中国可再生能源学会太阳能热发电专业委员会

Concentrating Solar Power Committee of Chinese Renewable Energy Society

CSTA

China Solar Thermal Alliance

Blue Book of China's Concentrating Solar Power Industry 2022

www.cnste.org

Foreword

China Solar Thermal Alliance (CSTA) is a non-profit organization that supports and promotes the development of solar thermal technology and industry with the strength of all CSTA’s members from universities, institutes and industry.

The Blue Book of China's Concentrating Solar Power Industry 2022 (Chinese version) was completed on Jan., 2023 by CSTA and the Concentrating Solar Power Committee of China Renewable Energy Society (CRES) in order to provide the reference for the industry and policy-makers.

The Chinese report was prepared by Ms. Fengli Du, the secretary-general of China Solar Thermal Alliance and Prof. Zhifeng Wang, Prof. of Institute of Electrical Engineering, Chinese Academy of Sciences, with review of expert committee of CSTA and approval by Academician, Prof. Yaling He for release.

In order to help the international community understand China's concentrated solar power development in general, we translated the report. But please understand that the translation may be insufficient.

The China Solar Thermal Alliance has the copyright of this Blue Book. The information and data contained herein can be used for reading and reference. Material in this publication that is attributed to third parties may be subject to separate terms of use and restrictions, and appropriate permissions from these third parties may need to be secured before any use of such material.

Where any text, data, or figure herein is reprinted or cited, the source thereof must be cited as: CSTA (2022), Blue Book of China’s Concentrating Solar Power Industry 2022, China Solar Thermal Alliance (CSTA), Beijing, 2023.

Zhifeng Wang,

Chairman of China Solar Thermal Alliance

Prof. of Institute of Electrical Engineering, Chinese Academy of Sciences

Blue Book of China's Concentrating Solar Power Industry 2022

China Solar Thermal Alliance (CSTA)
Concentrating Solar Power Committee of China Renewable Energy Society

February 2023

Blue Book of China's Concentrating Solar Power Industry 2022

Approved by: Dr.YalingHe, academician of the Chinese Academy of Sciences, prof. at the Xi'an Jiaotong University, director of the advisory board of China Solar Thermal Alliance

Coordinator: Dr. ZhifengWang, prof. Of Institute of Electrical Engineering, Chinese Academy of Sciences, chairman of the China Solar Thermal Alliance and Concentrating Solar Power Committee of China Renewable Energy Society

Editors: Fengli Du, secretary-general of China Solar Thermal Alliance and Concentrating Solar Power Committee of China Renewable Energy Society

Dr. Wang Zhifeng (chapter five and seven)

Translated by: Cheng Zhang

Reviewed by: the Advisory Board of China Solar Thermal Alliance

Acknowledgement: Owners of CSP demonstration plants, Dr. Fengwu Bai, Dr.Chun Chang, Dr. Zhiheng Lu, Dr. Dongqiang Lei, Dr. Ershu Xu, Mingchuan Wang, Song Hong, Qingfeng Dong

Table of Contents

1.Concentrating Solar Power Technology and its Position

1.1 Overview of concentrating solar power

1.1.1 Definition and main features

Concentrating solar power (CSP for short) systems convert solar energy into thermal energy and generate electricity through a thermal conversion process [1]. CSP systems use solar collectors at the front end and synchronous generator sets at the back end to generate electricity, and they are provided with large-capacity, long-cycle, high-security thermal storage (TES) systems. The basic operating principle of a CSP system is described below. The solar concentrator tracks the sun, reflects and focuses direct solar radiation onto the solar receiver to heat the heat transfer fluid inside the receiver and convert solar energy into thermal energy; thermal energy can directly exchanges heat with water to produce high temperature and high pressure (HTHP) steam to drive a turbine generator set to generate electricity or be stored in an energy storage tank and released to generate electricity when needed.

Depending on the form of solar concentration, the commercial CSP plants in the world can be classified into three main types, namely, solar tower plants, parabolic trough CSP plants, and linear Fresnel CSP plants. Solar tower plants use point focus collectors, while parabolic trough and linear Fresnel CSP plants use line focus collectors. One of the main features of a CSP plant is its ability to achieve 24h continuous and stable power generation. CSP plants are equipped with long-cycle, large-capacity TES systems that can support the long-term continuous operation of generator sets at night or at low loads when required by the grid. For the first CSP demonstration projects in China, the duration of thermal storage (the number of hours required to enable turbine generator sets to operate at full load) varies from six hours to 15 hours. Taking the following two CSP plants with the largest capacity as examples, the Shouhang Dunhuang 100MW solar tower plant has a storage capacity of 1.1GWh, and the China Shipbuilding New Power Urat 100MW parabolic trough CSP plant has a storage capacity of 1GWh. According to the typical weekly data of a solar tower plant with 7h thermal storage, the generator sets can operate continuously for 14 hours at 40% load factor when the molten salt storage tank is full at night. According to the research conducted by China Solar Thermal Alliance, the CGN Delingha 50MW parabolic trough CSP plant operated safely and continuously for 230.2 days from September 19, 2021 to May 7, 2022; the China Shipbuilding New Power Urat 100MW parabolic trough CSP plant generated power continuously for 12 days without downtime during the period from June 4 to June 15, 2022 including six cloudy days; the Qinghai SUPCON Delingha solar power plant achieved a record of 12 days of continuous operation (292.7 hours); the longest duration of uninterrupted power generation at the Shouhang Dunhuang 100MW solar tower plant is about 263 hours.

The method of energy storage at CSP plants is highly secure. The molten salt used at existing commercial CSP plants is a mixture of potassium nitrate and sodium nitrate. Since the world’s first CSP plant using molten salt as a heat transfer and storage medium was put into operation (Solar Two, USA, 1995), the CSP plants installed worldwide with a total installed capacity of 7GW (with a total storage capacity of more than 1000GWh) have not experienced any safety incidents such as explosion.

The use of CSP generators is a renewable energy-based power generation method that can give full play to coal-fired power plants. According to the results of an evaluation of grid-connected CSP demonstration projects jointly conducted by the China Renewable Energy Engineering Institute (CREEI), China Solar Thermal Alliance (CSTA), China Electric Power Planning & Engineering Institute (EPPEI), and China Electric Power Research Institute (CEPRI), CSP plants have multiple capabilities, such as quick response, synchronous support, active-power frequency regulation, reactive-power voltage control, and low-frequency oscillation suppression in power grids. The minimum technical output of most CSP plants can reach about 15%-20% Pe (design output), which is higher than that of conventional coal-fired power plants. The average load ramp-up rate and average load ramp-down rate of CSP plants are about 1.5%~3% Pe/min and about 2.5%-5% Pe/min, respectively, which are basically the same as the load ramp rates of conventional coal-fired power plants. In terms of frequency support, CSP plants are connected to the power grid with synchronous generators, can provide inertial support to the grid, and have multiple advantages such as high front-stage heat exchange efficiency and quick response for participating in grid frequency regulation. In terms of voltage support, as voltage support power sources, CSP plants can reduce the degree of grid strength reduction caused by the connection of wind power and PV power plants to the grid and play an important role in providing adequate voltage support and stabilizing the grid voltage. In terms of support for rotor angle stability, with their rapid thermal regulation capacity and the synchronous support provided by synchronous generators, CSP plants can quickly respond to the grid demand and play an important role maintaining the rotor angle stability in power systems.

1.1.2 Components and operating principles of CSP systems

CSP systems use different heat transfer fluids (HTF) to absorb heat. The main HTFs used in CSP systems include molten salts (binary nitrates, chloride salts), heat transfer oils (biphenyl and biphenyl ether mixtures), water, granules, and liquid metals. Materials such as molten salts, phase change materials (PCM), and concrete can be used as thermal storage (TES) media. Currently, molten salts are the most widely used commercial TES media. The components and operating principles of CSP systems with different HTFs are briefly described below.

A molten salt tower (MST) CSP plant can consist of four major systems, namely, solar concentration system, solar absorption system, TES and heat exchange system, and power generation system. The main components and equipment include heliostat, solar absorption tower, solar receiver, molten salt storage tank, steam generator, and turbine generator set. The basic operating principle of an MST CSP plant is described below. The heliostats arranged in a circular pattern around the solar absorption tower track the sun (azimuth and altitude angle adjustment/control), reflect and focus sunlight onto the solar receiver at the top of the solar absorption tower to heat the low-temperature molten salt pumped into the heat absorber by the cold molten salt pump. The heated molten salt (heated to about 565°C) flows into the high-temperature molten salt storage tank through a pipeline. When power generation is required, the high-temperature molten salt exchanges heat with water, generating HTHP steam that drives the turbine generator sets to generate electricity. The molten salt that has released heat is transferred through the steam generator to the low-temperature molten salt storage tank and then recirculated to the solar receiver at the top of the solar absorption tower for heating.

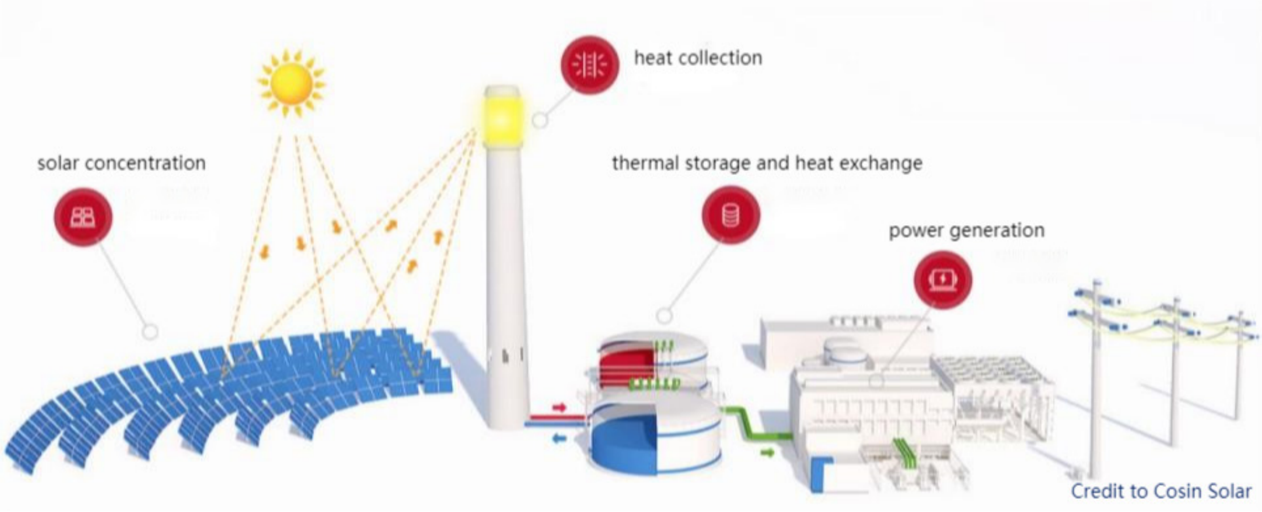


Figure: molten salt solar tower plant diagram

A parabolic trough CSP plant can consist of solar field, TES and heat exchange block, and power generation block. The main components and equipment include parabolic trough solar collector, oil-to-salt heat exchanger, hot molten salt tank, cold molten salt tank, steam generator, and turbine generator set. Several parabolic trough collectors are connected in series to form a standard collector loop, and a large number of standard collector loops are connected in parallel to form a solar field.

The basic operating principle of a parabolic trough CSP plant is described below. The parabolic trough solar collectors track the sun and collect solar radiation to heat the HTF circulating in the collectors. The hot HTF is transferred to the steam generator and releases thermal energy to heat the water, producing superheated steam that drives the turbine generator sets to generate electricity. The HTF that has released heat is routed back to the solar field to re-absorb heat. When the sunlight is strong during the daytime, part of the HTF will be transferred to the oil-to-salt heat exchanger and releases thermal energy to heat the molten salt, and the hot molten salt is stored in the hot molten salt tank. At night, the thermal energy of the molten salt in the hot molten salt tank is released to heat the HTF, and the heated HTF is transferred to the steam generator to heat the water, producing steam for continuous electricity generation.

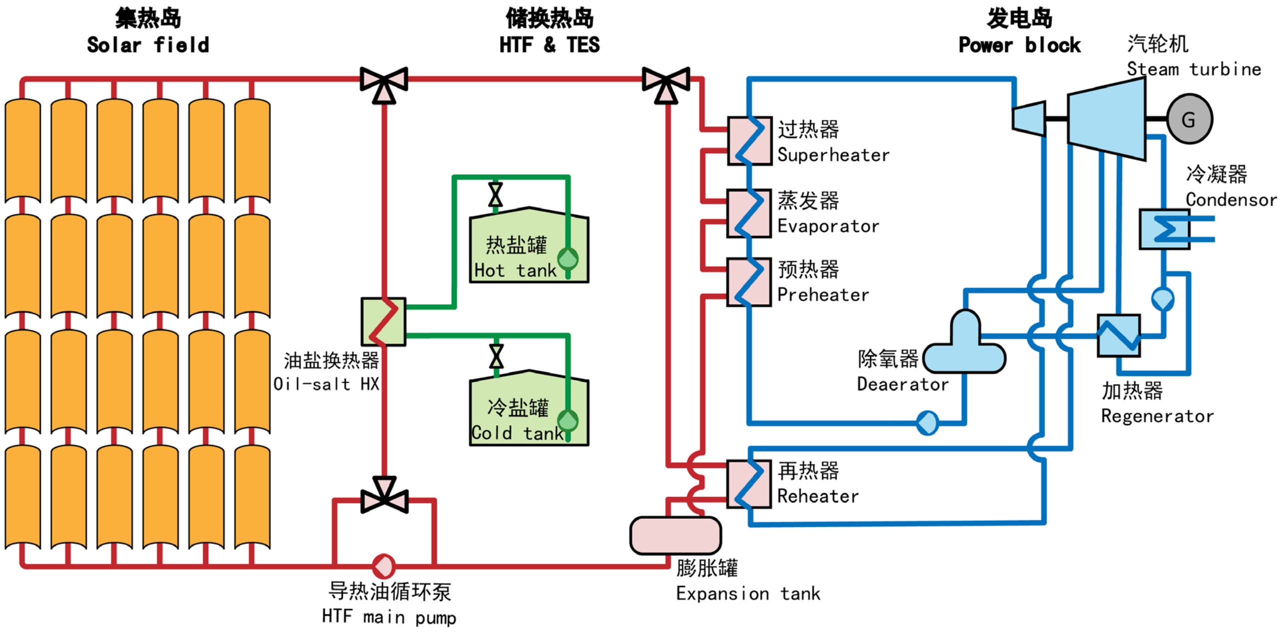


Diagram of a parabolic trough CSP plant (with conventional processes) (source: ROYAL TECH CSP)

A parabolic trough CSP plant can also be designed with decoupled processes. The operating principle of such CSP plant is detailed below. The parabolic trough solar collectors track the sun and collect solar radiation for heating the HTF. All hot HTF is routed to the oil-to-salt heat exchanger and transfers all of its heat to the molten salt. After the molten salt absorbs heat, its temperature rises, and the hot molten salt is stored in the hot molten salt tank. At this point, the solar thermal collection and storage process is complete. When power generation is required, the molten salt in the hot molten salt tank directly enters the steam generator and releases thermal energy to heat the water, producing superheated steam that drives the turbine generator sets to generate electricity. After the hot molten salt releases thermal energy, its temperature drops, and the cold molten salt is routed back to the cold molten salt tank for storage. At this point, the heat release and power generation process is complete. By decoupling the solar thermal collection and storage process and the heat release and power generation process, the impact of fluctuations in solar radiation at the front end on the stability of power generation at the back end can be minimized to the greatest extent possible.

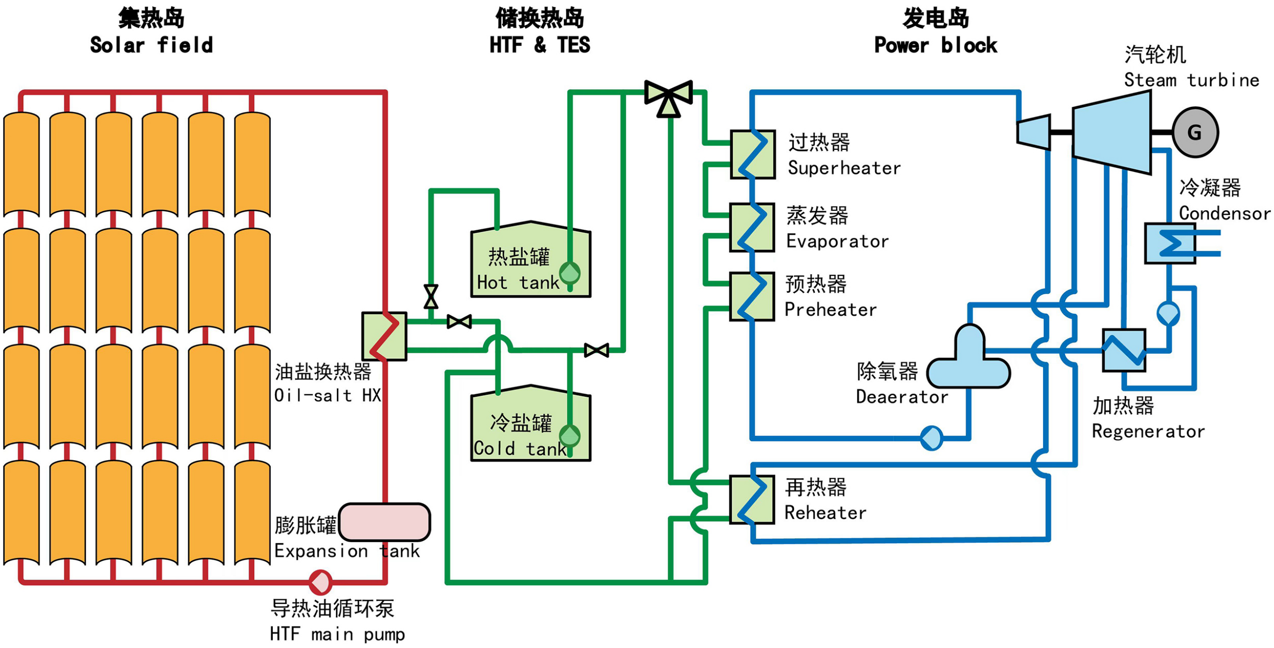


Diagram of a parabolic trough CSP plant (with decoupled processes) (source: ROYAL TECH CSP)

Molten salts can be used as the heat transfer and storage media in parabolic trough CSP systems. The operation process of a parabolic trough CSP plant that uses a molten salt as the heat transfer medium is described below. The parabolic trough solar collectors track the sun and collect solar energy to heat the molten salt. After the molten salt absorbs heat, its temperature rises, and the hot molten salt is stored in the hot molten salt tank. When power generation is required, the molten salt in the hot molten salt tank enters the steam generator and releases thermal energy to heat the water, producing superheated steam that drives the turbine generator sets to generate electricity. After the molten salt releases heat, its temperature drops, and the cold molten salt is returned to the cold molten salt tank for storage.

A linear Fresnel CSP plant that uses a molten salt as the heat transfer medium mainly consists of three systems, namely, solar field, thermal storage system, and power generation system. The main components and equipment include primary mirror reflector, secondary concentrator, tube receiver (these three components form the solar field), molten salt storage tank, steam generator, and turbine generator set. The basic operating principle of such CSP plant is described below. Multiple compactly arranged mirror reflectors form an arc-like structure. Through automatic tracking, the primary mirror reflectors focus sunlight into the compound parabolic concentrators above, and then the sunlight is reflected and converged to the vacuum tube receivers fixed in the concentrators, heating the molten salt inside the tubes. The hot molten salt is stored in the molten salt storage tank and used to produce the steam required for power generation through heat exchange at the required time.

