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Review of Solar Thermal Power Generation Technologies and Their Development

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Abstract:

Under the "dual carbon" goal, renewable energy is embracing a new leapfrog development, which puts forward higher requirements for the flexibility of the power system. Solar thermal power generation, with its regulation characteristics comparable to conventional thermal power units, can quickly and deeply participate in power grid peak shaving and frequency modulation, thereby enhancing the flexibility of the power system. It is a promising renewable energy generation technology. This paper introduces the operating principles and system structure of solar thermal power generation technology, summarizes the advantages and disadvantages of various power generation technologies, and analyzes the research progress of solar thermal power generation technology. Based on this, considering the current development status and demands of solar thermal power generation, the paper discusses the issues that need further attention and the future development direction of solar thermal power generation technology.

Keywords:

Solar energy
Solar thermal power generation
Flexible operation
Heat storage
Renewable energy accommodation
"Dual carbon" goal
Frequency and peak modulation

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1. Introduction

In recent years, with the increasing depletion of fossil fuels and the continuous intensification of environmental pollution, the penetration rate of wind power and photovoltaic power generation has been continuously increasing, occupying some space of conventional units and weakening the regulation ability of the power grid [1]. To ensure the safe, stable, clean, and efficient operation of the power system, there is an urgent need for flexible power sources to participate in power grid frequency and peak regulation, enhancing the flexibility of the power system [2].

Concentrating solar power (CSP), which integrates power generation and heat storage, has advantages such as flexible and controllable output. It can quickly and deeply participate in power grid peak shaving and is suitable for complementary operation with new energy sources such as wind power and photovoltaic power generation [2,3]. As a renewable energy power generation technology with great development prospects, it has attracted attention from countries worldwide and has been actively researched, promoted, and applied. As of the end of 2021, the cumulative installed capacity of global CSP stations was 6,692 MW. Among China's first batch of demonstration projects, seven tower-type, one trough-type, and one linear Fresnel-type CSP stations were connected to the grid with a total capacity of 550 MW. However, compared with wind power and photovoltaic power generation, the large-scale development of CSP still has a long way to go. Deep analysis of CSP operation characteristics under multiple uncertainties, research on flexible operation strategies and benefit evaluation of CSP participation in the power grid, is of great significance to help CSP become an important component of China's power supply structure [4].

This article analyzes the status quo of CSP technology at home and abroad, introduces the basic principles, common types, and system composition of CSP; discusses the operating characteristics, advantages, and disadvantages of different types of CSP; analyzes the research progress of CSP technology; and looks forward to the development direction of CSP technology.

2. Principles and system composition of CSP technology

The basic principle of CSP is to focus solar radiation energy around the power station through a large number of reflecting mirrors or concentrating mirrors onto a heat collecting area. The heat collecting area heats the working fluid, which absorbs solar radiation energy to generate high-temperature steam, driving a steam turbine generator set to generate electricity, thus converting solar energy into electrical energy [5-7]. A CSP station generally consists of a heat collecting system, a heat storage system, a steam generation system, and a power generation device, as shown in **Figure 1** [8].

2.1. Concentrating and heat collecting system

The concentrating and heat collecting system is the foundation of solar thermal power generation, mainly consisting of a concentrating mirror field and a heat absorber. The concentrating mirror field is composed of a large number of homogeneous concentrating devices (such as parabolic trough reflectors, flat heliostats, etc.) arranged in a certain pattern. Currently, the investment in concentrating mirror fields accounts for more than 60% of the total system investment in various solar power generation systems [9]. The solar energy absorbed by the concentrating mirror field is affected not only by factors such as the layout of the mirror field and reflectivity but also by external environments such as weather conditions and solar radiation intensity at the location of the mirror field. The heat collector directly converts the solar radiation energy gathered by the concentrating mirror field into heat energy, heating working fluids such as heat transfer oil and molten salt. The performance of the heat absorber directly determines the outlet temperature of the heat absorption medium. Due to factors such as the intermittency of solar heat sources and the corrosiveness of molten salt media, the heat absorber has high technical and technological requirements for material selection, optimized design, and reliability.

