented flexible retrofitting of thermal power plants using solid particle packed beds. The results indicated that the system achieved excellent cycle efficiency, reaching 65% cycle efficiency at low flow rates, along with 79% charging efficiency and 82% discharging efficiency. However, long-term direct contact with the heat exchange fluid may lead to structural deformation and degradation of the performance of thermal storage units. Therefore, system storage tanks with good performance are required[24].

(3) SHS TES system

Sensible heat storage technology is mature and exhibits favorable economic efficiency, thus having been widely applied in early demonstration projects. For instance, the heat-electricity decoupling retrofit and thermal storage project of Huaneng Dandong Power Plant, completed in 2020, utilized water as the thermal storage material, increasing its peak shaving capacity from 70% to 85%[28]. In current power peak shaving applications, water and concrete are the primary thermal storage materials. Based on a 600 MW coal-fired unit, Zhang et al.[29] analyzed and compared the peak shaving performance and cycle efficiency of hot water, concrete, and molten salt. The research results showed that under a thermal storage load of 90 MW, the system efficiency of water was 47.39%, and that of concrete was 45.32%, which were 9.86% and 7.61% higher than those of the thermal power unit under 50% load condition, respectively. The peak shaving depth of water was 2.40%, while the maximum peak shaving depth of concrete could reach approximately 5%. Overall, the performance of both is slightly inferior to that of molten salt thermal storage; however, their exergy efficiency and thermal efficiency are both higher than those of the unit under its own variable operating conditions.

In conclusion: Thermal storage technology plays an important role in power peak shaving. Overall, thermal storage technology can significantly improve the thermal efficiency, service life, and peak shaving depth of unit systems, but it is associated with considerable exergy loss. Molten salt thermal storage, featuring high heat capacity and long energy storage duration, is currently the most concerned thermal storage peak shaving technology. However, the relatively high material cost of molten salt is the main reason why molten salt thermal storage cannot be widely promoted on a large scale. Packed bed thermal storage has a compact structure and excellent heat exchange efficiency; its charging and discharging processes are completed in the same container, thus saving space, but long-term use imposes high requirements on the structural performance (thermal deformation) of the cavity. Although sensible heat storage is relatively inferior in terms of peak shaving performance and storage duration, its technology is widely used and mature, with excellent economic efficiency.

3.1.2 Hybrid energy storage in peak shaving coupled with TES

Apart from thermal storage, there exists a variety of energy storage technologies, such as electrochemical energy storage and mechanical energy storage. Electrochemical energy storage primarily encompasses lithium-ion batteries, sodium-ion batteries, etc., while mechanical energy storage can be classified into compressed air energy storage, flywheel energy storage, pumped-storage hydroelectricity, etc.[30-31]. Each energy storage method has its own merits and demerits. Therefore, when confronted with different scenarios, it is advisable to combine the advantages and disadvantages of various energy storage technologies to enhance the overall energy storage and operational efficiency through synergistic effects[32-33]. This section mainly introduces the hybrid energy storage peak shaving technology coupled with thermal storage.

(1) Battery energy storage coupled with TES

Battery energy storage is currently the most widely applied energy storage technology, featuring advantages such as high energy density, high cycle efficiency, and long service life, thus being extensively used in power peak shaving. However, it has high initial investment costs[34] and cannot recover low-grade heat generated from applications like heating and air conditioning. Therefore, coupling with thermal storage devices can be employed to achieve better regulatory performance and energy utilization efficiency. Zhang et al.[35] proposed a park peak-shaving and valley-filling strategy involving an electric-thermal hybrid energy storage system and conducted simulation studies. The results showed that the electric-thermal hybrid energy storage exhibits superior peak-shaving performance and economic benefits, and can effectively resist load fluctuations.