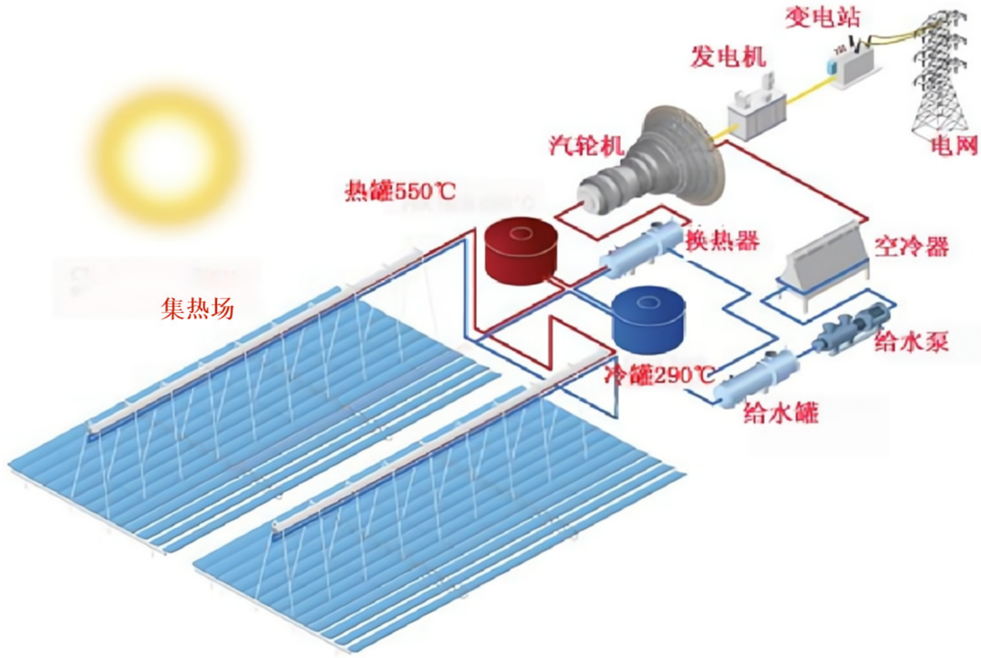


Diagram of a linear Fresnel CSP plant using a molten salt as the heat transfer medium (source: DCTC)

1.2 Role and positioning of CSP

1.2.1 Needs and challenges of new power systems

On March 15, 2021, the Central Financial and Economic Affairs Commission (CFEAC) proposed to replace fossil fuels with renewable energy sources, deepen the reform of the electric power system, and build a new power system with new energy as the mainstay. It is expressly stated in the Report to the 20th National Congress of the Communist Party of China (CPC) that China will work actively and prudently toward the goals of reaching peak carbon emissions and carbon neutrality, thoroughly advance the energy revolution, promote the use of coal in a clean and efficient way, and speed up the planning and development of a system for new energy sources. The new power system will serve as the core component of China's future energy system, which means that the proportion of electric power generated from renewable energy sources mainly represented by wind and sunlight will increase significantly. According to the research and forecast of academician Xiaoxin Zhou, with the rapid development of power generation from renewable sources such as wind and sunlight, the proportion of electricity capacity from non-fossil energy sources in the total installed power generation capacity will exceed 50% by the end of the “14th Five-Year Plan” period. The total installed capacity of wind and PV power plants is increasing continuously and will exceed that of coal-fired power plants in the period from 2025 to 2030. It will reach 1.61 billion kW by 2030, accounting for 41.5% of the total installed power generation capacity, 2.43 billion kW by 2035, accounting for more than 50% of the total installed power generation capacity and becoming the main part of the total installed power generation capacity, and 7.01 billion kW by 2060, accounting for more than 85% of the total installed power generation capacity [2].

Jianbo Guo, an academician of the Chinese Academy of Engineering, stated that the new power system is still operating under the mechanism of AC synchronous motors; the unique characteristics of new energy resources pose some challenges to the electric power system in terms of adequacy, such as great power fluctuations and difficulty in prediction, and more stringent requirements for the system's regulation capacity; long-term high output brings challenges to system safety and energy storage technology; long-term low output brings challenges to power supply guarantee; and the characteristics of new energy equipment bring safety challenges such as reduced system inertia, weak capacity of power supply support, and outstanding system stability problems [3]. Jizhen Liu, an academician of the Chinese Academy of Engineering, pointed out that the construction of a new power system requires the support of key technologies and breakthroughs on the power supply side, grid side, and load side; on the power supply side, efforts should be made to vigorously develop grid-friendly, advanced power generation technologies, multi-energy complementary systems, and flexible power generation technologies [4].

Wind and PV power plants are characterized by the absence of wind during extremely hot weather, the absence of light during peak hours at night, large installed capacity, and low power output. As efforts are being made to achieve the "dual carbon" (carbon peaking and carbon neutrality) goals, the proportion of wind and PV power plants characterized by intermittency and volatility in the electric power system is increasing continuously, and the shortcomings and problems of the electric power system, such as insufficient flexibility and inadequate regulation capacity, are becoming increasingly prominent, which will restrict the development of renewable energy at a higher proportion and a larger scale [5]. In the Notice on Encouraging Renewable Electricity Generation Enterprises to Build or Purchase Peak Shaving Capacity to Increase the Scale of Grid Connection issued by by National Development and Reform Commission (NDRC) and the National Energy Administration (NEA), stating that promoting renewable energy development is the key to reaching peak carbon emissions, consumption is the key to promoting renewable energy development, and grid access, peak shaving, and energy storage are the key to ensuring renewable energy consumption.

In the Carbon Peaking and Carbon Neutrality Action Plan (released by the State Grid Corporation of China (SGCC) in March 2021), it is stated that the SGCC will improve the grid-related performance of new-energy power generation units, accelerate the promotion and application of technologies for power generation from solar thermal energy, increase the proportion of power sources for flexible regulation, build power sources for peak peaking, develop "new energy + energy storage" and CSP, and improve the regulation capacity of the electric power system.

1.2.2 Role of CSP

Based on her research, Yaling He, an alternate member of the 19th and 20th CPC Central Committee and an academician of the Chinese Academy of Sciences, believes that, for the power supply and grid sides, the current electric power system is characterized by high proportion of renewable energy and high proportion of electric and electronic equipment, the continuous decline in the grid system's rotational inertia and inadequacy in the system's frequency and voltage regulation capacity pose serious challenges to system safety, and CSP plants with thermal storage (TES) facilities can achieve effective frequency regulation through the rotational inertia of turbine generator sets; in the flexibility-oriented revamping of thermal power plants, the TES power generation technology can convert the excess steam heat generated during plant operation at variable loads into thermal energy that is stored in the TES medium and released at the required time, which increases both peak shaving capacity and peak load capacity at lower investment and operating costs and has obvious advantages. Energy storage systems have outstanding advantages in terms of storage capacity, large-scale construction and operation costs, operating life, safety, and power output, especially for the consumption of intermittent new energy (wind power, PV, etc.) installed power. Such systems play an important role in building a new power system with new energy as the mainstay, ensuring the safe and stable operation of the electric power system, and especially consuming electricity intermittently generated from new energy resources (such as wind and solar energy). They are the backbone of large-scale energy storage in the future, have very broad prospects for development, and play an important role in the energy revolution [6].

Can Li, an academician of the Chinese Academy of Sciences, stated that, as a large number of wind and PV power plants are connected to the power grid, the corresponding energy storage technologies must be developed, and the scale of energy storage must be consistent with that of renewable energy. CSP technology is the most promising technology for large-scale energy storage and will ensure the large-scale development of wind and PV power generation. The scale of existing energy storage technologies is one or two orders of magnitude behind. Among these technologies, the chemical energy storage technology can achieve the GW level, but its scale is still two orders of magnitude behind the required scale, and the gap is huge. Other energy storage technologies, such as physical energy storage, pumped storage, and flywheel energy storage, are restricted by the existing conditions and cannot solve the problem at the root. After 2030, the role of CSP will become increasingly important. As one of most important technologies for replacing thermal power with renewable energy, CSP technology will become the technical path towards the "dual carbon" goals [7].

Zuoxiu He, one of the theoretical physicists of the first generation after the founding of the People's Republic of China and an academician of the Chinese Academy of Sciences, openly stated that, in addition to pumped storage, CSP energy storage is also a promising technology among new energy storage technologies. CSP is more advantageous than conventional PV power generation in terms of grid connection, and its conversion efficiency is much higher than that of the latter. Moreover, by storing excess heat during the daytime and releasing the stored heat at night to generate electricity, continuous power supply can be achieved, ensuring stable current and avoiding the grid access and peak shaving problems of new energy source-based power generation systems that are difficult solve. In addition, CSP plants with energy storage facilities have great potential and can provide not only electric power, but also steam and heat in industrial and commercial applications [8].

In Discovering the Value of Concentrating Solar Power in High-percentage Renewable Power Systems, it is pointed out by the Energy Internet Research Institute of Tsinghua University that CSP is both a renewable energy source and a flexible power source. Characterized by high flexibility and controllability, CSP systems can be effectively connected to the power grid to generate benefits relying on its renewable-energy nature and flexibility. By leveraging the operational flexibility of CSP systems, it is possible to realize the smoothing effect of CSP bundled with wind energy, solar PV energy, and other energy sources and improve the level of renewable energy consumption in regional energy consumption and bundled energy services. With a high proportion of renewable energy on the grid, CSP plays a significant role in providing support for power supply and is expected to become one of the key sources of power for regulation purposes in some regions. It can also play a role in using renewable energy to consume renewable energy. The results of simulation and calculation show that, taking Qinghai's power grid as an example and assuming that the proportion of renewable power generated in Qinghai remains unchanged, CSP can generate significant economic benefits, and a CSP plant can replace about four PV power plants in terms of installed capacity. With 22GW installed capacity of PV power plants and 7GW installed capacity of wind power plants, Qinghai's power grid can supply electricity in the form of clean energy (including the electric load within Qinghai and the electricity transmitted at extra-high voltage to Henan Province) for three consecutive days in the high-flow season. If CSP plants with a total installed capacity of 4GW are provided on top of these wind and PV power plants, Qinghai's power grid can supply electricity in the form of clean energy for 30 consecutive days during the high-flow season, which will be a world record in respect of continuous power supply [9].

The Report on Exploring the Low-carbon Transition of the Northwestern Power System-The Qinghai Template for Creating a Zero-carbon Power System issued by the Rocky Mountain Institute (RMI) states that CSP is a stable and controllable zero-carbon power source. CSP is a new, controllable energy source, and increasing the proportion of CSP capacity in the installed capacity of renewable-energy power plants can effectively mitigate the phenomenon of abandonment of wind and solar energy while reducing the dependence on purchased electricity during the low-flow season. According to the results of power system simulations under four scenarios involving different installed CSP capacities, an increase of only 3.0GW in the installed CSP capacity can reduce the same amount of thermal power and purchased electricity as 7.0GW of electrochemical energy. In the nearly zero-carbon-emission power system in 2030, under the scenario wherein the additional installed CSP capacity is 3.0GW and the ratios of the additional installed PV power capacity to the additional installed CSP capacity are about 18:1 and 8:1, the annual rate of wind energy abandonment will decrease from 6.8% to 6.2%, the annual rate of solar energy abandonment will decrease from 9.2% to 8.8%, the duration of utilization of gas (natural gas) power will decrease from 3,140 hours to 2,997 hours, and the share of purchased electricity will decrease from 5.4% to 4.9%. CSP can fill the power demand-supply gap in Qinghai during the period of insufficient power output from renewable-energy power plants, provide intraday flexibility, accelerate the process of minimizing the quantity of thermal power, reduce the dependence on purchased electricity, and generate great economic benefits [10].

The EPPEI simulated and calculated the peak shaving capacity of CSP in Xinjiang's power grid. The results show that, if CSP plants with capacities ranging from 1 GW to 5 GW are constructed and put into operation, the loss of electricity resulting from the abandonment wind and solar energy can be reduced by 10.2% to 37.6% [11].

It has been proven in practice that CSP is not only a solution to the utilization of new energy resources and a measure for improving the power systems' regulation capability, but it can also provide necessary basic support for ensuring the stability of power systems with large synchronous generators and for large-scale DC power transmission over extra-long distances and provide necessary rotational inertia, short-circuit capacity, and voltage and frequency support for power grids, especially weakly connected regional grids that have abundant wind and sunlight and are far from load centers. With efforts towards the strategic "dual carbon" goals and the application of a new generation of electric power systems, it is necessary to vigorously develop power sources with large energy storage capacities and synchronous generators connectable to power grids, such as CSP plants. Large-scale CSP systems can gradually replace high-carbon-emission energy sources such as thermal power, serve as a means of grid access and power regulation for renewable energy, and provide important support for power grids in which renewable energy accounts for a large proportion [12].

1.2.3 Positioning of CSP

The results of performance verification of grid-connected power plants and generator sets performed by the existing CSP plants in China show that CSP plants can not only operate continuously to generate electricity independently, but they can also be connected with power grids in both directions through their large-capacity thermal storage systems, convert on-grid peak power into thermal energy, store thermal energy for power generation [12], complement wind and PV power plants in terms of power generation, and increase the consumption of electricity intermittently generated from renewable energy sources. In the Action Plan for Carbon Dioxide Peaking Before 2030 released by the State Council, it is expressly stated that China will actively develop CSP, promote the establishment of comprehensive bases for generating power with renewable resources where solar thermal, PV, and wind power complement each other, and speed up the development of the new electric power system.

The Notice on Encouraging Renewable Electricity Generation Enterprises to Build or Purchase Peak Shaving Capacity to Increase the Scale of Grid Connection issued by NDRC encourages renewable electricity generation enterprises to build or purchase peak shaving capacity in order to increase the scale of grid connection and increase peak shaving resources from multiple channels. CSP plants, pumped-storage power plants, power plants based on novel energy storage technologies such as chemical energy storage, gas power plants, and coal-fired power plants that have undergone flexibility-oriented revamping should be included in the scope of peak shaving resources undertaking the task of renewable energy consumption. At the CSP Conference2021 held by CSTA, Tao Kong, deputy director of the New Energy Division of the Department of New and Renewable Energy of the National Energy Administration of China, expressed that some regions where new energy resources are developed and utilized on a large scale do not have favorable conditions for the development of flexible power sources such as pumped-storage and gas-fired power plants, it is difficult to build additional coal-fired power plants due to ecological protection and other reasons, and there is a lack of solutions to providing peak shaving capability for new energy sources. CSP plants have a variety of advantages, such as flexible and adjustable power output and long-term energy storage capability. Building CSP plants as peak-shaving power sources to generate electricity from solar thermal energy during peak hours in the morning and evening and perform peak shaving for PV power systems during the daytime is beneficial for mitigating the consumption problems arising during the rapid development of new energy sources. As the goals of reaching peak carbon dioxide emissions, achieving carbon neutrality, and building a new electric power system with new energy as the mainstay have been proposed, China's wind and PV power industry will develop at a faster pace in the long-term future, which will bring new opportunities for the development of the CSP industry. In the “14th Five-Year Plan” period, the National Energy Administration of China will continue to support the construction of CSP projects of a certain scale and the integration of CSP plants with wind and PV power bases in regions with high-quality resources, give full play to CSP plants in power regulation and system support, and ensure the sustainable development of the CSP industry by developing the electricity spot market and auxiliary service market as subsidies are withdrawn [13].

The 14th Five-Year Plan for a Modern Energy System issued by the NDRC and the NEA in 2022 put forward to speed up the construction of large wind and PV power bases in key regions such as deserts, Gobi, and desolate areas, actively develop CSP, promote the coordinated development and joint operation of CSP, wind and PV power generation facilities in regions such as Qinghai, Xinjiang, Gansu, and Inner Mongolia. In the Implementation Plan on Promoting the High-Quality Development of New Energy in the New Era issued by the NDRC and NEA which published by the General Office of the State Council, it is proposed to improve the compensation mechanism for peak-shaving and frequency-regulation power sources, strengthen the construction of projects such as CSP plants, and encourage the western regions with good solar conditions to use CSP as the peak-shaving power source. In the 14th Five-Year Plan for Renewable Energy Development issued by nine ministries and commissions including the NDRC, the NEA, and the Ministry of Finance, it is clearly stated that China will build CSP plants with long-term TES capability in regions such as Qinghai, Gansu, Xinjiang, Inner Mongolia, Jilin and other high-quality resource areas, to give full play to the energy storage and regulation capacity and grid system support capacity of CSP plants, so as to promote the integrated construction and operation of CSP, wind and solar PV power generation bases, and improve the stability and reliability of new energy power generation.

2. CSP Market

2.1 Technology start for MW-scale CSP system in China

The CSP system involves the integration of solar collection, heat exchange, thermal storage, solar power and other systems. It is a combination of optics, thermodynamics, materials science, mechanical and automation control disciplines and other technical fields, and it is different from both conventional electricity production and traditional solar thermal utilization, requiring interdisciplinary and cross-disciplinary system integration. Since the 11th Five-Year Plan, China has been studying the integrated technology of 1 MW CSP system. In 2006, the Ministry of Science and Technology (MOST) launched the key project titled "CSP Technology and System Demonstration" in the field of advanced energy technology under the National High Technology Research and Development Program (863 Program), which started the research and demonstration of integrated technology for the whole CSP system in China. Through the collaborative efforts of 11 units led by the Institute of Electrical Engineering of the Chinese Academy of Sciences, and after six years of unremitting efforts, on August 9, 2012, Asia's first megawatt-class experimental solar tower plant independently developed, designed and constructed by China achieved successful power generation. The project has achieved a number of technological breakthroughs in core equipment, coordination control, system integration, etc. The design technologies of high-precision solar concentrators, solar concentrator fields, direct superheat solar absorbers, thermal storage and power generation units and systems, as well as overall, solar concentrator field, mechanical, instrumentation and control and electrical design technologies have been comprehensively mastered, a number of independent innovations represented by the direct superheat steam generation process through optic-thermal field coupling have been achieved, a CSP technology R&D system and a standard specification system have been established, and the first national standard for CSP has been compiled, thus laying a foundation for the development of CSP technology in China.

Figure: China's First 1 MW Tower CSP Plant (Source: Institute of Electrical Engineering, Chinese Academy of Sciences, Photographed in 2012)

In 2011, China's first CSP project, the Erdos 50MW Parabolic Trough CSP Project, completed the concession demonstration bidding, and the National Energy Administration formally agreed that China Datang Corporation Renewable Power Co., Limited would be responsible for the construction and operation of the project, with a construction period of 30 months and a concession period of 25 years[14]. The project was not built due to the low winning electricity price. However, the launch of the concession project triggered wider market concerns and industry expectations. The state-owned enterprises such as China Huaneng Group, China Huadian Corporation and China Guangdong Nuclear Power Group, as well as some private enterprises such as Royal Tech and Rayspower Energy Group Co., Ltd. started to step into the CSP industry.

In July 2012, the "12th Five-Year Plan" project of the Ministry of Science and Technology (MOST), "Research and Demonstration of Parabolic Trough Solar Collection and Power Technology", was launched. China began to conduct research and demonstration of megawatt-scale parabolic trough CSP technology. In the project, relying on the collaboration between the Institute of Electrical Engineering of the Chinese Academy of Sciences and 13 technically superior units in China, and aiming at large-scale and low-cost CSP technology, research has been conducted on key equipment, key processes and testing technologies of parabolic through CSP, as well as system design, integration and operation technologies for parabolic through CSP. Based on the research on processes of curved glass hot bending and tempering, and considering the performance characteristics of domestic raw glass sheet, the project team proposed new parameters for high-speed heating process, and the corresponding quenching process and control parameters of high wind pressure and long wind fence, which overturned the ex-factory process parameters of foreign trough mirror reflector, and established a trough curved mirror reflector production line with an annual capacity of 1 million m2 based on such processes. Through in-depth research, the project team has established a method for accelerated aging of high-temperature vacuum solar collection & solar absorption coatings and proposed a formula for predicting the service life of solar absorption coatings. The project team has established a collector vacuum life prediction model based on multiple factors such as material outgassing, permeation, hydrogen absorption and leakage, with an error between the predicted data and the one-year vacuum change data of 3.9%, reaching the international advanced level. Based on the basic theories of heat transfer and engineering thermodynamics, the project team has proposed a dynamic capacity matching design method for solar absorption, thermal storage and steam generation systems on the basis of the research on the variation law of solar irradiation with time and by considering the intermittent and fluctuating nature of solar irradiation. The project team has completed the design, construction and commissioning for operation of the first 1MW parabolic trough CSP plant thermal system in China based on this method, and developed the first parabolic trough CSP system simulator in China; established the field test platform and kinetic test method for solar collection performance of trough solar concentrator, the formula of which has been adopted by the International Electrotechnical Commission (IEC) Solar Thermal Electric Plants Part 3-2: System sand Components. General Requirements and Test Methods for Parabolic-Trough Collectors". The implementation of the project has played a pioneering role in the industry for China's first CSP demonstration projects, thus bringing China's high-efficient and low-cost parabolic trough CSP R&D and equipment localization to a new level. It is of great significance in further enhancing the competitiveness of China's CSP products.

Figure: China’s First 1 MW Parabolic Trough CSP Plant (Source: Institute of Electrical Engineering, Chinese Academy of Sciences)

In October 2012, the 1.5MW Linear Fresnel Combined Cycle CSP Plant jointly developed and built by Huaneng Clean Energy Research Institute and Huaneng Hainan POWER Inc. was put into operation in Sanya, Hainan. The superheated steam generated by the project was connected to the steam make-up port of the generator set of Huaneng Nanshan Power Plant and supplied to the turbine for power generation [15].