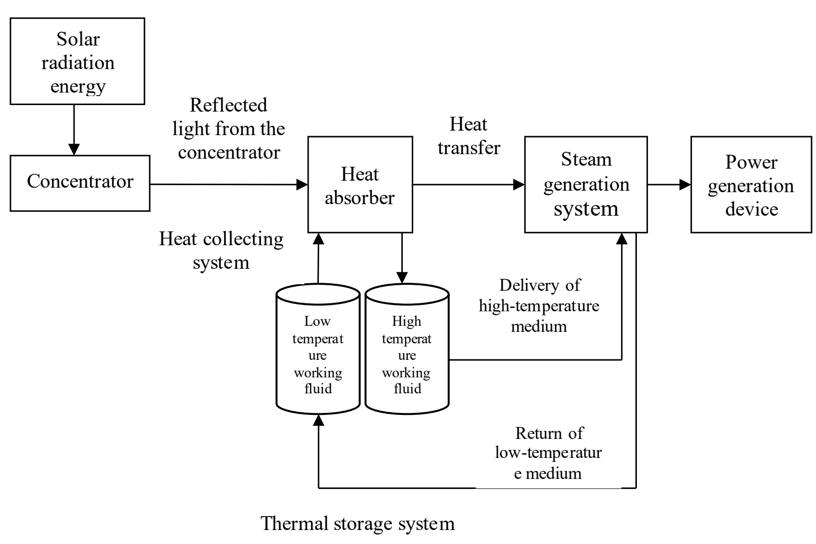

Figure 1. Composition of the CSP system

2.2. Heat storage system

The energy storage system is the key to achieving flexible and adjustable CSP output and 24-hour continuous and stable operation of CSP generation. Its heat storage capacity is closely related to the annual power generation of the electric field, the scale of the concentrating mirror field, and the total investment of the power station. Therefore, the design of the energy storage system needs to comprehensively consider factors such as heat storage capacity, heat storage cycle, and power generation economy [10].

2.3. Steam generation system

The main function of the steam generation system is similar to that of conventional thermal power plants, which is to achieve heat exchange between high-temperature fluid media (such as heat transfer oil and molten salt) and water working fluid, generating superheated steam to drive the turbine to do work. The difference is that the steam generation system of CSP stations has a fast heating rate, which can reach up to 10°C/min, enabling rapid turbine startup [11,12].

2.4. Power generation system

The performance of the power generation system is directly related to the economy of solar CSP. The equipment configuration of this system is similar to that of thermal power units, but compared to coal-fired units, the power generation system of CSP stations has better regulation performance. This requires the steam turbine to have characteristics such as frequent start-stop, rapid startup, low-load operation, and high efficiency [8,13].

3. Classification and characteristic analysis of CSP technologies

Based on the energy concentration method and structure, solar CSP technologies can be classified into four major categories: tower, trough, dish, and Fresnel.

3.1. Tower solar CSP

Tower-based power generation is a centralized solar thermal power technology. In this technology, a heat absorption tower standing several hundred meters high is erected at the center of a circular mirror field composed of thousands of independently controlled heliostats. The heliostats, which independently track the sun, concentrate sunlight onto a receiver at the top of the tower to generate high temperatures. This heat is then used to heat a working fluid, and the resulting superheated steam drives a turbine to generate electricity [14-16]. Tower-based CSP is illustrated in **Figure 2**.

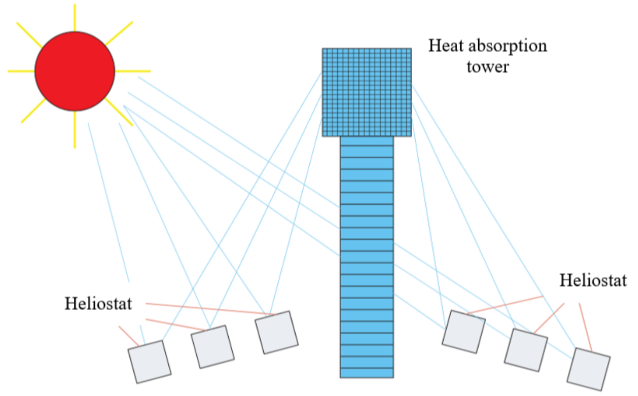

Figure 2. Tower solar thermal power generator

3.2. Trough solar CSP

Trough CSP utilizes the optical focusing principle of a parabolic surface to concentrate solar radiation, which is parallel to the main axis of the trough-shaped parabolic surface, onto a heat collecting tube. In practical applications, multiple trough-shaped parabolic concentrating collectors are combined in series and parallel to form a concentrating and heat collecting system. This system is used to absorb solar radiation energy and generate superheated steam to drive a generator set for power generation [5,17]. The structure of the trough CSP device is shown in **Figure 3**.