(2) Compressed air energy storage coupled with TES

Compressed air energy storage, characterized by large energy storage capacity, long storage cycle, and high system efficiency, is regarded as one of the most promising large-scale energy storage technologies[31]. Traditional compressed air energy storage requires additional fuel to increase air temperature and thereby enhance its work capacity. Moreover, the compression heat generated during the compression process is directly discharged, resulting in energy waste. Therefore, it can be coupled with a thermal storage system (the system diagram is shown in Figure 5) to recover the compression heat, and the stored heat can be used to heat the expander, realizing the energy storage and release cycle[36]. At present, there have been many demonstration projects for heat storage-type compressed air energy storage, such as the 300 MW advanced compressed air energy storage project in Dongping, Zhongshan, jointly developed by the Institute of Engineering Thermophysics, Chinese Academy of Sciences, and China Energy Storage Group. The total heat storage capacity of the heat storage array in this project reaches 8.3 TJ, with a designed heat storage efficiency of over 99%, featuring advantages such as high efficiency, large heat storage density, good economy, safety, and stability[37].

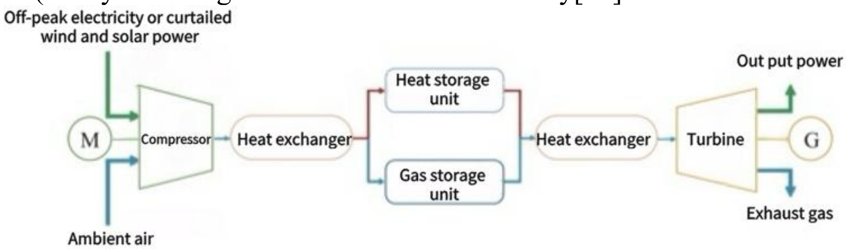

Figure 5. Thermal Storage-Type Compressed Air Energy Storage System[35]

3.2 Concentrated Solar Power

Solar energy has an almost unlimited reserve, and its power generation process can achieve nearly zero emissions, making it one of the most promising energy types at present. Solar energy in power generation is mainly divided into photovoltaic power generation and Concentrated Solar Power (CSP) generation[38]. Among them, CSP generation can better address the issues of intermittency and timeliness of solar energy; after being coupled with a thermal storage device, it can maintain power supply for a relatively long time even in the absence of sunlight. CSP generation has a long development history, and its power generation system (the basic system flow is shown in Figure 6) is relatively mature, which can be classified into tower-type, dish-type, trough-type, etc.[39-41].

At present, the development of thermal storage materials with enhanced performance is an important research direction in this field. Among them, molten salt serves as the primary thermal storage medium in CSP plants and can be categorized into three generations. The first and second generations are nitrate salts; for instance, in the Solar Two project in the United States in the 1980s, binary nitrate salts (solar salt) were used as the thermal storage medium. The third generation consists of new-type molten salts with superior performance, mainly including chloride salts, carbonate salts, and fluoride salts, etc.[40-43]. The characteristics of the main molten salt thermal storage materials currently used in solar thermal applications are summarized in Table 3 below.

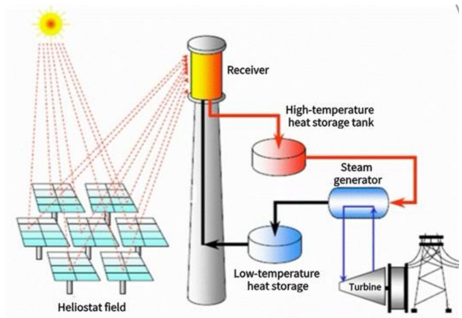

Figure 6. CSP Coupled With TES

Table 3. Common Molten Salt Thermal Storage Media for CSP Applications[42-45]

Molten salt	Advantages	Disadvantages
Nitrate	• Low cost, wide application. • Moderate thermal conductivity. • Medium energy storage density.	• Strong corrosiveness at high temperatures (above 600°C) • Instability at high temperatures (above 600°C)

Chloride	• High energy storage density. • Low cost. • High-temperature thermal stability.	• Strong corrosiveness
Carbonate	• High operating temperature (700–850°C) • High heat storage density	• Strong corrosiveness • High viscosity • Poor heat transfer performance
Fluoride	• Excellent heat transfer performance. • High heat storage density. • Wide thermal stability temperature range	• High cost • Strong corrosiveness

In general, the main development directions for molten salts used in solar thermal applications currently include: enhancing the stability and heat capacity of molten salts, reducing their corrosiveness, and the need for more comprehensive thermal property measurement methods, as well as more simulation experiments integrating materials and systems.