In July 2013, the 10MW Phase I Demonstration Project of Qinghai SUPCON Delingha Solar Tower Plant (5MW each for the east and west towers) supported by the National High Technology Research and Development Program was connected to the Qinghai power grid. The project team has developed an intelligent heliostat with a single reflective area of 2 m2, a high-precision intelligent tracking technology for heliostats and a large-scale heliostat field control system; Realized the overall solar concentration and solar collection of a large-scale heliostat cluster; Studied the dynamic modeling and optimal design of solar tower energy under different geographical and climatic environment; Designed a high heat flux solar receiver based on water mass, and the steam buffer & power generation energy circuit and equipment, and realized the PV energy conversion technology of the scaled-up CSP technology route[16]. In early September 2014, the National Development and Reform Commission approved its on-grid price (including tax) at RMB 1.2 per kWh, which is a on-grid price of CSP project firstly approved by the state, marking a solid step towards commercial operation of China's self-developed CSP technology. Supported by the National 863 Program "Research and Demonstration of 10MW Solar Tower Technology Based on Small-Size Heliostat", the SUPCON Delingha 10MW CSP Plant changed the heat transfer medium, i.e. water/steam, to molten salt, and achieved full-load power generation on August 21, 2016. The project fully demonstrated the level of

China's solar tower system integration technology with independent intellectual property rights, as well as the core equipment development capability to adapt to high cold and high altitude environment [17]. The project has cultivated another group of backbone enterprises including SUPCON (now renamed Cosin Solar), Hangzhou Boiler (now renamed Xizi Clean Energy), Hangzhou Steam Turbine, etc.

Figure: Qinghai SUPCON Delingha 10 MW (2×5 MW) + 50 MW Solar Tower Plant (Source: Cosin Solar)

In October 2013, Lanzhou Dacheng started the construction of 1MW Linear Fresnel CSP Project in Tibet. In October 2015, Lanzhou Dacheng built the 1MW Linear Fresnel CSP Plant on the roof of the production workshop [18].

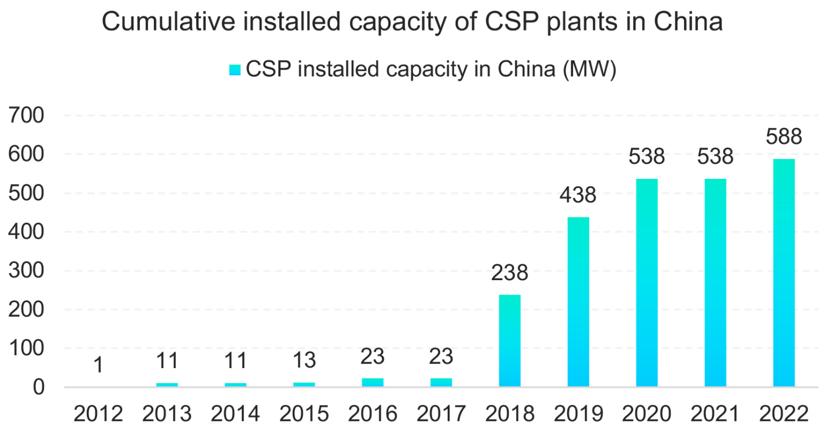
Figure: 1 MWe Linear Fresnel CSP Cogeneration Power Plant in Liuwu New District, Lhasa (Source: DCTC)

On December 26, 2016, within three months after the announcement of the first batch of China's CSP demonstration projects, Shouhang Hi-Tech Dunhuang 10MW Molten Salt Solar Tower Demonstration Project was successfully connected to the grid. After 5 years of technology reserve and 2 years of project construction, the project has become a 10 MW molten salt solar tower plant invested, developed, designed, constructed, operated and maintained entirely by the enterprise itself, injecting strong momentum into the industry development. As a pilot project, the 10MW solar tower plant not only provides experiments and tests for the system design and equipment selection of Shouhang Hi-Tech 100MW National Demonstration Project, but also reserves talents for larger-scale CSP projects, while exploring the operation mode that meets China's resource conditions and grid dispatching requirements.

Figure: Shouhang Dunhuang 10 MW+100 MW Solar Tower Plant (Source: Shouhang Hi-tech)

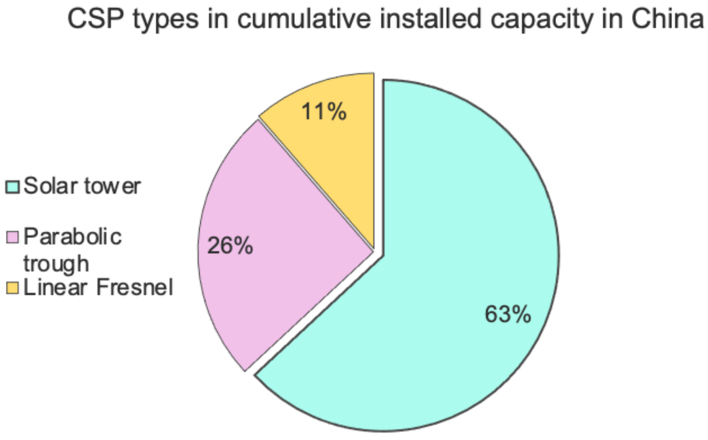
2.2 CSP installed capacity and CSP types in China

In 2022, a new CSP plant was connected to the grid in China. It is the Yumen XinNeng Secondary Reflective Solar Tower Demonstration Project, with an installed capacity of 50MW and thermal storage duration of 9 hours. According to the China Solar Thermal Alliance's statistics for CSP systems of MW-scale or above with the turbine generator, as of the end of 2022, the cumulative installed capacity of CSP in China was 588 MW, accounting for 8.3% of the global cumulative installed capacity of CSP.



Source: China Solar Thermal Alliance (CSTA)

Depending on different solar concentration forms, the installed capacity of solar tower plants accounted for about 63.1% of the cumulative installed capacity of CSP in China, the installed capacity of parabolic trough CSP plants accounted for about 25.5%, and the installed capacity of linear Fresnel CSP plants accounted for about 11.4%.

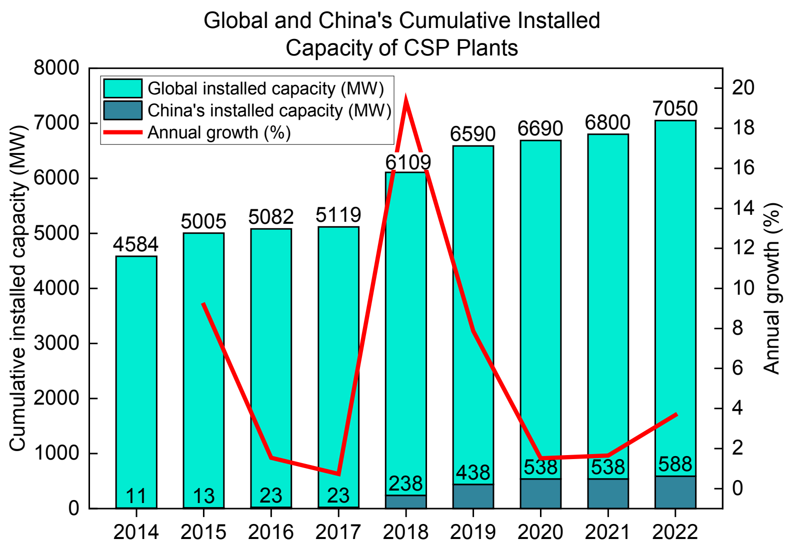


Source: China Solar Thermal Alliance (CSTA)

2.3 Global installed CSP capacity and CSP types

In 2022, a new CSP plant was built abroad. It is the parabolic trough 1 (PT 1) of the NOOR ENERGY 1 DUBAI 950 MW Hybrid Solar Project[19], with an installed capacity of 200 MW and thermal storage duration of 13.5 hours.

According to the comprehensive statistics of the China Solar Thermal Alliance, the cumulative installed capacity of global CSP plants was about 7,050 MW as of the end of 2022 (including the parabolic trough plants decommissioned after 30 years of operation in the United States). The cumulative installed capacity of global and Chinese CSP plants from 2014 to 2022 is shown in the figure below.

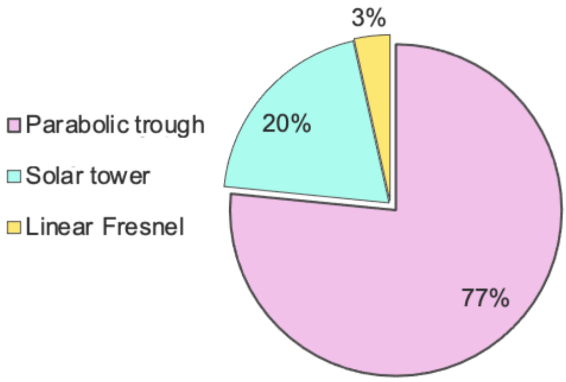


Source: China Solar Thermal Alliance (CSTA)

The development curve of global cumulative installed CSP capacity shows a high annual growth rate in 2018, which is mainly attributed to the fact that three of the first CSP demonstration projects in China were commissioned in 2018, with a total installed capacity of 200 MW.

The China Solar Thermal Alliance has conducted statistics on the solar concentration forms in the cumulative installed CSP capacity in countries and regions such as Spain, the United States, the Middle East, North Africa, South Africa, Israel, India, Chile, France and China. According to the results, the solar concentration forms of parabolic trough CSP plants accounted for about 77%, the solar concentration forms of solar tower plants accounted for about 20% and the solar concentration forms of linear Fresnel CSP plants accounted for about 3%.

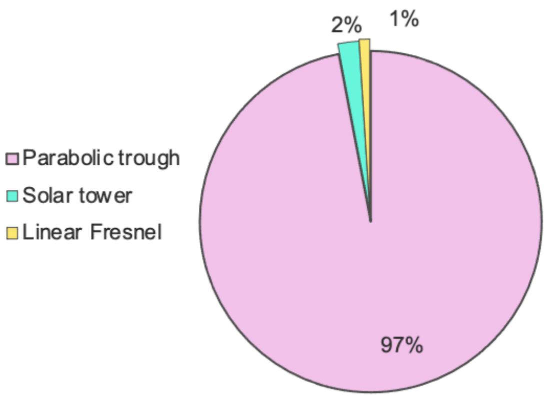
CSP types in cumulative installed capacity in global major countries and regions



Source: China Solar Thermal Alliance (CSTA)

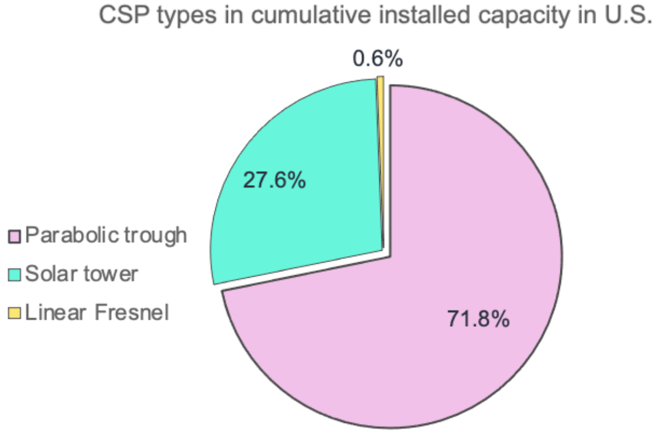
Spain still had the largest installed CSP capacity in the world, with about 2,300 MW. The parabolic trough CSP technology accounted for about 97% of the country's total installed CSP capacity. The main reason is that parabolic trough CSP technology is the first technology commercially deployed in the world. The U.S. commissioned nine parabolic trough CSP plants of various capacities during the period form 1984 to 1990, with a total net capacity of 354 MW. Commercially proven technologies are more likely to receive financing support from Spanish financial institutions.

CSP types in cumulative installed capacity in Spain



Source: China Solar Thermal Alliance (CSTA)

The U.S. currently has an installed CSP capacity of about 1,837 MW, with parabolic trough CSP technology accounting for about 71.8% and solar tower technology accounting for 27.6%. Commercial parabolic trough plants have been in operation for more than 30 years. SEGS 1 and 2 parabolic trough CSP plants, commissioned in 1984 and 1985, were decommissioned in 2015; SEGS 3 to 8 parabolic trough CSP plants, commissioned between 1986 and 1989, were decommissioned in 2021, with a total net capacity of 230 MW. SEGS 9 (net capacity: 80MW, total capacity: 88MW), commissioned in 1990, is still in operation.



Source: China Solar Thermal Alliance (CSTA)

2.4 Ongoing CSP projects in China

According to the Notice on Matters Relating to the Development and Construction of Wind Power and PV Power Generation in 2021 issued by the National Energy Administration in May 2021, projects outside the scope of affordable grid connection and with intention of grid connection can be connected to the grid by grid enterprises after implementing the conditions for grid connection through market-based methods such as self-build, joint construction and sharing or purchase of services. Grid connection conditions mainly include supporting the new pumped storage, thermal storage CSP, thermal power peak-shaving, new energy storage, adjustable load and other flexible regulation capacity. As one of the supporting options for implementing grid connection conditions, thermal storage CSP is complementary to PV, wind power and other fluctuating power sources, which can not only play the energy storage and peak-shaving capacity of CSP and reflect the role of solar thermal in supporting the development of new energy as a peak-shaving power source, but also take advantage of the rapid decline in the cost of wind power and PV in recent years, fully release the low-cost advantages of PV and wind power, fill the gap in electricity supply from PV power generation during peak electricity consumption periods, and effectively improve energy utilization efficiency and economic benefits.

In 2021, the State Council issued the Action Plan for Carbon Dioxide Peaking Before 2030 which clearly proposed to actively develop CSP, and promote the establishment of integrated (wind, PV, solar) renewable energy power generation base characterized by complementary regulation of CSP with PV power

& wind power. On May 30, 2022, the General Office of the State Council forwarded the Implementation Plan for Promoting the High-quality Development of New Energy in the New Era issued by the National Development and Reform Commission and the National Energy Administration, which proposed to innovate the development and utilization mode of new energy and accelerate the construction of large-scale wind power and PV bases mainly concentrated in on desert, Gobi and desert areas.

According to the statistics of the China Solar Thermal Alliance, under the guidance and support of relevant national policies, there are currently 29 CSP projects with a total installed capacity of about 3360MW in the list of large-scale wind power and PV base projects, new energy market-oriented grid connection and DC outbound projects announced by local governments (excluding projects under operation or planned to be built by enterprises). These projects are expected to be put into operation by 2023 or 2024. Among them, 9 CSP projects with a total installed capacity of 1300MW are listed in Qinghai Province; 5 CSP projects with a total installed capacity of 510MW are listed in Gansu Province; 13 CSP projects with a total installed capacity of 1350MW are listed in Xinjiang Uygur Autonomous Region.

Ongoing new CSP projects in north-west regions of China		
	Announced capacity (MW)	Project numbers
Xinjiang Autonomous Region	1350	13
Qinghai Province	1300	9
Gansu Province	510	5
Jilin Province	200	2

In addition, three isolated grid energy supply projects in the Tibet Autonomous Region, including CSP projects, have already started construction. National Energy Group Tibet Electric Power Co., Ltd has also conducted a pre-feasibility study on the planning and Phase I CSP (100MW) of the Integrated CSP + Wind & PV Power Project in Nakchu Amdo.

2.4.1 CSP projects in Gansu Province

In the first batch of large-scale wind power and PV base construction projects in Gansu Province and self-regulating new energy demonstration projects in Jiuquan city, Gansu, five projects were configured with CSP systems, with a total installed CSP capacity of 510MW.

"CSP+" Project under Construction in Gansu Province			
Project name	Investor	Project profile	Project construction situation
Jinta ZhongGuang "100MW CSP + 600MW PV" Project	Jinta ZhongGuang Solar Power Generation Co., Ltd.	The project has a total installed capacity of 700MW, with "CSP+" configuration adopted, including 100 MW CSP and 600MW PV. The center elevation of the solar receiver is 220 m, and the concrete tower is 195 m high. The designed annual power generation is 1.37 billion kWh. The CSP plant is designed with the tower molten salt technology and is equipped with a 9 h molten salt energy storage system. The project was commenced on March 25, 2022, and it is scheduled to be connected to the grid with full capacity for power generation by the end of 2023.	The site leveling works was officially launched on March 25, 2022. At present, the solar absorption tower, electric control building and air cooling system framework have been roofed, and the construction of storage tank foundation has been basically completed. It is estimated that all civil works will be completed in the first half of 2023 and all installation works will be completed in the second half.
CNNC Yumen "100MW CSP + 200MW Wind Power + 400MW PV" Project	CNNC Yumen Xin'ao New Energy Co., Ltd.	The project has a total installed capacity of 700MW. The CSP and PV power plant covers an area of 15 km2 and is located in the Huahai CSP and PV Base in Yumen; The wind farm covers an area of 30 km2 and is located in the Hongliuquan Wind-Solar Storage Comprehensive Energy Demonstration Base in Yumen. The project is scheduled to be connected to the grid with full capacity for power generation in December 2023.	The consortium of Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group, Energy China and Dunhuang Dacheng Shengneng New Energy Technology Co., Ltd., a wholly-owned subsidiary of Lanzhou Dacheng Technology Co., Ltd., is the general contractor of the 100MW CSP+TES Project, and the project has been fully constructed. More than 35,000 solar collector piles have been built, and the construction of assembly workshop, production office building, comprehensive living building and main workshop foundations has been completed.
Sun Sum (Three Gorges Corporation) Guazhou "100MW CSP + 200MW PV + 400MW Wind Power" Project	Sun Sum	The project has a total installed capacity of 700MW, including 100MW for CSP plants, 200MW for PV plants and 400MW for wind power plants. The CSP plant is designed with the tower molten salt technology, with an installed capacity of 2×50 MW, and is equipped with two solar absorption towers, and one ultra-high pressure, intermediate reheat, 8-stage heat recovery (tentative), axial exhaust and direct air-cooled condensing steam turbine (two towers and one machine mode), with a rated capacity of 1×100 MW.	China Gezhouba Group Electric Power Co., Ltd. (leader), Gansu Installation and Construction Group Co., Ltd. and Sun Sum are EPC contractors of the project. The project has entered the comprehensive construction stage, and the construction of 330 kV Qiaowan Booster Pooling Station and transmission line works, solar absorption tower foundation pouring, etc. has been completed.

"CSP+" Project under Construction in Gansu Province			
Project name	Investor	Project profile	Project construction situation
National Energy Group Dunhuang "100MW CSP + 600MW PV" Project	National Energy Group Gansu Electric Power Co., Ltd. and Lanzhou Dacheng Technology Co., Ltd.	The project has a total planned installed capacity of 700 MW, including 600 MW PV power generation project and 100 MW molten salt linear Fresnel CSP project. A supporting 330 KV pooling station will be built and connected to the 330 KV side of Shazhou 750 KV Substation through one circuit of 330 KV line. The project covers a total area of 21,547 mu, with a total investment of RMB 4.3 billion.	The project was filed in April 2022 and approved by the access system of State Grid Gansu Electric Power Co., Ltd. in September 2022. The feasibility study has passed the review.
110MW CSP + 640MW PV Pilot Project of Aksay Huidong New Energy Co., Ltd.	Aksay Huidong New Energy Co., Ltd.	The project has a total investment of RMB 5.06 billion, and is located in the 10 million kW CSP Base in the Sishili Gobi, Aksay, Jiuquan City, Gansu Province, with a total planned installed capacity of 750 MW (including 110 MW CSP + 640 MW PV). The project covers an area of about 20.6 km2, and will be connected to the grid for power generation by the end of 2023. It is scheduled to arrange the CSP plant in the southwest of the whole station area, with a land area of 3.15 km2 and energy storage duration of 8 h, mainly including heliostat field, solar thermal power island, administration and living area. It is scheduled to be connected to the grid for power generation by the end of 2023. After the project is completed, the average annual on-grid energy will be 1.7 billion kWh.	As the general contractor of the project, the East China Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group has carried out comprehensive construction of the project. The pouring of the main workshop foundation has been completed; the civil works such as solar absorption tower, main workshop and steam generator have been constructed to "0" meter in 2022.

2.4.2 CSP projects in Qinghai Province

In the first batch of large-scale wind power and PV base construction projects in Qinghai Province, key market-oriented grid connection projects in Qinghai Province in 2021, and the second batch of large-scale wind power and PV base construction projects, a total of 9 projects were configured with CSP systems, with a total installed CSP capacity of 1300MW.