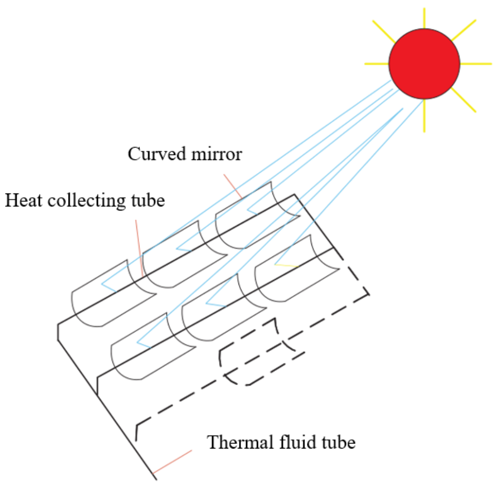

Figure 3. Trough solar thermal power generator

3.3. Dish solar CSP

The dish solar CSP system employs a dish-shaped concentrating system, where the solar radiation reflecting surface is arranged in a dish (or plate) form. Sunlight is reflected and focused onto a receiver through a dish-shaped parabolic reflector. The generated thermal energy drives a thermodynamic generator set through a Stirling engine installed at the focal point, as illustrated in **Figure 4**. Dish-type power generation utilizes point focusing, characterized by a high concentration ratio, high heat collection temperature, and low heat loss from the collector. Currently, the peak photoelectric conversion efficiency can reach approximately 30%. However, its single-unit capacity is limited by cost factors, resulting in a smaller individual power generation capacity, making it suitable for distributed power generation [5,18].

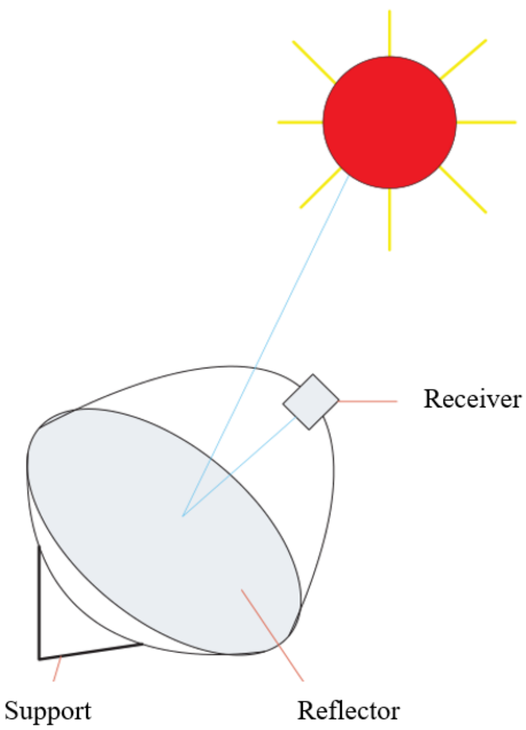

Figure 4. Dish-type solar thermal power generator

3.4. Fresnel solar CSP

Fresnel solar CSP employs a linear Fresnel solar concentrator. The linear Fresnel concentrating system evolved from the parabolic concentrating system. Its working principle is similar to that of trough CSP. However, unlike the trough system, the linear Fresnel mirror arrangement does not need to maintain a parabolic shape. Direct solar radiation is focused onto the top of a tower through a primary flat reflector and then onto a linear heat collector via a secondary reflector. This heats the working fluid, generates steam, and drives a turbine to generate electricity [5,9]. The linear Fresnel CSP device is shown in **Figure 5**.

