Blue Book of China's Concentrating Solar Power Industry 2023

China Solar Thermal Alliance
CSP Committee of China Renewable Energy Society

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Foreword

China Solar Thermal Alliance (CSTA) is a non-profit organization that supports and promotes the development of the concentrating solar power industry and technologies with the strength of all CSTA members including universities, institutes, and industry participants.

The Blue Book of China's Concentrating Solar Power Industry 2023 (Chinese version) was completed on January 2024 by CSTA and the Concentrating Solar Power Committee of China Renewable Energy Society (CRES) to provide reference for the industry and policy makers.

The Chinese version of the Blue Book was prepared by Prof. Zhifeng Wang, Prof. of the Institute of Electrical Engineering, Chinese Academy of Sciences, and Ms. Fengli Du, CSTA secretary-general, reviewed by the Expert Committee of CSTA, and approved by Academician Prof. Yaling He for release.

To help the international community understand the general development status of China's concentrating solar power industry, we have translated the Blue Book into English. Please understand that the English version may contain certain unintended errors or omissions.

Where any text, data, or figure herein is reprinted or cited, the source thereof must be cited as: Blue Book of China's Concentrating Solar Power Industry 2023, China Solar Thermal Alliance (CSTA), Beijing, 2024.

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Chapter I Overview of Concentrating Solar Power

1.1 Principles of concentrating solar power systems

Concentrating solar power (CSP) systems, also known as solar thermal electricity (STE) systems, are systems that generate electricity by converting solar energy into thermal energy and then converting heat (thermal energy) to work [1]. Such systems are mainly characterized in that they can generate electricity stably through solar concentrators and receivers at the front end in combination with synchronous generator sets and binary nitrate salt thermal energy storage (TES) system (or any other TES system) at the back end.

Depending on solar concentration modes, commercially applied CSP systems can be classified into three main types, namely, solar tower systems, parabolic trough CSP systems, and linear Fresnel CSP systems. Solar tower systems are point focusing systems, while parabolic trough and linear Fresnel CSP systems are line focusing systems. CSP systems can use different heat transfer fluids (HTFs) as heat absorbing media. The most common commercial HTFs are binary molten salt (also known as solar salt, which is a binary mixture of 60% sodium nitrate and 40% potassium nitrate in the molten state) and thermal oil (a mixture of biphenyl and diphenyl ether). The operating principles of CSP systems involving different HTFs and solar concentration modes are detailed in the following paragraphs. Solar tower systems using molten salt as the HTF and parabolic trough CSP systems using thermal oil as the HTF are currently the mainstream commercial CSP systems.

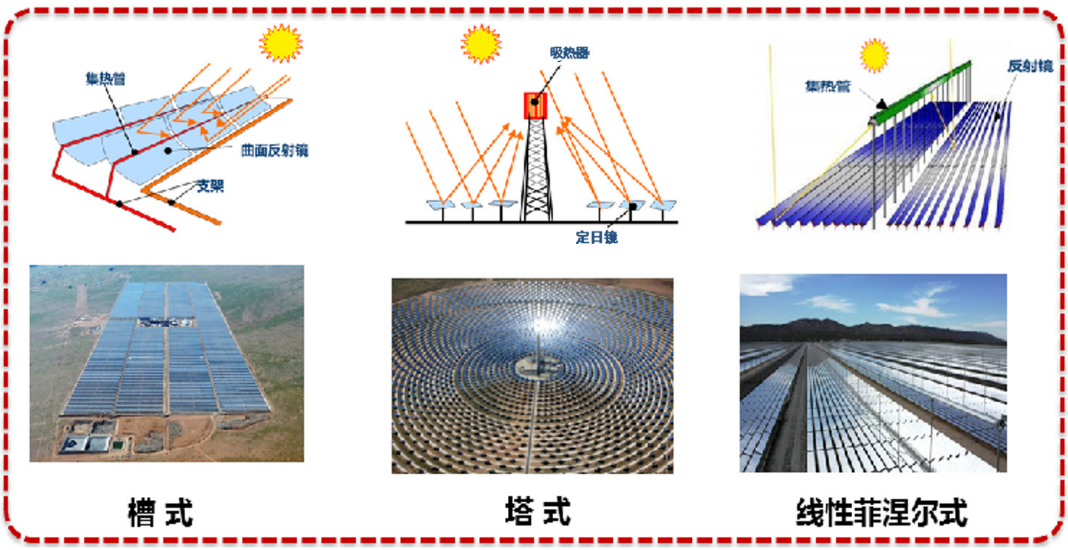


Fig. 1.1-1 Three mainstream types of solar concentration

A molten salt (MS) solar power tower system comprises four major units, namely, solar condensation unit, solar absorption unit, heat (thermal energy) storage and exchange unit, and electricity generation unit, and it consists primarily of heliostats, heat absorption tower, solar receivers, high-temperature (hot) and low-temperature (cold) MS storage tanks, steam generators, and turbine-generator unit (TGU). The basic operating principle of such systems is described below. Heliostats are arranged in a circular pattern around the heat absorption tower. By adjusting and controlling their azimuth and elevation angles, heliostats reflect and focus beams of sunlight onto the central solar receiver at the top of the heat absorption tower. The low-temperature liquid solar salt is transferred by the cold salt pump to the central solar receiver where it absorbs heat and its temperature rises to 565°C, and the hot MS is routed to the hot salt tank for storage. When electricity generation is required, the hot MS is transferred to the steam generator and exchanges heat with water, generating high-temperature and high-pressure (HTHP) steam. The HTHP steam drives the turbine-generator unit to generate electricity. After releasing heat in the steam generator, the MS is routed to the cold salt storage tank and then recirculated to the central solar receiver to absorb heat.

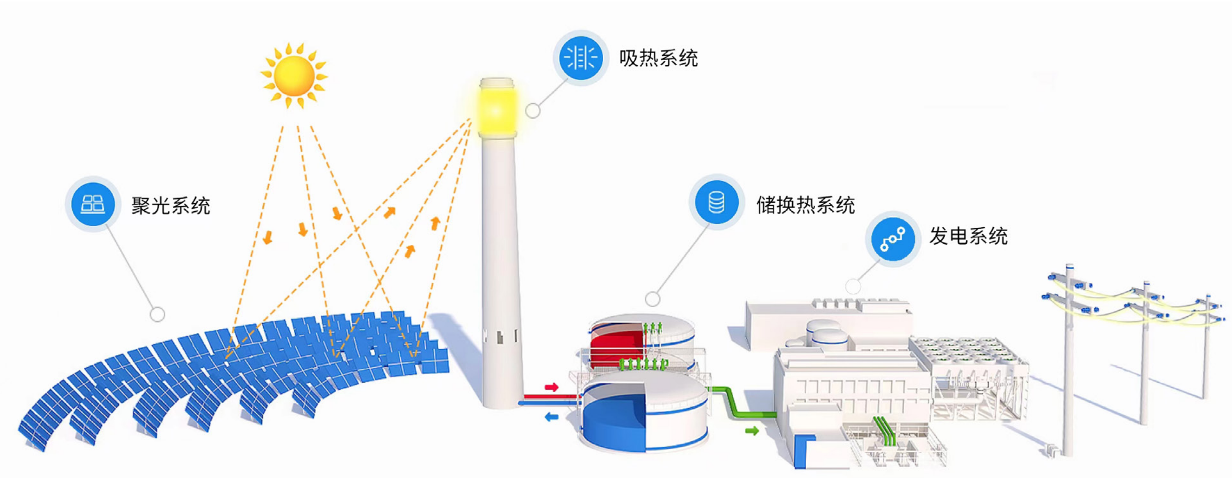


Fig. 1.1-2 Schematic diagram of an MS solar power tower system (Source: Cosin Solar)

In an MS solar power tower system, the molten salt serves as both heat transfer fluid and heat storage medium, and therefore the operation mode of such system is simple. In the TES block, the solar collection and electricity generation units are decoupled.

A parabolic trough CSP system using thermal oil as HTF mainly consists of parabolic trough collectors (which are composed of solar concentrators and receiver tubes), a heat storage and exchange system, a steam generation system, and turbine-generator units. The parabolic trough collectors are connected both in series and in parallel and arranged in modules, forming a collector field. The basic operating principle of a parabolic trough CSP system is detailed below. Solar concentrators track the sun through the single-axis solar tracking system and reflect sunlight onto receiver tubes to heat the HTF in these tubes. The hot HTF undergoes heat exchange in the steam generator, producing superheated steam that drives the turbine-generator unit to do work and generate electricity. The low temperature and low-pressure (LPLT) steam from the steam generator is condensed into liquid water in the condenser, and the liquid water is returned to the thermal oil (HTF) steam generator where it absorbs heat from the HTF and evaporates into steam again. After releasing heat in the steam generator, the HTF is routed back to the receiver tubes for heating, thus creating a closed circulation loop. When the solar irradiance is high, part of the thermal energy (heat) of the HTF can be stored in the molten salt tank after the HTF is routed through the oil-salt heat exchanger. When the solar irradiance is low, the thermal energy stored in the hot salt tank can be transferred to the oil-salt heat exchanger to produce steam for electricity generation. Similar to the case of MS solar power tower systems, the solar collection and electricity generation units in the TES block of a parabolic trough CSP plant are decoupled, thus eliminating the impact of fluctuations in solar radiation on the stability of the turbine-generator unit's output and enabling the plant to be connected to the grid and engage in electricity dispatch without reliance on solar radiation.

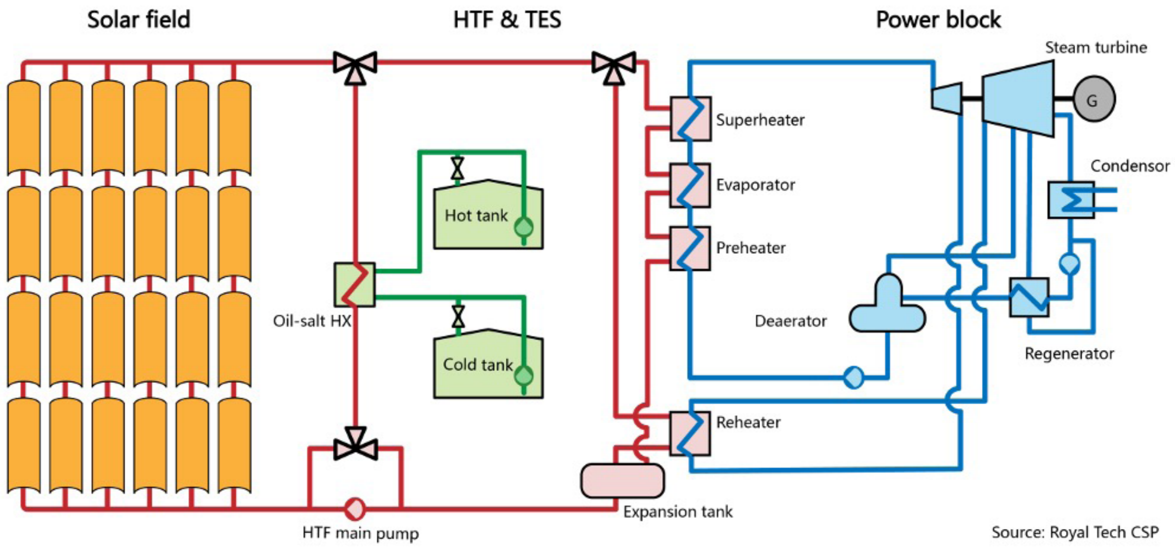


Fig. 1.1-3 Schematic diagram of a parabolic trough CSP system (conventional process) (Source: Royal Tech CSP)

The conventional process of a parabolic trough CSP plant using thermal oil as HTF can be simplified through the decoupling between the heat collection and storage process and the heat release and electricity generation process to minimize the impact of fluctuations in solar radiation at the front end on the stability of electricity generation at the back end. All of the heat collected by parabolic trough collectors in the collector field is circulated and transferred via the HTF to the cold molten salt. After the cold molten salt absorbs heat, it becomes hotter and flows into the hot salt tank for storage. At this point, the heat collection and storage process is complete. When electricity generation is required, the hot molten salt in the hot salt tank is transferred by the hot salt pump to the molten salt steam generator, where it releases heat to produce HTHP steam that drives the turbine-generator unit. After the molten salt releases heat and its temperature drops, it is routed back to the cold salt tank for storage. At this point, the heat release and electricity generation process is complete.

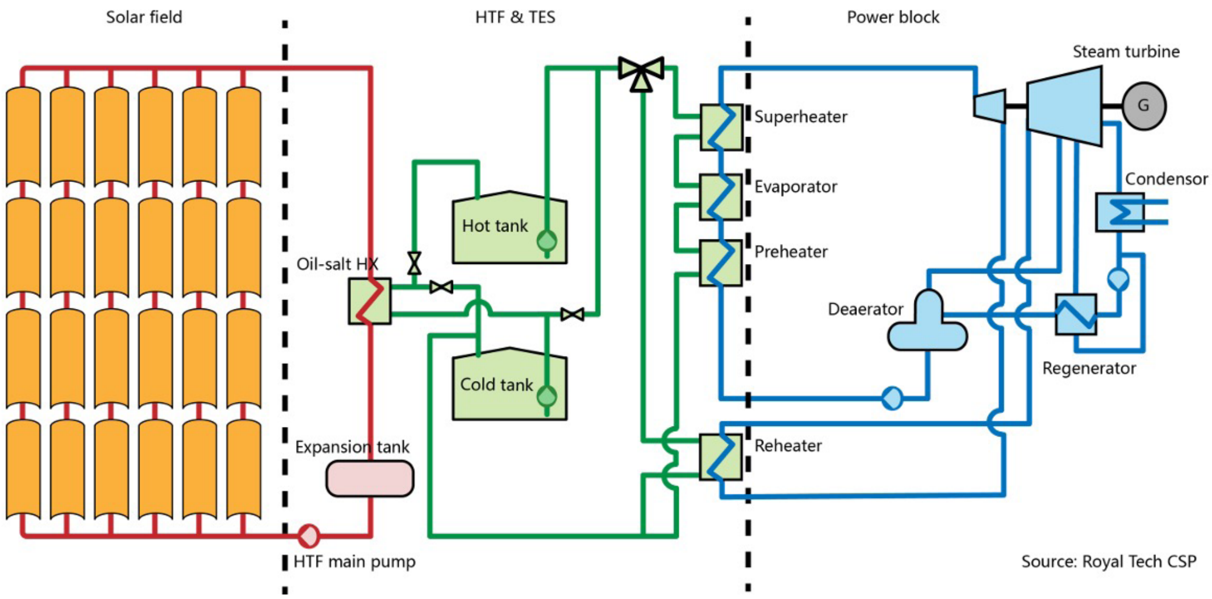


Fig. 1.1-4 Schematic diagram of a parabolic trough CSP system (decoupled process) (Source: Royal Tech CSP)

In a parabolic trough CSP system, the molten salt used can also serve as the heat transfer medium (HTM). The operation process of parabolic trough CSP systems is described below. The parabolic trough collectors track the sun and collect solar energy to heat the molten salt flowing in receiver tubes. The molten salt that has absorbed heat is stored in the hot salt tank. When electricity generation is required, the molten salt stored in the hot salt tank is transferred to the steam generator, where it releases heats and exchanges heat with water, producing superheated steam that drives the turbine-generator unit to generate electricity. After heat exchange, the molten salt is transferred to the cold salt tank for storage.

An MS linear Fresnel CSP system consists of linear Fresnel collectors (LFCs) that form a Fresnel collector field, hot and cold salt storage tanks, steam generator, and TGU. The Fresnel collector field comprises primary reflectors, secondary reflectors, and receiver tubes. The basic operating principle of a linear Fresnel CSP system is described below. Multiple rows of reflective mirrors (reflectors) are compactly arranged, forming a quasi-parabolic structure. The primary reflectors, which can automatically track the sun, reflect direct solar radiation (beams) onto the secondary reflectors above them, while the secondary reflectors reflect and focus solar beams onto the vacuum receiver tubes. The solar energy concentrated in the vacuum receiver tubes heats the molten salt in these tubes, and the heated (hot) molten salt is stored in the hot salt tank.

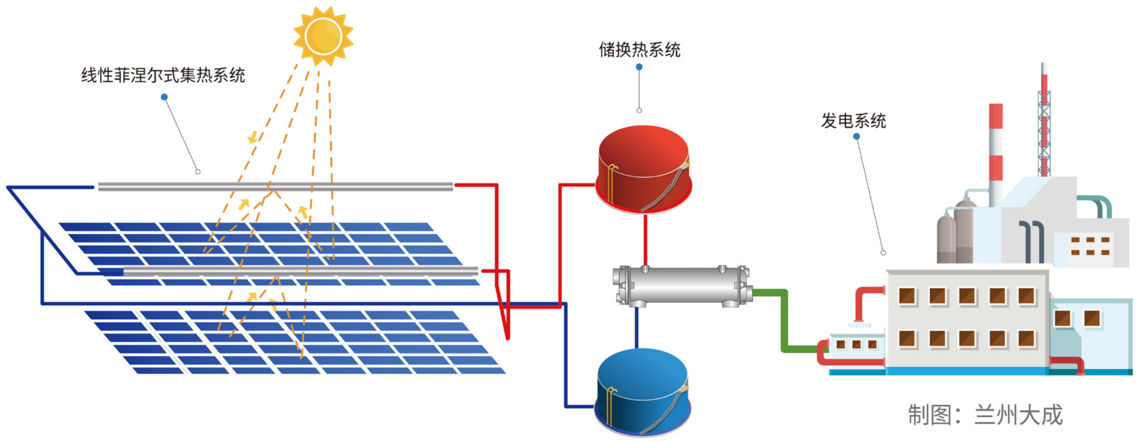


Fig. 1.1-5 Schematic diagram of an MS linear Fresnel CSP system (Source: Lanzhou Dacheng)

1.2 Role and positioning of CSP

In the Action Plan For Carbon Dioxide Peaking Before 2030 issued by the State Council of the People's Republic of China, it is stated that China will build a new electric power system where the share of renewable energy resources keeps increasing. In the Report to the 20th National Congress of the Communist Party of China, it is clearly stated that China will speed up the planning and development of a system for new energy sources. At the Working Conference on Ensuring Heating and Heat Supply in 2023 Winter and 2024 Spring held on November 16, 2023, the State-owned Assets Supervision and Administration Commission of the State Council (SASAC) proposed to promote the construction of peak-shaving power plants according to local conditions, increase investment in technological innovation, and speed up the construction of a new electric power system where renewable energy sources play a dominant role [2]. In 2023, the installed capacity of renewable power plants in China reached 1.45 billion kilowatts (kW), accounting for more than 50% of the total installed capacity of power plants in China and exceeding that of thermal power plants for the first time in history [3]. With the rapid increase in installed capacity of renewable power plants, the demand for various power sources for regulation purposes has been growing rapidly. At the 2024 National Energy Work Conference held on December 21, 2023, emphasis was placed on continuously improving the capability to ensure energy security, speeding up the construction of new energy and power systems, focusing on the implementation of actions to achieve the "dual carbon" goals, continuously optimizing and adjusting the energy structure, strengthening efforts to improve the safety and reliability levels of the replacement of conventional energy sources with renewable ones, and accelerating the green and low-carbon energy transition [4].

CSP is a green, low-carbon, and grid-friendly power source with dual functions, namely, peak shaving and energy storage. It can regulate and support renewable energy with renewable sources, provide higher long-term peak-shaving capability and higher moment of inertia for power systems, and serve as both peak-shaving and basic power supply in some areas. In addition, CSP offers an effective way to safely and reliably replace conventional energy sources with renewable ones, and it can provide effective support for speed up the planning and development of a system for new energy sources [5]. In the 14th Five-Year Plan for Renewable Energy Development issued by nine ministries and commissions including the National Development and Reform Commission (NDRC), the National Education Association (NEA) and the Ministry of Finance, it is clearly stated that China will orderly promote the development of CSP with long-term TES capability; in regions with high-quality resources such as Qinghai, Gansu, Xinjiang, Inner Mongolia, and Jilin, build CSP plants with long-term TES capability, fully leverage the capabilities of CSP plants in thermal energy storage, load regulation and provision of support for power systems, promote the construction and operation of CSP, wind power, and PV hybrid power plants, and improve the stability and reliability of renewable power generation. Developing CSP can ensure renewable energy consumption and promote the grid integration of renewable energy on a larger scale.

In the Notice of the General Department of the National Energy Administration on Promoting the Large-Scale Development of Solar Thermal Power (March 2023), it is clearly stated that it is necessary to fully understand the significance of large-scale development of CSP, give full play to the role of CSP in the new energy system where the share of renewable energy sources keeps increasing, and strengthen efforts to speed up the planning and development of a system for new energy sources. In the construction of renewable energy facilities, local energy authorities and enterprises should fully leverage the peak-shaving capacity of CSP plants and determine the capacity ratios of renewable energy bases or projects in a scientific and reasonable manner. Where conditions permit, provinces and regions are encouraged to investigate and enact financial, pricing, land, and other policies supporting the large-scale development of CSP as soon as practicable, plan the construction of 1,000 MW-scale and 10,000 MW-scale CSP plants in advance, and take the lead in developing CSP industry clusters.

1.3 CSP-related policies enacted in 2023

Policy	Enacted by	Time	Main content
Action Plan for Accelerating the Integration and Development of Oil and Gas Exploration and New Energy (2023-2025)	NEA	March 2023	Promote the construction of demonstration projects for the simultaneous production and comprehensive utilization of oil, gas and solar energy in key regions rich in oil, gas and solar energy resources, such as Xinjiang, Qinghai and Gansu, and make full use of solar energy concentration, collection and storage technologies to supply clean heat through clean oil and gas production processes and facilitate the development of low-carbon oil and gas resources.