"CSP+" Project under Construction in Qinghai Province			
Project name	Investor	Project profile	Project construction situation
Bid Section 1 of 3.4 Million kW Power Transmission Project of Qinghai-Henan DC Phase II of Hainan Base and 1.9 Million kW Power Transmission Project of Qinghai-Henan DC Phase II of Haixi Base.	CHN Energy (leader), and Northwest Engineering Corporation Limited	The project is located in Talatan, Gonghe County, Hainan Prefecture and it will build 900MW PV plant and 100MW CSP plant. The 100MW CSP plant is located in the south of Ecological CSP Park in Hainan Prefecture, about 33 km away from Gonghe County. The CSP project is a tower molten salt CSP plant, and it is scheduled to equip a heliostat field with a solar concentration area of 800,000 m2 and a 12 h thermal storage system.	The 100MW CSP project has been filed. The EPC bidding announcement of the project was issued.
Bid Section 2 of 3.4 Million kW Power Transmission Project of Qinghai-Henan DC Phase II of Hainan Base and 1.9 Million kW Power Transmission Project of Qinghai-Henan DC Phase II of Haixi Base.	SPIC Huanghe Hydropower Development Co., Ltd. (leader), Cosin Solar Technology Co., Ltd. and CNOOC Rongfeng Energy Co., Ltd.	The CSP project will be designed with the tower molten salt technology, and the "PV + Wind Power" project will be connected to the grid with full capacity at the same time before December 31, 2023.	The feasibility study report of the project was issued to review the inquiry and bidding of the project. The technical consulting and bidding for access system design of 100MW CSP project were initiated.
Bid Section 3 of 3.4 Million kW Power Transmission Project of Qinghai-Henan DC Phase II of Hainan Base and 1.9 Million kW Power Transmission Project of Qinghai-Henan DC Phase II of Haixi Base (900MW PV Project + 100MW CSP Project).	China Three Gorges Renewables (Group) Co., Ltd. (leader), and Shouhang Hi-Tech Energy Technology Co., Ltd.	The project is located in the south of Wutumeiren CSP Park in Golmud City, Haixi Prefecture, Qinghai Province, as a supporting power point project for the Qinghai-Henan DC Phase II. The CSP project is designed with the tower molten salt technology. The project is scheduled to be connected to the grid with full capacity on November 30, 2023.	The consortium of POWERCHINA NORTHWEST, Cosin Solar Technology Co., Ltd. and China Energy Engineering Group Zhejiang Thermal Power Construction Co., Ltd. won the bid for EPC of 100 MW CSP project. According to the division of labor of the consortium, Cosin Solar Technology Co., Ltd. will participate in the overall design and management of the project, and be responsible for the technical scheme, equipment integration and supply, and related commissioning and operation guidance services of the solar concentration and solar collection system.

"CSP+" Project under Construction in Qinghai Province			
Project name	Investor	Project profile	Project construction situation
Three Gorges Renewables Golmud 1 GW PV + 100MW CSP Project in Haixi Base	China Three Gorges Renewables (Group) Co., Ltd.	The project is located in the Wutumeiren CSP Base, Golmud City, Haixi Prefecture, Qinghai Province. The CSP project is designed with the tower molten salt technology. It is scheduled to build a new 110 kV booster station, which is connected to the low-voltage side of the new 330 kV booster station in PV area through one circuit of 110 kV line and connected to the Wutumeiren 750 kV Booster Station through two circuits of 330 kV lines. The project is scheduled to be connected to the grid with full capacity on November 30, 2023.	The consortium of Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group, Shouhang Hi-Tech Energy Technology Co., Ltd., PowerChina Sichuan Engineering Corporation Limited and Shanghai Investigation, Design & Research Institute Co., Ltd. won the bid for the EPC of 100 MW CSP project. According to the division of labor of the consortium, Shouhang Hi-Tech Energy Technology Co., Ltd. is responsible for the EPC management of the CSP project, and for providing the heliostat field equipment and control system, solar receivers and solar collection system, thermal storage system, air cooling system and other major CSP plant equipment; Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group and Shanghai Investigation, Design & Research Institute Co., Ltd. are responsible for the overall investigation and design of the whole site; PowerChina Sichuan Engineering Corporation Limited is responsible for the construction and installation of the main body of the project.

"CSP+" Project under Construction in Qinghai Province			
Project name	Investor	Project profile	Project construction situation
Qinghai SUPCON Delingha 135 MW Multi-energy Complementary Project	Cosin Solar Technology Co., Ltd.	The project covers an area of 9.52 km2, with an energy storage duration of 11.2 h and a heliostat field area of 1.45 million m2. It is estimated to use about 37,240 t molten salt. It is proposed to invest RMB 3.126 billion for the project. It is estimated that about 435 million kWh of clean electricity can be generated each year.	In terms of early development, the letters of PV project filing and preliminary work of CSP project have been prepared; the feasibility study report has been reviewed; the reports on boundary survey, environmental assessment, ground disaster and land saving have been prepared and reviewed; the water resources demonstration, flood control evaluation and soil and water conservation reports have been prepared.
CGN Solar Delingha 800MW PV + 200MW CSP Project	CGN New Energy Holdings Co., Ltd.	The project is located in the PV (CSP) Industrial Park in Delingha City, Haixi Prefecture, Qinghai Province, with a planned area of about 53,000 mu.	The commencement ceremony of the project was held in March 2022. Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST) was accepted to take charge of preliminary design of the project. Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group won the bid for design supervision. In November, 2022, Phase I 200MW CSP + TES Project and 330 kV booster station were subject to public bidding for supervision and procurement.

“CSP+” Project under Construction in Qinghai Province			
Project name	Investor	Project profile	Project construction situation
PowerChina Gonghe 1GW PV + CSP Project	Hainan Northwest Hydropower New Energy Co., Ltd.	The project is located in the Ecological CSP Park, Hainan Prefecture, Qinghai Province. The CSP project is designed with the tower molten salt technology, and connected to the Siming Substation through one circuit of 110 kV line . The CSP plant is provided with heat by the solar collection field and the molten salt electric heater and is additionally equipped with a 100MW/200MWh electrochemical energy storage system. After completion, the annual average power generation during the operation period is 213 million kWh, and the equivalent annual utilization hours are 2,130 h. It is estimated that the project will be completed in December 2024.	The project was filed in August 2022. The supervision and EPC bidding has been initiated.
Gonghe 1 GW Grid-Load-Storage Project of China Energy Engineering Group Jiangsu Power Design Institute Co., Ltd./ Jiangsu Meike Solar Technology INC	China Energy Engineering Group Jiangsu Power Design Institute Co., Ltd.	The project is located in the Ecological CSP Park, Hainan Prefecture, Qinghai Province. The CSP project is designed with the tower molten salt technology, and it is provided with heat by the solar collection field and the molten salt electric heater and is additionally equipped with a 100MW/200MWh electrochemical energy storage system. It is estimated that the project will be completed in December 2024.	/

"CSP+" Project under Construction in Qinghai Province			
Project name	Investor	Project profile	Project construction situation
Golmud Wutumeiren Multi-energy Complementary Project	China Green Development Qinghai New Energy Company	The project is located in Wutumeiren PV + CSP Park, Golmud City, Qinghai Province, with an estimated investment of RMB 19.575 billion and a total planned installed capacity of 3.3 million kW, including 3 GW PV project, 300MW CSP project (600MW electric heating molten salt heat storage system), 520MW energy storage system and 10,000 kilovar rotary condenser, and three 330 KV pooling substations. The overall project is scheduled to be completed within the "14th Five-Year Plan".	/

2.4.3 CSP projects in Jilin Province

According to the "Preference Announcement" issued by the People's Government of Baicheng City, Jilin Province on September 9, 2021, the total capacity of the Jixi Base Lugu DC Baicheng 1.4 million kilowatts kWh outgoing transmission project is 1.4 million kWh, including 800MW of wind power, 400MW of photovoltaic PV and 200MW of solar thermal power; there are two projects, Project No. 1 (1-1, 1-2) and Project No. 2 (2-1, 2-2) are both integrated projects, and the 100MW solar thermal project is a joint project, with two 220kV shared booster stations and 220kV liaison lines.The power generated by the project will be sent to the PV booster station and then gathered through the 220kV linkage to the wind power booster station for unified transmission. At present, both solar thermal power CSP projects have entered the construction stage.

CSP Project of Zhalute-Qingzhou DC Baicheng 1.4 GW Power Transmission Project in Jixi Base			
Project name	Construction site	Investor	Project profile
No.1 (100 MW CSP) Zhalute-Qingzhou DC 1.4 GW Power Transmission Project in Jixi Base	Bamian Township, Tongyu County, Baicheng City, Jilin Province	Tongyu Zhongji Thermal Power Generation Co., Ltd.	The CSP project is designed with the tower molten salt technology with single tower and single heliostat field, and is equipped with an 8 h thermal storage system, a steam generation system, a high-temperature and ultra-high pressure reheat straight condensing turbogenerator system and other auxiliary facilities. Meanwhile, it is equipped with a 40 MW electric heater, which can heat molten salt to store the abandoned wind electricity or PV electricity, and the electricity can be pooled to the booster station of PV plant through one circuit of 220 kV cable. The project is scheduled to be put into production in June 2024.
No.2 (100 MW CSP) Zhalute-Qingzhou DC 1.4 Million kW Power Transmission Project in Jixi Base	Da'an Zhongmachang in Baicheng	Da'an Guangtou Zhongneng Solar Thermal Power Generation Co., Ltd.	The CSP project is designed with the tower molten salt technology with single tower and single heliostat field (co-construction), and is equipped with a set of thermal storage and steam generation system, a set of high-temperature and ultra-high pressure reheat straight condensing turbogenerator system and other auxiliary facilities. Meanwhile, it is equipped with a 10 MW electric heater, which can heat molten salt to store the abandoned wind electricity or PV electricity, and the electricity can be pooled to the booster station of PV plant through one circuit of 220 kV cable.

2.4.4 CSP projects in Xinjiang Uygur Autonomous Region

On July 4, 2022, the Development and Reform Commission of Xinjiang Uygur Autonomous Region issued the Notice on the Issuance of the List of the Second Batch of Market-based Grid-connected New Energy Projects in the Xinjiang Uygur Autonomous Region in 2022. The total scale on the project list is 47,832.5MW, including 27,390MW of PV projects, 13,495MW of wind power projects, and 6,947.5MW of distribution and storage. There are 49 grid-consumption projects and 18 integrated source-grid-load-storage projects. The types of distribution and storage include solar thermal and electrochemical distribution and storage, among which 1.35 GW of CSP accounts for 19.43% of the distribution and storage scale. These 13 CSP projects are mainly located in Changji Prefecture (No. 1), Hami City (No. 2-5), Turpan (No. 6-9), Bazhou (No. 10-11) and Bole region (No. 12-13). The maximum installed capacity of the CSP projects is 150MW, while the installed capacity of the rest is 100MW; The energy storage duration is between 8 and 12 hours. These projects are expected to be connected to the grid by 2024.

The Second Batch of Market-oriented Grid-connected New Energy Projects in Xinjiang Uygur Autonomous Region with CSP + TES Projects in 2022			
No.	Project name	Investor	Project profile
1	Luneng Fukang Multi-energy Complementary (and New Energy Market-oriented Grid-connected) Project	Luneng New Energy (Group) Co., Ltd.	The project is built by Luneng New Energy (Group) Co., Ltd., with an investment of about RMB 6 billion. The project will build a 100MW CSP plant, with a thermal storage duration of 8 h and 900MW PV facilities provided. The PV facilities are scheduled to be put into operation before the end of March 2023, and the CSP plant is scheduled to be put into operation before September 20, 2024.
2	EnergyChina Hami "CSP+TES" Multi-energy Complementary Integration Green Power Demonstration Project	China Energy Engineering Investment Corporation Limited	The project is located in Santanghu Town, Balikun County, Hami City. The project has a total installed capacity of 1.5 GW, including 1.35GW PV plant, 150MW CSP plant and supporting 220 kV booster pooling station, with a total investment of RMB 8.2 billion. After the project is put into operation, it can transmit 3 billion kWh of clean electricity to the power grid every year.
3	Three Gorges Renewables Hami	China Three Gorges Renewables (Group) Co., Ltd.	The project includes 900MW PV project and 100MW CSP project.
4	Hami North 900MW PV Project + 100MW CSP Project	Xinjiang Silk Road Kunyuan Energy Co., Ltd.	The project area is located in Wurijinfeng Gobi Desert, northeast of Santanghu Township, Balikun County, Hami City. It is scheduled to build the 900MW PV and 100MW CSP demonstration projects, with a thermal storage duration of 8 h. Two 220 kV booster pooling stations will be built in the site area according to the power grid situation of the autonomous region.
5	Datang Shichengzi 1 Million kW "CSP + PV" Integrated Clean Energy Demonstration Project	Datang Xinjiang Power Generation Co., Ltd.	The project is located in the west of Shichengzi PV Park, Yizhou District, Hami City, Xinjiang, about 18 km away from northwest of Hami City. It is scheduled to build the 900MW PV and 100MW CSP projects and be connected to the grid for power generation on September 24, 2024.

6	Turpan Toksun County Wusitonggou CSP + PV Integration Project	Consortium of PowerChina Renewable Energy Co., Ltd. and Xinjiang Zhongan Ruida New Energy Technology Co., Ltd.	The project is located 6 km south of Provincial Highway S301, in (Wusitonggou) Toksun County, Turpan City, Xinjiang, and north of Wusitonggou Reservoir. The project covers a total area of 249.83 ha, and will build 900MW PV and 100MW CSP projects. After the project is completed, it will be connected to the new 220 kV pooling station and electricity will be transmitted to the 220 kV substation of the system.
7	Haitai Solar CSP + PV Integration Project	Haitai Solar	It is scheduled to build the 900MW PV and 100MW CSP projects.
8	Solar Thermal and PV Power Generation Integration Project of SPIC Henan Electric Power Co., Ltd.	SPIC Henan Electric Power Co., Ltd.	With a total investment of RMB 6 billion and total installed capacity of 1 GW, it is planned to construct 900MW PV and 100MW CSP plants, with two supporting 220 kV booster stations.
9	Solar Thermal and PV Power Generation Integration Project of China Energy Engineering Group Zhejiang Thermal Power Construction Co., Ltd.	China Energy Engineering Group Zhejiang Thermal Power Construction Co., Ltd.	The project is located in Shanshan County in Turpan of Xinjiang with a total investment of RMB 5.403 billion, mainly to construct 100MW solar thermal energy storage and 900MW PV generation project, with two supporting 220 kV booster pooling stations. The project is planned to put into production for solar thermal energy storage on July 30, 2024.
10	SPIC 100,000 kW Solar Thermal Energy Storage and Supporting 900MW PV Market-based Grid-connected Generation Project in Ruoqiang	SPIC Xinjiang New Energy Co., Ltd.	The project is located in Tiemulike Township in Ruoqiang County of Xinjiang Province. The installed capacity of solar thermal project is 100MW, with tower molten salt technology adopted and a duration of 24 months (tentative); 900MW PV project will be constructed in batch: batch 1 is 100MW PV with a duration of 4 months (tentative); subsequent works shall be carried out in batch according to actual needs, with a duration of 20 months.

11	100MW Solar Thermal Power Generation (Energy Storage) and 900MW PV Demonstration Project in Ruoqiang	Ruida Energy Development Co., Ltd. of Xinjiang Power Construction Co., Ltd.	The project is situated 170 km to the southeast of Ruoqiang County in Bayingol Mongolian Autonomous Prefecture of Xinjiang, with a total installed capacity of 1GW, including 100MW solar thermal power generation project. It adopts tower molten salt CSP technology and covers a planned land of 1,896.6 ha.; the supporting 900MW PV generation project adopts 540 Wp efficient single-crystal double-sided solar cell module and covers a planned area of 2,995.9 ha., with installed capacity of 994.70592 MWp for the DC side.
12	Bozhou 100MW Thermal-storage Solar Thermal Power Generation and Supporting 900MW New Energy Project of Xinhua Hydropower Company Limited	Xinhua Hydropower Company Limited	The project is situated at the north of G219 national highway to the west of Bole City. It has a total installed capacity of 1GW, including 100MW molten salt tower solar thermal energy storage power plant with energy storage duration of 8 h, 900MW ground centralized PV power plant and relevant subsidiary facilities. The total investment of the project is RMB 6.5 billion.
13	"Solar Thermal Energy Storage and New Energy" Integration Base Project of Jinghe Xinhua New Energy Co., Ltd.	Jinghe Xinhua New Energy Co., Ltd.	The project is located in Akqi Farm in Jinghe County and has a total installed capacity of 1GW including 100MW molten salt tower solar thermal energy storage power plant with energy storage duration of 8 h, 900MW ground centralized PV power plant and relevant subsidiary facilities. The total investment of the project is RMB 6.5 billion.

2.4.5 CSP projects in Tibet Autonomous Region

New CSP Projects in Tibet Autonomous Region		
Project name	Investor	Project profile
CGN "Zero-carbon" CSP + TES Demonstration Project in Ngari Plateau	Tibet Branch of CGN New Energy Holdings Co., Ltd.	The project is located in Shiquanhe Town, Ga'er County, Ngari, Tibet, with estimated investment of RMB 2.76 billion. It is planned to construct 1 set of 100MW PV power plant and 50MW CSP and heating power plant. Molten salt trough technology will be adopted and 480 solar collectors assembly will be installed according to the design, which is divided into 160 collecting circuits and owns a collecting area of 825,600 m2, with thermal storage duration of 16 h. 108 collecting circuits will be first constructed and put into operation in Phase I, with a collecting area of 557,280 m2. 16 h thermal storage system, steam generation system and high-temperature & ultra-high pressure reheat condensing turbogenerator system and other auxiliary facilities will be constructed.
Green Comprehensive Development and Utilization of 10,000 t Battery Grade Lithium Carbonate Energy Supply Project in Zabuye Salt Lake, Tibet	Tibet Zabuye Lithium Industry High-tech Co., Ltd.	The project is located at the south of Zabuye Salt Lake about 165 km (straight-line distance) to the north of Zhongba County, Shigatse. According to the announcement of Tibet Mineral Development Co., Ltd. in February 2022, it is the supporting project of lithium carbonate project, which provides packaged dispatching and operation schemes for isolated power system operation, power grid emergency and comprehensive energy of lithium carbonate plant. As an isolated network system of renewable energy, the project refers to a thermoelectric integrated energy system composed of power supply (solar thermal + PV), load (electricity, steam), energy storage (thermal storage + electrochemical energy storage), power transformation & distribution and control system, including 40 MW solar thermal system, 35 MW PV system (AC side) and electrochemical energy storage of 20 MW/40 MWh.
CHD Tibet Energy Co., Ltd. PV and Solar Thermal Power Generation Integration Project in Seni District, Naqu City	CHD Tibet Energy Co., Ltd.	The project is situated in Naqu Town, Seni District, Naqu City and about 7 km (straight-line distance) from the downtown, with an elevation of about 450-4,600 m. The planned area is about 7,000 mu and planned installed capacity is 120 MW PV (including 96 MWh energy storage) and 50 MW solar thermal power generation (feasibility study result shall prevail). The solar thermal project, as a guarantee measure in 2023-2025, will be completed in mid and later period of the "14th Five-year Plan".

3. Operations of National CSP Demonstration Projects

To promote the industrial development of CSP technology in China, in September 2015, the National Energy Administration issued the Notice on the Organization of CSP Demonstration Project Construction, deciding to organize the construction of a number of CSP demonstration projects. The Notice proposed to, through the construction of demonstration projects, form a domestic solar thermal equipment manufacturing industry chain, expand the scale of the CSP industry and foster a number of system integrators with comprehensive engineering construction capabilities to meet the needs of the subsequent development of CSP. In September 2016, the National Energy Administration issued the Notice on the Construction of CSP Demonstration Projects, identifying a total of 20 CSP demonstration projects in the first batch, with a total installed capacity of 1,349MW, distributed in Qinghai Province, Gansu Province, Hebei Province, Inner Mongolia Autonomous Region, and Xinjiang Autonomous Region. After the announcement of the list of demonstration projects, the project investment enterprises actively carried out different degrees of demonstration project construction work according to the actual situation, in order to make projects be completed and put into operation as required, and play the role of demonstration and leading of projects.

The CSP demonstration project is the first large-scale demonstration project of CSP utilization in China. As of the end of 2022, there were 9 grid-connected CSP demonstration projects with a total capacity of 550MW; Among them, there were 6 tower projects, 2 parabolic trough projects and 1 linear Fresnel project. After continuous elimination of defects and gradual improvement of operation and maintenance experience, the performance of each plant has been improved to different degrees compared to 2021. Through the research and evaluation of the China Solar Thermal Alliance, it was found that the demonstration projects have played a significant role in guiding the construction of CSP industry chain, the independent development of core equipment, and the training of talent teams. Through the implementation of CSP demonstration projects, China has fully mastered the core technologies of solar concentration, solar absorption, thermal storage, heat exchange, and power generation with complete intellectual property rights, the environmental-adaptive design technologies of equipment in high-altitude and high and cold regions, and the construction and operation technologies of plants, laying a solid foundation for the subsequent large-scale development of CSP technology.

3.1 CSNP Urat 100MW Parabolic Trough CSP Plant

Located in Urat Middle Banner, Bayannur City, Inner Mongolia, CSNP Urat 100MW Parabolic Trough CSP Plant of China Shipbuilding New Power Co., Ltd (CSNP) is the largest single parabolic trough CSP plant with the longest thermal storage duration among the first batch of national CSP demonstration projects. The plant officially started construction in June 2018, and achieved the first grid connection on

January 8, 2020, the full-load power generation on December 16, 2020, and full commissioning of the molten salt energy storage system on July 13, 2021.

Since the commissioning, the plant has achieved continuous, stable and high-load operation, generating about 540 million kWh of electricity in total. In January 2022, the generator set was scheduled for maintenance. From February to December 2022, the set generated 310 million kWh of electricity. From June 4 to 15, 2022, the set generated a total of 22.32 million kWh of electricity for 12 consecutive days without shutdown under cloudy conditions for six days.