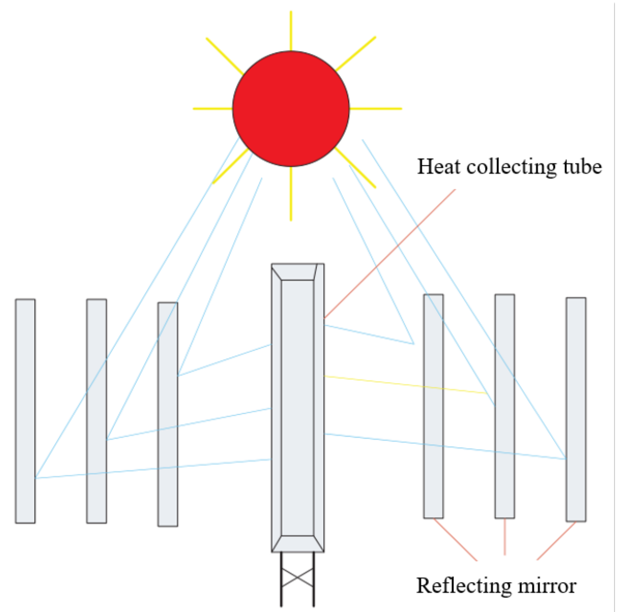

Figure 5. Linear Fresnel CSP arrays

3.5. Comparison of technical characteristics of various types of CSP technologies

Due to differences in the structures of the concentrating systems, the heat collection methods of CSP, and the operating parameters of various components within the CSP system (**Table 1**), the four CSP technology routes mentioned above exhibit varying operational performances and levels of promotion and application [5,9].

In summary, both dish and tower solar thermal power generation technologies exhibit high optical efficiency in their concentrating mirror fields. The energy in the processes of concentrating solar heat and converting it into thermal energy is more concentrated, leading to higher system operating temperatures and efficiencies. Dish systems are limited by the scale and cost of individual units, with current demonstration projects having a capacity at the kW level. Tower systems, on the other hand, feature a complex solar island control system and high maintenance costs, but they offer advantages such as high concentration ratios, high photothermal conversion efficiency, and short heat transfer paths. These characteristics make tower systems highly suitable for

Table 1. Characteristics of four generation technologies

Project		Trough	Tower	Dish	Linear Fresnel
Concentrating mirror field	Concentration method	Line focus	Point focus	Point focus	Line focus
	Secondary reflection	No	No	No	Yes
	Tracking control	Simple	Complex	Simple, flexible	Simple
	Concentration ratio	30~80	600~1500	1000~1400	25~100
	Mirror efficiency	Low	High	High	Low
Heat collection and storage	Heat collection method	Heat recovery in widely distributed receivers	Cavity-concentrated reception	Cavity receiver, thermodynamic generator set	Heat recovery in widely distributed receivers
	Energy storage	Heat storage possible	Heat storage possible	No	Heat storage possible
	Absorber operating temperature/°C	350~740	500~1200	700~1000	270~550
Steam generation system	Power cycle mode	Rankine cycle	Rankine cycle, Brayton cycle	Stirling cycle	Rankine cycle
	Efficiency/%	30~40	30~40	30~40	30~40
System peak efficiency/%		21	23	29	20
System investment cost		Medium	High	High	Medium
Maturity	Degree of commercialization	Commercialization	Commercial pilot	Demonstration	Demonstration
	Installed capacity already built	100MW	200MW	kW level	50MW

large-scale, high-capacity commercial applications. As a result, tower solar thermal power generation systems are considered a potentially significant technological approach, accounting for approximately 20% of the total installed capacity of solar thermal power generation worldwide [19,20].

Parabolic trough solar thermal technology is currently the most mature and widely used solar thermal power generation technology, accounting for approximately 76% of the total installed capacity [19,20]. This technology features simple structural components for concentrating and collecting solar heat, as well as easy energy collection and tracking control. However, compared to tower systems, parabolic trough systems have lower concentration ratios, larger heat dissipation areas, and correspondingly lower efficiencies and operating temperatures.