Notice of the General Department of NEA on Promoting the Large-scale development of CSP	General Department of NEA	March 2023	Fully understand the importance of large-scale CSP development; actively carry out research on large-scale CSP development. The competent energy authorities of key CSP provinces/regions such as Inner Mongolia, Gansu, Qinghai, and Xinjiang should actively promote the planning and construction of CSP projects, promptly adjust relevant plans or implementation plans for CSP projects based on research findings, plan PV and CSP projects in an overall coordinated manner, reasonably arrange or reserve sites for CSP plants, promote the large-scale development of the CSP industry during the construction of local renewable energy bases, and strive to increase the national CSP capacity by about 3,000 MW every year during the "14th Five-Year Plan" period. Launch a number of CSP projects as soon as practicable based on renewable energy bases built in desert and Gobi areas, and improve the technical level of CSP projects. In the construction of renewable energy bases, local energy authorities and enterprises should fully leverage the peak-shaving capacity of CSP plants and determine the capacity ratios of renewable energy bases in a scientific and reasonable manner. The technical levels of planned CSP plants under construction shall not be lower than those of national demonstration projects. The single unit capacity and configuration (such as solar mirrors and TES systems) of CSP plants should be optimized. In principle, the solar field area of each 100 MW CSP plant shall be no less than 800,000 m^2.
2023 Energy Work Guidance	NEA	April 2023	Push forward the grid connection and startup of the first batch of large-scale wind and PV power plants in key areas such as Gobi and desert areas, build the second and third batches of power plants, and actively promote the large-scale development of CSP.
Notice on Organizing and Launching Renewable Energy Development Pilot and Demonstration Projects	NEA	October 2023	Launch and complete a number of demonstration projects with advanced technologies, reasonable economic benefits, and good prospects for extensive application, including low-cost CSP demonstration projects, by 2025. Focus on supporting the innovation and application of new CSP technologies, including large-capacity units, high-efficiency solar thermal collection systems, technologies and equipment (components), low-cost solar field technologies, high-capacity TES systems, high-precision intelligent control systems, and other technological innovations and applications; achieve the demonstration application of low-unit-cost (per kWh) CSP plants, and promote CSP cost reduction, efficiency improvement and large-scale development.

Notice on Further Standardizing the Administration of Electricity Business License for Renewable Energy Projects	NEA	November 2023	The permitting process for CSP plants at the end of their design service life shall be completed in accordance with the permit renewal policies and standards for coal-fired power plants.
Gansu Province Action Plan for Carbon Dioxide Peaking	People's Government of Gansu Province	May 2023	Explore new CSP development modes, strengthen CSP technology research and development (R&D), plan and launch "CSP + wind power and PV" hybrid projects; strengthen efforts to increase the total installed capacity of renewable power plants in Gansu Province to a level higher than 130,000 MW by 2030; promote R&D and extensive application of advanced, applicable technologies; carry out demonstration projects in which renewable energy accounts for a large proportion, such as demonstration projects for large-scale application of molten salt TES systems for heating, electricity generation, and hydrogen production.
Shanxi Province Implementation Plan for Peaking Carbon Dioxide Emissions and Achieving Carbon Neutrality under Scientific and Technological Support (2022-2030)	Shanxi Provincial Department of Science and Technology, Shanxi Provincial Development and Reform Commission, Shanxi Provincial Department of Industry and Information Technology, Shanxi Provincial Department of Ecology and Environment, Shanxi Provincial Department of Housing and Urban-Rural Development, Shanxi Provincial Department of Transportation, Shanxi Provincial Energy Administration	June 2023	Develop high-efficiency and low-cost technologies and equipment for solar collection, large-scale TES, TES with phase change materials (PCMs), and multi-energy complementary heating; accelerate the transformation of new technologies such as high-efficiency PV technologies, new PV power generation and energy storage technologies, and technologies for intelligent operation and maintenance of solar power plants/stations.

Notice of Qinghai Provincial Energy Administration on Promoting the Large-scale Development of CSP During the "14th Five-Year Plan" Period	Qinghai Provincial Energy Administration, Northwest China Energy Regulatory Bureau of NEA, Qinghai Provincial Development and Reform Commission, Qinghai Provincial Department of Natural Resources, Qinghai Forestry Department	July 2023	Carry out competitive allocation of PV-CSP hybrid power plants based on the electricity demand during the "14th Five-Year Plan" period and the following conditions: PV/CSP capacity ratio, solar mirror-TES system configuration, peak shaving and frequency regulation, technical performance, and CSP project experience (including the performance of construction contracts). In principle, the maximum renewable energy/CSP ratio for projects involved in competitive allocation shall not exceed 6:1. For each 100 MW power plant, it is recommended that the solar field area should be no less than 800,000 m^2, the TES duration should be more than 6 hours per day (at least 2,190 hours per year), and the technical level of the plant should not be lower than those of national demonstration projects. The land used for PV-CSP hybrid projects shall be managed in accordance with the Notice of the General Office of the Ministry of Natural Resources, the Office of the National Forestry and Grassland Administration, and the General Department of National Energy Administration on Works Related to the Standardized Use and Management of Land Supporting the Development of the PV Power Generation Industry and the detailed rules for the implementation thereby promulgated by Qinghai Province. For local consumption-oriented CSP projects included in the renewable energy development and construction plan of Qinghai Province for 2021 and 2022 and completed on schedule, the electricity prices should be determined based on the benchmark prices for electricity from coal-fired power plants. From 2023 to 2025, all PV-CSP hybrid projects acquired through competitive allocation will participate in market-based transactions. TThe electricity prices for CSP projects should be in accordance with the Notice of NDRC on Further Deepening the Market-Oriented Reform of Coal-Fired Power On-Grid Tariffs. Green electricity will preferably participate in various power markets in Qinghai Province according to applicable market trading rules. PV-CSP hybrid projects may not be equipped with other capacity-regulating facilities. Fully leverage the capabilities of CSP plants in baseload supply and ancillary services. In market transactions, electricity from CSP plants should be dispatched in a scientific way based on the principle of giving priority to green electricity while leveraging the capabilities of CSP plants in peak load supply, peak shaving, and other load regulation tasks. It is recommended that CSP plants be equipped with natural gas furnaces and high-power electric heaters for molten salt heating. When self-generated electricity is used to heat the molten salt through high-power electric heaters, electricity grid and capacity fees shall not be charged.

Qinghai Province Implementation for Carbon Dioxide Peaking in the Energy Sector	Qinghai Provincial Development and Reform Commission, Qinghai Provincial Energy Administration	August 2023	Improve clean energy supply capabilities supported by multiple poles, steadily develop CSP; leverage the advantages of CSP in flexible adjustment, grid support and renewable energy consumption, promote the development and construction of diversified CSP systems; explore innovative modes of technology development, promote the application of CSP-PV hybrid/integrated power plants by deploying demonstration projects; speed up the construction of multiple 100 MW CSP plants, promote the development of key components, key materials such as molten salts, and system integration technologies; strengthen efforts to develop core technologies and industrial chain advantages with independent intellectual property rights; improve the peak-shaving capacity of multi-energy complementary TES systems; carry out the demonstration of joint commissioning and operation of CSP and power systems in the peak-shaving scenario, and improve the safety and stability of power systems.
Opinions on Promoting High-quality Development of Inner Mongolia and Striving to Write a New Chapter of Chinese-style Modernization	State Council	October 2023	Accelerate the construction of large-scale wind-PV farms, supporting power supply systems, and external transmission lines in desert and Gobi areas such as Kubuqi, Tengger, Ulan Buh, and Badain Jaran; push forward the construction of the power transmission line from the Hunshandake Sandy Land to the Beijing-Tianjin-Hebei region; adhere to the principle of developing both large-scale central plants and distributed ones, equip CSP plants with high-efficiency TES and peak-shaving devices, and actively promote CSP development.
Inner Mongolia Autonomous Region Action Plan for Doubling New Energy Capacity	General Office of the People's Government of Inner Mongolia Autonomous Region	November 2023	By 2030, when the local consumption of electricity generated from renewable energy sources reaches 400,000 GWh, the load flexibility/regulation capacity should reach about 30,000 MW, including 1,000 MW for CSP systems and 20,000 MW for novel TES systems. Strengthen efforts to improve the power system's regulation capacity; push forward the execution of CSP demonstration projects; plan the layout of CSP plants based on the construction of renewable energy bases in desert and Gobi areas, plan the layout of renewable energy projects or reserve CSP project sites in an overall and coordinated manner, promote the implementation of CSP demonstration projects, and strive to increase the total installed capacity of additional grid-connected CSP plants by 200 MW during the "14th Five-Year Plan" period.

Detailed Implementation Rules for the Management of Grid Connection and Operation of Power Plants in Northwest China, Detailed Implementation Rules for the Management of Electric Auxiliary Services in Northwest China	Northwest China Energy Regulatory Bureau of NEA	November 2023	These *Detailed Implementation Rules* apply to CSP plants having installed capacity of not less than 50 MW and dispatched by national and regional dispatch centers. The latest revision of these *Detailed Rules* will be officially implemented upon completion of simulation and trial operation.

Chapter II CSP Market in China

2.1 China's total installed CSP capacity

In 2023, there were no additional CSP plants connected to the power grid in China. As of the end of 2023, the cumulative installed capacity of all MW-scale CSP plants in China is 588 MW, including 11 CSP plants with maximum installed capacity of 100MW and minimum installed capacity of 10 MW.

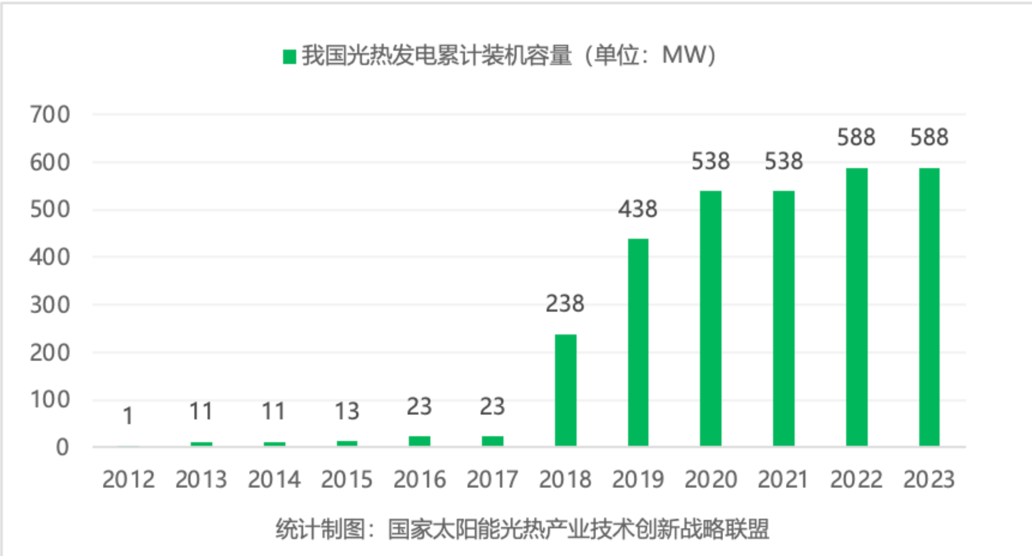


Fig. 2.1-1 China's total installed CSP capacity (as of the end of 2023)

2.2 Global installed CSP capacity

In 2023, three additional CSP plants with a total installed capacity of 500 MW were connected to power grids in foreign countries. These three plants are components of the Noor Energy 1 solar project in Dubai, which is a 950 MW hybrid CSP and solar photovoltaic (PV) power station undertaken by Shanghai Electric Group Company Limited. The hybrid station has solar PV capacity of 250 MW and CSP capacity of 700 MW, including one 100 MW tower-type power plant and three 200 MW trough-type power plants (#1-#3). The comprehensive feed-in tariff is USD 0.073 per kWh, and the design service life of the hybrid station is 35 years. Parabolic trough CSP plant #1 was successfully connected to the power grid on November 29, 2022. The 100 MW tower-type power plant started operating at full load in February 2023 after nearly four months of commissioning [6]. The 200 MW trough-type power plant #2 was connected to the power grid in October 2023 [7], and the 200 MW trough-type power plant #3 was connected to the power grid in December 2023 [8].

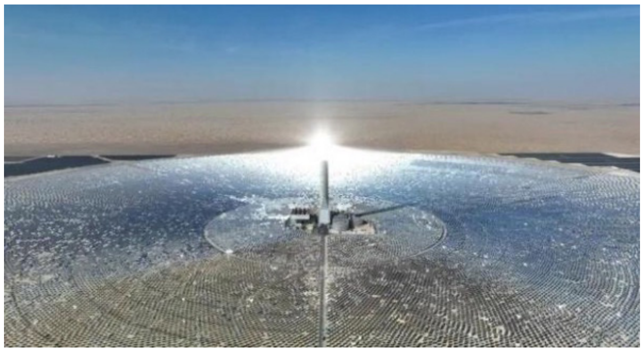


Fig. 2.2-1 NOOR ENERGY 1 solar project (Source: Shanghai Electric Group Company Limited)

According to statistics from China Solar Thermal Alliance (CSTA), as of the end of 2023, the global installed capacity of CSP plants (including eight parabolic trough CSP plants which were built in the United States in the 1980s and have been decommissioned, with a total installed capacity of 274 MW and maximum operating time of more than 30 years) has reached 7,550 MW. The growth in global installed CSP capacity in recent years is shown in the figure below.

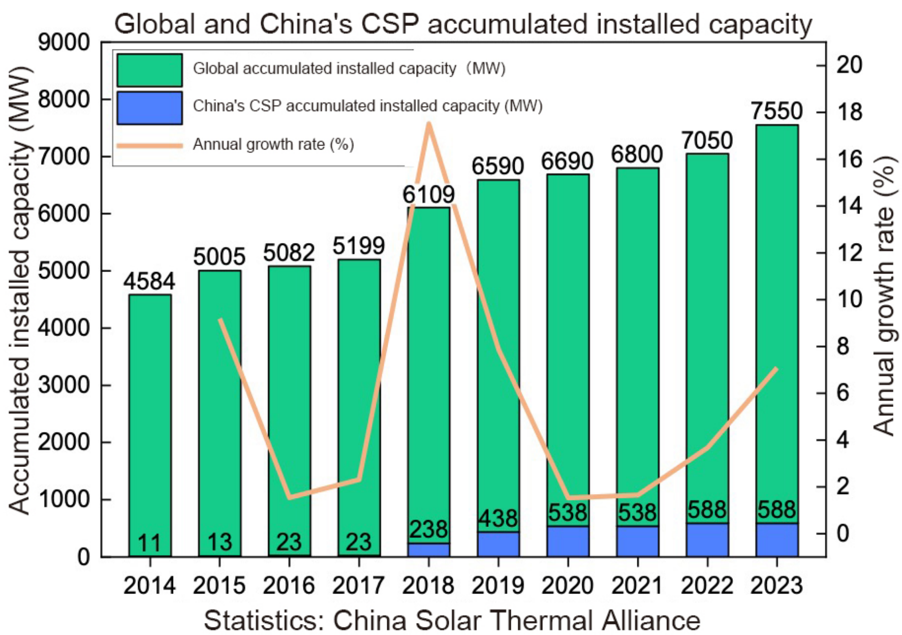


Fig. 2.2-2 Global installed CSP capacity

2.3 Types of CSP plants

CSTA has compiled statistics on the proportions of various types of domestic and foreign CSP plants by the mode of solar concentration. As of the end of 2023, among the grid-connected CSP plants in China, MS solar tower plants account for about 64.9%, parabolic trough CSP plants account for about 26.3%, and MS linear Fresnel CSP plants account for about 8.8%. The contributions of these three types of CSP plants to the cumulative installed capacity of MW-scale CSP plants in China are about 63.1%, 25.5%, and 11.4%, respectively.

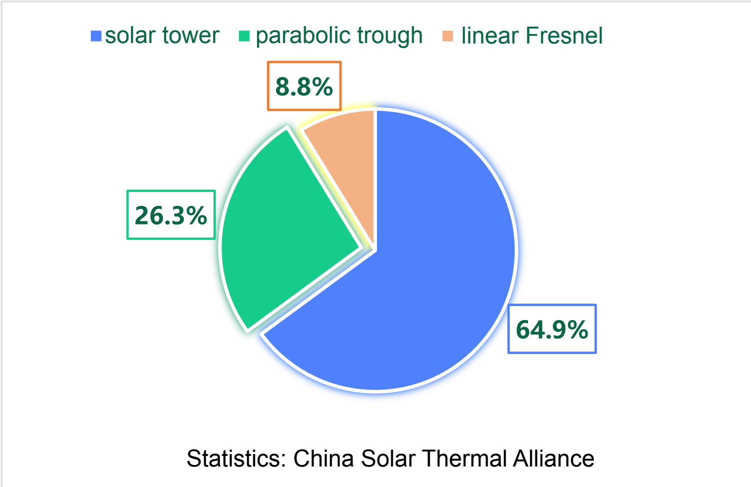


Fig. 2.3-1 Proportions of various types of grid-connected CSP plants in China

From a global perspective, in the total installed capacity of CSP plants around the world (mainly in countries and regions such as Spain, the United States of America (USA), the United Arab Emirates (UAE), Saudi Arabia, Kuwait, North Africa, South Africa, Israel, India, Chile, France, Italy, and China) as of the end of 2023, solar tower plants account for about 75.5%, parabolic trough CSP plants account for about 20.9%, and linear Fresnel CSP plants account for about 3.6%.

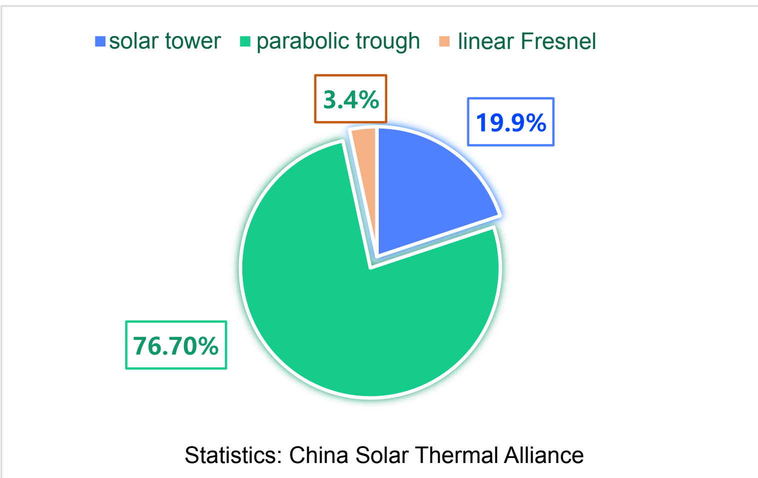


Fig. 2.3-2 Proportions of various types of CSP plants in the global installed CSP capacity

Comparative analysis shows that solar tower plants account for the largest proportion in China, while parabolic trough CSP plants for the largest proportion in the world. The main reason is that the earliest commercial CSP plants in the world employ parabolic trough technology. All of the nine SEGS power plants built in USA in the 1980s, with a total installed capacity of 354 MW, have used parabolic trough technology (without TES system). Similarly, parabolic trough technology is also used at Europe's first commercial CSP plant (with a molten salt TES system). In 2007, the Spanish government passed a feed-in tariff regime (Royal Decree 661/2007) [9] to promote the development of CSP technology.

However, for construction projects such as CSP plants, financial institutions including banks require reference cases as a condition for increasing the credit limit. Therefore, almost all of the CSP plants built in Spain are of parabolic trough type, and the installed capacity of parabolic trough CSP plants accounts for about 97% of Spain's total installed CSP capacity (which is approximately 2,300 MW). Additionally, in USA's total installed CSP capacity, which ranks second in the world, the installed capacity of parabolic trough CSP plants accounts for about 71.8%.

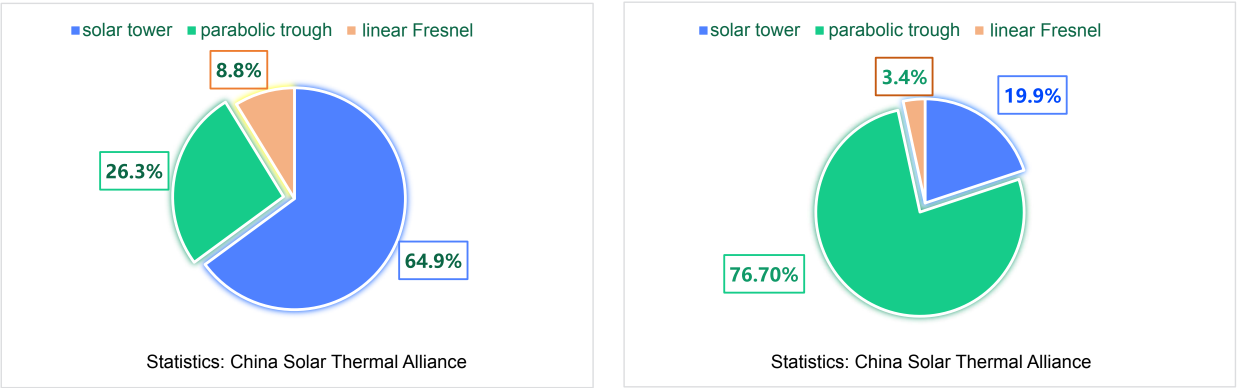


Fig. 2.3-3 Proportions of various types of grid-connected CSP plants in China's total installed CSP capacity (left) and the global installed CSP capacity (right)

In China, experts have been organized to review the proposals of CSP projects recommended by regional development and reform commissions (energy administrations). In September 2016, NEA published the list of the first batch of CSP demonstration projects (20) distributed in Qinghai Province, Gansu Province, Hebei Province, Inner Mongolia Autonomous Region, and Xinjiang Autonomous Region, with a total installed capacity of 1,349 MW. These CSP demonstration projects include nine solar tower plants, seven parabolic trough CSP plants, and four linear Fresnel CSP plants [10]. They represent China's first attempt towards large-scale CSP development through demonstration projects, which creates opportunities to conduct large-scale verification of all types of CSP plants (technical routes) under China's unique climatic conditions, make breakthroughs in the development of key technologies and equipment, establish a complete industry chain, develop system integration capabilities, and thereby promote the advancement of CSP technology and the development of CSP industry. However, due to multiple factors such as the complexity of CSP systems, the incompleteness of the CSP industry chain, the lack of clarity in policies concerning postponed/delayed startup, and the short construction period and land issues in Northwest China, the completion rates of solar power plants, parabolic trough CSP plants, and linear Fresnel CSP plants as of the end of 2021 (time of delayed grid connection) are only 44.4%, 28.6%, and 25%, respectively.