The project is designed, constructed, commissioned, operated and maintained by China Shipbuilding Industry Group Power Co., Ltd. At present, the indicators of the plant have reached or even exceeded the design value. The plant only took one year to complete the rising of power generation capacity and achieve the standard at one time of commissioning. The optical indicator - interception rate has been tested by European third-party authoritative laboratory and reached 98%, which is 1 percentage point higher than the current international level. The highest generated output reached 105.54MW and the highest daily power generation reached 2.192 million kWh, both exceeding the design value. At a high latitude of 41.5°, the operation efficiency of the localized parabolic trough solar collector exceeded expectations.

3.2 Shouhang Hi-tech Dunhuang 100MW Solar Tower Plant

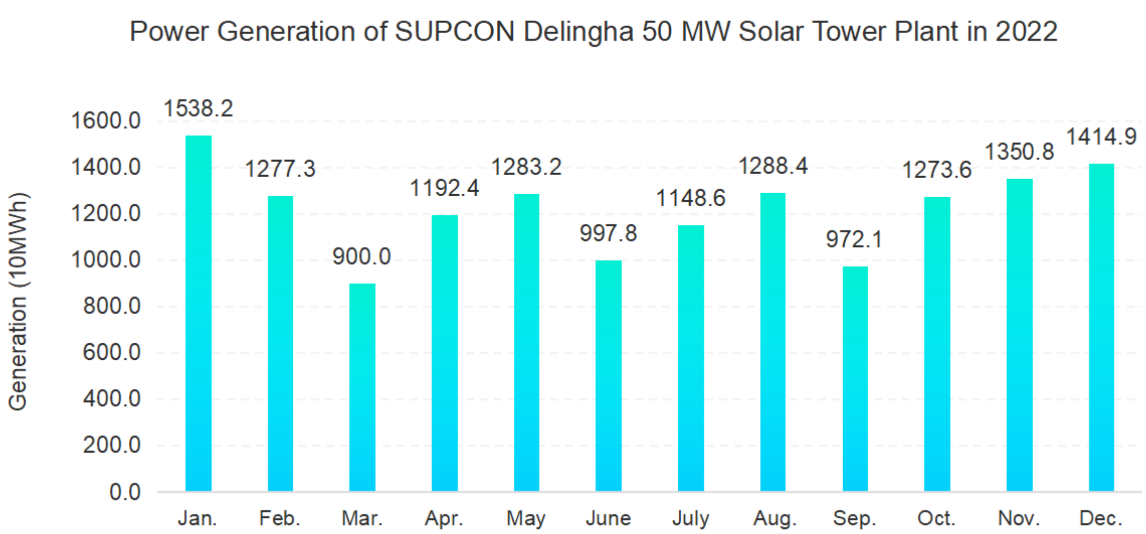
Shouhang Hi-Tech Dunhuang 100MW Solar Tower Plant is the first 100MW-class solar tower plant in China. The plant is located in West Photoelectric Industrial Park, Qili Town, Dunhuang City, Gansu Province, and is equipped with an 11h thermal storage system and a heliostat field reflection area of 1.4 million m2. The plant achieved full-load operation in June 2019. In 2022, after system optimization, the heliostat field efficiency and all other system performance indicators of the set have been significantly improved. Among them, the monthly power generation in June 2022 exceeded 33.79 million kWh, with a year-on-year increase of 91.2%. The maximum daily power generation of the plant reached 2,216,500 kWh, with an increase of 197,600 kWh compared to 2021; The maximum uninterrupted power generation duration was approximately 263 hours, with an increase of 47 hours compared to 2021. The power consumption rate was approximately 1% lower than in 2021.

Based on the actual power generation in the first half of the year, the total annual power generation of the plant in 2022 should reach at least 250 million kWh, which is expected to be more than 25% higher than the previous year. However, due to the wear of the main shaft caused by the design defect of the No. 3 turbine bearing pad oil baffle, the set has been shut down for several long periods since July 2022 to deal with the worn part of the main shaft. At the same time, the line maintenance scheduled by the power grid company exceeded the time limit, resulting in a total of 77 sunny days of shutdown throughout the year. According to the DNI measurement during the shutdown period, the shutdown directly caused a reduction of 52.77 million kWh of power generation. In addition, due to the reduction of the shaft diameter caused by the wear of the turbine main shaft, the set can only operate at 50% of the load from July 14, 2022 to the present, and the maximum safe operating load cannot exceed 60%, resulting in an annual power generation of approximately 197,416,314 kWh in 2022.

3.3 Qinghai SUPCON Delingha 50MW Solar Tower Plant

Qinghai SUPCON Delingha 50MW Solar Tower Plant is the first demonstration project in China to take the lead in reaching the design value. It is located in the West Exit PV (Thermal) Industrial Park, Delingha, Qinghai Province. It was invested and constructed by Qinghai SUPCON Solar Power Generation Co., Ltd. The plant is equipped with a 7h molten salt energy storage system, with a heliostat field daylighting area of 542,700 m2 and a designed annual power generation of 146 million kWh, which can save 46,000 tons of standard coal and reduce carbon dioxide emissions by about 121,000 tons per year after it is fully put into operation. The project adopts the core technology of molten salt solar tower plant, which is independently developed by Zhejiang Cosin Solar Technology Co., Ltd. who fully owns the intellectual property rights. More than 95% of the equipment has been localized. The overall design of the plant, the process package technology of the thermal storage and heat exchange system, the equipment of the solar concentration and solar collection system, and guidance in system commissioning and operation & maintenance were provided by Zhejiang Cosin Solar Technology Co., Ltd.. The plant was connected to the grid on December 30, 2018, put into full-load operation on April 17, 2019, and handed over for production and operation in July 2019.

In 2022, the plant generated 146.4 million kWh of electricity, achieving a designed annual power generation of 100.3%. From September 28 to October 7, 2022, the set was shut down for 10 days due to grid maintenance; If this factor is excluded, the power generation in 2022 would be 103.18% of the design value.



3.4 CGN Delingha 50MW Parabolic Trough CSP Plant

CGN Delingha 50MW Parabolic Trough CSP Plant is located in the west exit PV (thermal) industrial park, Delingha, Qinghai Province, and it is the earliest project to start and complete among the first national CSP demonstration projects. The project site is 3,000 m above sea level, with extreme low temperature of -30℃ , which is the world's first large-scale parabolic trough CSP plant in high and cold and high altitude region. The plant is equipped with 9h molten salt thermal storage system, and heliostat field daylighting area of 620,000 m2. The technical route is "parabolic trough oil-conducting solar concentration and solar absorption + binary molten salt and thermal storage + turbine".

In 2022, the plant achieved an on-grid energy of 120.7 million kWh and 2,414 full-load equivalent utilization hours for the year. During the period, the highest daily on-grid energy of 865,000 kWh and the highest monthly on-grid energy of 14,011,800 kWh exceeded the highest level in history. During the period from April to June 2022, the monthly power generation exceeded 12 million kWh. The operation and maintenance level and the power generation capacity of the plant were significantly improved. From September 19, 2021 to May 7, 2022, the set have been operated safely for 230.2 consecutive days.

By continuously summarizing the long-cycle, low-load and variable operation and maintenance strategies of the solar thermal sets and taking many effective measures, the equipment availability and on-grid energy of the plant have been greatly improved, the operation and maintenance level has been continuously improved, and the operational effectiveness has made a historic breakthrough. In 2022, the equipment availability rate increased from 65% to 98%, and the power generation capacity of the sets increased by 53.7%.

3.5 PowerChina Gonghe 50MW Solar Tower Plant

PowerChina Qinghai Gonghe 50MW Solar Tower Plant is located in the ecological CSP park, Gonghe County, Hainan Prefecture, Qinghai Province. The average altitude of the park is 2,880 m, and the total area of the project is 2.12 m2. The plant is equipped with a 6h thermal storage system, and 30,016 heliostats, with a single heliostat size of 20 m2 and a total heliostat field aperture area of about 600,000 m2. The molten salt solar receiver has a rated output of 230MWth, a design temperature of 650℃ and an inlet and outlet temperature of 290/565℃ . It is made of nickel-based alloy. The turbine is an ultra-high pressure, single-reheat and 8-stage direct air-cooled turbine with a rated power of 50MW.

The project was commenced on May 8, 2018. The set was connected to the grid on September 19, 2019 and it passed the national demonstration acceptance on April 25, 2021. The production and operation period of the plant is 25 years, and the investment per unit kilowatt is RMB 23,883.12 /kW.

3.6 Lanzhou Dacheng Dunhuang 50MW Linear Fresnel CSP Plant

Lanzhou Dacheng Dunhuang 50MW Linear Fresnel CSP Plant is the world's first molten salt linear Fresnel CSP plant that achieved commercial operation. The project is located in the PV industrial park, Qili Town, Dunhuang City, Gansu Province. It adopts Lanzhou Dacheng's high-temperature molten salt linear

Fresnel solar concentration and solar absorption technology with independent intellectual property rights. The plant has a thermal storage duration of 15 hours and a 24h continuous power generation capacity in normal weather.

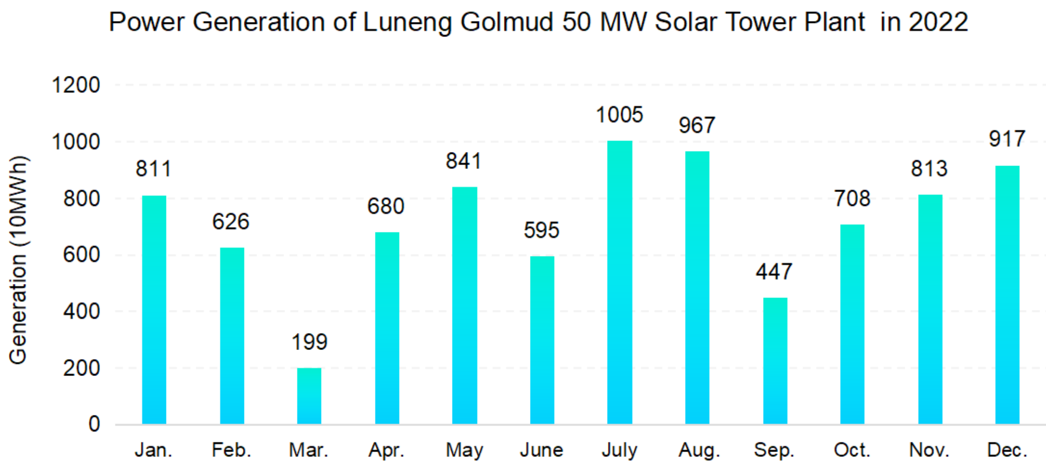
The project was connected to the grid for power generation on December 31, 2019, and commissioned in early June 2020 for the thermal-state salt injection. The solar collector field system was connected to the grid for power generation and operation on June 18, 2020. The project was the first to realize the commercial operation of molten salt linear focusing technology, and implemented the normalized molten salt injection and discharge in a pioneering manner during daily operation, which solves the technical difficulties in low-heat-loss operation relying on molten salt linear focusing technology. The molten salt linear Fresnel collector has passed international authoritative third-party testing and domestic expert evaluation, both of which rated it to reach the international advanced level.

In 2022, after operation optimization and O&M strategy adjustment, the plant gradually entered the power generation rising stage. The monthly power generation of May, June and July, 2022 exceeded 10 million kWh, and the total annual power generation increased by 45.85% compared with that of 2021.

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

Luneng Haixi Prefecture Multi-energy Complementary Integration and Optimization (National) Demonstration Project has a total installed capacity of 700MW, including 200MW of PV power, 400MW of wind power, 50MW of CSP, and 50MW battery storage. The supporting 330kV convergence station and national multi-energy complementary demonstration center are the world's first multi-energy complementary technology innovation project integrating wind, PV, thermal storage and load regulation. As an important part of the multi-energy complementary project, CSP with 12h molten salt thermal storage system is responsible for peak-shaving for intermittent power sources such as wind power and PV. The CSP plant was connected to the grid at a time on September 19, 2019 and it completed the 120h reliable operation on August 27, 2020; On May 14, 2021, the CSP plant completed the grid-connected joint test and the AVC system achieved the closed-loop operation.

Through continuous optimization of operation, the plant production has gradually stabilized and improved. In 2022, the plant generated 86,089,500 kWh of electricity, with an increase of 16,590,000 kWh compared to 2021. The maximum daily power generation of the plant is 1,096,200 kWh, and the maximum monthly power generation is 10,673,775 kWh.



3.8 EnergyChina Hami 50MW Solar Tower Plant

PowerChina Hami 50MW Solar Tower Plant is located in Iwu County, Hami City, with a total investment of RMB 1.58 billion. A total of 14,500 heliostats are installed in the solar concentrator field, with a single heliostat area of 48.5 m2 and thermal storage duration of 13 hours. For the first time, the project adopts the design of double heat tank + single cooling tank and the first domestic direct air-cooled turbine with ultra-high temperature, ultra-high pressure, single intermediate reheat, double cylinders, axial exhaust and Stage 8 regeneration for CSP.

The project officially started construction on October 19, 2017 and it was first connected to the grid on December 29, 2019. The project was connected to the grid at 01:26 a.m. on June 18, 2021, and it generated electricity at full capacity on September 6. From August 26 to September 27, 2021, the system operated continuously for more than 240 hours; From September15 to 19, the plant operated continuously for 5 days, with 4.16~24 hours of uninterrupted operation per day, and an average value of 8.674 hours; Under the design meteorological conditions, the turbine operated continuously for more than 1 hour per day at more than 90% of the design output for 5 days, with an average value of 1.3 hours.

4. CSP Industry Chain in China

4.1 System and characteristics of CSP industry chain [5]

The CSP industry chain is long, which covers R&D, design, manufacturing, installation, operation and maintenance, etc.

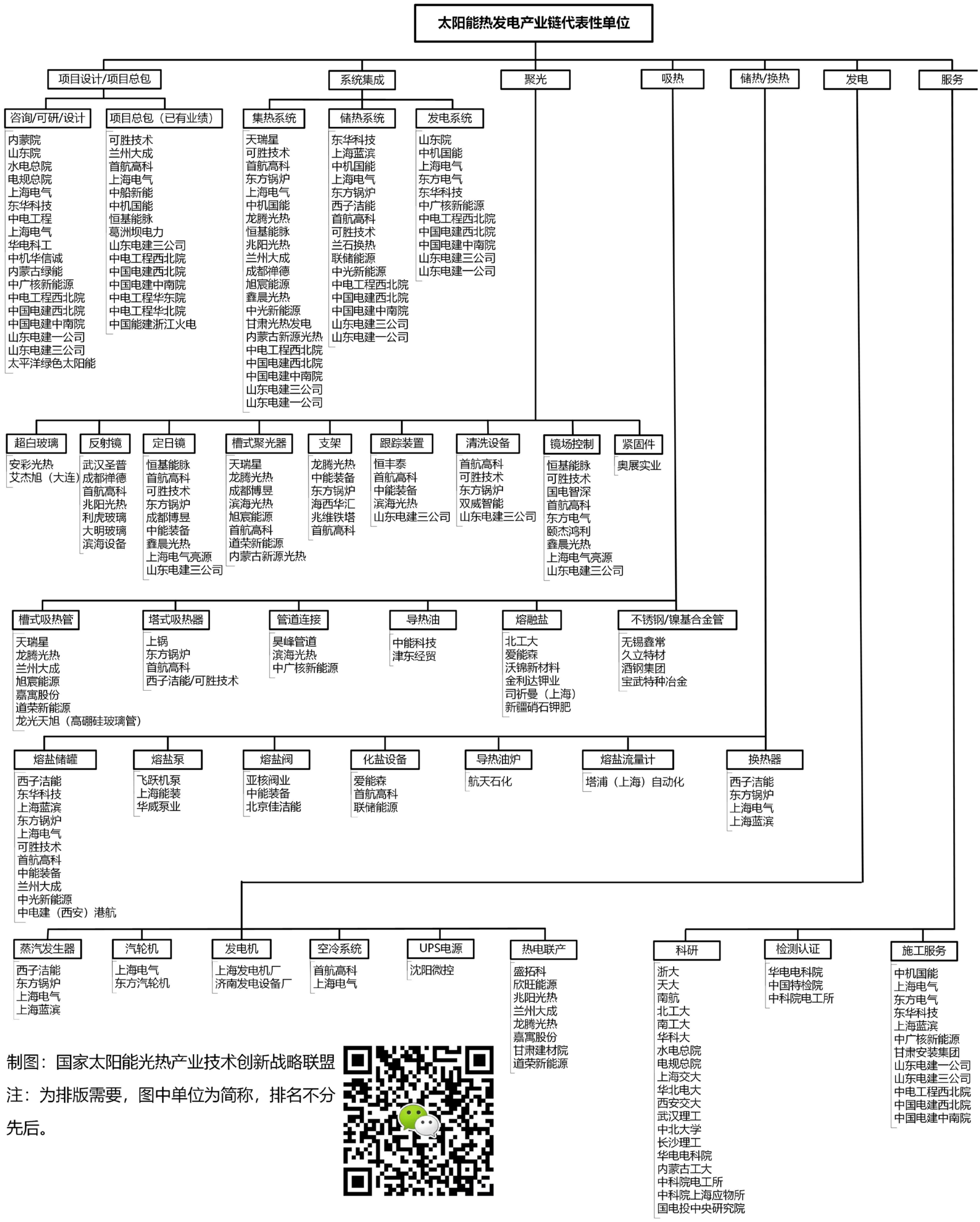
Among them, the R&D system mainly includes relevant universities and colleges, major research institutes and research departments of enterprises; The design system mainly includes design units engaged in power generation industry, design units of new and renewable energy, and design units with corresponding qualifications; The manufacturing system mainly includes major manufacturing enterprises (state-owned enterprises, private enterprises, joint ventures), production units of universities, colleges and research institutes, etc.; The installation system mainly includes professional power installation units and industrial construction & installation units.

The main feature of China's CSP industry chain is that the industry chain, with the easy-to-acquire, safe and abundant raw materials as the starting point and starting point, such as steel, cement, ultra-clear glass, high-temperature solar absorption, heat transfer and thermal storage materials (thermal oil, molten salt), insulation materials, etc., drives the development of core equipment of the industry chain with independent intellectual property rights, such as mirror reflector, heliostat, tower receiver, parabolic trough concentrator, parabolic trough receiver tube, high-precision gear box, bracket, local controller, thermal storage device/ system, sliding steam turbine, etc. In the first batch of national CSP demonstration projects, the localization rate of equipment and materials exceeded 90%, and the reliability and advancement of technology and equipment have been effectively verified after the plant has been put into operation. Among them, in the Qinghai SUPCON Delingha solar tower plant and the CNSP parabolic trough CSP Plant, the proportion of components and materials for China's self-developed equipment reached 95%.

4.2 Main representative players of China's CSP industry chain

According to the incomplete statistics of the China Solar Thermal Alliance, the number of enterprises and institutions engaged in products and services related to the CSP industry chain in China is about 600. Among them, the number of enterprises engaged in solar concentration, heat collection and thermal transfer and storage systems unique to the CSP industry accounts for about 55% of the total number of enterprises in the industry, with the largest number of enterprises engaged in the field of solar concentration, about 170.

According to the research on the CSP industry chain conducted by the CSP Committee of China Renewable Energy Society, including the direct and indirect employers in the CSP industry from plant design, equipment manufacturing, plant construction to the plant operation and maintenance in China are about 59,000. The main representative players of CSP industry chain in China can be found in the following chart .The English table can be found in the annex.



制图：国家太阳能光热产业技术创新战略联盟

注：为排版需要，图中单位为简称，排名不分先后。

4.3 Manufacturing capacity of CSP components and materials

Driven by China's first CSP concession bidding project in 2009 and the first batch of national CSP demonstration projects started in 2015, after more than a decade of development, China has now established a full CSP industry chain, and has the product supply capacity to support the large-scale development of CSP. According to the rough statistics of the China Solar Thermal Alliance, the current manufacturing capacity of key product components in China can support the construction of at least 3GW CSP projects per year (without considering the temporary supply shortage that may be caused by centralized construction and procurement). The following table shows the production line capacity of key components/materials related to CSP in China.

Table: Production Line and Capacity of Key Components/Materials of CSP in China

Production line of key components	Quantity (piece)	Production capacity
Solar mirror glass sheet	5	92,000,000 m2
Parabolic trough glass reflector	6	23,500,000 m2
Flat mirror	6	33,600,000 m2
Parabolic trough vacuum tube receiver	10	1 million pieces
Tracking device	21	20,000 sets
Heat transfer oil (Mixture of biphenyl and diphenyl ether)	2	40,000 t (biphenyl output)

4.4 Application of key components/materials for CSP in China

According to the statistics of the China Solar Thermal Alliance on relevant manufacturers and owners, the eight national CSP demonstration plants have used a total of 6.913 million m2 of mirror reflector, with domestic supply accounting for about 91%, and 215,000 tons of molten salt supplied by domestic enterprises. In the three line-focus CSP projects (parabolic trough and linear Fresnel), 102,300 solar receiver tubes and 10,000 tons of thermal oil were used, with domestic supply accounting for 73.1% and 78.9% respectively.