While Fresnel-type solar thermal power generation uses a Fresnel-structured concentrating mirror instead of a parabolic surface, reducing the production difficulty and cost of the concentrating mirror, the overall system efficiency still needs improvement. Currently, the only completed linear Fresnel solar thermal power generation project in China is the 50 MW project in Dunhuang, Lanzhou.

4. Research status of solar thermal power generation technology

4.1. Modeling and operating characteristics of solar thermal power generation

Solar thermal power generation systems are dynamic systems that integrate and coordinate the control of multiple subsystems, including solar heat collection, heat transfer and storage, heat exchange, and power generation. Therefore, analyzing the accumulation and flow of energy within the system and the operating characteristics of solar thermal power generation at different time scales is essential for optimizing its operation and enhancing its efficiency and benefits

[4]. Current models for solar thermal power generation characteristics often consider the internal heat conversion relationships within the solar thermal power plant or represent the relationship between heat and electricity as a functional relationship [21]. When studying simplified internal energy flow processes in solar thermal power plants, static models suitable for scheduling operations and economic analysis are established. Sioshansi and Denholm [22] simplified the dynamic process of internal energy exchange in a solar thermal power plant and developed an hourly static energy flow model. However, this model did not consider factors such as heat rejection and unit ramp rates. Models that do not consider ramp rates, reserves, and other factors cannot be directly applied to grid scheduling problems involving CSP plants. Chen *et al.* [23] improved the static energy flow model and proposed a scheduling model based on the participation of solar thermal power plants. Zhang *et al.* [24] reasonably simplified the energy flow within and between the various subsystems of solar thermal power generation, establishing a static energy flow mathematical model oriented toward optimizing power generation. In terms of establishing thermodynamic dynamic models considering heat exchange, Li [25] studied a real-time dynamic simulation model of the thermal system of a conventional parabolic trough solar thermal power plant, using the SEGS Unit VI in the United States as the subject. Based on the simulation model, the dynamic characteristics of this type of power plant were analyzed. Geng *et al.* [26] developed a thermodynamic simulation model for a medium- to low-temperature parabolic trough solar thermal power generation system with thermal storage devices, conducting hourly simulations for four typical days: spring equinox, summer solstice, autumn equinox, and winter solstice. Li [27] established thermodynamic dynamic equations for each link in a tower solar power generation system and further studied the overall efficiency of a 1 MW tower solar thermal power plant in Yanqing, Beijing, based on the model and actual operating data. Alferidi *et al.* [8] developed a probabilistic model for CSP to determine the impact of solar radiation and temperature variations on power system reliability. The study also used this model to evaluate the effects of various factors, such as system load, installed capacity, and site parameters, on the capacity credibility and effective carrying capacity of solar thermal power generation.

4.2. Optimization methods for power systems incorporating CSP

In recent years, the integration of CSP plants as flexible resources into power systems to support grid flexibility has become a research hotspot. Starting from the characteristics of CSP plants, Xiao and Wang [21] established a coordinated optimal scheduling model for CSP-wind-photovoltaic systems, with the goals of maximizing system revenue, maximizing load-following capability, and smoothing wind power output fluctuations. By utilizing the flexible power output characteristics of CSP plants, this model performs peak shaving and valley filling for wind and photovoltaic power generation, smoothing the output curve. Such research has achieved optimized operation of CSP, wind, and photovoltaic power generation systems under different operating conditions and control modes [28-30].

In terms of source-load coordinated scheduling, Zhao [31] studied the coordinated scheduling problem and bidding curve optimization for CSP and multiple source-load resources in a joint CSP-photovoltaic power plant. A diversified coordinated scheduling strategy for CSP and multiple source-load resources was proposed, improving the economic efficiency and flexibility of scheduling when aggregating CSP plants with multiple source-load resources. Liu *et al.* [32] addressed the problem of how to achieve flexible coordinated scheduling of source-load in a CSP-wind power system across multiple time scales. They constructed a multi-time scale source-load coordinated scheduling model for power systems incorporating CSP and wind power, which not only improves the flexibility of power system scheduling but also solves the peak shaving problem caused by large-scale wind power integration [33]. Cui *et al.* [14] proposed a source-grid-load coordinated scheduling method that effectively improves the local renewable energy consumption capacity by utilizing CSP plants as regulatory resources. Considering the participation of CSP plants in peak shaving ancillary services in power system scheduling, Cui *et al.* [34] developed a pricing model for CSP plants participating in peak shaving services and proposed a scheduling method for thermal power and

CSP plants to jointly participate in peak shaving ancillary services. This approach enhances the wind and solar power consumption level in the power system while reducing operating costs.