2.4 New CSP projects

With the accelerated construction of large wind-PV power plants in desert and Gobi areas, the number of CSP plants as one of the options for market-oriented grid-connected power systems has been increasing continuously. According to statistics from CSTA, in addition to the first and second batches of large wind-PV power plants and other CSP plants with TES (the list of these projects can be found in the Blue Book of China's Concentrating Solar Power Industry 2022), there are about 12 [11-17] new CSP plants announced or put in the list by the local government in 2023, with a total installed capacity of 1,350 MW (as detailed in Table 2.4-1). Among these plants, the Aksay 50 MW CSP Plant (with a high-temperature molten salt TES system) of Gansu CSP Co., Ltd. is among the first batch of CSP demonstration projects approved by NEA and a major provincial project of Gansu in 2021. The resumption ceremony for the plant was held on August 16, 2023 [18].

Table 2.4-1 List of new CSP plants to be constructed announced in China in 2023

No.	Project	CSP capacity
1	"Transmission of Xinjiang's Power to Chongqing": Hami-Chongqing ± 800 kV UHVDC (ultra-high voltage direct current) Transmission Project, a renewable energy project	200 MW (100 MW by Huadian Xinjiang Power Generation Co., Ltd. and 100 MW by Chongneng Xinjiang Electric Power Development Co., Ltd.)
2	Huaneng (CHG) Urat Rear Banner 300 MW CSP Plant of the Wind, PV and CSP (with TES) Hybrid Project	300 MW
2	Hesheng Electrical Industry (Shanshan) Co., Ltd. 235 MW PV-CSP Hybrid Project in Shanshan County, Turpan	250 MW
3	PetroChina Tuha Oilfield Company 10,00 MW Wind, PV and CSP (with TES) Hybrid Project in eastern Shanshan	100 MW
4	CGN 700 MW PV, CSP and Wind-powered Hydrogen Production Demonstration Project in Yumen, Gansu	100 MW
5	Gansu CSP Co., Ltd. Aksay 50 MW High-temperature MS Parabolic Trough CSP Project	50 MW
6	Assurance-oriented Grid-connected Renewable Energy Projects in Tibet in 2023	350 MW (five projects, as detailed in Table 2.4-2)

Prepared by: China Solar Thermal Alliance

Table 2.4-2 New CSP projects in the Tibet Autonomous Region announced in 2023

No.	Project	PV (MW)	CSP (MW)	Participant
1	450 MW PV + 150 MW CSP Hybrid Power Plant in Damxung County, Lhasa	250	100	China Power Engineering Consulting (Group) Corporation (CPECC)

2	CGN 500 MW PV + 100 MW CSP Hybrid Power Plant in Umatang, Lhasa	125	50	CGN Wind Energy Limited
3	PV + CSP Hybrid Power Plant in Seni District, Naqu	250	100	SDIC Power Holdings Co., Ltd.
4	PV + CSP Hybrid Power Plant in Nie Rong County, Naqu	125	50	SDIC Power Holdings Co., Ltd.
5	PV + CSP Hybrid Power Plant in Anduo County, Naqu	125	50	Tibet Development and Investment Group Co., Ltd. (TDIG)
Note: According to the Plan for the Development and Construction of Wind, Photovoltaic and Other Renewable Energy Projects in 2023 issued by Xizang Autonomous Region Development and Reform Commission (Tibetan Development and Reform Commission Energy [2023] No. 302), the total installed capacity of new wind farms, PV power plants, and other renewable energy projects in 2023 is 5,735 MW, and the installed capacity of assurance-oriented grid-connected power plants is 3,730 MW, including 600 MW from wind farms, 2,780 MW from PV power plants, and 350 MW from CSP plants. The minimum TES capacity of pure PV power plants is 1.444 GWh. The competent energy authorities of various regions (municipalities) should organize competitive allocation according to the annual installed capacity of power plants to be built. CSP, wind power and PV projects will be simultaneously connected to the grid and put into full operation by the end of October 2024.				
Prepared by: China Solar Thermal Alliance				

According to the statistics compiled by CSTA, as of the end of 2023, there are approximately 43 CSP plants under construction or planned to be constructed (included in the list of government approved projects) in various provinces and autonomous regions in China, with a total installed capacity of 4,800 MW. These plants are expected to be completed no later than 2025, and some of these plants, with a total installed capacity of 1,200 MW, are expected to be completed by 2024.

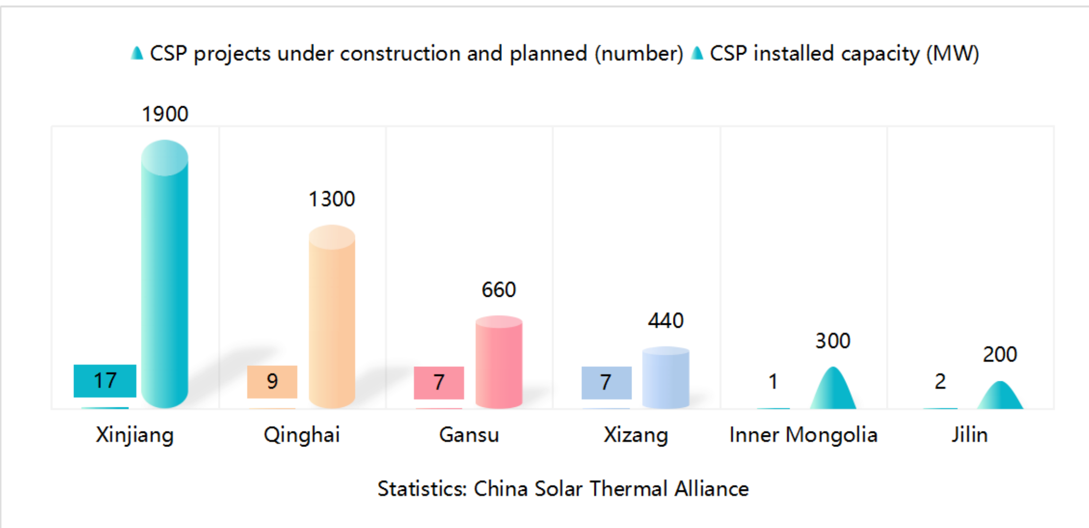


Fig. 2.4-2 CSP projects under construction or to be constructed in China (as of the end of 2023)

Chapter III Operation of CSP Demonstration Projects in China

As of the end of 2023, most of the grid-connected CSP plants in operation in China are among the first batch of CSP demonstration projects approved by NEA. According to relevant documents issued by NDRC, the feed-in tariff for CSP plants included in the list of NEA approved CSP demonstration projects and connected to the grid at full capacity before the end of 2021 is RMB 1.15 Yuan/kWh, and the central government does not grant subsidies to the first batch of CSP demonstration projects connected to the grid after 2021. In China, seven CSP demonstration projects with a total installed capacity of 450 MW were successfully connected to the grid before the end of 2021. In addition, as one of the first multi-energy complementary system integration and optimization demonstration projects approved by NEA (National Energy Planning [2017] No. 37), the wind-PV-hydro-thermal multi-energy complementary system in Haixi Prefecture, including a 50 MW solar tower plant, was completed in 2019. In 2023, with the accumulation of operating experience and the gradual improvement of operating level, the performance of CSP demonstration plants improved continuously, these plants gradually entered a period of stable electricity generation, and their electricity generation increased significantly. This chapter summarizes the operating conditions of CSP demonstration plants. We're grateful to the owners of these CSP plants for their contributions to the content of this chapter.

3.1 CGN Delingha 50 MW Parabolic Trough CSP Plant

The CGN Delingha 50 MW Parabolic Trough CSP Plant, which has a total investment of about RMB 1.7 billion and a total area of 2.46 km2, was connected to the grid and put into operation in October 2016. The collector field of the plant covers an area of 620,000 m2. A total of 190 standard parabolic trough collectors (loops) of ET-3 type are used to collect solar energy. Thermal oil is used as the heat transfer medium (operating temperature: 293-393°C), and thermal energy (heat) is stored in two binary molten salt (nitrate mixture) tanks for 9 hours. Electricity is generated by the MTHP (medium-temperature and high-pressure) turbine-generator unit (the main steam turbine operates normally at 381°C, and the temperature for TES and electricity generation is 370°C).

In 2023, the plant operation and maintenance team carried out quality and efficiency improvement in an all-round way; increased the plant's electricity generation capacity through key renovation works such as overhaul, solar collector angle correction and precision adjustment, increasing system flow rate, molten salt filling, and insulation repair; continued to carry out fine adjustment, energy conservation and consumption reduction. In 2023, the plant fed 110.40 GWh of electricity to the grid (13.40 GWh of electricity lost during the overhaul).

In 2023, the maximum daily power/electricity output of the plant to the grid reached 1.02 GWh, representing a year-over-year (YoY) increase of 18.3%, and the maximum monthly electricity generation reached 16.26 GWh, representing a YoY increase of 16%, both of which exceed the highest levels in history. On July 6, 2023, the active power output of the plant reached 50.9 MW, which is 20.9% more than the maximum load of 42 MW in the previous year, and the plant operated at full load once again after four years. The annual electric output of the plant in 2024 is expected to increase by about 30 GWh compared to 2023, and the electricity generation of the plant to the grid in 2024 is expected to exceed 140 GWh. In 2024, the CGN Delingha 50 MW Parabolic Trough CSP Plant will continue to take the lead in the CSP industry as a demonstration project and contribute to the high-quality development of the CSP industry and efficient operation and maintenance of CSP plants.

3.2 Shouhang Hi-Tech Dunhuang 100 MW Solar Tower Plant

The Shouhang Hi-Tech Dunhuang 100 MW Solar Tower Plant is China's first 100 MW-scale solar tower plant. The plant was connected to the grid for the first time on December 28, 2018 and started operating at full load in June 2019. The annual electric output of the plant in recent years is 86.4717 GWh in 2019, 137 GWh in 2020, representing a YoY increase of 58.3%, and 200 GWh in 2021, representing a YoY increase of 46.2%. In 2022, due to defects in purchased steam turbines, experts proposed that the maximum operating load of the plant should not exceed 63% of full load. For this reason, the electricity generation of the plant in 2022 is the same as that in 2021.

In 2023, the electricity generation of the plant (from January to November 2023) reached a record high of 235 GWh, representing an increase of 21% compared to the same period last year. In 2023, since the maximum operating load of the plant remained below 63% of full load, the electricity generation of the plant decreased by 65.79 GWh due to the abandonment of a large amount of solar energy. The operating data of the Shouhang Hi-Tech Dunhuang 100 MW Solar Tower Plant is given in the table below.

Table 3.2-1 Operating data of the Shouhang Hi-Tech Dunhuang 100 MW Solar Tower Plant

Period/Year	Electricity generation (GWh)	YoY growth	Description
2019	86.4717	/	The plant was connected to the grid for the first time on December 28, 2018 and started operating at full load in June 2019.
2020	137	58.30%	/
2021	200	46.20%	/
2022	200	0	In 2022, due to defects in purchased steam turbines, experts proposed that the maximum operating load of the plant should not exceed 63% of full load. This affects electricity generation by the plant.
January-November 2023	235	21%	In 2023, since the maximum operating load of the plant remained below 63% of full load, the electricity generation of the plant decreased by 65.79 GWh due to the abandonment of a large amount of solar energy. The replacement of the high-pressure cylinders of some steam turbines began in December 2023.

Prepared by: Shouhang Hi-Tech/China Solar Thermal Alliance

As of September 2023, the monthly electricity generation of the plant is 31.92 GWh, the duration of continuous (uninterrupted) electricity generation is 338.21 hours, and the auxiliary power consumption rate of the plant is 8%. The analysis of the plant's operating data in 2023 shows that the operating parameters of the solar concentration and collection system and the heat storage and exchange system have improved significantly, except for the electricity generation system. The high-pressure cylinders of some steam turbines were replaced during the period from the end of 2023 to the beginning of 2024, and system upgrades and renovations will be carried out. Therefore, the electricity generation of the plant is expected to reach a record high in 2024.

3.3 Qinghai SUPCON Delingha 50 MW Solar Tower Plant

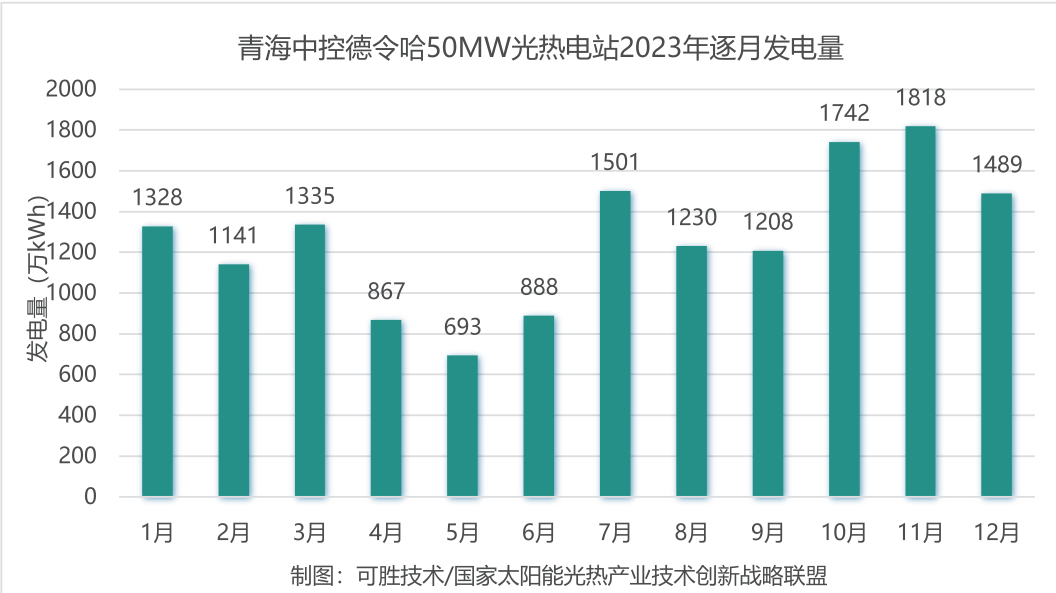
The Qinghai SUPCON Delingha 50 MW Solar Tower Plant, financed and constructed by SUPCON Solar Power (Qinghai) Co., Ltd., is located in the West Delingha Export Solar PV Park in Qinghai Province. This plant is equipped with a 7-hour molten salt TES system and a heliostat field with an aperture area of 542,700 m^2, and its design annual electric output is 146 GWh. Once put into full operation, the plant can save 46,000 tons of standard coal and reduce CO_2 emissions by approximately 121,000 tons each year. The plant uses the core technology for solar electricity generation with molten salt TES independently developed by Cosin Solar Technology Co., Ltd. and complete with intellectual property rights. More than 95% of the plant equipment is domestically manufactured.

The plant was connected to the grid on December 30, 2018, started operating at full load on April 17, 2019, and was handed over for production in July 2019. The cumulative electricity generation of the plant in the first full year after its handover is 122 GWh, which is the highest level of electricity generation of similar plants around the world in the same period. For both 2020 and 2021, the annual electric output of the plant is more than 100 GWh, accounting for more than 95% of the plant's design annual electricity output if the impact of steam turbine problems is excluded. The annual electric output of the plant in 2022 is 146.4 GWh, accounting for 100.3% of the design annual electricity output. From September 28 to October 7, 2022, the plant was shut down for 10 days due to grid maintenance. If the impact of the shutdown is excluded, the annual electric output of the plant in 2022 can reach 103.18% of the design annual electricity output.

The annual electric output of the plant in 2023 is 152.4 GWh, accounting for 104.38% of the design annual electricity output. In 2023, the plant operated stably throughout the year, and its electricity generation reached the design annual electricity output 10 days ahead of schedule. Despite the fact that the total direct solar irradiance in 2023 is slightly lower than that in 2022, the annual electric output of the plant in 2023 is still 4.13% higher as compared to 2022.

The monthly electricity generation of the plant in 2023 is shown in the figure below. The monthly electricity generation of the plant in November 2023 is 18.18 GWh, which is the highest level achieved since the startup of the plant. In addition, the ratio of the actual daily electricity generation of the plant for 129 days of the year to the planned/design daily electricity output is higher than 100%. The monthly electricity generation of the plant for May and June

2023 is relatively low. The main reason is the decrease in total direct normal irradiance (DNI) during the rainy season. Another reason is the 7-day shutdown of the plant due to the inspection of special equipment such as molten salt and steam pipelines performed by the local institute of special equipment inspection, resulting in a decrease of 2.11 GWh in the plant's electricity generation in 2023 (if the impact of such inspection is excluded, the electricity generation of the plant in 2023 is expected to reach 105.83% of the design annual electricity output).



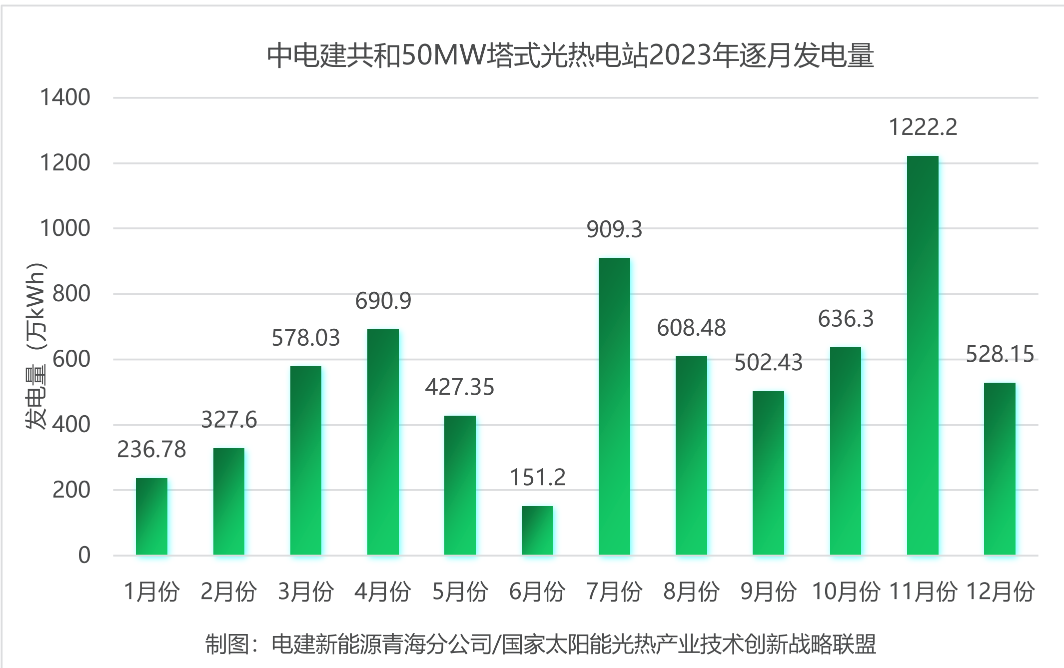
Since its handover for production in July 2019, the plant has operated stably for four years and six months. Through continuous optimization of the operation strategy, the plant has set new records for daily, monthly, and annual electric output. As of the end of 2023, the plant has generated 573.8 GWh of electricity. The exceptional operating performance of the plant has fully demonstrated that China's core CSP technologies and equipment are advanced and reliable, providing a solid foundation for the implementation of large wind power and CSP projects.

3.4 PowerChina Gonghe 50 MW Solar Tower Plant

The PowerChina Gonghe 50 MW Solar Tower Plant is the only operating CSP plant of PowerChina Renewable Energy Co., Ltd. (a subsidiary of PowerChina) and the first CSP plant financed, designed, constructed, operated and maintained by PowerChina. The plant is located in the Ecological Solar Power Generation Park of Gonghe County, Hainan Prefecture, Qinghai Province. The Ecological Solar Power Generation Park has an average elevation of 2,880 m and a total area of 2.12 km2. The PowerChina Gonghe 50 MW Solar Tower Plant uses a molten-salt power tower to collect solar energy for electricity generation. It consists of a solar tower fitted with a solar energy collector (whose center is located at an elevation of 210 m), a heliostat field composed of 30,016 heliostats, a molten salt TES system with adequate capacity to ensure the continuous operation of the turbine-generator unit at full load for about 6 hours, and a turbine-generator unit. The steam turbine used at the plant is China's first high-temperature, ultra-high-pressure, double-cylinder, double-shaft, intermediate reheating, axial exhaust, 8-stage condensing direct air-cooled steam turbine, with a power rating of 50 MW. The turbine-generator unit is connected to the 110 kV booster station at the plant using the generator-transformer-line unit wiring method and then connected to the grid 330 kV booster/gathering station via a primary 110 kV overhead line.

The construction of the plant was commenced on May 6, 2018. The plant was connected to the grid on September 19, 2019 and accepted as a CSP demonstration plant on April 22, 2021, thus becoming the fourth grid-connected CSP demonstration plant in China.

Since the plant was put into operation, all personnel have worked closely together, overcome numerous challenges, and deeply investigated the plant performance, refined management and operation strategy. In 2023, the performance and electricity generation of the plant gradually improved. The electricity generation of the plant in 2023 is 68.187 GWh, which is equivalent to 100.275% of the target annual electricity output, and the amount of electrical energy exported from the plant to the grid in 2023 is 67.573 GWh, which is equivalent to 108.99% of the target amount.



3.5 EnergyChina Hami 50 MW Solar Tower Plant

The EnergyChina Hami 50 MW Solar Tower Plant is the first solar thermal power plant independently financed, designed, constructed, operated and maintained by China Energy Engineering Corporation Limited (EnergyChina). It is located in the Naomao Lake Solar Power Park in Yiwu County, Hami City, Xinjiang, covering a total area of 1,087.26 acres. The plant uses a molten-salt power tower to collect solar energy for electricity generation and consists of a solar tower whose top is located at an elevation of 220 m, a heliostat field composed of 14,500 Stellio heliostats, a molten salt TES system with adequate capacity to ensure the continuous operation of the turbine-generator unit at full load for about 13 hours, and a turbine-generator unit. The steam turbine used at the plant is the first high-temperature, ultra-high-pressure, double-cylinder, double-shaft, intermediate reheating, axial exhaust, 8-stage condensing direct air-cooled steam turbine of Dongfang Electric Corporation (DEC), with a power rating of 50 MW, which is connected to Xinjiang's power grid via a primary 110 kV overhead line using the generator-transformer-line unit wiring method.