3.3 Other Related Applications

(1) Renewable energy consumption

Currently, renewable energy in China is growing rapidly; however, renewable energy exhibits strong intermittency and temporal imbalance. For instance, in northern regions, the peak period of wind power generation typically occurs from 2:00 a.m. to 8:00 a.m., which coincides with the electricity consumption valley period, leading to significant wind curtailment. Therefore, to address such energy waste, energy storage technologies are required for the accommodation of new energy. Thermal storage technology is one of them. Ren et al.[46] integrated thermal storage with heat pumps to participate in wind power accommodation. The study found that, for the case building, under the premise of meeting users' heat demand, the operating cost during the heating season was reduced by 13%, non-renewable energy consumption was decreased by 11%, and wind power accommodation of 3348 kWh was achieved.

However, it must be noted that the primary technologies for renewable energy accommodation at present are battery energy storage and pumped hydro storage[47-48], while research related to thermal storage is relatively limited.

(2) Waste heat recovery

Thermal storage technology can recover low-grade heat that most other energy storage technologies fail to retrieve, and it can also recover heat with relatively high temperatures, which enables it to play an important role in the field of waste heat recovery[49]. In power systems, there is a large amount of waste heat. For example, the flue gas emitted from boilers in thermal power plants still has a certain temperature, resulting in flue gas heat loss. Guo et al.[50] proposed a power generation device coupling flue gas waste heat recovery with low-temperature thermal storage, which improved the system efficiency. In addition to thermal power plants, nuclear power plants also generate a large amount of waste heat during operation, maintenance, or in case of faults. Li et al.[51] designed a stepped phase change bed thermal storage system for nuclear power waste heat recovery. The research showed that this system device can increase the solid-phase participation rate of materials by 97.9%, with an effective heat release time of 541 minutes, and the effective heat storage and release amounts reaching 1037.23 kW·h and 998.69 kW·h, respectively.

(3) Microgrid

Against the backdrop of the current growth trend of renewable energy, the number of distributed energy sources primarily focused on local accommodation is gradually increasing. To address the issue of grid connection for the large number of distributed energy sources, microgrid technology has been proposed[52]. A microgrid is a power distribution method, in which energy storage systems can play a role in stabilizing operation, peak shaving, and frequency modulation. Thermal storage technology, with relatively high energy density, is suitable for microgrids with limited space and demand for high energy output[4].

(4) Distributed energy coupled with cold storage

In addition to thermal storage, cold storage is also an equivalent form of thermal storage technology, which utilizes excess energy for refrigeration instead of direct heat storage. Currently, cold storage is mainly categorized into water-based cold storage and ice-based cold storage, both of which have been well-established in applications with traditional distributed energy sources. The core design concept of cold storage in distributed energy systems is to utilize waste heat or off-peak electricity for cold storage[45].

4. Conclusion

Thermal storage is an important direction in energy storage technologies and has shown tremendous potential amid the trend of energy structure transformation. This paper systematically summarizes the main applications of current thermal storage technologies in power systems.

(1) Thermal storage technologies: Thermal storage technologies play a crucial role in energy recovery and system efficiency improvement, with each of the three thermal storage methods possessing unique characteristics. Sensible heat technology exhibits favorable economic performance but requires enhancement in the thermal properties of materials. In contrast, latent heat storage and chemical heat storage typically demonstrate better thermal properties; however, their safety and economic viability still need to be improved to prepare for large-scale application in the future.

(2) TES in Power systems: In power peak shaving, there remains a need to optimize exergy efficiency, heat-electricity conversion efficiency, and material economy of the system. Furthermore, it is essential to integrate with other energy storage technologies based on practical conditions to leverage respective strengths and mitigate weaknesses, thereby achieving better results. In solar thermal power generation, it is necessary to optimize new energy storage materials to reduce costs and improve safety and stability. Beyond the aforementioned areas, thermal storage technologies have shown significant potential in other power system applications, but more research on specific cases is still required.

Under the current trends, the main research direction of thermal storage technology in power systems in the future will be to address issues of efficiency and cost to achieve large-scale popularization. With technological advancements, thermal storage technology and other energy storage technologies will achieve large-scale development. By then, renewable energy will truly replace traditional fossil energy as the dominant energy source, thereby realizing genuine sustainable development.

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