4.3. Integration strategies for multi-energy systems incorporating CSP

The integration of energy storage systems enables CSP generating units to have energy time-shifting characteristics and rapid regulation capabilities [34]. Currently, scholars are combining CSP with wind power, photovoltaics, energy storage, and thermal storage systems to construct multi-energy complementary power generation systems. Dai *et al.* [35] proposed a coordinated control strategy suitable for grid scheduling in a wind power-CSP plant joint system. They established a multi-objective optimization model for wind-solar complementarity with thermal storage devices. Zheng *et al.* [36] comprehensively considered the impact of the coordinated operation of CSP plants and hydrogen energy storage on integrated energy system scheduling. They proposed a low-carbon optimized operation strategy for integrated energy systems incorporating CSP plants and hydrogen energy storage, optimizing system operational flexibility and improving energy utilization efficiency. Zang *et al.* [37] studied the energy coupling relationship in a wind power-CSP-biomass hybrid power plant. They found that the thermal storage system of the CSP plant and the biomass boiler not only improved the operational flexibility of the hybrid power plant but also increased its bidding volume in the electricity market by optimizing its operation strategy, resulting in higher electricity market revenue. Sakellaridis *et al.* [38] constructed a model for a joint wind power, pumped hydro storage, and CSP power generation system based on their energy storage and regulation characteristics. They evaluated the operational reliability of the system. Peng *et al.* [39] utilized the controllable power output characteristics of CSP plants and aggregated them into a virtual power plant combining wind, solar, and thermal power. They proposed a two-stage optimal scheduling model for the virtual power plant, fully tapping into the regulation potential of CSP and increasing power plant revenue through internal collaborative optimization. Zhao *et al.* [40] addressed the shortcomings of integrated energy systems by studying the construction of a multi-energy virtual power plant that combines wind power, photovoltaics, CSP, and energy storage batteries. Zeng *et al.* [41] focused on a multi-energy coupled regional integrated energy system involving CSP plants. They constructed a simplified model of a regional integrated energy system with CSP participation and found through simulation that the involvement of CSP plants improves the utilization efficiency of renewable energy and the coordinated optimization capabilities of the regional integrated energy system.

4.4. Optimal configuration of CSP plants

Energy storage systems are crucial for ensuring continuous and stable operation of CSP plants, as well as providing adjustable performance. Therefore, optimizing the configuration of thermal storage system capacity parameters and assessing the economics of CSP's flexible participation in wind-photovoltaic complementary operation are current research hotspots.

Kueh *et al.* and other scholars [42,43] studied the impact of thermal storage systems on the operation of CSP plants and identified important factors influencing thermal storage capacity. Boukelia *et al.* [44] compared and analyzed eight different configurations of parabolic trough solar thermal power plants based on molten salt and thermal oil as heat transfer media, considering energy efficiency, thermoelectric efficiency, environmental protection, and economics. The results showed that solar thermal power plants equipped with molten salt thermal storage and fuel backup systems have the highest overall efficiency. The Levelized Cost of Electricity (LCOE) is the most commonly used parameter in economic research and analysis of solar thermal power plants [45]. Praveen *et al.* [46] targeted the minimum LCOE during the year of highest electricity generation by optimizing the performance of a proposed CSP plant through variations in the solar multiple and full-load hours of the thermal storage system (TES). Boukelia *et al.* [47] studied the optimization of parameters such as the solar multiple and thermal storage capacity of a 50 MW photovoltaic-CSP hybrid power generation model in Algeria to minimize the LCOE of the combined power station. In terms of studying the optimal configuration of thermal storage capacity considering economic dispatch in CSP generation scheduling, Cui *et al.* [48] comprehensively considered the impact of peaking costs of thermal power units and thermal storage costs on the capacity configuration of thermal storage systems, proposing a method to configure thermal storage capacity in CSP plants that reduces peaking costs of thermal power units. Yao [49] explored the balance point between the configuration cost of thermal storage devices and dispatch economics, considering factors such as the generation cost of thermal power units, environmental benefits and operation and maintenance costs of CSP grid integration, and system spinning reserve costs to determine the optimal thermal storage capacity configuration for CSP plants. Kost *et al.* [50] found that different subsidy mechanisms and operational strategies affect the optimal photovoltaic capacity ratio and optimal thermal storage capacity for CSP.