The construction of the plant was commenced on October 19, 2017. The plant was connected to the grid on December 29, 2019 and accepted as a demonstration plant in November 2021. 2023 is a critical year for managing and improving the performance of the main plant equipment. The maximum monthly electricity generation in 2023 is 15.0751 GWh, and the maximum daily electricity generation in the year is 869,000 kWh.

3.6 Lanzhou Dacheng Dunhuang 50 MW Linear Fresnel CSP Plant

The Lanzhou Dacheng Dunhuang 50 MW Linear Fresnel CSP Plant is located in Dunhuang Optoelectronics Industrial Park in Qili Town, Dunhuang City. The plant consists of a high-concentration linear Fresnel collector system developed by Lanzhou Dacheng Technology Co., Ltd. with independent intellectual property rights, in which a molten salt is used as the heat collection, transfer and storage medium, a molten salt TES system with adequate capacity to ensure the continuous operation of the plant at full load for about 15 hours, and a conventional HTHP turbine-generator unit. As the world's first commercial line-concentrating CSP plant using a molten salt as its working fluid, the Lanzhou Dacheng Dunhuang 50 MW Linear Fresnel CSP Plant has numerous advantages such as high wind resistance of the collector field, small land footprint, simplified equipment and processes, convenient cleaning, operation and maintenance, and low initial investment.

The construction of the plant was commenced in June 2018. The plant was connected to the grid on December 31, 2019 and started generating electricity at full load on a monthly basis in 2021. During the operation of the plant, daily molten salt charging and discharging operations were pioneered, the operation challenges associated with the high-temperature molten salt in the line-focusing system were overcome, and the cost-effectiveness, reliability and safety of the plant were improved. In 2023, some systems of the plant were further optimized and upgraded to improve its operation and maintenance strategy and operational stability. The actual performance of the optimized solar collector circuit has exceeded the design performance level. Plant upgrading is estimated to be fully completed in 2024.

3.7 CSNP Urat 100 MW Parabolic Trough CSP Plant

The CSNP Urat 100 MW Parabolic Trough CSP Plant is designed, constructed, commissioned, operated and maintained by China Shipbuilding New Power Co., Ltd. (CSNP). It ranks first in terms of single-unit capacity and thermal storage period among the first batch of national CSP demonstration projects for which Royal Tech CSP Limited has participated in the development, investment and construction processes. The plant is located in Bayannur, Inner Mongolia. The construction of the plant was officially commenced in June 2018, and the plant started operating (generating electricity) at full load in December 2020. In July 2021, the molten salt TES system was put into full operation, and the plant achieved 24-hour continuous and stable high-load operation.

The cumulative electricity generation of the plant since its startup is approximately 870 GWh. For 2023, the annual electric output from pure CSP is about 330 GWh, the maximum monthly electricity generation from pure CSP is 52.3 GWh, and the maximum daily electricity generation from pure CSP is 2.216 GWh. Obviously, these electricity production indices are greater than design values. The electricity generation of the plant for the year in which it was put into operation meets the target/design electricity output for that year.

During the construction of the plant, CSNP successfully obtained more than 100 patents, set five world records, built a well-trained talent team for the R&D, design, management and operation of CSP plants, acquired system integration capabilities, and developed some core technologies. Strict and refined quality control has ensured that the intercept factor of the parabolic trough collectors used at the plant is higher than 98% (while the current international level is 97%). The plant is designed with a service life of 35 years, and it has been constructed according to the optimized design and has taken a leading position internationally. The successful completion of this project has facilitated the development and application of key CSP products inside and outside CSNP and promoted the localization of parabolic trough CSP systems.

3.8 Luneng Golmud Multi-energy Complementary Project 50 MW Solar Tower Plant

The Luneng Golmud Multi-energy Complementary Project 50 MW Solar Tower Plant is part of the Luneng Haixi Multi-energy Complementary System Integration and Optimization National Demonstration Project—the world's first multi-energy complementary project that integrates wind power, PV, CSP, TES, and load regulation (which is a technological innovation project consisting of a 200 MW PV power plant, a 400 MW wind farm, and a 50 MW TES system in addition to the solar tower plant). The plant is located at an elevation of 2,800 m in the Golmud East Export Photovoltaic Park, Golmud City, Qinghai Province. An MS solar power tower is used to collect solar energy for electricity generation. The plant mainly consists of a solar concentration and absorption system, a heat storage system, a steam generation system, a HTHP (540°C/14MPa) pure condensing reheat steam turbine-generator system, and other ancillary facilities. The heliostat field consists of 4,400 heliostats, each with an area of 138 m2, and the total aperture area of heliostats is 610,000 m2. The height of the concrete solar tower is 147.4 m, the height of the central solar receiver is 40.7m, and the power rating of the central solar receiver is 280 MW. The TES period is 12 hours. The turbine-generator unit consists of an impulse turbine and a generator. One end of the generator is connected to the high-pressure cylinder of the impulse turbine, and the other end is connected to the low-pressure cylinder of the impulse turbine. The high-pressure cylinder rotates at a speed of 10,031 rpm and is connected to the generator through a reduction gearbox. The low-pressure cylinder rotates at a speed of 3,000 rpm and exhausts steam axially. The generator uses a brushless excitation system and a direct air-cooled exhaust system.

The plant was commenced on May 8, 2018 and connected to the grid on September 19, 2019 and has become China's first solar tower plant that has the longest TES period and can generate electricity stably and continuously 24 hours a day. From the operation of the plant, it has been found that CSP plants can effectively solve the problems with renewable energy projects (such as the intermittency of renewable energy generation/supply), provide support for grid peak sahving and frequency regulation, stabilize the transmission capacity of the grid, effectively solve the problem of "wind and solar energy abandonment", and play an active role in demonstrating the effectiveness of CSP projects and promoting energy transition in China. For 2023, the annual electric output of the Luneng Golmud Multi-energy Complementary Project 50 MW Solar Tower Plant is 91.0276 GWh, the maximum daily electricity generation is 1.0962 GWh, and the maximum monthly electricity generation is 10.6738 GWh.

Chapter IV Development of China's CSP Industry

4.1 China's CSP industry Capacity

During the "11th Five-Year Plan" period, research on MW-scale CSP system integration technologies and demonstration projects was initiated under the leadership of the Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS). After over 10 years of development, numerous CSP plants, especially the first batch of CSP demonstration projects approved by NEA, have been completed, significantly improving China's CSP industry support capabilities. According to incomplete statistics from CSTA, there are about 600 enterprises providing supporting services for CSP projects in China, including about 245 suppliers of products, equipment and services related to the solar collector systems of solar tower plants, parabolic trough CSP plants, and linear Fresnel CSP plants (including ultra-white glass sheets, solar reflectors/reflective mirrors, solar concentrators, control systems, solar tracking mechanisms/devices, hydraulic drives, speed reducers, receiver tubes and tubing materials, rotary joints, supports/brackets, mirror coatings, thermal oils/HTFs, thermal oil valves, thermal oil pumps, hot-dip galvanizing, solar radiation measurement, mirror production lines, and mirror testing) and about 135 suppliers of products, equipment and services related to the heat storage systems of various CSP plants (including molten salts, molt salt storage tanks, insulation materials, molten salt pumps, molten salt valves, salt melting, heating furnaces, electric heaters, and electric heat tracing).

In 2023, in order to prepare for the construction of CSP plants in large wind and solar power complexes, the suppliers of critical materials and products increased production capacity by extending their own industrial chains or building new production lines, thereby enhancing the capability to supply critical materials and products supporting the development of the CSP industry. For molten salts, in May 2023, Yuntu Holdings (002539), which has its own mineral reserves including 250 million tons of salt reserves and 180 million tons of coal reserves and the longest salt, phosphorus and coal chemical industry chain in the industry, established a subsidiary named Hubei Yuntu Molten Salt Technology Co., Ltd. as a professional molten salt R&D, marketing and service platform. In September 2023, Qinghai Salt Lake Wojin Thermal Storage Technology Co., Ltd. was founded to revitalize Salt Lake assets through equity investment, resume production of the original 0.40 MTA molten salt project in Qinghai Salt Lake, improve the production capacity to ensure molten salt supply to CSP plants, and help reduce the costs of molten salt thermal energy storage. For the production of ultra-white glass and mirrors for CSP plants, relying on the local high-quality mineral resources such as low-iron silica sand in Yumen, Gansu Kaisheng Daming Solar Energy Technology Co., Ltd. built a new 600 t/d photothermal ultra-white float glass production line, creating an important closed loop from raw materials to deep processing and laying a solid foundation for reducing costs of solar mirrors. In October 2023, Inner Mongolia Baichuan Solar Technology Co., Ltd. introduced a tempered-glass parabolic mirror production line complete with process equipment, auxiliary equipment and Rioglass tempering technology from RioHuan (Inner Mongolia) Solar Co., Ltd. (a subsidiary of Spanish company "Rioglass" in China) and built a new plane mirror production line capable of producing 10 million m2 of high-precision solar mirrors per annum. For critical materials for receiver tubes at solar tower plants, Wuhan Jinniu Stainless Steel Pipe Technology Co., Ltd. is dedicated to the localization of such products and has introduced an advanced production line with CNC laser welding machines and related testing equipment, with an annual production capacity of 1,500 tons of nickel-based alloy (receiver) tubes.

CSTA has compiled incomplete statistics with respect to production and supply capacity for some critical CSP materials and components (as detailed in Table 4.2-1).

Table 4.2-1 Production capacity of some Chinese companies for critical CSP materials and components

Product	Company (listed in alphabetical order)	Production capacity
Ultra-white glass	Dalian Yaopi Glass Co., Ltd.	Ultra-white glass: 700 tons/day, annual production capacity: 2 GW
	Henan Ancai Hi-tech Co., Ltd.	Ultra-white glass: 600 tons/day, annual production capacity: 2.5GW (3-15 mm thick)
	Gansu Kaisheng Daming Solar Energy Technology Co., Ltd.	Ultra-white glass: 600 tons/day
Solar reflectors/ mirrors	Beijing TeraSolar Photothermal Technologies Co., Ltd	Mirrors of Fresnel reflectors: 5 million m^2/year Mirrors of Fresnel concentrating collectors: 3 million m^2/year
	Chengdu Chande New Energy Storage Technology Co., Ltd.	Parabolic mirrors: 3.5 million m^2/year; Flat mirrors for solar tower plants: 6 million m^2/year
	Gansu Kaisheng Daming Solar Energy Technology Co., Ltd.	Parabolic mirrors: 3.6 million m^2/year; Flat mirrors: 10 million m^2/year
	Lanzhou Dacheng Technology Co., Ltd.	Fresnel primary mirrors: 3 million m^2/year Fresnel secondary mirrors: 500,000/year Annual supply capacity of an MS linear Fresnel collector field with complete equipment: 300 MW
	Inner Mongolia Baichuan Solar Technology Co., Ltd.	Parabolic mirrors: 3.5 million m^2/year; Flat mirrors: 6.5 million m^2/year
	Shanxi Guoli Tianneng Technology Co., Ltd.	Parabolic mirrors: 2 million m^2/year
	Shouhang High-Tech Energy Technology Co., Ltd.	Parabolic mirrors: 2 million m^2/year; Flat mirrors: 5.6 million m^2/year
	Wuhan Sunnpo Solar Technology Co., Ltd.	800 MW/year (reflective mirrors for parabolic trough CSP plants, solar tower plants, linear Fresnel CSP plants, secondary reflectors, parabolic dish reflectors and concentrators)
Solar vacuum tubes	Beijing TRX Solar Technology Co., Ltd.	200 MW
	Royal Tech CSP Limited	320,000
	Lanzhou Dacheng Technology Co., Ltd.	60,000 (molten-salt receiver tubes)
	Shandong Huiyin New Energy Technology Co., Ltd.	200,000
High-temperature nickel-based alloy (receiver) tubes	Wuhan Jinniu Stainless Steel Pipe Technology Co., Ltd.	1500 t

Speed reducers	Hengfengtai Precision Machinery Co., Ltd.	
Nitrates	Hubei Yuntu Molten Salt Technology Co., Ltd.	Sodium nitrate and sodium nitrite: 150,000 tons/year
	Jiangxi Jinlida Potassium Industry Co., Ltd.	Potassium nitrate: 220,000 tons/year
	Golden Potassium Technology Co., Ltd.	Potassium nitrate: 150,000 tons/year
	Qinghai Salt Lake Wojin Thermal Storage Technology Co., Ltd.	Molten salt-grade potassium nitrate, sodium nitrate, calcium nitrate, and various high-, medium- and low-temperature molten salts: 400,000 tons/year
	Shanxi Wojin New Materials (Bingsheng Chemical) Co., Ltd.	Molten salt-grade potassium nitrate, sodium nitrate, calcium nitrate, and various high-, medium- and low-temperature molten salts: 180,000 tons/year
	Sinkiang Nitrate Minerals Co., Ltd.	Sodium nitrate: 70,000 tons/year
Heat transfer fluids	Jiangsu Zhongneng Chemical Technology Co., Ltd.	Thermal oil: 30,000 tons/year
	Shexian Jindong Economic and Trade Co., Ltd.	Thermal oil: 36,800 tons/year (including 25,000 tons of diphenyl ether per year)
Molten salt pumps	Jiangsu Feiyue Pump Co., Ltd.	Hundreds of industrial molten salt pumps per year
	Shandong Huawei Pump Co., Ltd.	40 long-axis molten salt pumps per year
Molten salt valves	Shanghai Yahe Valve Completion Co., Ltd.	More than 5,000 molten salt valves per year
	Beijing Jiajie New Energy Saving Technology Co., Ltd.	Annual supply capacity: 16 high differential pressure regulating valves for the lower tower, 200 regulating valves, 400 shut-off valves, 50 multi-function self-locking butterfly valves dedicated for molten salt service, which is sufficient for eight solar power plants, two linear Fresnel or parabolic trough CSP plants
Thermal insulation materials	Hubei Shuoli New Material Technology Co., Ltd.	Thermal insulation materials for solar power towers (central receivers), thermal insulation systems at the inlet and outlet of parabolic trough collector loops, and new thermal insulation systems for storage tanks: 25,000 tons/year
Stainless steel pipes	Wuhan Jinniu Stainless Steel Pipe Technology Co., Ltd.	10,000 t
	Wuxi Xinchang Steel Pipe Co., Ltd.	HT molten salt, HTF and electric heating pipes: 15,000 tons/year
	Sinosteel Stainless Steel Pipe Technology (Shanxi) Co., Ltd.	HT molten salt and HTF pipes: 10,000 tons/year
Prepared by: China Solar Thermal Alliance		

4.2 Main players in China's CSP industry

The main links of the CSP industry chain, critical materials and equipment, and representative entities in the CSP industry are listed below for reference.

太阳能热发电产业链及代表性单位（1）

项目咨询/可研/审查

- 东华科技
- 国核电力院
- 华中电力试研院
- 江西电建公司
- 内蒙古电力勘测设计院
- 内蒙古绿能新能源
- 山东电建三公司
- 山东电建一公司
- 山东电力工程咨询院
- 上海电气电站集团
- 西班牙ARI Solar
- 中电工程华北院
- 中电工程华东院
- 中电工程西北院
- 中电工程新能源
- 中广核新能源
- 中国电建西北院
- 中国电建中南院
- 中国能建甘肃院
- 中核战略规划院
- 中机华信诚
- [审查】
- 电规总院
- 水电总院

工程总包

- 东华科技
- 敦煌大成晟能（联合体）
- 甘肃安装集团（联合体）
- 河北建设集团安装工程
- 恒基能脉新能源（联合体）
- 可胜技术
- 兰州大成
- 山东电建三公司
- 山东电力工程咨询院
- 上海电气
- 上海院（联合体）
- 首航高科
- 水电一局（联合体）
- 西北水电（联合体）
- 浙江华业电力（联合体）
- 中船新能
- 中电工程华北院
- 中电工程华东院
- 中电工程西北院
- 中电建湖北电力（联合体）
- 中国电建河北院（联合体）
- 中国电建核电工程（联合体）
- 中国电建江西院（联合体）
- 中国电建四川工程（联合体）
- 中国电建西北院
- 中国电建中南院
- 中国能建葛洲坝电力（联合体）
- 中国能建浙江院（联合体）
- 中机国能
- 华中电力试研院（联合体）
- 中能建西北城建（联合体）
- 中能建西北电力
- 中能建浙江火电

设计/工程/设备监理

- 安徽能建工程监理
- 北京中唐电工程咨询
- 达华集团中达联
- 福建闽能咨询
- 甘肃光明电力工程监理
- 甘肃华研工程管理咨询
- 河北兴源工程建设监理
- 黑龙江电力建设监理
- 内蒙古电力勘测设计院
- 山东诚信工程建设监理
- 上海宝钢工程咨询
- 四川元丰管理
- 西北电力工程监理
- 西北电力建设工程监理
- 新疆昆仑工程咨询管理
- 浙江华东工程咨询
- 中电工程西北院
- 中国电建福建院
- 中国电建西北院
- 中国电建中南院
- 中国能建新疆院

项目调试/运维

- 华中电力试研院
- 江西电建
- 可胜技术
- 兰州大成
- 青岛华丰伟业
- 山东电建三公司
- 上海电气
- 首航高科
- 中船新能
- 中电工程西北院
- 中电哈密太阳能
- 中光新能源
- 中广核新能源
- 中国电建西北院
- 中国电建中南院

集热系统集成

- 北京天瑞星
- 成都禅德
- 东方锅炉
- 甘肃光热
- 恒基能脉
- 可胜技术
- 兰州大成
- 龙腾光热
- 山东电建三公司
- 上海电气亮源
- 首航高科
- 鑫晨光热
- 旭宸能源
- 兆阳光热
- 中船新能
- 中电工程西北院
- 中国电建西北院
- 中国电建中南院

储热系统集成

- 东方锅炉
- 东华科技
- 可胜技术
- 兰石换热
- 蓝星北化机
- 联储能源
- 山东电建三公司
- 山东电建一公司
- 山东三维石化
- 上海电气
- 上海蓝滨石化
- 首航高科
- 中电工程西北院
- 中电建核电工程
- 中国成达工程
- 中国电建西北院
- 中国电建中南院

蒸发系统集成

- 东方锅炉
- 哈尔滨锅炉厂
- 哈尔滨汽轮机厂
- 上海锅炉厂
- 西子洁能

科研/检测

- 北工大
- 电规总院
- 国电投中央研究院
- 华北电大
- 华电电科院
- 华科大
- 南工大
- 南航
- 内蒙古工大
- 上海交大
- 水电总院
- 天大
- 武汉理工
- 西安交大
- 长沙理工
- 浙大
- 中北大学
- 中科院电工所
- 中科院上海应物所
- [检测】
- 华电电科院
- 中国特检院
- 中科院电工所

说明：考虑页面排版，本图仅做典型列示，按单位简称拼音排序

制图：国家太阳能光热产业技术创新战略联盟

太阳能热发电产业链及代表性单位（2）

- 聚光系统
  - 超白玻璃：安彩光热 大连耀皮 凯盛大明
  - 反射镜：百川光热 滨海设备 成都禅德 凯盛大明 首航高科 武汉圣普 兆阳光热
  - 定日镜：东方锅炉 恒基能脉 可胜技术 山东电建三公司 上海电气亮源 首航高科 鑫晨光热 中能装备
  - 槽式聚光器：北京天瑞星 成都博昱 甘肃光热 龙腾光热 首航高科 中船新能
  - 聚光器支架：东方锅炉 海西华汇 可胜技术 龙腾光热 首航高科 兆维铁塔 中能装备
  - 跟踪装置：滨海光热 恒丰泰 山东电建三公司 首航高科 中能装备
  - 控制系统：东方锅炉 恒基能脉 可胜技术 山东电建三公司 上海电气亮源 首航高科 鑫晨光热 颐杰鸿利
  - 反射镜镜面漆：威士伯（上海）
  - 紧固件：奥展实业
  - 清洗设备：可胜技术 山东电建三公司 首航高科 中船双威 中广核新能源
- 吸热系统
  - 槽式吸热管：北京天瑞星 皇明太阳能 兰州大成 龙腾光热 山东汇银
  - 塔式吸热器：东方锅炉 哈尔滨锅炉厂 上海锅炉厂 首航高科 西子洁能/可胜技术
  - 柔性连接：滨海光热 昊峰管道 中广核新能源 中国电建中南院
  - 保温隔热材料：湖北烁砺新材料
  - 导热油：中能科技 津东经贸
  - 硝酸熔盐：青海盐湖 山东爱能森 司祈曼（上海） 沃锦新材料 新疆硝石钾肥 云图熔盐
  - 吸热器管材：金牛不锈钢 久立特材 无锡鑫常 中纲不锈钢
- 储热/换热系统
  - 熔盐储罐：东方锅炉 东华科技 蓝星北化机 上海蓝滨石化 首航高科 西子洁能
  - 熔盐电加热器：华源前线 慧金科技 可胜技术
  - 熔盐泵：飞跃泵业 华威泵业
  - 熔盐阀：北京佳洁能 上海亚核阀业 中能装备
  - 化盐服务：联储能源 山东爱能森 首航高科 沃锦新材料 中船新能 中国能建湖南火电
  - 加热炉：航天石化
  - 熔盐流量计：塔浦（上海）自动化
  - 换热器：东方锅炉 兰石换热 上海蓝滨石化 西子洁能
  - 蒸汽发生器：东方锅炉 哈尔滨锅炉厂 上海锅炉厂 上海蓝滨石化 西子洁能
- 发电系统
  - 汽轮机：东汽 哈汽 上汽
  - 发电机：济南发电设备厂 上海发电机厂
  - 空冷系统：首航高科 上海电气斯必克
  - UPS电源：沈阳微控
  - 热电联产：东华科技 兰州大成 龙腾光热 欣旺能源 兆阳光热

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制图：国家太阳能光热产业技术创新战略联盟

Chapter V Overview of CSP R&D Projects in China

5.1 National Science and Technology Projects

As of 2023, there are eight CSP-related national key R&D projects under implementation (as shown in Table 5.1-1, arranged according to their start time). The main research areas of these projects and the results achieved in 2023 are presented below. We owe special thanks to all project managers for sharing project progress information for 2023 .