Table: Usage of Key Equipment/Materials for 8 CSP Demo Plants in China

Short name of project	Thermal storage (hr)	Reflector (m^2)	Molten salt (ton)	Receiver tube (Piece)	Heat transfer oil (ton)
DCTC 50MW Molten Salt LFC Plant	15	1270000	24000	22000	/
EnergyChina Hami 50MW Solar Tower Plant	13	719902	16000	/	/

Short name of project	Thermal storage (hr)	Reflector (m^2)	Molten salt (ton)	Receiver tube (Piece)	Heat transfer oil (ton)
Luneng Golmud 50MW Solar Tower Plant	12	610000	16000	/	/
Shouhang 100MW Solar Tower Plant	11	1400000	30000	/	/
CNSP Urat 100MW Parabolic Trough plant	10	1150000	73130	52800	7500
CGN Delingha 50 MW Parabolic Trough CSP Plant	9	620000	36000	27500	2000
SUPCON Delingha 50 MW Solar Tower Plant	7	542700	10093	/	/
POWERCHINA Gonghe 50 MW Solar Tower Plant	6	600320	9300	/	/
Subtotal		6912922	214523	102300	9500

Table: Usage and Supply of Related Equipment/Materials for some 50MW Molten Salt Solar Tower Plant in China

No.	Name of equipment or material	Usage per project	Supplier's capacity (from plant owner's survey)
1	Heliostat	27,000 × 20 m^2 heliostats	100,000 sets
2	Molten salt	1.5 t	500,000 ~ 1,000,000 t
3	Stainless steel	1200 t	More than 1 million tons
4	Cement	26,000 sets	More than 100 million tons
5	Carbon steel (including steel bars)	9,000 t	More than 100 million tons
6	Thermal insulation materials	130 t	More than 10,000 t
7	Molten salt storage tank	2 sets	More than 100 sets
8	Molten salt heat exchanger	10 sets	More than 500 sets
9	Valve	280 sets	More than 10,000 sets
10	Molten salt solar receiver	1 set	More than 20 sets
11	Glass	700,000 m^2	More than 50 million m2

No.	Name of equipment or material	Usage per project	Supplier's capacity (from plant owner's survey)
12	Receiver tube	34 t	/
13	Molten salt solar receiver coating	0.3 t	/
14	Molten salt flowmeter	10 sets	/
15	Molten salt pump	10 sets	/
16	Molten salt valve	120 sets	/
17	Infrared thermal imager	8 sets	/

According to the feedback from the owner of the demonstration project, the domestic core equipment used in the solar thermal demonstration plant, such as the heliostat, heliostat field control system, solar receiver and heat exchanger, are running stably and all performance indicators can meet expectations. Imported molten salt pump occurred problem of vibration exceeded the design value in the early stage of operation, but after rectification, it has been under basically stable operation. The domestic molten salt pump has been placed on trial, and kept in basically stable operation. However, the effect of long-term operation of China-made molten salt pump needs further verification. The domestic turbine generator sets repeatedly suffered vibration ultralimit of high-pressure cylinder in idling during the normal shutdown and other problems, resulting in a longer shutdown of the CSP plant. The reason mainly includes the lack of experience and the lack of targeted design optimization in the design phase for the operational characteristics of the CSP plant. After several times of rectification of the turbine itself and the piping of the supporting thermal system, the problem has been basically solved and the generator set can achieve long and stable operation. Through the construction, operation, and optimization of the demonstration project, there is no longer a bottleneck for the main equipment for solar tower plants in this stage. The next step is to promote the localization of imported equipment and materials such as cold and hot molten salt pumps and solar receiver materials through more CSP projects, gradually increase the localization ratio of such equipment, continue to optimize systems and key processes, so as to improve system efficiency, reduce costs, and enhance the economics of CSP plants for larger scale application.

4.5 Breakthroughs in key equipment technology and application in China

After more than a decade of accumulation of technology and small demonstration projects, China has achieved independent production and application of key devices for CSP, such as high-precision parabolic solar concentrators, trough vacuum solar receiver tubes and mirror reflectors, and has gradually strengthened the industrial base. Moreover, through the construction of large-scale CSP projects, the missing links related to the industry chain have also been made up. Through the construction of the first CSP demonstration projects, China has made a major breakthrough in high-temperature molten salt pumps, molten salt valves, molten salt tower solar absorbers (materials), high-temperature molten salt flow meters, flexible connectors for parabolic trough plant and other products.

In the bidding for the first batch of CSP demonstration projects, all high-temperature molten salt pumps are required to be foreign molten salt pump products. In the enterprises represented by Jiangsu FEIYUE Machine and Pumps, through technology R&D, and utilization and verification in the form of standby pump in the demonstration plant, after nearly two years of operation, the performance of the domestic high-head cold salt pump has been proved to be basically reliable and stable, which has been recognized by the project owner and successfully won the bid in the CSP project of the wind and PV new energy base.

The molten salt valve has a key role although its investment ratio is small. It has been monopolized by a few international brands, which results in high price and difficulty in fault responsibility identification and after-sales service. With the construction of CSP demonstration projects, Shanghai YAHE Valve , Beijing Jiajieneng New Energy Saving Technology and other valve companies have successfully developed a series of molten salt valves for CSP plant based on the characteristics of solar thermal molten salt and specific working conditions, of which, the special molten salt non-return valve is the first in the world. Nearly 300 molten salt valve products manufactured in China have been used in several test platforms and CSP demonstration projects, most of which have been in operation for more than two years. In addition, cost reduction has also be carried out for the domestic molten salt valves. For example, Shanghai YAHE Valve, after optimizing design, has successfully developed a molten salt valve that can significantly reduce the cost of electric tracing by more than 60%. For a 100MW solar tower project, only two devices, i.e. the large differential pressure regulating valve on lower tower and the non-return valve at outlet of molten salt pump, can save investment costs of nearly RMB 10 million.

In terms of the high-temperature molten salt solar tower receiver, China's relevant steel enterprises have cooperated with demonstration project owners to produce nickel-based alloy that can be used to produce high-temperature solar tower receiver. Some metal alloy enterprises, jointly with domestic well-known universities, has achieved milestone results in the independent development of nickel-based thin-walled welded tubes for solar receiver. The enterprises including Cosin Solar / Xizi Clean Energy (formerly Hangzhou Boiler), Shanghai Boiler, Shouhang High-tech Energy can provide more than 30 molten salt solar receivers annually.

In terms of the high-temperature molten salt flow meter, the molten salt, as a heat transfer fluid, has a operating temperature of more than 250℃ at the cold end, and 500 ~ 600℃ at the hot end. Its density, viscosity and other physical and chemical properties also change with temperature. The freezing point of molten salt is relatively high. This poses a challenge to the daily measurement of fluid flow in tubes. Based on the large temperature fluctuations of molten salt in operation, as well as high-temperature and low-temperature condensation, corrosion, salt spray and other characteristics of the molten salt itself, TOPFM (Shanghai) Automation has developed the ultrasonic molten salt flow meter for the CSP plant, up to 600℃ .

In terms of the parabolic trough flexible connector, the parabolic trough solar collector can not be separated from the flexible connection. Its main function includes: Connection of vacuum solar collector tube and hot and cold sink tube, compensation of axial displacement of the vacuum solar collector tube, compensation of azimuthal rotation displacement of solar collector. The metal hose assembly for rotary joint developed by China's enterprises has achieved engineering verification applications, with cumulative application number over 1,000 sets.

In addition, the area suitable for the construction of CSP plants in China is located in the northwestern regions, where the winter is severe. In order to promote the plant start-up, and the condensation prevention of oil-conducting system and thermal storage system during the cold winter period, Beijing Aerospace Propulsion Institute has developed an oil-conducting furnace suitable for CSP plant based on the professional technologies of combustion, heat transfer and control with liquid rocket engine, with the efficiency of oil-conducting furnace reaching more than 92% and the application effect of innovative design reaching international advanced level.

5. Overview of China's CSP R&D Projects

The distribution of research contents in SCI paper on CSP technology published globally in 2022 is described in the figure below, which shows a predominance of engineering aspects. Production of fuel with solar thermal chemistry is also a hot topic. This method involves solar pyrolysis and catalyzation to produce fuels, such as hydrogen, carbon monoxide and methane, and utilization of gas and liquid fuels to generate electricity.

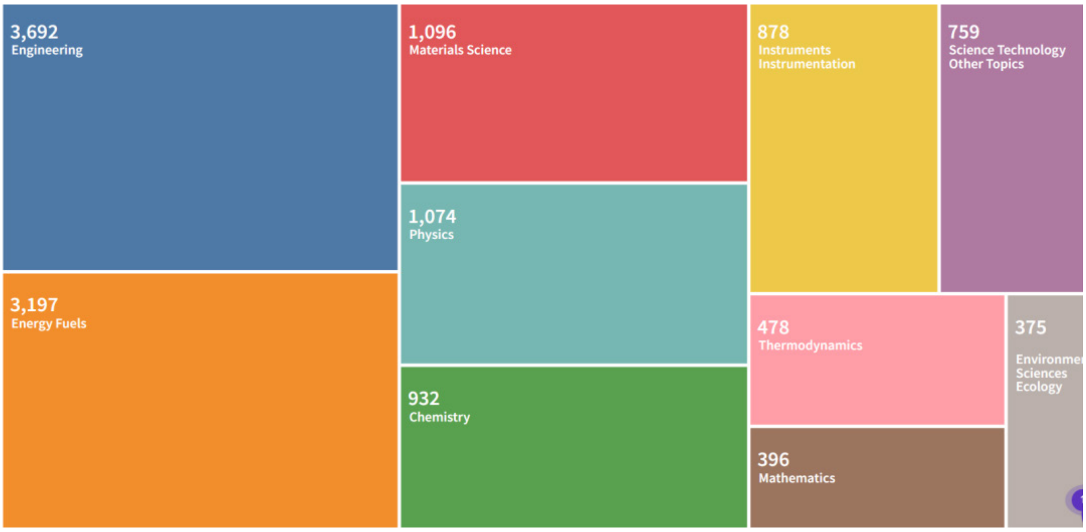


Figure: Distribution of SCI Articles on CSP in 2022

5.1 Projects funded by National Natural Science Foundation of China

The Discipline of Engineering Thermophysics and Energy Utilization, Department of Materials Science and Engineering, National Natural Science Foundation of China (NSFC) funded a total of 21 projects in CSP in 2022, with a total funding of RMB 8.06 million, including 8 general programs, 12 youth projects, and 1 regional and international cooperation and exchange project. It involves efficient solar spectrum absorption mode and regulation with solar particle and liquid, efficient full-spectrum utilization based on dynamic regulation of solar, PV and CSP, solar desalination, solar-thermal-driven hydrogen production, energy conversion by coupling of solar photothermal and CO2, and solar thermal storage. As can be seen from the figure, in terms of CSP, SCI papers funded by National Natural Science Foundation of China took the first share worldwide, playing a major role in the advancement of CSP science.

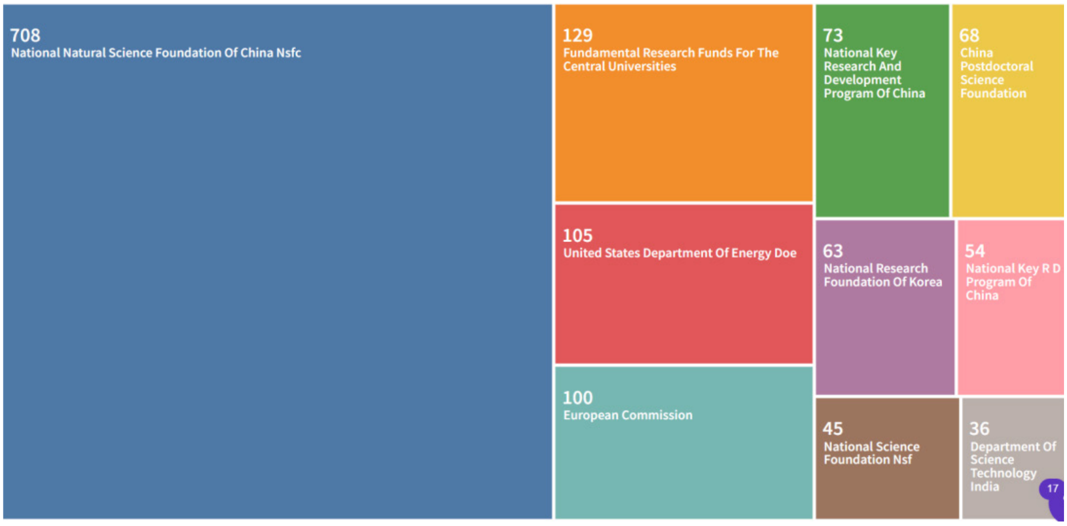


Figure: Distribution of Funding Institutions for SCI Articles in 2022

5.2 CSP projects funded by National Key R&D Program of China

In 2022, the National Key R&D Program of China on CSP has four projects established, as follows：

Project I：

Project Name: Theory and method of high-flux concentrating solar thermochemical conversion and energy storage

Project Lead Unit: Xi'an Jiaotong University

Project Leader: Wei Jinjia

Cooperation Unit: Zhejiang University, Institute of Electrical Engineering of the Chinese Academy of Sciences, Technical Institute of Physics and Chemistry in CAS, Fuzhou University, and Beijing Institute of Petrochemical Technology

Implementation Period：2021.12.01—2026.11.30

Project Overview: Conventional solar energy storage technology has the problem of low energy storage density and low exothermic temperature, which seriously restricts the large-scale application of clean and sustainable CSP technology. The high-flux solar concentration thermochemical conversion and energy storage system has the advantages of high energy storage density and efficiency, and high reaction temperature, and it is one of the most promising technologies for large-scale solar energy storage application. To address the bottleneck of low energy storage density and low exothermic temperature of conventional solar energy storage system, the project will, focusing on two key scientific issues, namely, the constitutive relationship and reaction thermodynamic/kinetic performance mechanism of co-doped modified solar thermochemical energy carriers, and the enhanced mechanism of non-stationary, multi-scale, multi-field coupling and synergistic high-flux solar concentration thermochemical conversion and energy storage process, establish the theory of enhanced thermochemical conversion and energy storage by multi-scale coupling of light, heat, force, flow, chemical and acoustic fields under non-stationary high-flux solar concentration conditions, propose the construction and preparation method of high-performance thermochemical energy carriers, develop efficient suppression techniques for sintering and agglomeration of energy carrier particles, build efficient integrated solar energy storage devices and systems for solar concentration & collection and chemical energy storage and realize their application verification, and develop innovative theories and methods for large-scale solar thermochemical conversion and energy storage with high energy density, high reaction temperature and long cycle life, so as to provide key support for stable and continuous solar thermal utilization. Research Goals: (1) Development of outdoor high-flux solar concentrator with thermal power ≥ 15 kW and peak heat flux ≥ 1.6 MW/ m2; (2) Development of highly reactive anti-sintering fine particle energy carriers with reaction temperature ≥750 °C and energy storage density ≥1,200 kJ/kg, with performance degradation not exceeding 30 % after ≥2000 cycles; (3) Development of high-flux solar concentration & direct solar absorption fluidized bed reaction unit and acoustically stimulated fluidized bed exothermic reaction unit with a conversion rate of ≥85 %; (4) R&D of integrated solar energy efficient storage demonstration device system for solar concentration & collection - chemical energy storage, with solar thermochemical energy storage efficiency ≥ 60 %, thermal power ≥ 15 kW, reaction unit conversion rate ≥ 85 %, exothermic temperature ≥ 750 ℃ , and energy storage density ≥ 1,200 kJ/kg.

Project II：

Project Name: Research on the mechanics of high-temperature molten salt storage tank for CSP and life prediction ("China-US Government Cooperation Project", a key project of "International Cooperation in Science and Technology Innovation between Governments")

Project Lead Unit: Institute of Electrical Engineering of the Chinese Academy of Sciences

Project Leader: Zang Chuncheng (C), Dr. Mark Mehos (US)

Cooperation Unit: Northwest Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group, CGN Solar Energy Development Co., Ltd., Harbin Turbine Company Limited, NREL (US)

Implementation Period: 2023.01.01—2025.12.31

Research Goals: Aiming at the problem of leakage failure and life loss caused by corrosion and thermal fatigue of high-temperature molten salt storage tank under complex working conditions, carry out mechanical research and life prediction of high-temperature molten salt storage tank, optimize the life prediction model through experimental verification, develop the molten salt storage tank structure design software with life prediction function by considering the engineering practice of commercial CSP plants, and break through the technical difficulties in long life prediction of large-capacity molten salt storage tanks, so as to provide technical guidance for life evaluation, structural design optimization and safe operation of molten salt storage tanks in CSP plants.

Project III:

Project Name: CPC Key Technology Research on Concentrating Solar Interfacial Evaporation Desalination System ("China-US Government Cooperation Project", a key project of "International Cooperation in Science and Technology Innovation between Governments")

Project Lead Unit: Institute of Electrical Engineering of the Chinese Academy of Sciences

Project Leader: Wang Tengyue (C), Dr. Lun Jiang (US)

Cooperation Unit: National Center for Nanoscience and Technology, China Mining University, Winston Cone Optics Co.Ltd (US)

Implementation Period: 2023.01.01—2025.12.31

Research Goals: Desalination using solar thermal is an important low-carbon and clean way to alleviate the global scarcity of freshwater resources and energy shortage. Solar interfacial evaporation can localize the processes of solar collection, photothermal conversion and evaporation to the water-air interface, keeping the water temperature close to the ambient temperature and minimizing heat loss. However, in actual application, the outdoor ambient temperature is low, the solar irradiance is low, and the convection and radiation heat loss between the interfacial evaporator and the environment is large, which causes the surface temperature to be low and limits the evaporation rate. In addition, it is difficult for the vapor to diffuse rapidly and the natural condensation efficiency is low in the outdoor natural state. The project proposes an asymmetric compact CPC concentrating solar interfacial evaporation desalination system to promote the interfacial evaporation technology from the laboratory to the outdoor practical engineering application. Research Goals: (1) Design of interfacial evaporator with enhanced photothermal conversion based on equilibrium excitation elements, achieving integrated layered porous grade structure design of solar absorption/evaporation/insulation, with photothermal conversion efficiency ≥95%; (2) Development of an asymmetric compact CPC concentrating interfacial evaporation system with a total daylighting area of no less than 100 m2 based on the interfacial evaporator to meet the outlet vapor temperature ≥70°C; (3) Design of a tubular phase-to-phase exchanger based on a hydrophilic and hydrophobic composite heat exchange surface, and establishment of a multi-effect humidification-dehumidification desalination system driven by solar CPC steam thermal source to achieve a daily water production of ≥8kg per square meter of the interfacial evaporator.

Project IV:

Project Name: Research on Key Technologies for Stable Power Output of Secondary Reflective Solar Tower-PV Combined Power Plant ("China and Spain Government Cooperation Project", a key project of "International Science and Technology Innovation Cooperation between Governments").

Project Lead Unit: Xinchen Solar Thermal (Shanghai) New Energy Co., Ltd.

Project Leader: Xie Wentao (C), Raúl Navío Gilaberte (Spain)

Cooperation Unit: Shanghai Jiao Tong University, Alia Energy Consulting SL (Spain)

Implementation Period: 2023.01.01—2025.12.31

Research Goals: Consider the new cycle design from multiple perspectives, such as cycle efficiency and specific power, and carry out the design of system configuration technology scheme and target optimization; Perform simulation and analysis of the response characteristics of the system performance parameters under different operating conditions, and comprehensive analysis of the system evaluation indicators and target optimization.; Carry out theoretical modeling of coupled key components for integration of absorption-storage-heat exchange, and research on the optimal matching of supercritical CO_2 power cycle characteristics with storage and exothermic characteristics; Carry out research on the mechanism of supercritical CO_2 dynamical cycle operation with matched secondary mirror reflector field.

The project innovations include:

1) Establishment of a secondary reflection tower solar collection system coupled with new components for integration of absorption-storage-heat exchange; R&D of a secondary reflection tower concentrating system based on the full closed-loop control of the heliostat field and new key components for integration of absorption-storage-heat exchange based on solid particles and other high-temperature materials, significantly improving the optical efficiency and thermal conversion efficiency.

2) Development of 600°C thermal source-driven high-efficient supercritical CO_2 power generation technology; Development of a new power cycle with high parameters and high flexibility through various technical approaches such as recompression of the working medium, intermediate graded cooling and internal multiple heat recovery, so as to improve cycle efficiency.

3) Propose a configuration and scheduling optimization method to ensure the economic and smooth operation of the combined solar-PV power plant; Couple the thermal storage link of CSP, and enhance the economy of the combined power plant through PV power generation. Develop a general intelligent optimization method and a corresponding scheduling and operation control strategy to ensure the economic and smooth operation of the combined power plant.