4.5. Comprehensive benefit evaluation of CSP

CSP, with its comparable regulation performance to conventional power sources, can provide peaking and backup services to the grid and promote the integration of renewable energy sources such as wind and solar. Therefore, the benefit evaluation of CSP not only considers its own operational benefits but also includes objective benefits such as capacity benefits from replacing conventional units, electricity benefits from multi-energy complementary generation with other power sources, and flexibility services benefits such as providing peaking. Fu *et al.* [51] proposed an equivalent annual cost method for comprehensively evaluating the capacity and electricity benefits of CSP, considering unit startup and shutdown, as well as cross-day regulation of energy storage sources. Sha *et al.* [52] conducted a quantitative analysis of the flexible operation benefits of CSP plants from three perspectives: operational economics, peaking effectiveness, and green electricity benefits, focusing on the optimal operation of an interconnected system with a high proportion of renewable energy at the sending end connected via UHVDC and including CSP plants. Chen *et al.* [23] analyzed the objective benefits of CSP plant integration in terms of generation costs, renewable energy integration, and improved utilization of transmission lines, assuming full acceptance of CSP generation.

Relevant literature further combines the electricity market to study and analyze the operational strategies of CSP plants participating in the market, aiming to maximize their market revenue. He *et al.* [53] established an optimal bidding strategy for CSP plants in the day-ahead energy, reserve, and regulation markets to improve the operational efficiency of CSP plants, considering the uncertainties of solar energy and market prices. Liang *et al.* [54] constructed a market transaction decision model based on a multi-oligopoly Cournot model, considering CSP generators as the main market players in the spot electricity market. Zhao *et al.* [55] proposed an optimal operation strategy for CSP plants in the day-ahead and real-time electricity markets, considering the non-random uncertainties of CSP plant thermal production, the random uncertainties of market prices, and the risks associated with CSP plants, thereby enhancing the economic benefits of CSP.

Based on the literature mentioned above, it can be inferred that in the current stage of optimizing the operation of power systems incorporating CSP generation, scholars have primarily focused on studying the integration of CSP stations into wind-photovoltaic combined generation, addressing uncertainties associated with wind and photovoltaic power, and promoting flexible scheduling strategies for high-proportion renewable energy power systems. However, there is a paucity of research on the reliability of CSP generation capacity and methods to support safe and flexible grid operation after integration into the power system from a holistic perspective. When exploring integration strategies for wind-photovoltaic-thermal-storage multi-energy complementary energy systems in the context of CSP, existing studies often consider the formation of a "CSP+" multi-energy complementary generation model on the power supply side, combining CSP with photovoltaic, wind power, and energy storage. Nevertheless, further exploration and research are needed to investigate the operational strategies of CSP stations within multi-energy integrated systems such as electricity/heat/cooling/gas, and their ability to provide capacity support and regulation for power systems. Regarding optimal CSP configuration, the majority of current research focuses on optimizing the heat collection and storage efficiency of individual CSP stations. Some studies have examined heat storage parameter configuration strategies that consider scheduling economy [56]. However, there are few reports on the optimal capacity matching method for the flexible participation of CSP stations in grid regulation while maximizing the efficiency of the power system. In terms of comprehensive benefit evaluation of CSP generation, some literature has studied and analyzed the operation strategies of CSP stations participating in the electricity market in specific scenarios from the perspective of CSP station operating income. These studies, however, have not comprehensively considered and analyzed uncertain influencing factors such as CSP operation mode, heat storage duration, renewable energy penetration rate, peak shaving demand, and grid constraints, as well as the benefit evaluation method of CSP stations under multiple optimization objectives.