On November 13, 2023, the National Natural Science Foundation of China (NSFC) issued the Guidelines for the "Dual Carbon" Special Project (II) of the Department of Engineering and Materials Sciences—"Basic Research on Low-Carbon Science in the Field of Engineering and Materials", announcing the ten major funded projects, including the project titled "Comprehensive utilization of full-spectrum solar PV and CSP with thermal energy storage". The objective of this science project is to explore the thermodynamic limits for full-spectrum solar energy utilization, analyze the effects of multiple factors and scales during solar energy capture on the transmission and conversion of solar thermal energy (STE), reveal the influence of coupled physical fields including light, temperature and stress fields on spectrally selective absorption, energy conversion and system operation under extreme energy flow conditions, propose a method for the comprehensive evaluation of full-spectrum solar energy utilization technologies, and establish a coordinated control method for energy transmission, conversion, storage and release in next-generation high-temperature solar PV-CSP-TES systems. The funding period for this special project is 3 years (from 2024 to 2026). For this project, 10-12 research items are planned to be funded, and the average amount of fund for each item is RMB 2 million.

Table 5.1-1 CSP-related national key R&D projects under implementation in 2023

No.	Project Name	Lead entity	Director/Chief Scientist
1	Resarch on key issues in supercritical CO_2 CSP systems (basic research)	IEECAS	Prof. Wang Zhifeng
2	Design of high-performance bionic TES materials and processes	Nanjing University of Aeronautics and Astronautics	Prof. Liu Xianglei
3	Broadband metasurface solar concentrator and collector systems	Wuhan University of Technology	Prof. Guan Jianguo
4	Theory and method for high-flux solar-to-chemical energy conversion and storage	Xi'an Jiaotong University	Prof. Wei Jinjia

[1] The information related to the progress of national key R&D projects is provided by Wang Zhifeng, Liu Xianglei, Guan Jianguo, Wei Jinjia, Sun Xiaofeng, Wu Yuting, Xie Wentao, and Zang Chuncheng.

5	Development and application of HT molten salt resistant special alloys for CSP systems	Institute of Metal Research, Chinese Academy of Sciences (IMRCAS)	Prof. Sun Xiaofeng
6	Wide-temperature-range HT molten salt TES technology	Beijing University of Technology	Prof. Wu Yuting
7	Research on key technologies for stable power output of CSP-PV hybrid plants with reflective secondary concentrators	Xinchen Solar (Shanghai) New Energy Co., Ltd. (Chines Side)	Prof. Xie Wentao
8	Mechanics research and service life prediction for HT molten salt storage tanks in CSP systems	IEECAS (Chines Side)	Mrs. Zang Chuncheng
Prespared by: China Solar Thermal Alliance			

5.1.1 Research on key issues in supercritical CO_2 CSP systems (basic research)

The purpose of this project is to study the key components for solar concentration, solar collection, TES and electricity generation in supercritical CO_2 CSP systems and system integration theories and methods. The key scientific problems to be solved include the design theories and methods for high-efficiency HT solar receivers, the impact of heat storage and release mode on system performance, and the interaction between supercritical CO_2 cycles and conversion of heat to work in steam turbines.

The main scientific and technological achievements of the project are detailed below. 1) Ceramic particles for stable operation in high-temperature environments have been developed, which have solar absorptance of 0.94, specific heat capacity of 1.16 kJ/(kg·K), high performance in heat absorption and storage, and high wear resistance; 10 t pilot-scale production of heat-absorbing ceramic particles has been completed, and a set of methods for testing the thermophysical properties of heat absorption and storage materials have been established. 2) The principle and method of a novel high-efficiency supercritical CO_2 system for CSP plants have been established, a complete prototype of 200 kW supercritical CO_2-based generator units has been built, the technologies for the commissioning, operation and maintenance of supercritical CO_2-based generator units have been improved, and an integrated technology system for 100 kW-scale supercritical CO_2-based generator units has been developed. 3) A 200 kW supercritical CO_2-based CSP demonstration platform has been built. 4) An outdoor experiment has been conducted on a supercritical CO_2 solar concentration and collection system. The cumulative operating time of the system is more than 167 hours, the temperature of ceramic particles at the outlet of the solar receiver is 872°C, and the maximum temperature rise per unit distance is 324°C/m.

5.1.2 Design of high-performance bionic TES materials and processes

TES technologies can effectively solve the problems caused by the mismatch between renewable energy/thermal energy supply and demand in terms of time, space and intensity, maximize energy utilization in the entire system while minimizing energy utilization costs, and play a strategically important role in building a "clean, low-carbon, safe, and efficient" modern energy system and promoting the supply-side reform of China's energy industry and the transformation of energy production and utilization modes. Existing TES technologies have a variety of problems, such as low thermal conductivity (less than 5 W/m·K), low TES density (less than 200 kJ/kg), low TES efficiency, and low system reliability. These problems have become bottlenecks restricting the development of CSP, heating, waste heat recovery, and other related technologies. Therefore, it is imperative to develop TES technologies with high efficiency and high reliability.

This project aims to break through traditional thinking patterns and conduct research on heat storage, transfer and release processes based on multiple disciplines including heat transfer, materials science, and bionics. An integrated volume method for solar energy conversion and storage has been proposed; the mechanisms of transmission of multi-scale photons and phonons in bionic porous materials have been investigated; a method for preparing bionic porous composites under controlled conditions and improving the reliability of such composites has been established; bionic optimization has been carried out at multiple levels (material-unit-system) to overcome the restrictions of conventional methods; revolutionary TES materials characterized by high TES density, quick response, and high reliability have been developed; and a dynamic control strategy for long-life high-reliability, and high-efficiency TES systems has been established.

In 2023, the project team prepared a silicon carbide-based (MXene-based) composite TES material with enhanced thermal conductivity and mechanical properties, thus breaking through the bottleneck caused by the high intrinsic brittleness of conventional ceramic matrix composites (CMCs); developed a multi-source (photothermal/electrothermal) driven composite TES material with TES density of 291.37 J/g and thermal conductivity of more than 51.82 W/(m·K), achieving the integration of photothermal/electrothermal energy conversion and storage; proposed a method for designing three-period minimal curved surface-based TES units made of bionic porous phase change materials (PCMs), significantly reducing the heat storage/release time by more than 80%; carried out bionic optimization at multiple levels (material-unit-system) based on bionic prediction and optimization algorithms and fuzzy logic, thereby overcoming the restrictions of conventional methods; and established a dynamic control strategy for long-life, high-reliability, and high-efficiency TES systems.

5.1.3 Broadband metasurface solar concentrators and solar energy collection systems

Existing solar concentrators require the use of high-precision paraboloids and complex solar trackers, resulting in high operation and maintenance costs, which restricts the rapid development of the CSP industry. This project aims to develop planar metasurface solar concentrators, change the original space-controlled solar concentration mode of existing parabolic solar concentrators to phase-controlled solar concentration to effectively concentrate broadband solar radiation at a wide angle, eliminate the need of solar tracking, and reduce the operating costs of solar concentrators.

For this project, the important achievements made in 2023 are detailed below. 1) A basic theory for the design of planar solar concentrators was established based on transformation optics; a method for designing metasurfaces for efficient light field control was developed, and the structural design of 100 mm × 200 mm dielectric metasurface solar concentrators with a theoretical solar concentration efficiency of 55% in the wavelength range of 400-1000 nm was completed. 2) Large-area nano-pattern cross imprinting and nano-transfer printing technologies were developed, achieving efficient and high-precision fabrication of small-area molds and large-area patterns; the negative pressure enhanced capillary filling technique (Contact Litho in Vacuum) was proposed, achieving reliable high-precision nanoimprinting of high-aspect-ratio (HAR) structures at an accuracy level of ≤ 0.05 μm; the large-area high-precision scanning ion beam etching technique was developed, and a prototype of solar concentrators with an effective concentration area of 300 mm × 600 mm and a concentration ratio of 10 was fabricated. 3) A model of planar metasurface solar collector systems was built, and the "light-heat-force" coupling mechanism of novel evacuated tube collectors was revealed; a method for band-wise mitigation of chromatic dispersion on solar receivers using planar metasurface concentrators was proposed, and a type of receiver tube with a variable cutoff wavelength selective absorption film was developed. For this type of receiver tube, the emissivity of the non-concentrating area of the selective absorption film is lower than 0.05, the emissivity of the concentrating area of the selective absorption film is lower than 0.10, the solar absorptivity is higher than 0.95, the heat loss is less than 200 W/m, and the operating temperature can be higher than 500°C. In addition, the molten salt system design and equipment selection for broadband metasurface-based concentrator systems have been completed.

5.1.4 Theory and method for high-flux solar-to-chemical energy conversion and storage

This project aims to overcome the bottlenecks of conventional solar TES systems such as low TES density and low heat release temperature and study high-efficiency solar-to-chemical energy conversion and storage technologies with high TES density, high heat release temperature, and long life cycle. A series of innovations and key technologies (as detailed below) have been achieved in numerous areas such as the mechanism of multi-field coupled energy storage, composition and production of energy carriers, solar thermochemical reaction unit and operation control, TES system integration and evaluation.

1) The theory of thermochemical conversion synergistically enhanced by multi-scale coupling of multiple fields including light, heat, force, flow, chemical and sound fields under non-steady high-flux light-concentrating conditions has been established, and the related mathematical model has been built. The errors in modeling and experimental results are less than 16.9%. 2) An experimental platform for testing long heat absorption and release cycles of calcium-based energy carriers has been built based on a 2.2 kW solar concentrator simulator, a method for fabricating and producing high-performance chemical energy carriers has been established, and a variety of high-performance chemical energy carriers have been successfully developed. For these energy carriers, the reaction temperature is 800°C, the initial energy storage density ranges from 1,030 kJ/kg to 1,285 kJ/kg, and the performance degradation after 1,000 cycles is 8.0-29.5%. 3) A direct moving bed endothermic reaction unit with a conversion rate of 85.7% and its experimental test system have been built, a fluidized bed exothermic reaction unit with a heat release temperature of 667°C and a conversion rate of 84.6% and its experimental test system have been built, and a scheme for real-time control of the endothermic and exothermic reaction units and a scheme for adjusting/controlling the structure of energy carriers have been developed. 4) An outdoor high-flux solar concentration and tracking unit with thermal power of 27 kW and peak heat flux density of 1.9 MW/m^2 has been built; the implementation plan for an integrated high-efficiency solar thermochemical energy storage system (an integrated demonstration system) that combines solar energy collection

with chemical energy storage has been completed; and a platform for onsite dynamic performance testing of the high-efficiency solar thermochemical energy storage system has been built, for which the measurable temperature is 1,100°C, the measurable energy flux density is 3 MW/m^2, and the frame rate is 10,000 frames per second. The advancements and achievements listed above provide strong support for the construction of subsequent demonstration systems of the project.

5.1.5 Development and application of HT molten salt resistant special alloys for CSP systems

This project aims to meet the needs of low-cost efficient electricity generation and sustainable development of the CSP industry by studying key scientific topics such as composition optimization and microstructure control for HT alloys/stainless steels, corrosion control for special alloys in HT molten salt environments, the design of heat resistant coatings, and the coupling mechanism of multiple photophysical effects, developing special alloys, HT molten salts, heat absorbing coatings, and other critical materials required for heat collection, storage and exchange units/components of next-generation CSP systems, making technological breakthroughs in batch production of materials, and finally achieving the integration of critical materials into CSP systems and the application of demonstration CSP systems.

The main research achievements of this project are detailed below. A high-temperature Ni-W-Cr alloy resistant to 800°C molten salt corrosion has been developed based on a design concept combining solid solution strengthening with grain boundary strengthening. High-strength ODS steels have been produced through in-situ oxide dispersion and precipitation achieved by micro-alloying. Through thermodynamic calculation and experimental verification, the phase diagrams and formulas of nitrate molten salts that are highly stable at 600°C and two ternary chloride salts have been obtained. A method for increasing the heat absorption rate of coatings by producing multiple light effects induced by refractory oxides and cross-scale pores has been proposed, and the design of an ultra-high temperature molten salt (800°C chloride) environmental testing device has been completed.

5.1.6 Wide-temperature-range HT molten salt TES technology

This project aims to meet the needs of electric/heat pump TES electricity generation and peak shaving plants, deep peak shaving systems of thermal power plants, new-generation CSP systems, and multi-energy complementary energy systems for large-capacity and long-term TES storage under high temperature conditions, make breakthroughs in key technologies for the optimal design of wide-temperature-range HT molten salt TES systems, molten salt mixtures with low melting point, high decomposition temperature, low cost and low corrosivity, large-capacity HT molten salt storage tanks and their foundations, HTHP high-differential-pressure molten salt heat exchangers, HV molten salt heaters, and system integration and control, and complete the verification and demonstration of the 10 MWh HT molten salt TES system.

In 2023, the project team developed a low-cost molten salt mixture with a melting point of 133.3°C and a decomposition temperature of 734°C; obtained a insulation material that has high strength and high thermal conductivity and can withstand a test voltage of 16,000 V at 660°C for one (1) minute without experiencing a flashover or breakdown; completed the installation and trial operation of the 10 MWh HT molten salt TES system; proposed three

(3) schemes for novel energy systems based on HT molten salt TES, conducted a system optimization analysis, and selected two structural schemes for large-capacity HT (660°C) molten salt storage tanks, namely, single-layer structure and double-layer structure; built an integrated numerical model involving coupled flow, heat and stress fields in molten salt-water/water vapor heat exchangers and molten salt-supercritical CO_2 heat exchangers, preliminarily identified the characteristics of the distribution of multiple physical fields in heat exchangers, and established the correlation between heat transfer and flow resistance

5.1.7 Research on key technologies for stable power output of CSP-PV hybrid plants with reflective secondary concentrators

This project aims to develop a novel solar concentration technique with reflective secondary concentrators, key components for integrated heat absorption/collection, storage and exchange, and a high-parameter, high-flexibility supercritical CO_2 power generation technology; establish a capacity allocation and scheduling method for CSP-PV hybrid plants; achieve low-cost stable operation and grid connection of CSP plants. In 2023, the project team independently completed the design and development of key components such as novel heliostat components and integrated heat absorption, storage and exchange devices, studied the overall theoretical performance of CSP-PV hybrid plants, jointly applied for four (4) patents and published two (2) papers in SCI journals. In the future, the project team will continue to deepen technology cooperation and exchange in areas such as heliostat fields, heat absorption, storage and exchange properties of solid particles, supercritical CO_2 power cycles, and optimal scheduling and control of CSP-PV hybrid plants.

5.1.8 Mechanics research and service life prediction for HT molten salt storage tanks in CSP systems

This project aims to solve the problems caused by corrosion and thermal fatigue in HT molten salt storage tanks under complex operating conditions, such as leakage, failure, and reduction in service life; carry out mechanics research and service life prediction for HT molten salt storage tanks; experimentally verify and optimize the service life prediction model; develop a structural design software suite capable of predicting service life based on the engineering practices of commercial CSP plants; overcome technical difficulties in predicting the service life of large-capacity molten salt storage tanks; and provide technical guidance for assessing the service life of molten salt storage tanks at CSP plants, optimizing the structural design of molten salt storage tanks, and ensuring the safe operation of molten salt storage tanks.

The main achievements of the project are detailed below. 1) Based on the temperature test data of HT molten salt storage tanks at commercial solar tower plants and parabolic trough CSP plants, the distribution characteristics and patterns of temperature fields in molt salts and storage tanks have been studied to provide supporting data from boundary load analysis for investigating the mechanical properties of molt salt storage tanks. 2) A numerical model for making structural and temperature field calculations of molten salt storage tanks has been built, the distribution of stress in key areas/parts of molten salt storage tanks at varying temperatures and liquid molten salt levels has been analyzed to provide a theoretical reference for strain testing of molten salt storage tanks, and the strain testing plan for HT molten salt storage tanks has been determined. 3) Based on the structural characteristics and operating conditions of molten salt storage tanks, the theoretical basis for predicting the service life of molten salt storage tanks has been investigated, and the theories of fatigue strength of the nominal stress and structural strain methods have been studied. 4) A platform for accelerated fatigue testing of molten salt storage tanks has been designed, and the accelerated fatigue testing plan has been studied. 5) The mechanics research method and simulation/calculation results for HT molten salt storage tanks used at solar power plants have been shared and discussed with the National Renewable Energy Laboratory (NREL), and the mechanical simulation model has been further improved.

5.2 CSP standards

5.2.1 National standards

According to the rough statistics of CSTA, as of 2023, there are two (2) published national standards related to CSP, two (2) CSP-related national standards under approval, and 11 CSP-related national standards under preparation or revision; as of the end of 2023, China has published 33 standards related to CSP (including thermal energy utilization), including two (2) standards under approval.

Table 5.2-1 CSP-related Chinese national standards published or under approval in 2023

No.	Standard	Prepared by	Managed by	Status
1	Corrosion of metals and alloys — Test method for high temper ature corrosion testing of metallic materials by immersing in molten salt or other liquids under static conditions (GB/T 42912-2023)	Xi'an Thermal Power Research Institute Co., Ltd., etc.	National Steel Standardization Technical Committee	Issued on August 06, 2023
2	Self-cleaning coated glass for solar photovoltaic and solar thermal power generation (GB/T 43083-2023)	Lion Trunk (Beijing) Technology Co., Ltd., etc.	National Industrial Glass and Special Glass Standardization Technical Committee	Issued on September 07, 2023
3	Concentrating solar power plants— Part 1-3: General, Meteorological dataset format (20212983-Z-524)	Datang Renewable Energy Research Institute Co., Ltd., etc.	National CSP Standardization Technical Committee	Under approval
4	Technical Standard for linear Fresnel CSP plants	China Electricity Council, etc.	Ministry of Housing and Urban-Rural Development/ China Electricity Council	Under approval

Prepared by: China Solar Thermal Alliance

Table 5.2-2 CSP-related national standards under preparation or revision

No.	Standard	Prepared by	Managed by
1	Test method for determining the heat loss coefficient of parabolic trough receiver tubes	IEECAS, etc.	National CSP Standardization Technical Committee
2	Technical requirements for molten salt thermal energy storage systems of solar thermal power plants	Cosin Solar Technology Co., Ltd., etc.	National CSP Standardization Technical Committee
3	Technical specifications for main control systems of solar power tower plants	CEEC (China Energy Engineering Corporation Limited) Technology Development Co., Ltd., etc.	National CSP Standardization Technical Committee
4	Specifications for solar energy resource assessment of solar power plants	Public Meteorological Service Center, China Meteorological Administration	National Climate and Climate Change Standardization Technical Committee
5	Technical requirements for heat collection systems of solar power tower plants	Cosin Solar Technology Co., Ltd., etc.	National CSP Standardization Technical Committee
6	Technical requirements for grid connection, scheduling and operation of solar thermal power plants	China Electric Power Research Institute (CEPRI), etc.	National CSP Standardization Technical Committee
7	Characteristics of direct and indirect active sensible heat storage systems of solar thermal power plants	Cosin Solar Technology Co., Ltd., etc.	National CSP Standardization Technical Committee
8	Technical requirements for heliostats at solar power plants	Cosin Solar Technology Co., Ltd., etc.	National CSP Standardization Technical Committee
9	Technical requirements for thermal energy storage/heat transfer media of solar thermal power plants—Part 1: Molten salt	Cosin Solar Technology Research Institute Co., Ltd., etc.	National CSP Standardization Technical Committee
10	Solar thermal power plants— Part 3-2: Systems and components-General requirements and test methods for large-size parabolic trough collectors	Royal Tech CSP Limited, etc.	National CSP Standardization Technical Committee
11	Code for solar power projects (a compulsory code for construction projects)	/	Ministry of Housing and Urban-Rural Development
12	Code for operation of solar power tower plants	CEEC Technology Development Co., Ltd.	National CSP Standardization Technical Committee

Prepared by: China Solar Thermal Alliance

5.2.2 Industry standards

In 2023, NEA issued the plan for preparing energy industry standards in 2023, including 13 CSP-related standards involving project construction, management and methods (Table 5.2-3). The preparation of these standards is to be completed by 2024 or 2025. The standards numbered 1-9 are managed by the China Electricity Council and relevant standardization technical committees or managed in a unified manner by the National CSP Standardization Technical Committee. The Guidelines for the Selection of Molten Salt Valves is managed in a unified manner by the National Standardization Technical Committee on Valves for Power Plants in the Electric Power Industry. The standards numbered 11-13 are managed by the General Institute of Water Resources and Hydropower Planning and Design (GIWP).

Table 5.2-3 NEA CSP-related industry standards for the energy sector prepared in 2023

No.	Standard	Prepared by	Scope of application and main content
1	Code for the design of molten salt electrical heat tracing systems for solar thermal power plants	PowerChina Northwest Engineering Corporation Limited, etc.	Scope of application: design of electric heat tracing systems of solar thermal power plants using solar salt as the heat transfer and storage medium Main content: general provisions, terms, electric heat tracing system design (general requirements, basic data, heating cable selection, heating power calculation, division of electric heating circuits, spare heating cables, electrical, instrumentation and control systems), identification/making, installation and testing requirements, etc.
2	Technical specification for anti-condensation and anti-freeze protection and thermal insulation of solar thermal power plants	PowerChina Zhongnan Engineering Corporation Limited, etc.	Scope of application: design of anti-condensation and anti-freeze protection and insulation of solar thermal power plant equipment, pipelines and accessories Main content: general provisions, terms and symbols, basic requirements, anti-condensation protection design and calculations, anti-freeze protection design and calculations, thermal insulation design and calculations, etc.
3	Code for energy conservation design of solar thermal power plants	PowerChina Zhongnan Engineering Corporation Limited, etc.	Scope of application: energy conservation design of newly built, expanded, and renovated parabolic trough CSP plants, solar tower plants and linear Fresnel CSP plants. The design of parabolic dish CSP plants can be performed with reference to this code. Main content: general provisions, terms, basic requirements, technical requirements for heat collection, storage and exchange systems, steam turbine generators, electrical, instrumentation and control systems, and other systems/facilities (hydraulic systems, buildings, HVAC systems).