6. Investment Costs of CSP Plants

6.1 Construction cost and composition of solar tower plant

6.1.1 Investment composition of 50MW solar tower power plant with 7h thermal storage

Solar thermal power is a technology- and capital-intensive industry with a long industry chain, with many disciplines involved. The investment of the project is greatly influenced by the scale of installed capacity and thermal energy storage time. In the "Whole Life Cycle Cost Tariff Analysis of Solar Power Tower Generation", Dr. Xin Li and Dr. Xiaohui Zhao et al. divided the construction cost of 50MW solar power tower generation into solar island cost, thermal power generation island cost, thermal energy storage system cost, site preparation cost, power plant supporting and infrastructure cost and overhead cost according to the system function, and the specific percentage of each part is shown in the following figure.

The solar island mainly includes the concentration system and the heat absorption system; among them, the cost of the heliostat accounts for about 75%, the cost of the mirror field control system accounts for 10%, the receiver accounts for 6%, and the cost of the solar tower accounts for 9%. The thermal power island mainly includes thermal system and auxiliary equipment, water circulation, water treatment system, heat exchange equipment, thermal control system, electrical system, grid access system and instrumentation valve piping, etc.[23]

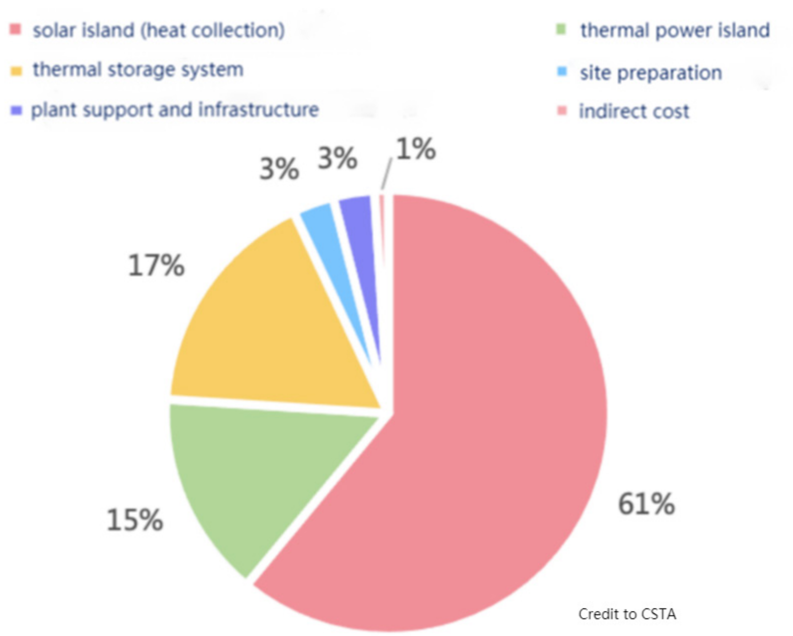


Figure: Investment composition of 50MW solar tower power plant with 7-hour thermal storage

Taking the development of Qinghai Supcon Delingha 50MW solar power tower demonstration project jointly invested by Cosin Solar and Zhejiang Zhongguang New Energy Company as an example, which covers an area of 3.3 square kilometers, with a 200m high solar tower, about 27,000 heliostats and 7 hours of thermal energy storage. It consumed about 550,000 square meters of glass, 20,000 tons of steel, 10,000 tons of molten salt, 30,000 tons of cement [25].

From the manufacturing point of view, among the investment cost of solar field, heat collection and thermal storage subsystems, the proportion of materials is lower than 30%, among them, steel accounts for about 53%, molten salt accounts for about 21%, and glass accounts for about 17% [25], and the manufacturing and processing cost is higher than 50%, and the packaging, transportation, installation and other costs is lower than 20%.

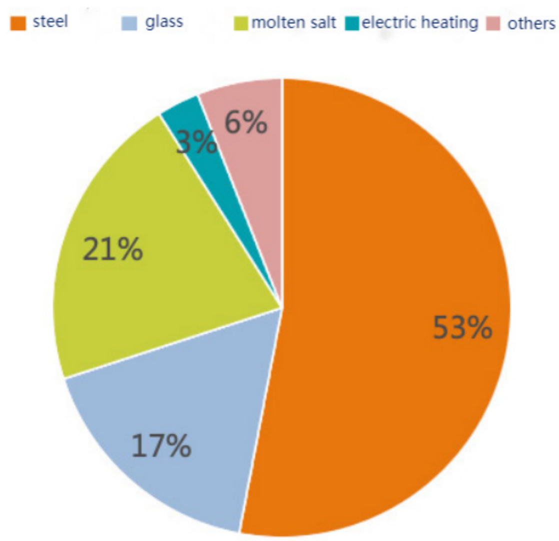


Figure: the cost proportion of raw materials in solar field, heat collection and thermal storage subsystems of Qinghai Supcon Delingha 50MW solar tower plant

6.1.2 Investment of 100MW solar power tower plant with 12h thermal storage system

According to the report <Analysis of the Cost Reduction Path for Solar Thermal Power in China> organized by the China Solar Thermal Alliance, the total investment of a 100MW solar tower plant with 12-hour thermal energy storage is between 2.5 billion and 3 billion yuan.

According to the function, the investment of the power plant mainly occurs in the heat collection system (solar concentration system, heat absorption system), thermal energy storage and exchange system (including thermal energy storage system, steam generation system), thermal system, water supply system, water treatment system, electrical system of thermal control system, subsidiary production engineering and site related engineering and other costs. As can be seen from the figure below, these three subsystems account for about 77% of the overall cost, and are the most important factor in determining the cost of a solar thermal power plant.

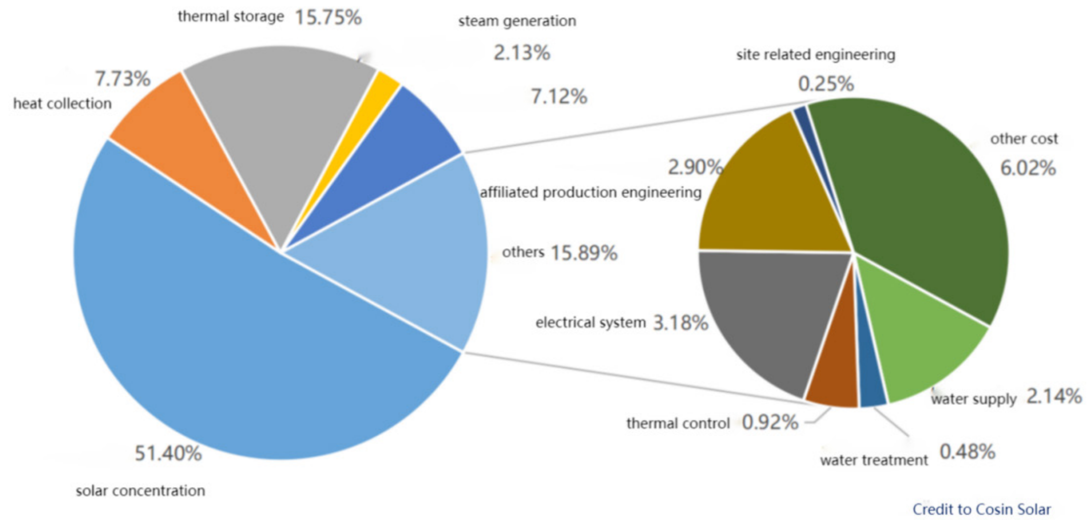


Figure: Investment composition of a100MW solar power tower plant with 12h thermal storage system

It should be noted that as the scale of the power plant becomes larger, or the storage time increases (according to different boundary conditions, the storage time should have an optimal value), the number of heliostats will increase accordingly, so that the proportion of solar island in the investment costs will also increase; however, the annual utilization hours of the power plant and the electricity generated will increase, so the overall economy of the power plant may improve.

6.2 Construction cost and composition of parabolic trough power plant

6.2.1 Investment composition of 50MW parabolic trough power plant with 4h thermal storage system

In 2013, commissioned by the National Energy Administration, the China Solar Thermal Alliance and other organizations carried out the study on China's Solar Thermal Power Industry Policy Mechanism. In the study, Clinton Foundation was invited to participate and analyze the cost of solar thermal power project in China based on the data supplied by the industry[33]. The selected case plant was the first solar thermal power project in China, namely, Erdos 50MW parabolic trough solar power plant, which completed the concession bidding in 2011.

The local normal direct radiation value (DNI) of the case power plant is 1900kWh/m^2/year, and the initial investment of the project includes solar collector, thermal energy storage, heat exchange, thermal power generation and other auxiliary systems and facilities (such as heating, production and office facilities, etc.), excluding the construction of grid infrastructure. The one-time initial investment in the case power station is about 1.456 billion yuan, of which, the cost of solar field equipment (mainly composed of concentrators, evacuated tube, local controllers and installation fees, etc.) accounts for 50% of the construction cost of the whole power station; the thermal energy storage system and thermal oil system account for 22% of the total investment, mainly the investment cost of molten salt and storage tanks; the engineering design and construction cost accounts for about 10% of the total investment cost; and the steam turbine sets accounts for about 4% of the total cost. The composition of the investment in this case is shown in the figure below.

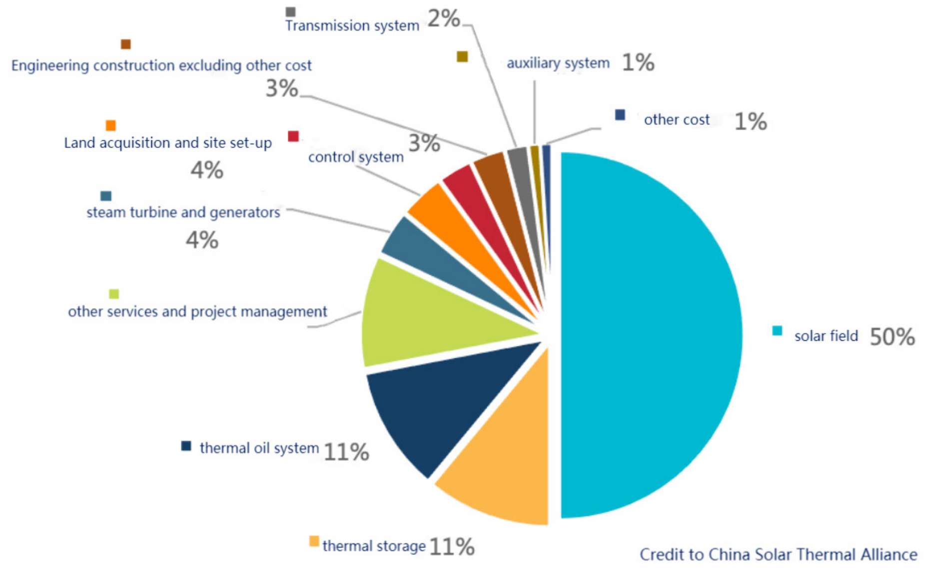


Figure: Investment composition of China's a 50MW parabolic trough plant with 4h thermal storage system

6.2.2 Investment composition of 100MW parabolic trough power plant with 10h thermal storage system

The figure below shows the investment composition of a typical parabolic trough solar power plant with an installed capacity of 100MW and 10 hours of thermal energy storage in China. The total investment of this power plant is about 2.8 billion yuan, mainly composed of heat collection system, steam generation system, thermal energy storage system, thermal system, water supply system, water treatment system, thermal control system, electrical system, auxiliary production engineering, site related engineering and others. Among them, the heat collection system accounts for about 52% and the thermal energy storage system accounts for about 18%.

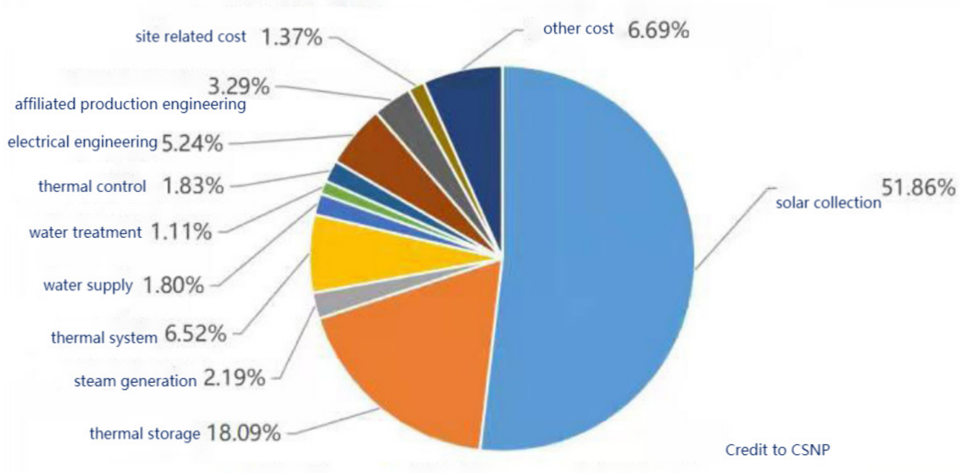


Figure: Investment composition of one 100MW parabolic trough power plant with 10h thermal storage system

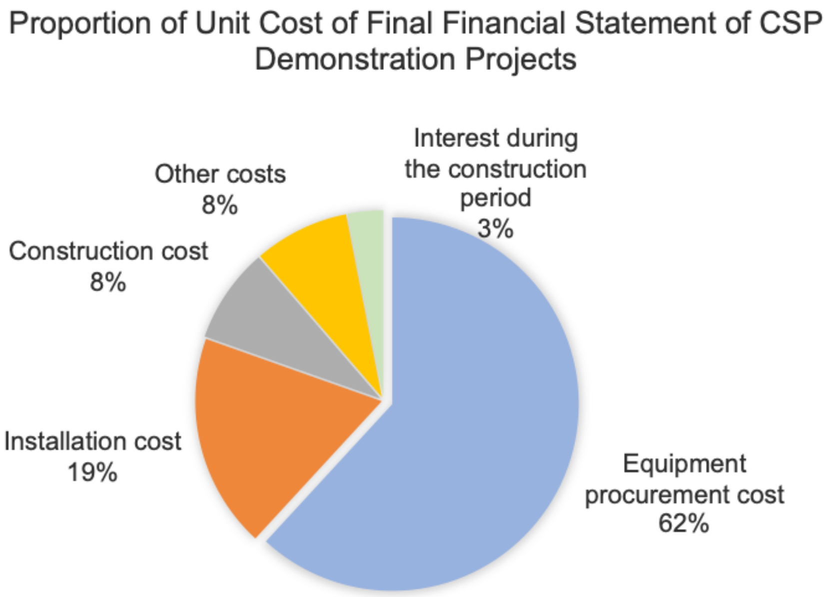
6.3 Thermal storage duration and LCOE

From the point of view of system configuration, the installed capacity, thermal storage duration and heliostat field area of a CSP plant are closely related to the economy of the plant. In general, in order to store energy for a longer period of time, the area of the solar collection field needs to be increased. In this case, the cost of initial investment increases.

According to the evaluation of the economy of the first batch of national CSP demonstration plants with different thermal storage duration, the estimated and final unit cost of the 7h solar thermal project is the lowest, at RMB 23,915 / kW and 22,417 /kW, respectively, and the estimated and final unit cost of the 15h solar thermal project is the highest, at RMB 34,965 / kW and 41893 /kW, respectively. This reflects that the longer the thermal storage duration, the higher the unit cost. However, it should be noted that the power generation of the plant will increase due to the increase in the storage duration, which may result the decrease of the LCOE (Levelized Cost of Energy) . The storage duration needs to be optimized according to the actual situation. There will be an optimal value of thermal storage for different meteorological conditions, available land area, and plant configuration.

6.4 Proportion of final unit cost of CSP demonstration projects

According to the Study on the Current Situation and Prospects of Domestic and Overseas CSP Development jointly conducted by China Renewable Energy Engineering Institute, China Solar Thermal Alliance, China Electric Power Research Institute, and China Electric Power Planning & Engineering Institute, the proportion of final unit costs of the five CSP demonstration projects is shown in the figure below, including 60% for the equipment purchase cost, 18% for the installation project cost, and 3% for the construction period interest.



Source: China Electric Power Planning & Engineering Institute

7. Challenges and Countermeasures for CSP Development in China

It is easy for CSP to configure large-capacity, long-duration, safer and low-carbon thermal storage system and allocate the conventional turbine generator sets. The system, characterized by rotary inertia and grid synchronizer, is a flexible regulation power. It is greatly suitable for the urgent need, of safe and stable operation of the grid, for rapid peak-shaving power source under the current high proportion of unstable renewable energy power grid connection, which can lay a safe and stable foundation for the construction of new energy-based power system. In 2022, China opened a large renewable energy base construction, gradually forming a large renewable energy power supply layout of CSP + PV + wind power. CSP plays a role in regulating the stability of the power system. In this scenario, main issues in the large-scale development of CSP include the reduction of solar concentrator cost, the increase of heat collection system temperature, the improvement of thermoelectric conversion efficiency, and the improvement of reliability in frequent high-power heat charging/discharging of thermal storage equipment and systems.

Reducing solar concentrator cost and improving solar concentrator field efficiency have been major issues in advancing the industrialization of CSP. In September 2021, the Department of Energy (DOE) established the DOE's Heliostat Consortium (HelioCon) with the participation of National Renewable Energy Laboratory, Sandia National Laboratories, and the Australian Solar Thermal Research Institute. From 2021, DOE has allocated USD 25 million to support HelioCon study for five years. HelioCon is working with the industry to meet DOE's 2030 target of USD 50/m2 for heliostat cost (including field installation) and this cost was USD 140/m2 in 2022. In September 2022, HelioCon published the Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power detailing the development of heliostat technology for CSP.

The development of CSP is accompanied by PV. As of the end of 2021, more than 843 GW of PV systems were installed worldwide, with an increase of nearly 21 times over 2010. The newly-installed PV systems in 2021 reached 133GW, with an increase of 13% over 2020, becoming the largest renewable energy increased in 2021. The global LCOE of scaled PV power plant increased from USD 0.417/kWh in 2010 to USD 0.048/kWh in 2021, with a reduction in the PV power cost of 88%. The global weighted average installation cost of PV systems in 2021 was USD 857/kW, which was 82% lower than that in 2010 and 6% lower than that in 2020 (Source: RENEWABLE POWER GENERATION COSTS IN 2021, IRENA 2022).

As of the end of 2022, according to the statistics of China Solar Thermal Alliance, the CSP systems installed worldwide cumulatively exceeded 7.05 GW, with an increase of 5.26 times over 2010.

7.1 Reduction of unit kW cost and O&M cost

The global LCOE of CSP has declined by 70% over a decade from USD 0.358/kWh in 2010 to USD 0.114/kWh in 2020. The global weighted average unit kW cost of CSP systems in 2021 was USD 4,746/

kW, down by 50% from 2010, with contribution proportion of each component in the cost reduction to the reduction as follows. The installed cost of the plant accounted for 64%, the increase of capacity factor accounted for 17%, the operation and maintenance (O&M) accounted for 10%, and the weighted average capital cost accounted for 9%. (Source: RENEWABLE POWER GENERATION COSTS IN 2021, IRENA 2022)

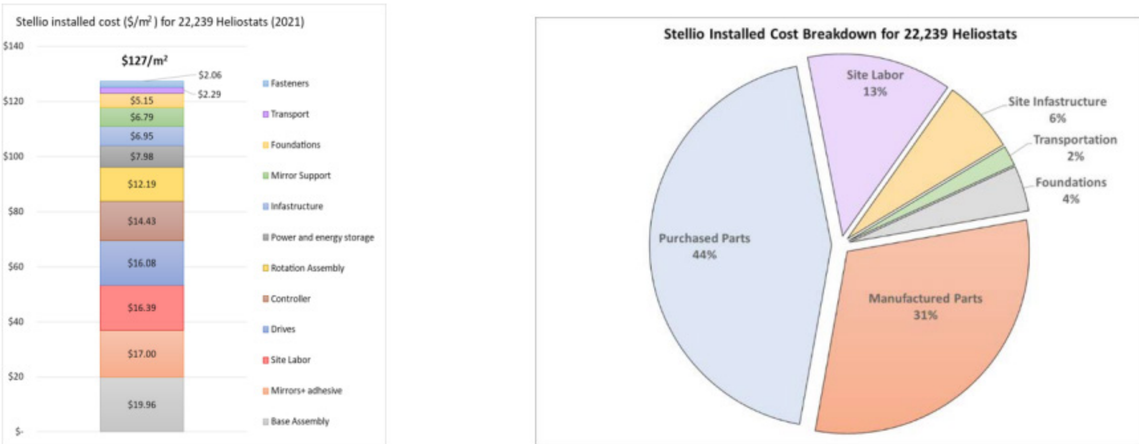
It is important to note that the unit kW cost of CSP system is related to the thermal storage duration due to the investment in thermal storage. In 2021, the unit kW cost of CSP was USD 9,090/kW, only 4% lower than that in 2010. However, this increase should be interpreted with caution, as only one CSP plant with 17.5h thermal storage system was connected to the grid in 2021, namely, the 110 MW Cerro Dominador Solar Tower Plant in Atacama Desert, Chile. The thermal storage duration (17.5 hours) of the plant driven up the unit kW cost of CSP in 2021 (Source: RENEWABLE POWER GENERATION COSTS IN 2021, IRENA 2022).