5. Outlook on solar thermal power generation technology

Solar thermal power generation, as a stable and reliable new energy power generation technology, is an indispensable technical means to achieve China's energy transformation goals. This technology involves the integration and coordination of multiple systems such as solar energy collection, heat transfer and storage, and power generation. In future development, attention should be paid to the following aspects:

(1) Research on key technologies and equipment for high-temperature solar thermal energy collection/storage: Solar thermal power generation systems have the advantages of high power generation efficiency, high economy, and suitability for large-capacity development when operating at high temperatures. Therefore, it is crucial to conduct research on high-temperature heat collection/storage technologies and promote the development of solar thermal power generation towards high operating parameters and large capacities.

(2) Solar thermal power prediction: Solar thermal power generation mainly utilizes direct normal irradiance from the sun, which is greatly affected by clouds. Environmental factors such as irradiance in different natural resource environments will impact solar thermal power collection and energy storage systems. Research should be conducted on how to improve the prediction accuracy of solar thermal power to better provide a decision-making basis for efficient and economic operation of solar thermal energy storage systems and power station output.

(3) Research on solar thermal operation characteristics: The establishment of "dual carbon" goals has pressed the "fast forward button" for the development of new energy sources such as wind and solar, posing higher requirements on the acceptance and regulation capabilities of power systems. In the future, comprehensive consideration should be given to the high uncertainty on both the source and load sides and dynamic characteristic analysis of various types of solar thermal power stations under different operating conditions should be carried out based on actual operation situations. Mathematical models of solar thermal power generation equipment at different time scales should be constructed to analyze the operational characteristics of different types of solar thermal power generation capacities, such as reliability and support for grid security, and to improve grid stability and flexibility. Research should also be conducted on the coordinated optimization configuration and scheduling strategies of different types of solar thermal power generation participating in high-proportion new energy transmission grids to enhance grid operation efficiency and economy.

(4) Standards related to solar thermal power generation: Currently, solar thermal power generation technology is in its early stages in China, with various technologies operating independently and lacking clear standards that fully correspond to the actual operation of solar thermal power generation, making it difficult to provide strong support for the industry. In the future, combining the actual operation of solar thermal power generation, in-depth research should be conducted on the selection methods of configuration parameters for different types of solar thermal capacities from the perspectives of system stability, dynamic performance, and economy. Corresponding control strategies

for different proportions of solar thermal participation in grid peak shaving and frequency regulation, as well as standards for "solar thermal + wind and photovoltaic" multi-energy complementary integrated operation, should also be proposed.

(5) Cost-benefit evaluation of solar thermal power generation: Currently, the high investment cost of solar thermal power generation is a major factor affecting the development of solar thermal power stations. Therefore, analyzing and evaluating the economy and comprehensive benefits of solar thermal power generation is key to enhancing its competitiveness. Further exploration is needed in terms of cost optimization of solar thermal power stations and the benefits of solar thermal participation in grid peak shaving and multi-energy complementary power generation with other power sources. This includes improving the economy of solar thermal power stations and reducing LCOE through technical configuration aspects such as solar thermal power generation technology materials, optimization of solar island heat collection system planning, and heat storage capacity configuration. Additionally, considering the overall peak shaving and other ancillary service demands of the power grid in the context of the electricity market, analysis should be conducted on the operational modes and decision-making analysis models of flexible solar thermal power station participation in grid regulation to maximize the benefits of the power system. This will help to tap into the benefits of solar thermal power generation providing flexibility services such as peak shaving and its multi-energy complementary power generation benefits with other power sources.

6. Conclusion

To enhance the flexibility of high-proportion renewable energy power systems, a comparative study was conducted on four types of solar thermal power generation systems. Solar thermal power generation integrates power generation and energy storage, offering advantages such as flexible and controllable output. It is a promising renewable energy power generation technology. This article introduced the technical principles and system structure of solar thermal power generation, reviewed the current research status of solar thermal power generation technology, and explored the issues and research directions that need attention in the future of solar thermal power generation. It is hoped that this article will provide references for future research and development of high-performance solar thermal power generation.

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Disclosure statement

The authors declare no conflict of interest.

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