4	Code for document filing and archives arrangement of solar thermal power projects	PowerChina Northwest Engineering Corporation Limited, etc.	Scope of application: Document archiving and archives arrangement of solar thermal power projects Main content: general provisions, terms and definitions, management responsibilities, preparation, collection and collation of project documents, collection and collation of audio and video files, collection and collation of electronic documents, filing of project documents, classification and handover of project documents, etc.
5	Technical code for heat collection systems of solar tower plants with secondary reflectors	Shanghai Survey, Design and Research Institute Co., Ltd., etc.	Scope of application: design of heat collection systems for newly built, renovated, and expanded solar tower plants with secondary reflectors Main content: technical specifications and testing requirements for heliostat fields, heat absorption systems, and system coordination of solar tower plants with secondary reflectors
6	Technical supervision code for environmental protection at solar thermal power plants	CGN Delingha Solar Energy Co. Ltd., etc.	Scope of application: technical supervision of environmental protection at solar thermal power plants Main content: scope and technical requirements for technical supervision of environmental protection at solar thermal power plants
7	Technical supervision code for steam turbines at solar thermal power plants	CGN Delingha Solar Energy Co. Ltd., etc.	Scope of application: technical supervision of steam turbines that have a single-unit capacity equal to or higher than 6 MW and are frequently started up and shut down (including dual-speed steam turbines) at solar thermal power plants Main content: scope and technical requirements for technical supervision of steam turbines at solar thermal power plants
8	Technical supervision code for heat collection systems of solar thermal power plants	CGN Delingha Solar Energy Co. Ltd., etc.	Scope of application: technical supervision of heat collection systems of parabolic trough CSP plants, solar tower plants, and linear Fresnel CSP plants Main content: scope and technical requirements for technical supervision of heat collection systems of solar thermal power plants
9	Technical supervision code for heat storage and exchange systems of solar thermal power plants	CGN Delingha Solar Energy Co. Ltd., etc.	Scope of application: technical supervision of heat storage and exchange systems of parabolic trough CSP plants, solar tower plants, and linear Fresnel CSP plants Main content: scope and technical requirements for technical supervision of heat storage and exchange systems of solar thermal power plants
10	Guidelines for the selection of molten salt valves	HE Harbin Power Plant Valve Company Limited	Scope of application: welded molten salt valves, mainly including globe valves, butterfly valves, and regulating valves Main content: structural forms of molten salt valves, requirements and documents for the selection of molten salt valves, selection of molten salt valves, etc.

11	Procedure for the preparation of planning reports for wind-PV-CSP hybrid projects	GIWP, etc.	Scope of application: planning of new and expanded wind-PV-CSP hybrid projects Main content: scope, terms, basic requirements, basic data, resource analysis, project site selection, construction conditions, technical route, planned installed capacity, electricity generation estimation, electricity connection, environmental impact, soil and water conservation, preliminary investment estimation and cost-benefit analysis, implementation measures, conclusions and recommendations
12	Procedure for the preparation of feasibility study reports for wind-PV-CSP hybrid projects	PowerChina Northwest Engineering Corporation Limited, etc.	Scope of application: preparation of feasibility study reports for wind-PV-CSP hybrid projects Main technical content: general provisions, basic requirements, basic data, project overview, project tasks and scale, solar and wind energy resources, site selection, design of wind-PV-CSP hybrid systems, design of CSP and PV electricity generation systems, wind turbine selection and layout, electricity generation estimation, electrical, general layout, construction organization plan, preliminary environmental impact assessment, investment estimation, preliminary analysis of financial benefits, conclusions and suggestions
13	Code for economic evaluation of multi-energy complementary projects	PowerChina Northwest Engineering Corporation Limited, etc.	Scope of application: economic evaluation of wind-solar-TES multi-energy complementary systems in the planning, pre-feasibility study, feasibility study and other project stages Main technical contents: general provisions, basic requirements, financial evaluation, national economic evaluation, economic comparison and selection of technical solutions, financial evaluation of renovation and expansion projects, appendices, etc.
Prepared by: China Solar Thermal Alliance			

5.3 Award-winning projects in 2022-2023

In 2022-2023, awards were conferred to some technological achievements of CSP projects (as listed in Table 5.3-1).

Table 5.3-1 Award-winning technological achievements of CSP projects (ranked randomly)

No.	Project	Completed by	Award
1	Key technologies and industrialization of molten salt linear Fresnel concentrator/ collector systems	Lanzhou Dacheng Technology Co., Ltd., etc.	First Prize of Gansu Provincial Science and Technology Progress Award
2	Key technologies and application of high-efficiency heat storage and exchange equipment with heat transfer media	Xizi Clean Energy Equipment Manufacturing Co., Ltd., etc.	Second Prize of Zhejiang Provincial Science and Technology Progress Award
3	R&D and industrialization of green production technology for high-performance heat transfer media/materials	Shexian Jindong Economic and Trade Co., Ltd.	Second Prize of Hebei Provincial Science and Technology Progress Award
4	Research on solar thermal energy storage technologies based on the Qinghai-Tibet Plateau	CGN Delingha Solar Energy Co., Ltd., etc.	Third Prize of Qinghai Provincial Science and Technology Progress Award
5	Key technologies and packaged equipment of high-temperature heat pumps and electricity-heat combination for renewable energy consumption	State Grid Jiangsu Electric Power Co., Ltd., etc.	Second Prize of Jiangsu Science and Technology Award
6	A deep peak-shaving system for combined heat and power (CHP) plants and its operation method	Huadian Electric Power Research Institute Co., Ltd.	Third Prize for Invention Patents of Zhejiang Provincial Intellectual Property Award, First Prize of China Electricity Council's Electric Power Science and Technology Innovation Award
7	Key technologies for performance optimization and operation improvement of smart solar tower plants	PowerChina Northwest Engineering Corporation Limited	First Prize of Technology Innovation Award under China Renewable Energy Society's Science and Technology Award

8	Key technologies and equipment for solar concentration and collection	Cosin Solar Technology Co., Ltd.	First Prize of China Electricity Council's Electric Power Science and Technology Innovation Award 2023
9	Technology for efficient heliostat field arrangement and aiming strategy for solar tower plants and its application	PowerChina Northwest Engineering Corporation Limited, etc.	Second Prize of China Electricity Council's Electric Power Science and Technology Innovation Award 2023
10	A complete set of key technologies for the design/ engineering, installation and commissioning of the world's first molten salt linear Fresnel CSP plant	PowerChina Sepco1 Electric Power Construction Co., Ltd.	Second Prize of China Installation Association's (CIA) Science and Technology Progress Award
11	Hami 50 MW molten salt solar tower plant	CPECC Northwest Electric Power Design Institute Co., Ltd	Second Prize of China Survey and Design Association's (CSDA) Electric Power Industry Engineering Design Award
12	Key technologies for high-efficiency thermodynamic cycles of thermal energy at medium and low temperatures and their application	Tianjin University (Zhao Li's research group), etc.	Second-class Award for Technological Invention under the Science and Technology Award of the Chinese Society of Engineering Thermophysics (CSET)
13	MW-scale electrode type molten salt heaters	CEEC Hangzhou Runpaq Energy Equipment Co., Ltd	Second prize of China Electricity Technology Market Association's (CETMA) "Golden Apple Award" for scientific and technological achievements in the electric power industry
14	Molten salt thermal energy storage units and technologies for 100 MW-scale solar tower plants	Shouhang High-Tech Energy Technology Co., Ltd.	Third Prize for Technological Innovation under China Renewable Energy Society's (CRES) Science and Technology Award, Award for Leading Technologies on the "Innovation China" Series List (Green and Low-Carbon Field)

15	Research and demonstration application of key technologies for "source-grid-load-storage integration" in Ulanqab	China Three Gorges Corporation (CTG), etc.	Third Prize for Industrial Promotion under CRES's Science and Technology Award
16	Basic key technologies and engineering applications of thermal insulation for large HT molten salt storage tanks	CPECC Northwest Electric Power Design Institute Co., Ltd	First Prize of CEEC Science and Technology Award
17	Study and application of key technologies for solar field control systems of large solar tower plants	SEPCOIII Electric Power Construction Co., Ltd.	First Prize of CEEC Science and Technology Award
18	Research on the development of large-aperture parabolic trough collectors and their performance and applicability in China	CPECC Northwest Electric Power Design Institute Co., Ltd	Second Prize of CEEC Science and Technology Award
19	Design of molten salt heat storage and exchange systems and key manufacturing and construction techniques	PowerChina Northwest Engineering Corporation Limited, etc.	Third Prize of CEEC Science and Technology Award
20	Theory and method for three-dimensional construction of medium- to low-temperature thermodynamic cycles driven by solar thermal energy	Tianjin University (Zhao Li's research group)	First Prize of Tianjin Renewable Energy Society's Science and Technology Award
21	Parabolic mirrors and high-parameter molten salt heat collection systems	Inner Mongolia Baichuan Solar Technology Co., Ltd.	Second Prize in the 8th Innovation and Entrepreneurship Competition held in the Ejin Horo Banner, Inner Mongolia Autonomous Region
22	Molten salt systems and processes for surface treatment	Shanghai Institute of Applied Physics, Chinese Academy of Sciences	23rd China International Industry Fair (CIIF) "Innovation Leadership Award"
Prepared by: China Solar Thermal Alliance			

Chapter VI Technical and Economic Aspects of CSP

6.1 Electricity prices and investment costs of CSP projects

The cost-effectiveness of power generation projects is closely related to electricity prices. According to the *Notice of the National Development and Reform Commission on Matters Related to the 2021 New Energy Feed-in Tariff Policy* (NDRC Pricing Document [2021] No. 833), from 2021 onwards, the electricity prices for newly approved (registered) CSP projects shall be determined by competent provincial authorities (pricing authorities) and may be determined through competitive allocation if conditions allow. If the electricity price for a CSP project is higher than the local benchmark price of coal-fired power plants, the part within the benchmark price will be settled by the responsible power grid enterprise.

Currently, the electricity price of CSP plant in Xinjiang Autonomous Region and Gansu Province is RMB 0.262 Yuan/kWh and RMB 0.3078 Yuan/kWh respectively. Inner Mongolia Autonomous Region implements a Market-based pricing mechanism of "benchmark price + upward and downward fluctuations", which is the benchmark electricity price is as that of coal-fired power plants; the price in western Inner Mongolia is RMB 0.2829 Yuan/kWh, and in eastern Inner Mongolia is RMB 0.3035 Yuan/kWh; in principle, the ranges of upward and downward fluctuations shall be no more than 10% and 15%, respectively. For local consumption-oriented CSP projects that are included in the renewable energy development and construction plan of Qinghai Province in 2021 and 2022 and completed on schedule, the price shall be RMB 0.3247 Yuan/kWh. For CSP projects that are completed behind schedule in Qinghai Province, the electricity prices shall be equal to the parity price (RMB 0.2277 Yuan/kWh).

Under the new situation involving the removal of subsidies, the focus of national CSP development strategy on desert and Gobi areas, and the accelerated construction of large wind and PV energy generation bases, CSP plants are constructed in the form of wind-PV-CSP hybrid projects. For the system configuration of CSP plants, consideration should be given to reducing initial investment while meeting the requirements in respect of installed capacity, energy storage duration, and system/equipment safety. Compared with the first batch of CSP demonstration projects in China, most of the existing CSP + renewable power plants are equipped with large-capacity electric heaters to absorb the abandoned solar photovoltaic and wind energy; the function of CSP plants in the power grid has changed from "serving as independent power sources for generating electricity as much as possible" to "energy storage and peak shaving", and their energy storage duration has been optimized and adjusted to about eight (8) hours based on project needs. By comparing the costs (feasibility study) of a 100 MW solar tower plant in Yumen (which is among the first batch of CSP demonstration projects in China) and the 100 MW CSP plant of the Turpan CSP + renewable energy project, CPECC Northwest Electric Power Design Institute Co., Ltd. [19] has found that the solar field area has been reduced from 1,400,000 m^2 to about 656,000 m^2; the prices of major equipment such as the solar field, steam turbine, steam generator, power generator, and molten salt storage tanks have decreased significantly; the unit price of molten salt used at the 100 MW CSP plant of the Turpan CSP + renewable energy project has increased by about 100% compared to the first batch of

CSP demonstration projects. In general, the unit cost of a 100 MW solar tower plant has been reduced by about 45.6% from RMB 29,770 Yuan/kW to RMB 16,209 Yuan/kW.

It is to be noted that the cost of a CSP plant with molten salt TES is closely related to the solar irradiance and meteorological conditions in the region/province where the plant is located, as well as the policies and requirements of the region/province with respect to the energy storage period, the ratio of solar thermal energy to renewable energy, and electricity prices for CSP projects. Due to the change in the functional position of CSP plants, the annual operating (electricity generation) hours and equipment utilization rate of CSP plants have decreased, resulting in an increase in the amortized cost of equipment and a slight decrease in plant cost per kWh.

CSTA has compiled statistics (Table 6.1-2) on the award of EPC contracts for some 100 MW CSP plants under construction according to the bid and contract award information published on various bidding websites. The maximum and minimum EPC contract prices are about RMB 1698 million and RMB 1199 million, respectively. However, it should be noted that, although these CSP projects have the same installed capacity, they are different from one another in aspects such as project site (including solar irradiance and meteorological conditions), scope of work, scope of service, technical route, solar field area (1.30 million m^2 at maximum, 0.44 million m^2 at minimum), thermal energy storage period (ranging from 8 hours to 12 hours), and financial management model. Therefore, the EPC prices of different CSP projects are not comparable.

Table 6.1-1 Award of EPC contracts for some CSP plants under construction (arranged in random order)

No.	Project	EPC contractor
1	CNNC Yumen 100 MW CSP project	Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group, Dunhuang Dacheng Shengneng New Energy Technology Co., Ltd.
2	100 MW CSP Plant in Bid Section 3 of the Three Gorges (CTG) Qingyu DC Power Outbound Transmission Project Phase II	PowerChina Northwest Engineering Corporation Limited, Cosin Solar Technology Co., Ltd., China Energy Engineering Group (CEEC) Zhejiang Thermal Power Construction Co., Ltd.
3	Qinghai Golmud 1,100 MW Solar Power Plant in Three Gorges New Energy Haixi Solar PV Park	Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group, Shouhang High-Tech Energy Technology Co., Ltd., PowerChina Sichuan Engineering Corporation Limited (SCECC), Shanghai Survey, Design and Research Institute Co., Ltd.
4	PowerChina Xinjiang Ruida (Ruoqiang) New Energy 100 MW CSP + 900 MW PV Demonstration Project	SOCOL Corporation Limited, PowerChina Jiangxi Electric Power Engineering Co., Ltd., Shandong Electric Power Construction Corporation III (SEPCOIII)

5	100 MW CSP Plant of the PowerChina New Energy CSP + PV Hybrid Project in Wusitong, Toksun County, Turpan	PowerChina Zhongnan Engineering Corporation Limited, SOCOL Corporation Limited, PowerChina Nuclear Engineering Company Limited, PowerChina Hebei Electric Power Engineering Co., Ltd.
6	SDIC Ruoqiang 100 MW CSP + 900 MW PV Project	North China Power Engineering Co., Ltd. of China Power Engineering Consulting Group, Shouhang High-Tech Energy Technology Co., Ltd.
7	Three Gorges New Energy Hami 10,00 MW Hybrid CSP + PV Demonstration Project	Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group, China Energy Engineering Group Central China Electric Power Test and Research Institute Co., Ltd.
8	Northern Hami 900 MW PV + 100 MV CSP Project	Shouhang High-Tech Energy Technology Co., Ltd., North China Power Engineering Co., Ltd. of China Power Engineering Consulting Group, China Energy Engineering Group Northwest City Construction Co., Ltd.
9	No. 2-1 (100 MW CSP) Plant of the CGN Jixi Base DC 1,400 MW DC Power Outbound Transmission Project in Lugu County, Baicheng City, Jilin	PowerChina Zhongnan Engineering Corporation Limited
10	Three Gorges SunSum Guazhou 700 MW "Solar Thermal Energy Storage +" Project	China Gezhouba Group Electric Power Co., Ltd., Gansu Province Installation & Construction Group Co., Ltd., SunSum Technology Co., Ltd.
11	CEEC Hami "Solar (Thermal) Energy Storage" Multi-energy Complementary Integrated Green Electricity Demonstration Project	Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group
12	100 MW CSP Plant in Bid Section 1 of the CHN Energy Qingyu DC Power Outbound Transmission Project	PowerChina Northwest Engineering Corporation Limited
13	Xinhua Hydropower Bozhou 100 MW CSP Project	PC (procurement and installation) contractor: Gansu Province Installation & Construction Group Co., Ltd., SunSum Technology Co., Ltd.
14	Xinhua Hydropower Jinghe New Energy 100 MW CSP Project	PC (procurement and installation) contractor: PowerChina Sichuan Engineering Corporation Limited, Shouhang High-Tech Energy Technology Co., Ltd.
Prepared by: China Solar Thermal Alliance		

6.2 Technical and economic comparison between CSP with molten salt TES and PV + other novel energy storage systems

In 2022, CSTA launched a common technology research project titled "*Technical and Economic Comparison between CSP with Molten Salt TES and PV + Other Novel Energy Storage Systems*". After independent application by interested participants and voting by the expert committee of CSTA, Cosin Solar Technology Co., Ltd. undertook the research project with a grant of RMB 50,000. The project was completed in 2023. The main findings of the research will be shared in this section.

Energy storage techniques such as molten salt thermal energy storage (MS TES), pure electric heating MS TES, pumped hydro energy storage (PHES), compressed air energy storage (CAES), and electrochemical energy storage (EES) are suitable for large-scale, long-term, and long-life energy storage and peak shaving scenarios in power systems. Unlike CSP plants with MS TES, CSP plants with pure electric heating MS TES systems are not equipped with solar concentrators or collectors, at which electric heaters are used to heat the MS TES systems by absorbing abandoned solar PV and wind energy. The other systems/parts of these two types of CSP plants are completely identical. Based on the solar resources of Delingha City, Qinghai Province and without considering the geographical constraints at the project site, the economic aspects of CSP plants with MS TES and solar PV projects with other energy storage systems were comparatively analyzed while ensuring the same overall on-grid power curve.

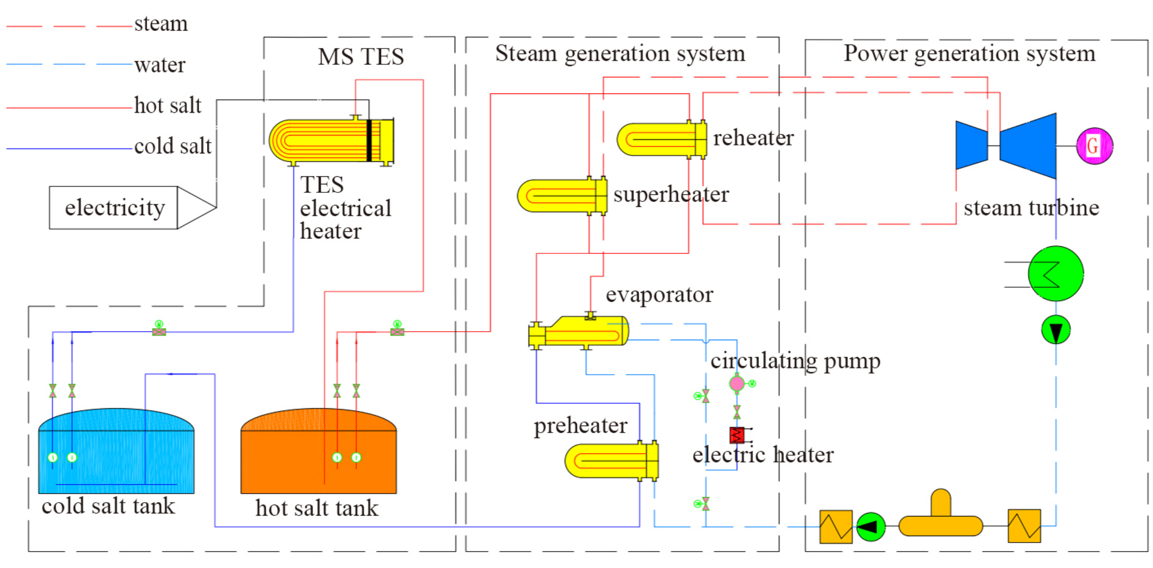

Fig. 6.2-1 Schematic diagram of a pure electric heating MS TES system

The unit cost of solar PV systems used for the research is RMB 2.8 Yuan/Wp. As the energy storage period increases from 2h to 12h, the unit cost of MS TES decreases from 2,567 Yuan/kWh to 1,153 Yuan/kWh, the unit cost of pure electric heating MS TES decreases from 2,117 Yuan/kWh to 708 Yuan/kWh, the unit cost of EES decreases from 1500 Yuan/kWh to 1250 Yuan/kWh, the unit cost of PHES decreases from 2,350 Yuan/kWh to 892 Yuan/kWh, and the unit cost of CAES (artificial storage) decreases from 3,250 Yuan/kWh to 958 Yuan/kWh. These calculation results show that, when the energy storage period is between 2h and 7h, the unit cost (per kWh) of PV + EES is the lowest; when the energy storage period is longer than 7h, the unit cost of CSP + MS TES is the lowest. CSP + MS TES, PV + pure electric heating MS TES, and PV + PHES systems have similar unit costs. When the energy storage period increases from 2h to 12h, the unit cost of CSP + MS TES is the lowest, and the unit cost of PV + CAES (artificial storage) is higher than those of the other three types of energy storage systems. In general, CSP plants with MS TES are more cost-effective than solar PV power plants with other energy storage systems.

Table 6.2-1 Unit costs (per kWh) of CSP + MS TES and PV + different energy storage systems (Unit: Yuan/kWh)

Energy storage period (h)	Annual electric output (million kWh)	CSP + MS TES	PV + pure electric heating MS TES	PV + EES	PV + PHES	PV + CAES (efficiency: 70%)	PV + CAES (efficiency: 60%)
2	104	1.6523	1.6631	0.9512	1.6481	2.1735	2.2081
4	221	1.0238	1.1071	0.8323	1.0513	1.2730	1.3077
6	321	0.8764	0.9721	0.8296	0.9053	1.0402	1.0748
8	419	0.8052	0.8894	0.8296	0.8298	0.9191	0.9538
10	531	0.7388	0.8259	0.8134	0.7671	0.8283	0.8630
12	641	0.6926	0.7825	0.8052	0.7291	0.7711	0.8057

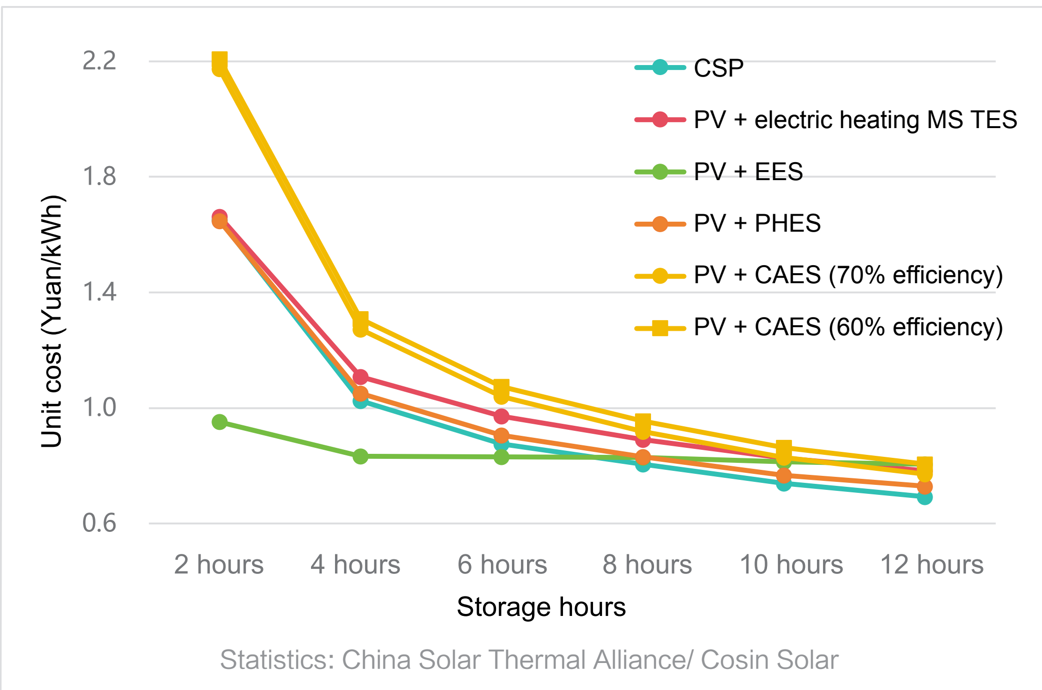

Fig. 6.2-2 LCOE (per kWh) of CSP + MS TES and PV + different energy storage systems

The research suggests that China's CSP industry is currently in the stage of large-scale development and rapid technological progress, and with the reduction of costs and the improvement of power generation efficiency, the unit cost (per kWh) of CSP plants with ME TES will further decline. The unit cost of solar tower plants is estimated to decline to 0.5287-0.5312 Yuan/kWh (including expenses for operation and maintenance optimization) by 2026. Compared with other power sources, CSP plants have a lower-carbon life cycle and superior on-grid performance. With the deepening of the electricity market reform and the establishment and maturation of green power trading and emissions trading markets, the values of CSP plants in load regulation, support services, and green and low-carbon development will be reflected in project income, and the cost-effectiveness of CSP plants will be greatly improved.

6.3 CSP cost reduction pathways

6.3.1 Solar tower plants

The cost of a solar tower plant, including the initial investment for the plant and the support costs incurred throughout the entire lifecycle of the plant, is affected by many factors and mainly related to factors such as construction, operation and maintenance expenses, annual electric output, financial expenses, and taxes. The factors affecting the cost of solar tower plants are listed in the table below (classified according to the significance of their impacts).

Table 6.3-1 Factors affecting the cost of solar tower plants

Direct factors	Indirect factors
Cost	Loan-to-value ratio (LVR)
Operation and maintenance expenses	Loan interest rate
Electricity generation	Auxiliary power consumption rate
Internal rate of return (IRR) *	Value-added tax (VAT), income tax
Operating period (year)	Installed capacity
Land costs	Energy storage period
Costs allocated to power generation companies for outbound transmission lines	Construction time
Direct normal irradiance (DNI)	Year-over-year investment ratio
	Repayment method (equal principal and equal interest payments)
	Loan period (year)
	Depreciation method and period (year)
	Wind speed
	Ambient temperature

* Note: It refers to the discount rate for capital when the net present value within the life cycle of the project is 0.

[2] The information contained herein is sourced from the report on a common technology research project launched by CSTA and undertaken by Cosin Solar Technology Co., Ltd.

The research has found that the annual equivalent utilization hours of thermal, hydroelectric, PV and wind power plants (the ratio of the annual electric output of a plant to the rated electric power of the plant) basically remain constant. Therefore, the investment per kWh is usually used to reflect the cost-effectiveness (economic viability) of a solar tower plant. The investment per kWh and annual equivalent utilization hours of a solar tower plant increase as the energy storage period increase. As the investment per kWh increases, the initial investment will increase accordingly, but the annual equivalent utilization hours will also increase, due to which the final converted cost of electricity per kWh may decrease. Therefore, the investment per kWh cannot accurately reflect the cost-effectiveness of a solar tower plant, and only the cost of electricity per kWh over the life cycle of a solar tower plant (levelized cost of electricity (LCOE)) can reflect the cost-effectiveness of the plant more reasonably. The LCOE of a solar tower plant is the minimum feed-in tariff that can ensure the balance of payments while achieving a certain rate of return on capital (discount rate) throughout the entire life cycle of the plant.

Taking Delingha City, Qinghai Province as the project site (where the DNI is 2,009 kWh/m^2 and the total irradiance is 1,850 kWh/m^2) and based on the configuration in which a solar field area of 0.80 million m^2 and an energy storage period of 10 hours are provided per 100 MW installed capacity of a solar tower plant, Cosin Solar Technology Co., Ltd. analyzed the cost-effectiveness of three configuration plans for solar tower plants with varying installed capacity and calculated the cost of electricity per kWh based on an IRR of 6.5%.

Table 6.3-2 Configuration plans and cost-effectiveness comparison for solar tower plants with varying installed capacity

Item (unit)	Plan A	Plan B	Plan C
Installed capacity (MW)	100	200	300
Configuration/type	One power tower + One turbine-generator unit	One power tower + One turbine-generator unit	Two power towers + One turbine-generator unit
Steam turbine efficiency rating	45.49%	45.89%	46.30%
Total reflection area (10,000 m^2)	80	160	240
Central receiver (power tower) center elevation (m)	220	250	230
Central receiver rated power (MWt)	416	780	600×2
Thermal energy storage period (h)	10	10	10
Total amount of molten salt (t)	22,125	44,646	67,376
Static investment (10,000 Yuan)	163,463	277,428	410,578
Static investment per kWh (Yuan/kW)	16,346.3	13,871.4	13,685.9
Annual electric output (million kWh)	233	455	698

Feed-in power (million kWh)	219	424	656
Offline auxiliary power consumption rate (%)	3.46	3.21	3.03
IRR	6.5%	6.5%	6.5%
Cost of electricity per kWh (Yuan/kWh)	0.8487	0.7369	0.6981

The calculations made under the conditions listed above show that, when the installed capacity of a solar tower plant increases from 100 MW to 200 MW, the investment per kWh decreases significantly; when the installed capacity of the plant increases from 200 MW to 30 0MW, the investment per kWh does not decrease significantly. The reason is that the investment for the configuration consisting of two power towers and one turbine-generator unit includes the costs of the second (additional) power tower and the molten salt pipeline between the two towers. For a solar tower plant that has an installed capacity of 300 MW and consists of two power towers and one turbine-generator unit, the LCOE of the plant is approximately 0.6981 Yuan/kWh. As the installed capacity of a solar tower plant increases, the steam turbine's efficiency rating increases, the auxiliary power consumption rate decreases, the feed-in power from the plant increases significantly, and consequently, the LCOE of the plant decreases significantly. The LCOE of a 300 MW plant is 17.7% lower than that of a 100 MW plant.

The cost reduction pathway for a solar tower plant with an installed capacity of 300 MW and a thermal storage period of 10 hours was analyzed. The investment structure of such a power plant is shown in Fig. 6.3-1. The costs of solar concentrator and receiver systems and heat absorption, storage and exchange systems (heat storage and steam generation systems) account for nearly 70% of the total investment for the plant. Such costs are an important factor determining the total investment for a solar tower plant.

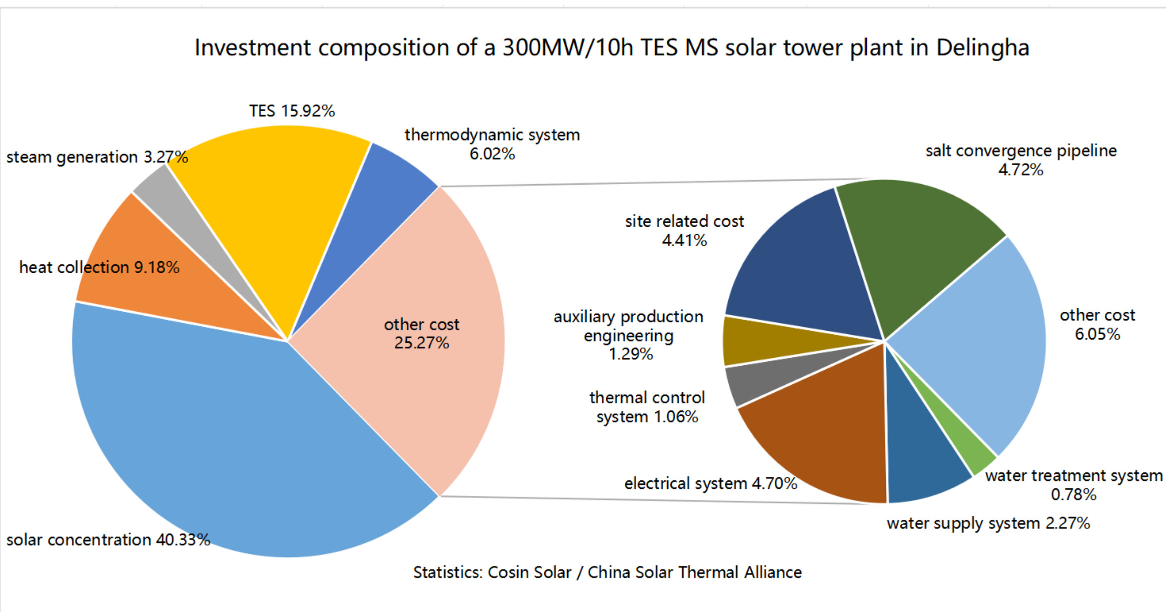

Fig. 6.3-1 Investment structure of a 300 MW solar tower plant in Delingha with 10h thermal energy storage

1) Cost reduction resulting from economies of scale

CSP plants have significant economies of scale. The larger the scale of a solar tower plant, the lower the cost of the plant. A solar tower plant operating at an expanded scale can attract more upstream and downstream suppliers, gradually establish a complete and stable supply chain, and reduce supply costs by purchasing main equipment and raw materials in batches. After scale expansion, the market mechanism will facilitate cost reduction in the industry, drive suppliers to source low-cost, high-quality alternative materials and carry out technological innovation, accelerate the localization of critical equipment and materials, improve the advancement and reliability of locally manufactured equipment, and thereby achieve cost reduction and efficiency improvement. In addition, as developers and participants become more experienced, the risks and trial-and-error costs will be reduced, and the design and construction durations will be significantly shortened.

Based on calculations and considering the competitive advantages gained through standardized operations, centralized procurement and scale expansion for all systems, it is estimated that, by 2026, the reduction in the total cost of a single plant arising from large-scale development (scale expansion) can be reduced by 10.28%-10.76%, and if the plant's electricity generation remains unchanged, the cost of electricity per kWh will be 0.6321-0.6351 Yuan/kWh. The cost reductions for various systems of solar power plants resulting from large-scale development are summarized in Table 6.3-3.

Table 6.3-3 Cost reductions for various systems of solar tower plants resulting from large-scale development by 2026

No.	System	Ratio of the system's cost to the total cost of the plant	Reduction in the system's cost	Cost reduction measures	Reduction in the total cost
1	Solar concentration system	40.33%	9.8%	Use of proven production processes such as batch production for solar reflectors/mirrors, frames, transmission equipment, controllers, etc.; centralized procurement; standardization of civil works for heliostat installation	3.96%↓
2	Solar absorption system	9.18%	15.3%	Localization of receiver tubes; improvement in material processing efficiency and tooling; centralized procurement	1.40%↓
3	Heat storage and exchange system	19.19%	11.8-14.3%	Full competition for molten salts, molten salt pumps, storage tanks, heat exchangers, electric heat tracing devices, instruments, valves, etc.; standardized production; centralized procurement	2.26%-2.74%↓

4	Thermal system	6.02%	20%	Standardized design of steam turbines, thermal system, and other systems instead of customized design	1.20%↓
5	Other systems*	14.8%	9.8%	-	1.46%↓
Total		-	-		10.28%-10.76%↓
* Note: Other systems include water treatment, water supply, electrical, and thermal control systems, molten salt pipelines, and ancillary production facilities/systems.					

2) Reduction in LCOE resulting from operation and maintenance optimization

The first batch of CSP demonstration plants have accumulated considerable operation and maintenance experience and established relatively mature cost management systems. As an existing solar tower plant accumulates operation experience, the reliability and performance of plant equipment will improve continuously in practice, the automation level of the plant will further improve, and the costs of plant maintenance and the number of operation and maintenance personnel will decrease accordingly, resulting in reduced LCOE. The operation and maintenance costs of a solar tower plant include labor costs, maintenance expenses, insurance expenses, material costs and other expenses.

It is expected that, by 2026, the reduction in LCOE resulting from reduced operation and maintenance costs will reach 0.07 Yuan/kWh, and the LCOE of a solar tower plant with an installed capacity of 300 MW and a thermal energy storage period of 10 hours can be further reduced to 0.5597-0.5623 Yuan/kWh.

3) Reduction in LCOE resulting from technological improvements and advances

Making technological improvements and advances based on existing technology systems is the most direct and effective way to improve efficiency and reduce costs. For second-generation solar power plants using molten salts as heat transfer and storage media, the main technological improvements that can be made include the improvement of solar field efficiency, the optimization of TES equipment, and the optimization of molten salt technologies.

(1) Improvement of solar field efficiency: Using new transmission devices and optimizing the heliostat design can reduce the quantity of steel used and improve the solar concentration efficiency. The solar field efficiency can be improved from the perspectives of control and operation by further optimizing the solar field control strategy.

(2) Optimization of TES equipment: Research has found that the amount of molten salt used and the volume of molten salt storage tanks can be reduced through a configuration combining high-level and low-level tanks, in which low-level tanks are provided in addition to the conventional molten salt storage tanks and a minimum liquid level is specified for each tank (for example, the minimum liquid level for long-axis pumps is 1 m). In addition, for low-level tanks, less expensive locally manufactured short-axis pumps can be used to replace the long-axis pumps used in previous projects.

(3) Optimization of molten salt technologies: Novel molten salts that can operate at high temperature over a broad temperature range should be used. On the one hand, the thermoelectric efficiency of the system increases with increasing values of system parameters; when the electricity generation of the system remains unchanged, the required amount of heat to be absorbed will decrease, and the costs of solar concentration, solar collection, and heat storage and exchange systems will therefore be reduced. On the other hand, as the temperature difference in the MS TES system increases, the amount of thermal energy stored per unit weight will increase, the amount of molten salt used will decrease, and the cost of the heat storage and exchange system will be further reduced.

Calculations show that, with the optimization of solar field design and the successful application of HT molten salts and low-level molten salt tanks, the overall cost of a solar tower plant will decrease by 16.18%-16.67%, and the LCOE of the plant can be further reduced to 0.5287-0.5312 Yuan/kWh (including operation and maintenance optimization costs).

In summary, with the expansion of single-unit capacity and industry scale, operation and maintenance optimization, and technology optimization, the LCOE of solar tower plants will decrease significantly. It is predicted that the LCOE of a solar tower plant will be about 0.61 Yuan/kWh in 2025 and decrease to about 0.53 Yuan/kWh by 2027.

6.3.2 Parabolic trough CSP plants [3]

Owing to the standardized design and modular production of parabolic trough collectors (PTCs), the parabolic trough CSP technology is particularly suitable for large-scale power plants. In the context where the target market capacity has been determined and the supporting production chains are becoming increasingly mature, this technology has huge potential in cost reduction. The cost reduction process for parabolic trough CSP plants can be divided into two stages.

1) Stage I: large PTCs + heat transfer by HTF + molten salt TES

At this stage, the costs of CSP plants are mainly reduced by achieving economies of scale through the construction of large-capacity single-unit power plants or multi-unit power plants relying on the technical solution consisting of "large PTCs + heat transfer by HTF + molten salt TES". The cost reduction measures that can be taken are detailed below.

(1) The preliminary verification results show that the use of low-cost large-aperture PTCs with new structural forms can reduce steel consumption by about 20% while ensuring that the same structural strength. In addition, PTCs can be further optimized based on completely independent PTC designs and onsite load conditions to reduce the quantity of materials required and the initial investment.

(2) While keeping the total aperture area unchanged, increasing the aperture size of PTCs from 5.8m to 8.6m can reduce the number of solar collector loops by about 40%, reduce the number of solar trackers, flexible connections and foundations by 40%, and reduce the number of HTF pipelines and the quantity of insulation materials accordingly, which is favorable for reducing the initial investment.

[3] The information contained herein is provided by Royal Tech CSP Limited.

(3) It is recommended to use long receiver tubes with large diameters to reduce the flow resistance. This can reduce welding costs during the construction phase and reduce pump power loss, auxiliary power consumption (quantity), and operation and maintenance costs during the operation phase.

The economies of scale of large-capacity single-unit power plants or multi-unit power plants (with single-unit capacity ≥ 200 MW or multiple-unit capacity ≥ 2 × 150 MW) can increase the purchase volume of various equipment and components, facilitate continuous and stable mass/batch production in the supply chain, reduce the unit cost of equipment and components, dilute indirect costs such as design and overhead costs, and reduce the initial investment. In addition, the unit cost of plant operation and maintenance during the operation phase can be reduced through centralized management, operation and maintenance of large-scale projects.

Calculations show that, taking the Urad 100 MW parabolic trough CSP plant (which is among the first batch of CSP demonstration projects in China) as a reference, the LCOE of parabolic trough CSP plants can be reduced to about 0.61 Yuan/kWh by taking the measures listed above. This goal is achievable in the current stage.

2) Stage II: super large PTCs + molten salt heat transfer and storage

In this stage, the technical solution consisting of “super large PTCs + molten salt heat transfer and storage” is the main driving force for cost reduction, and the installed capacity of parabolic trough CSP plants can be further increased to 2 × 300 MW or higher levels. The specific cost reduction measures are detailed below.

(1) The aperture size of PTCs can be further increased to 14 m. In this way, the quantities of solar collector loops, solar trackers, flexible connections, foundations, HTF pipelines and pipe insulation materials can be further reduced compared with those in the previous stage (Stage I).

(2) Novel vacuum receiver tubes with ultra-low heat loss can be used, which can reduce heat loss by about 30% compared with conventional receiver tubes. In this case, the design efficiency of PTCs can be increased from the original level of 73.5% to 75% to improve the heat collection efficiency of the mirror field and increase the electricity output of the plant.

(3) High-performance double-glass composite mirrors can be used to increase the absolute reflectance of parabolic reflectors by 2%-3%, thus increasing the plant’s electricity generation capacity. In addition, the use of such mirrors can improve the resistance of parabolic reflectors to aging, maintain stable reflectance of parabolic reflectors for longer periods, and reduce the operation and maintenance costs of the plant.

(4) It is recommended to use a large integral reflector design to increase the surface stability of parabolic mirrors under wind load and further reduce the amount of material used while maintaining the same optical efficiency. In addition, the reduction in the number of parabolic mirrors/reflectors can also reduce the complexity and cost of assembly.

(5) The use of molten salts as heat transfer and storage media can eliminate the need for thermal oils and related auxiliary systems such as heat exchange, expansion, overflow, purification, regeneration, and nitrogen sealing systems, simplify the design and operation mode of the plan, help reduce the initial investment and plant operation and

maintenance costs, significantly reduce molten salt consumption, and further reduce the initial investment.

Calculations show that, by taking the measures listed above, the LCOE of parabolic trough CSP plants can be further reduced to 0.4-0.5 Yuan/kWh. It is expected that this goal can be achieved before 2030 after one or two rounds of project implementation in the previous stage.

In addition, considering the progress of R&D and the maturity levels of related technologies, it is highly likely that intermediate/transitional technical solutions such as “large PTCs + molten salt heat transfer and storage” will appear during the implementation phase. The target LCOE for such solutions is between the two target values mentioned above, and the measures for achieving the target are the same as the previously described ones.

6.3.3 MS linear Fresnel CSP plants [4]

By investigating the industrialization of the MS linear Fresnel technology based on experiences in the investment, construction and operation of the first batch of CSP demonstration projects and taking into account the bidding situation and program optimization for CSP projects under construction, the cost reduction pathways for MS linear Fresnel CSP have been determined. The specific cost reduction measures are detailed below.

1) Large-scale development of CSP plants and industry chain

(1) Increasing the number of CSP projects will increase the bargaining power in the CSP industry and the number of participants in the CSP industry chain and significantly reduce the costs of CSP plants.

Since the completion of the first batch of CSP demonstration projects, the construction of hybrid CSP projects has led to a significant increase in the market capacity for CSP projects, new vendors and domestic manufacturers have successively participated in the manufacturing and supply of critical equipment such as reflectors, molten salt pumps, and molten salt valves, and the costs of CSP equipment have begun to decrease gradually with the large-scale construction of CSP projects. Given the prices and conditions for the bulk purchasing of materials such as steel and glass, more suppliers will participate in the CSP market as the scale of the CSP market increases. With the further expansion of the CSP market scale and the further accumulation of CSP technologies and products, the costs of CSP plants will continue to decline, and the bargaining power in the industry will further increase.

It is expected that, through large-scale development, the costs of MS linear Fresnel CSP plants will be reduced by more than 20% by 2025 compared to those of the first batch of CSP demonstration projects.

(2) The development of hybrid CSP + projects and the increase in the scale of single-unit CSP plants will significantly reduce the construction and development costs of CSP plants.

The CSP industry is developing towards hybrid CSP + plants and CSP plants with large single-unit capacity. At large energy bases, CSP plants with large single-unit capacity play an important role in peak shaving and renewable energy regulation. Unlike the first batch of CSP demonstration projects (which have been developed separately), large-capacity hybrid CSP plants will be developed in an integrated manner for all aspects, including interfacing with

[4] The information contained herein is provided by Lanzhou Dacheng Technology Co., Ltd.

governmental authorities, completion of preliminary procedures and formalities, and technical evaluations and studies. For CSP plants, especially those with line focusing systems, as their scale increases, it is only required to linearly increase the solar field area, and the investment for heat storage and exchange systems and conventional islands does not need to be increased accordingly. In addition, the current strategy/policy for cluster development in forms such as CSP industrial park is likely to further enhance the synergistic relationship between CSP plants and equipment supply and reduce the amount of supporting investment. Therefore, the large-scale development of CSP will significantly reduce the unit development and construction cost (per kWh) of CSP plants.

It is estimated that, by 2025, the construction and development costs of hybrid CSP plants and CSP plants with large single-unit capacity can be reduced by 3-5% compared with the first batch of CSP demonstration projects.

(3) Technological innovation, optimization and experience accumulation in the CSP industry

Through the implementation of the first batch of CSP demonstration projects, a number of talent talent teams capable of performing technology research and development, system design, construction, commissioning and operation of CSP plants have been established, thus providing the platform and basis for the use and operation of critical equipment, the optimization of system design, and the commissioning, operation and maintenance of CSP plants. The purpose of eliminating deficiencies, optimizing system design and acquiring experience in plant operation has been achieved through the deployment of the first batch of CSP plants. It is expected that, through design optimization and operation plan upgrading, the overall project success rate and electricity generation will be improved, and the plant construction and operation costs will be reduced. The construction and operation costs of MS linear Fresnel CSP plants are expected to be reduced by approximately 5% by 2025.

In, through the verification and optimization of the first batch of CSP demonstration projects and continuous technological innovation and improvement, the overall efficiency of CSP plants will improve continuously. For the linear Fresnel technology, the use of lightweight structures, the improvement of heat collection efficiency, the optimization of materials for components such as supports, and other technological innovations can significantly reduce the construction costs of linear Fresnel CSP plants. It is expected that the costs of such plants will be reduced by more than 10% by 2025.

(4) Long-period energy storage and CSP/PV capacity ratio optimization can help improve the cost-effectiveness of CSP plants in the new electric power system.

As renewable energy generation systems, CSP plants can regulate the load of electricity from other renewable sources and are provided with long-term energy storage systems. The position of CSP plants in the new power system has gradually changed from CSP demonstration plants capable of generating electricity continuously 24 hours day to renewable power sources capable of regulating peak load on the power grid. Therefore, the optimization of the solar field capacity and energy storage capacity of CSP plants, the optimization of the ratio of CSP to other energy sources in hybrid CSP projects, the satisfaction of grid dispatching needs by CSP plants, and the engagement of CSP plants in spot transactions can significantly improve the cost-effectiveness of CSP plants and enable CSP plants to truly realize the market value offered by their long-term energy storage capability and provide a more stable, reliable, and cost-effective renewable energy solution for the new electric power market.

In summary, large-scale development, continuous technological innovation and system optimization, and supports from related policies and power market will all contribute to cost reduction for CSP projects. Calculations show that, by 2025, the LCOE of MS linear Fresnel CSP plants with single-unit capacity higher than 300 MW will be reduced by about 50% compared with the first batch of CSP demonstration projects, and the cost-effectiveness of such plants will therefore be significantly improved.

Chapter VII Whole Lifecycle Carbon Emission of CSP Plants

Taking the 135 MWe solar tower plants in Northwestern China as research objects, Zhu Xiaolin et al.[20] from Cosin Solar Research Institute Co., Ltd. calculated the carbon emissions over the whole lifecycle of such plants. The parameters and conditions set for their research are as follows: plant life cycle: 25 years; average annual direct normal irradiance: 2,015 kWh/m^2; mirror field area: 1.45 million m^2; average annual solar-cell efficiency: 14.9%; period of thermal energy storage in cold and hot molten salt tanks: 11.2 hours; cooling method: direct air cooling. For a single solar tower plant, the design annual electric output taking into account peak load regulation is 435 GWh, and the annual amount of electricity fed into the grid by the plant taking into account auxiliary power consumption is 395 GWh. The life cycle of a solar tower plant can be divided into four phases, namely, plant equipment and material manufacturing phase, construction and installation phase, operation and maintenance phase, and abandonment phase.

The research has found that the carbon emissions per kWh by a solar tower plant over its whole life cycle is 22.7 gCO_2e/kWh, which is a low level of carbon emissions per unit by similar power plants at home and abroad. In addition, it has also been found that the carbon emissions per kWh by a solar tower plant over its life cycle decline as the average annual DNI and TES period increase, and the rate of such decline gradually decreases.

Carbon emissions per kWh in the four stages of the life cycle of a solar tower plant: the carbon emissions per kWh during the equipment and material manufacturing phase are the highest, accounting for 87.40% of the total carbon emissions per kWh by the plant over its whole life cycle; the carbon emissions per kWh during the operation and maintenance phase account for 7.16% of the total carbon emissions per kWh by the plant over its whole life cycle; the carbon emissions per kWh during the abandonment phase are 0.75 gCO_2e/kWh, account for 3.33% of the total carbon emissions per kWh by the plant over its whole life cycle; the carbon emissions per kWh during the equipment and material manufacturing phase are the lowest. The carbon emissions per kWh in the four stages are presented in the table below.

Calculations show that the total electricity output of 135 new solar tower plants (each with a capacity of 135 MWe) is equivalent to 1% of the electricity generated by all thermal power plants in China, and these new solar tower plants can reduce CO_2 emissions by 49 million tons per year and by 1.225 billion tons over their whole lifecycle.

Table 7.2-1 Whole lifecycle (WLC) carbon emissions (per kWh) of 135 MWe solar tower plants in Northwestern China

LCA phase	Carbon emissions per kWh (g CO_2e/kWh)	Proportion	Description
Equipment and material manufacturing phase	19.8	87.4%	For a single solar tower plant, the carbon emissions per kWh by the mirror field are the highest (7.87 g CO^2e/kWh), accounting for about 40.8% of the total WLC carbon emissions per kWh by the plant. The reason is that the fabrication of heliostats at a solar tower plant requires large quantities of steel and glass. The carbon emissions per kWh by the TES system are 4.04 g CO_2e/kWh, accounting for about 20.9% of the total WLC carbon emissions per kWh by the plant. Specifically, the carbon emissions per kWh by the hot and cold salt tanks account for 49.7% and 12.9% of the carbon emissions per kWh by the TES system, respectively. The reason is that the hot and cold salt tanks are constructed of large quantities of materials, and their weights are 2248 t and 2120 t, respectively. The carbon emissions per kWh by the account for about 9.8% of the total WLC carbon emissions per kWh by the plant. The solar tower and its foundation consume large amounts of high-grade reinforced concrete.
Construction and installation phase	0.48	2.11%	The carbon emissions per kWh in the construction stage are 0.41 g CO_2e/kWh, and the carbon emissions per kWh in the installation stage account for a relatively small proportion.
Operation and maintenance phase	1.62	7.16%	The carbon emissions per kWh during the operation and maintenance phase include emissions from one-time energy consumption for plant commissioning, electricity consumption for heating, and energy consumption for employee canteens and transportation. The energy consumption modes adopted during the operation and maintenance of different types of CSP plants have great impacts on the carbon emissions per kWh by these plants.
Abandonment phase	0.75	3.33	The carbon emissions per kWh during the dismantling of plant buildings and equipment account for 57.33% of the total carbon emissions per kWh during the abandonment phase.

Chapter VIII Challenges and Recommendations for CSP Development in China

8.1 Challenges faced by China's CSP industry

8.1.1 China's CSP industry is developing rapidly, and the costs of CSP plants are declining rapidly but are still higher than those of solar PV and wind power plants.

In September 2016, NEA organized the implementation and construction of a number of CSP demonstration projects in order to promote the development of China's CSP industry, create a domestic CSP equipment production chain, and develop system integrators. For these projects, the benchmark electricity price approved by NDRC 1.15 Yuan/kWh (which is the same as that of solar PV-generated electricity in 2011; the total installed capacity of solar PV power plants in China as of 2011 is 3 GW). Through the construction of CSP demonstration projects, China has fully mastered the core technologies for solar concentrators, receivers, and heat storage and exchange systems of CSP plants and technologies for the design, integration, construction and operation of CSP plants suitable for application in in high-altitude alpine areas in China, broken foreign monopoly in the CSP industry, and developed CSP technologies with complete intellectual property rights. In addition, the number of enterprises and institutions engaged in the CSP industry and their product supply capacity have increased significantly. These advances have provided a solid foundation for the future development of China's CSP industry.

In the Notice of the National Development and Reform Commission on Matters Related to the 2021 New Energy Feed-in Tariff Policy, it is stated that, after 2019, China will improve the policy for CSP-generated electricity prices at the opportune time and gradually reduce the prices of electricity generated by newly constructed CSP plants based on the development status of the CSP industry and the reduction of electricity generation costs. However, according to the Opinions on Promoting the Healthy Development of Non-hydro Renewable Power Generation issued by the Ministry of Finance in January 2020, new CSP projects will no longer receive financial subsidies/assistance from the Chinese government. According to the Notice of the National Development and Reform Commission on Matters Related to the 2021 New Energy Feed-in Tariff Policy (NDRC Pricing Document [2021] No. 833), from 2021 onwards, the electricity prices for newly approved (registered) CSP projects shall be determined by competent provincial authorities (pricing authorities) and may be determined through competitive allocation where conditions allow; if the feed-in tariff for a CSP project is higher than the local benchmark price of electricity generated by coal-fired power plants, the part of the feed-in tariff within the benchmark price will be settled by the responsible power grid enterprise.

As of the end of 2023, the total installed capacity of grid-connected CSP plants in China is only 570 MW; China's CSP industry is in the early stage of development, and the LCOE still remains at high levels; therefore, unlike the wind power industry that has been developed under subsidies for decades, the CSP industry does not have conditions for grid parity. In addition, importance has not been attached to the quality of electricity from CSP plants, and the value of CSP plants in promoting renewable energy consumption has not been evaluated in a scientific manner and reflected in electricity prices.

8.1.2 The CSP industry chain is complete with supporting services, but the limited number of CSP plants cannot provide sufficient driving force.

The application of CSP technologies started later in China compared with the case in other countries. The world's first commercial solar power plant was built in the 1980s (in the United States), and Europe's first commercial solar power plant was put into operation in 2007. In comparison, China's first 50 MW solar power plant was put into operation in 2018. CSP involves complex systems and multiple disciplines such as thermodynamics, heat transfer, optics, materials science, and automatic control. Through the construction of CSP demonstration projects, China's overall technical capability for CSP development has been improved to such an extent that it is basically on par with the level of second-generation commercial CSP plants in foreign countries, and the design, operation and maintenance of some CSP plants in China have reached the international leading level. However, due to the high initial investment of CSP projects and the absence of favorable national feed-in tariff policies and subsidies, there is a lack of activity in CSP investment; the opportunities for iterative upgrading of CSP technologies are insufficient; standardization and centralization have not been achieved in some aspects, such as design, construction, and equipment manufacturing; economies of scale have not been fully achieved; the cost of electricity per kWh still remains at high levels. These factors limit the large-scale development of China's CSP industry. Moreover, the renewable energy + grid-forming energy storage technology is gradually maturing, and the costs of powerful battery energy storage systems that have emerged with the development of electric vehicles are declining continuously. Therefore, how to rapidly reduce costs and improve efficiency is a huge challenge for the development of China's CSP industry.

8.1.3 CSP plants have been used for peak shaving, but their installed capacity is insufficient to reflect their values.

CSP is a renewable power generation technology that is capable of being adjusted flexibly and supporting power systems, and it is the only renewable energy technology having the potential to replace coal-fired power plants. However, the main purpose of the first batch of CSP demonstration projects is to verify the feasibility of the CSP technology. For existing large wind and solar power bases, the installed capacity and system configuration of CSP plants are subject to the economic considerations for grid parity, CSP plants are positioned as "power sources for peak shaving", and their installed capacity accounts for a relatively small proportion of the total installed capacity of energy bases (the CSP to wind/PV capacity ratio is 1:6 or 1:9), making it difficult for them to support the power grid/system. In addition, there is no quantitative data demonstrating the values of CSP plants in the construction of a new electric power system where renewable energy plays a dominant role, including the role played by CSP plants in improving grid stability and increasing the installed capacity of wind and PV power plants, and such values have not been reflected in electricity prices.

8.2 Recommendations for the development of China's CSP industry

8.2.1 The first recommendation is to investigate and develop a two-part electricity pricing system for CSP plants during the transition from subsidy removal to market-based development.

The initial investment for CSP plants is high. Currently, CSP plants at existing large wind/solar energy bases are positioned as "power sources for load regulation" and developed together with wind/solar farms in an integrated manner. Under the prevailing operation strategy for such energy bases, PV power plants operate during noon hours when solar radiation is high, while CSP plants only generate electricity during peak hours in the morning and evening, and the annual service hours of CSP plants have decreased from about 4,000 hours to 2,000 hours or even lower levels. It is recommended to first carry out a market-oriented reform of the current electricity pricing mechanism for renewable energy bases; investigate and develop a two-part electricity pricing system for CSP plants; determine the applicable electricity prices and national compensation standards for CSP plants based on the costs of typical CSP plants across China; create relatively stable profit expectations and income sources for CSP plants; give full play to the role of CSP plants in providing load regulation and ancillary/supporting services to the electric power system, and thereby increase the proportion of electricity from renewable sources at renewable energy bases.

In addition, it is recommended to, based on CSP capacity pricing, couple and monetize the electric energy value (medium- to long-term or spot electricity markets), load regulation value (auxiliary services) and environmental value (CCER, green electricity, green certificates) of CSP, improve activity in investment for CSP projects, ensure the continuous healthy operation of the CSP industry, and promote renewable energy consumption at a larger scale in the context of gradual de-coaling and "dual carbon" goals. In the future, with the development of China's electricity market and the continuous improvement to top-down design, the prices of electricity generated by CSP plants will eventually be determine by the market rather than the government, the competitive advantage of CSP plants in the electricity market will be enhanced continuously, and CSP plants will adapt to the needs of system load regulation in the current stage and baseload power supply in the future, thus ensuring the long-term adequacy of electricity generation capacity in the electric power system.

8.2.2 The second recommendation is to conduct research on the grid support capability of CSP plants as soon as practicable.

Due to economic considerations for grid parity, the CSP/PV capacity ratios of large renewable energy projects are very low, and the role of such projects in improving grid stability and reliability still remains unclear. The low capacity ratios of large renewable energy projects are probably far from sufficient to meet the power quality and transmission requirements. It is recommended to conduct research on the grid support capability of CSP plants as soon as practicable; build renewable energy bases based on the characteristics of DC power transmission from 10,000 MW-scale large energy bases, the characteristics of the power grid in West China, and the electricity demand of end users to provide

[5] The content of this section is mainly compiled by researcher Wang Zhifeng at IEECAS.

100% renewable energy and participate in peak load and frequency regulation in the electric power system; conduct research on the optimization of grid operation and control strategies; optimize the transmission and consumption capacity configuration and control of large energy bases based on the analysis and study of the characteristics of various energy storage technologies and the response characteristics of energy storage systems; verify the actual performance of CSP plants in peak load regulation and their grid support capacity using project data; determine the coefficients and periods corresponding to electricity prices based on the load characteristics of the areas receiving electricity; use electricity prices that can truly reflect the relationship between electricity supply and demand; implement incentive programs to fully leverage the role of CSP plants in peak load regulation in the electric power system/grid.

8.2.3 The third recommendation is to continuously summarize the experiences of existing commercial CSP plants, make technological innovation, and reduce costs. The specific recommended measures are detailed in the following paragraphs.

1) The first measure is to extend the service life of core equipment and improve their reliability. Since CSP plants integrated with solar PV and wind power stations will need to be started up and shut down frequently and operate at significantly different loads in the future, thermal stress problems may occur frequently in solar receivers, heat storage and exchange equipment, and steam turbines. The fatigue and safety issues arising from frequent startups and shutdowns are not to be neglected. Therefore, it is necessary to conduct relevant research and further improve the safety and reliability of materials and equipment. It is recommended to conduct research on equipment such as 100 MW-scale solar receivers, molten salt storage tanks, thermal shock-resistant steam turbines, and large-capacity steam generators and carry out the research, development and validation of lightweight parabolic trough collectors (PTCs) with large apertures and intercept factors and related products such as supports/brackets, mirrors, and receiver tubes.

2) The second measure is to optimize the cloud coverage management strategy. Cloud coverage is an important factor affecting heat collection and electricity generation at CSP plants. Short-term obstruction by clouds and passing of clouds can lead to great changes in solar irradiance on the receiver surface, affecting the service life of solar receivers and safe operation of CSP plants. An optimal strategy for cloud coverage management can reduce the impact of thermal shock on plant equipment and reduce operational risks. It is recommended to develop more accurate short-term cloud coverage/solar irradiance forecasting systems.

(3) The third measure is to improve the efficiency of the collector field. The low-cost PV heating molten salt technology has a huge impact on the collector fields of CSP plants. Among the systems of a CSP plant, the collector field has the highest cost of capital. On the one hand, it is necessary to develop low-cost solar collectors, collector field control systems, and mirror self-cleaning technologies based on the needs of existing commercial CSP plants, improve the dynamic accuracy of solar collectors, and reduce spillage losses in solar collector systems. On the other hand, it is necessary to adopt new solar concentration/collection methods to reduce cosine loss and truncation loss, improve the average annual optical efficiency of collector fields, and use smaller collector fields to increase energy output, thereby reducing the costs of collector fields.

(4) The fourth measure is to improve the performance of critical materials. It is necessary to develop high-temperature and high-stability photo-thermal conversion materials, high-temperature and high-performance heat transfer materials, high-temperature, high-power, long-life and low-cost "thermal energy charge/storage/release" materials, and flexible reflective materials.

(5) The fifth measure is to organize specialized third-party technicians to summarize the experiences of CSP demonstration projects and test/evaluate the demonstration CSP plants in operation. It is recommended to test the performance parameters of the core equipment, subsystems, systems and auxiliary equipment of demonstration CSP plants, prepare detailed test reports, review experiences and lessons learnt, and develop equipment design methods, operation procedures, system design specifications, and accident management guidelines based on the test data.

(6) The sixth measure is to promote the development and application of precision measuring instruments in China. Considering that most of the testing and measuring instruments used in China are imported products, it is recommended to focus on the development and engineering application of instruments such as high-energy flow density measurement systems, error measurement instruments for production lines, onsite solar concentrators and parabolic trough collectors, and HT molten salt and solids flow meters.

8.2.4 The fourth recommendation is to carry out demonstration projects for cutting-edge CSP technologies and continue to deepen basic research.

Technological innovation is a driving force for the sustainable development of the CSP industry. It is recommended to contact research on disruptive cutting-edge technologies as soon as practicable; provide support for the research and development of new CSP technologies and the implementation of demonstration projects for such technologies; carry out basic research on low-cost solar concentration techniques covering the shape of the sun, the energy properties of solar radiation, adaptive control methods for curved optical surfaces, the effects of high-density concentrated solar energy on surface microstructures, solar-to-chemical energy conversion, storage and reaction equipment, and supercritical steam generators; carry out research and demonstration projects for 20-50 MWe CSP plants with HT supercritical CO_2 power cycles based on the basic research conducted on solar energy generation with supercritical CO_2 during the "13th Five-Year Plan"; carry out R&D and demonstration of cutting-edge technologies for CSP plants using environmentally friendly heat transfer and storage media and 50 MW-scale solar thermochemical gas-fired power plants; carry out theoretical research on cutting-edge CSP technologies such as energy conversion based on the second-law efficiency and electricity generation coupling solar concentration and HT hydrogen fuel cell systems.

8.2.5 The fifth recommendation is to launch CSP demonstration projects with large single-unit capacity as soon as practicable.

It is necessary to promote the implementation of large-capacity, low-cost CSP plants; further improve the flexibility and load regulation capacity of such plants by strengthening the research, development, testing and demonstration of new equipment and new technologies; speed up the process of technological improvement and equipment upgrading; improve the electricity generation efficiency of CSP plants; reduce the costs of electricity generation per unit; enhance the competitiveness of CSP plants in the electric power market. Therefore, it is recommended to carry out demonstration projects for large CSP + hybrid energy bases with large single-unit capacity and high capacity ratios as soon as practicable, summarize the characteristics of such energy bases with respect to electricity generation and peak shaving, and increase the capacity of CSP plants to the 1,000 MW scale to support the construction of the new electric power system where renewable energy plays a dominant role.

8.2.6 The sixth recommendation is to promote the application of multi-energy complementary low-carbon power generation technologies where CSP plays a dominant role.

It is recommended to promote the application of multi-energy complementary power generation technologies in which CSP, thermal power and nuclear power complement each other, CSP is combined with the HT hydrogen fuel cell technology, or CSP and biomass energy complement each other; for large energy bases, consider the use of 1,000 MW-scale hybrid energy systems where CSP and thermal power are integrated and CSP plays a dominant role. The objective is to increase the peak shaving capacity by 4 times and reduce coal consumption per kWh by 70%.

8.2.7 The eighth recommendation is to launch centralized demonstration projects for multiple types of novel CSP plants with thermal energy storage and study the role and characteristics of such plants in the power grid/system.

Energy storage technologies such as MS TES (molten salt thermal energy storage), pure electric heating MS TES, CAES (compressed air energy storage), and EES (electrochemical energy storage) are all suitable for long-term energy storage and peak shaving scenarios for large-scale and long-life CSP plants in the power system. For regions where the resource conditions are equivalent to those of Qinghai or Gansu, it is recommended to launch centralized demonstration projects for CSP technologies with pure molten salt TES, PV + pure electric heating MS TES, CAES and EES, investigate the power generation characteristics of these technologies in different seasons and under different meteorological conditions, and evaluate the actual grid support capacity/performance of such technologies while ensuring the same overall on-grid power curve.

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