In 2022, several CSP plants in operation around the world have proven their capability to generate electricity at full capacity 24 hours a day, 7 days a week. CGN Delingha 50MW Parabolic Trough CSP Plant has operated continuously for 230 days from 2021-2022, which provides solid data to enhance the value of the plant. As mentioned earlier, the cost of solar concentration, solar absorption and thermal storage systems accounted for a high percentage of the total investment of CSP plant. According to research report of the China Solar Thermal Alliance, for solar tower plants built in China, equipment acquisition cost accounted for about 73% of the total investment, installation cost accounted for about 12%, cost of construction works accounted for about 9%, and others accounted for about 6%. Among them, the main ways to reduce the equipment acquisition cost are described in the table below.

Table: Potential Ways to Reduce Cost of CSP

Equipment	Potential ways to Reduce Cost	Reduction of power plant cost (≥, absolute value)
Solar field	Heliostat: reduced steel consumption, improved production efficiency, new transmission structure and competitive benefits; heliostat field control system: cost of software and hardware is decreased.	10.7%~15.4%
Solar receiver system	Localization of materials, optimization of processing and industrial scale	1.03%~1.49%
Thermal storage and exchange system	Optimization of tank design, mature processing and centralized procurement; localization of molten salt valve and molten salt pump; reduced operation and maintenance costs; large-scale development of molten salt	3.59%~5.66%
Thermal power system	Design optimization and centralized procurement	1.4%~2.1%

The cost of heliostats have an important impact on the unit cost of solar tower plant. In 2021, the cost of heliostat after installation is $140/m^2, the goal of DOE is to reduce to $50/m^2 in 2030. The cost distribution of the heliostat field of Energypower Hami Solar Tower Power Plant in Xinjiang Region in 2022 and some project in Zhangjiakou, Hebei Province can be found below.



(a) Cost breakdown of a single heliostat (b) Cost breakdown of a utility-scale heliostat field

Figure: sbp Stellio heliostat cost breakdown (Source: Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power, 2022 Heliocon)

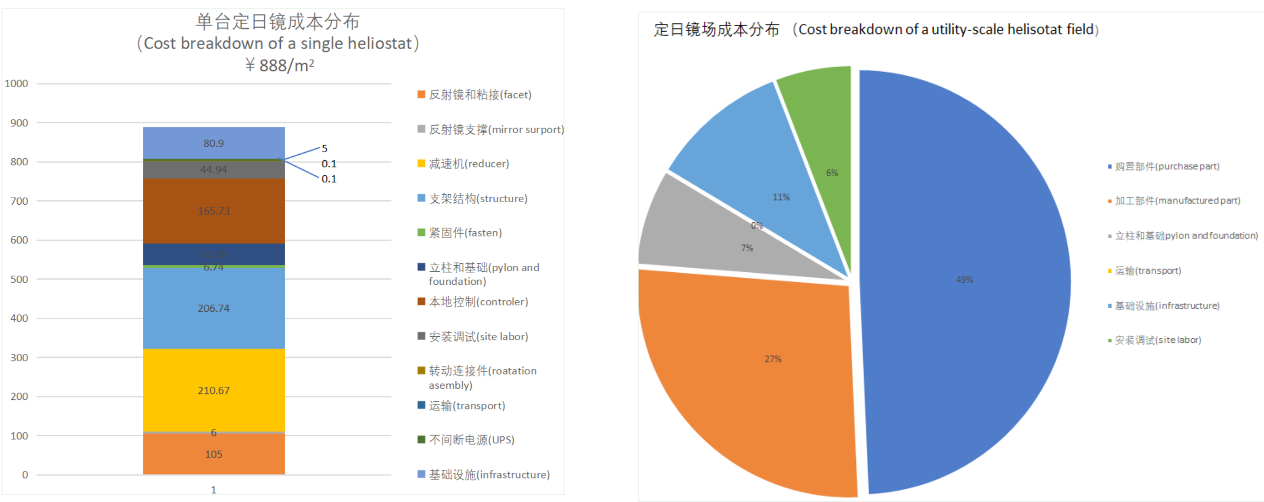


Figure:the cost distribution of heliostat of some solar tower concentration system in Zhangjiakou, Hebei Province (Source: IEE-CAS, Dahua Engineering Management Group)

From January to July 2022, China's total social electricity consumption in the east, central, west and northeast regions was 2,284.5, 948.1, 1436.1 and 261.5 billion kWh, with an increase of 1.7%, 7.5%, 4.2% and 0.1%, respectively. It can be seen that due to the westward shift of energy-consuming industries, resulting in a faster increase in electricity consumption in the central and western regions, the power transmission cost of the western energy bases decreased, which is beneficial to the closing of the price gap between CSP plant and local coal-fired thermal power plant.

7.2 Efficiency improvement

The basic process of CSP involves solar concentration, heat transfer and thermoelectric conversion. The conversion of solar energy into electrical energy in the form of heat requires several energy conversion and transmission processes. Starting in 2022, there’s no more subsidies for new CSP plants. CSP hybrid with PV and wind power is regarded as the most promising form of CSP development in the future. In this case, the curtailed electricity from PV and wind power that cannot be connected to the grid was input into the storage system of CSP. The traditional design theory of CSP plant should consider the problem of efficient power conversion after the input of high-grade electricity, in order to achieve low storage cost and flexible peak-shaving.

CSP technology, like other energy sources that use thermoelectric conversion to generate electricity, has a disciplinary system based on the discipline of engineering thermophysics, and intersects with optics, mechanics, information, materials and other disciplines. The figure below shows the energy transfer composition of a typical solar tower plant. As can be seen from the figure, the solar concentration, solar absorption and thermoelectric conversion processes are the main parts that constitute the energy and efficiency loss of the system, accounting for 97% of the total loss. Therefore, the key to improve the efficiency of CSP lies in improving the efficiency of solar concentration and thermoelectric conversion processes, especially the efficiency of thermoelectric conversion process. Most of the domestic and international studies also focus on such two processes.

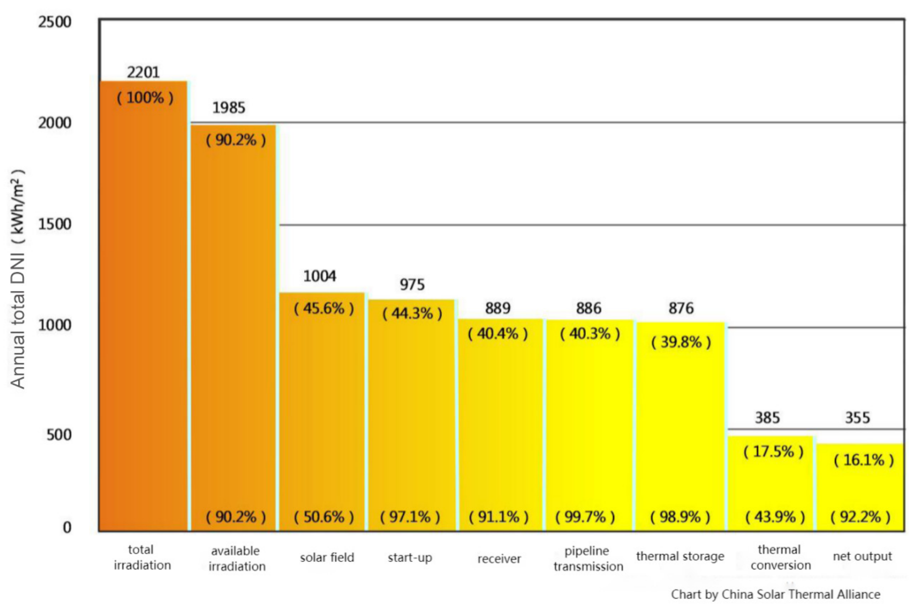


Figure: Efficiency and energy loss of a typical CSP plant

For the existing molten salt tower plants, by optimizing all parts listed in the figure below, the efficiency of CSP system can be improved by 12% to 27%.

Table: Items should be optimized from the point of view of the project engineering

Items	Optimization	Increased value (≥, absolute value)
Heliostat field cleaning	Cleanliness	2~6% ↑
Cloud prediction	Curtailment	2~4% ↓
Mirror surface	Reflectivity	0.4~1% ↑
Heliostat field layout optimization	Solar field efficiency	0.4~0.7% ↑
Inception efficiency optimization	Inception efficiency	1~2% ↑
Receiver coating	Receiver surface absorptivity	1~2% ↑
Steam turbine	Steam turbine efficiency	1~1.5% ↑
Reliability model of equipment	Equipment availability	1~2% ↑
Optimized operation strategy of the plant	Electricity generation	1~2% ↑
Using solar PV power for part of the electricity consumption	Self consumed power rate	4~6% ↓
Insulation performance improvement	Self consumed power, thermal storage efficiency	/
Economic improvement due to optimal scale	Cost	0.02yuan↓

7.3 Suggestions on CSP technology and industry development in China

In the future, China's CSP industry needs to work around the following ten aspects:

1. Thermodynamic analysis of coupled solar collection and wind & PV abandonment systems. Because of the interconversion of solar radiation, electricity, thermal, and thermoelectricity, an efficiency model based on the second law of thermodynamics is urgently needed. Due to the presence of electricity, the role of chemical energy in storage may also appear in the system, requiring a careful and systematic study of the system from the perspective of thermal economics.

2. Research on thermoelectric conversion method of million-kilowatts scale. In 2022, the capacity ratio of CSP to PV and wind power was typically 1:9. The molten salt tank for 100MW CSP plant is designed to cope with the impact of 900MW or 1000MW PV and wind power influx. Therefore, in the thermal storage part, the million-kilowatts high-power molten salt electric heating method is also the content to be researched intensively after 2022.

3. Test on CSP plants in operation that are included in national demonstration projects. It is necessary

to conduct detailed performance test on CSP plants operated since the end of December 2018, including performance parameters of core equipment, subsystems and full systems, and auxiliary equipment, prepare detailed test and scientific research report, sort out the lessons learned based on the data, derive the equipment design methods, operating specifications, system design specifications and accident handling program, and summarize a number of industry and national standards, which is essential for the future development of CSP in China.

4. High-temperature solar collection, thermal storage and heat exchange: Thermal storage is an important factor in the continuity of CSP. The problem of thermal storage involves the coupling of materials and thermal science, in which solid thermal storage and molten salt thermal storage above 800°C are more promising thermal storage materials to cope with hybrid plants in the future. Research is necessary on highly reliable thermal storage materials and systems, design methods for molten salt solar absorption and thermal storage systems with inherent safety, etc. Basic research on thermochemical thermal storage should be enhanced. Thermal storage unit and heat exchanger that can withstand frequent thermal shock are also necessary research content; For solar absorption particles, the research should focus on their wear resistance.

5. Solar concentrator: The cost of solar concentrator accounts for about 50% of the overall CSP plant investment. The global cost indicators of CSP heliostat do not differ significantly from the parabolic trough solar concentrator. In the future, the focus will be on improving the accuracy of solar concentrator and reduce the overflow loss of solar receiver. For this, optical measurement and calibration system for solar concentrator error needs to be developed. For solar tower plant, the heliostat error is also an important factor affecting the heliostat usage. The heliostat error was reduced from 3 mrad to 2 mrad, and the heliostat area used in the Dunhuang 100MW Plant in Gansu was reduced by 2.4%.

6. Solar receiver: Solar receivers work under high temperature, non-uniform and non-stationary heat flow boundary conditions and need to have a certain fatigue resistance life. Safety is the most important indicator of the receiver. It is necessary to perform coupling exploration on materials of solar receiver and operation-related mechanical and heat transfer characteristics, so as to develop solar receivers with inherent safety and long life. In terms of high temperature solar receivers above 800°C, particle solar receiver is currently the only viable approach. Research on the reliability of such receiver under outdoor wind conditions and the mass loss of absorbed particles should be enhanced. Since solar absorption particles are also used for thermal storage, coupling research should be conducted on solar absorption, thermal storage and heat release, and the law of high-density radiation transfer in the particle solar receiver should be studied to obtain the best integrated efficiency of solar collection, thermal storage and full-system heat release.

7. Special equipment for solar-powered components production line: The key solar-powered components production line technology has been slow to develop in China. The current research results

in the production line of glass mirrors, solar absorber tubes, solar concentrators, and special turbine are not enough to support the needs of large-scale industrialization. It is necessary to improve the quality control technology and process of products in large-scale practice, and establish the production lines and production processes for solar concentration, solar absorption and heat transfer components.

8. Research on performance testing equipment: high energy flow density measurement system, solar concentrator error measurement instrument in the production line and field, concentrating error test instrument for parabolic trough solar collector, and high-temperature particle flow meter.

9. Technical specifications and standards: Establish specifications and standards for the evaluation of the performance of core materials, equipment and systems for CSP. Through continuous R&D and attention to new solar concentration forms, optimal design of solar concentration system, solar receiver technology adapted to different forms of thermal power generation technology, different types of working media and operating temperatures, thermal storage materials and thermal storage systems, and high-efficient thermoelectric conversion technology, promote China's CSP technology to high parameters - high efficiency - low cost -base load direction.

10. Supercritical CO2 CSP technology: 800°C solar receiver continuously operated for 1,000h without overhaul, solar concentrator field with energy flow density of 1,200 kW/m2, 50MWth-class particle/CO2 heat exchanger, and 10MW supercritical CO2 compressor turbine.

Appendix

Main Representative Players of CSP Industry Chain in China

Project Design / Project Turnkey
Consultation/feasibility study/design
Inner Mongolia Construction Survey Design Institute Limited Liability Company
Shandong Electric Power Engineering Consulting Institute Corp., Ltd
China Renewable Energy Engineering Institute (CREEI)
China Electric Power Planning and Engineering Institute (EPPEI)
Shanghai Electric Group
East China Engineering Science and Technology Co., Ltd.
China Power Engineering Consulting Group
Shanghai Electric Group
China Huadian Corporation Ltd. (CHD)
Sinomec Huaxin Electric Engineering Co., Ltd.
LENON
CGN New Energy Holdings Co., Ltd.
Northwest Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Southeast Engineering Corporation Limited (POWERCHINA SOUTHEAST)
SEPCO1 Electric Power Construction Corporation
SEPCO3 Electric Power Construction Corporation
Pacific Green Solar Technologies Inc. (PGST)
EPCs with recorded project
Cosin Solar Technology Co., Ltd.
Lanzhou Dacheng Technology Co., Ltd.
Shouhang Hi-tech
Shanghai Electric Group
China Shipbuilding Industry Group Power
China Guoneng Power Group Co., Ltd.
Henderson Energy Pulse New Energy Technology Co., Ltd.

China Gezhouba Group Electric Power Co., Ltd.
SEPCO3 Electric Power Construction Corporation
Northwest Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Southeast Engineering Corporation Limited (POWERCHINA SOUTHEAST)
East China Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
North China Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
China ENERGY Engineering Group Zhejiang Thermal POWER Construction Co., Ltd.
System integration
Solar collection system
Beijing TRX Solar Technology Co., Ltd.
Cosin Solar Technology Co., Ltd.
Shouhang Hi-tech
Dongfang Boiler Co., Ltd. (DBC)
Shanghai Electric Group
China Guoneng Power Group Co., Ltd.
Royal Tech CSP Ltd.
Sun Sum
Terasolar
Lanzhou Dacheng Technology Co., Ltd.
Sundhy Solar
Inner Mongolia Xuchen Energy Co., Ltd.
China BCP Solar Technology
Zhejiang Zhongguang New Energy Technology Co., Ltd.
Gansu Light Heat Generation Co., Ltd.
Inner Mongolia Xinyuan Light Heat Co., Ltd.
Northwest Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Southeast Engineering Corporation Limited (POWERCHINA SOUTHEAST)
SEPCO3 Electric Power Construction Corporation

SEPCO1 Electric Power Construction Corporation
Thermal storage system
East China Engineering Science and Technology Co., Ltd.
Shanghai Lanbin Petrochemical Equipment Co., Ltd.
China Guoneng Power Group Co., Ltd.
Shanghai Electric Group
Dongfang Boiler Co., Ltd. (DBC)
Xizi Clean Energy Equipment Manufacturing Co., Ltd.
Shouhang Hi-tech
Cosin Solar Technology Co., Ltd.
LS Heat Exchange
Liantes Energy Co., Ltd.
Zhejiang Zhongguang New Energy Technology Co., Ltd.
Northwest Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Southeast Engineering Corporation Limited (POWERCHINA SOUTHEAST)
SEPCO3 Electric Power Construction Corporation
SEPCO1 Electric Power Construction Corporation
Power generation system
Shandong Electric Power Engineering Consulting Institute Corp., Ltd
China Guoneng Power Group Co., Ltd.
Shanghai Electric Group
Dongfang Electric Corporation
East China Engineering Science and Technology Co., Ltd.
CGN New Energy Holdings Co., Ltd.
Northwest Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Southeast Engineering Corporation Limited (POWERCHINA SOUTHEAST)
SEPCO3 Electric Power Construction Corporation
SEPCO1 Electric Power Construction Corporation
Solar concentration

Solar ultra-clear glass
Henan Ancai Solar Co., Ltd.
Aijiexu Special Glass (Dalian) Co., Ltd.
Mirror reflector
Wuhan Sunnpo Solar Technology Co., Ltd.
Sundhy Solar
Shouhang Hi-tech
Terasolar
Shanxi Lihu Glass Group
Zhejiang Daming Glass Co., Ltd.
Shandong Binhai Machinery Equipment Co., Ltd.
Heliostat
Shouhang Hi-tech
Cosin Solar Technology Co., Ltd.
Dongfang Boiler Co., Ltd. (DBC)
Bo Yu Chengdu New Energy Co., Ltd.
China Energy Equipment
China BCP Solar Technology
Shanghai Electric BrightSource Solar Energy Co., Ltd.
SEPCO3 Electric Power Construction Corporation
Sun Sum
Trough solar concentrator
Beijing TRX Solar Technology Co., Ltd.
Royal Tech CSP Ltd.
Bo Yu Chengdu New Energy Co., Ltd.
Tianjin Binhai Concentrating Solar Power
Inner Mongolia Xuchen Energy Co., Ltd.
Shouhang Hi-tech
Hebei Daorong New Energy Technology Co., Ltd.
Inner Mongolia Xinyuan Light Heat Co., Ltd.
Support
Royal Tech CSP Ltd.
China Energy Equipment

Dongfang Boiler Co., Ltd. (DBC)
Haixi Huahui Chemical Machinery
Shandong Zhaowei Steel Tower Co., Ltd.
Shouhang Hi-tech
Tracking device
Hengfengtai Precision Machinery Co., Ltd.
Shouhang Hi-tech
China Energy Equipment
Tianjin Binhai Concentrating Solar Power
SEPCO3 Electric Power Construction Corporation
Cleaning equipment
Shouhang Hi-tech
Cosin Solar Technology Co., Ltd.
Dongfang Boiler Co., Ltd. (DBC)
China Shipbuilding Industry Shuangwei Intelligent Equipment Co., Ltd.
SEPCO3 Electric Power Construction Corporation
Heliostat field control
Cosin Solar Technology Co., Ltd.
Beijing Guodian Zhishen Control Technology Co., Ltd.
Shouhang Hi-tech
Dongfang Electric Corporation
Qingdao Yijiehongli Technology Co., Ltd.
China BCP Solar Technology
Shanghai Electric BrightSource Solar Energy Co., Ltd.
SEPCO3 Electric Power Construction Corporation
Sun Sum
Fasteners
AUZEN INDUSTRY COMPANY LIMITED
Solar absorption
Tube receiver
Beijing TRX Solar Technology Co., Ltd.
Royal Tech CSP Ltd.
Lanzhou Dacheng Technology Co., Ltd.

Inner Mongolia Xuchen Energy Co., Ltd.
Jiayu Group
Hebei Daorong New Energy Technology Co., Ltd.
Shandong Longguang Tianxu Solar Power Co., Ltd. (High borosilicate glass tube)
Solar tower receiver
Shanghai Boiler Co., Ltd.
Dongfang Boiler Co., Ltd. (DBC)
Shouhang Hi-tech
Xizi Clean Energy Equipment Manufacturing Co., Ltd./Cosin Solar Technology Co., Ltd.
King Bull Group
Pipe connection
Jiangsu Haofeng Pipeline Equipment Co., Ltd.
Tianjin Binhai Concentrating Solar Power
CGN New Energy Holdings Co., Ltd.
Heat transfer oil
Jiangsu Zhongneng Chemical Technology Co., Ltd.
Shexian Jindong Economic and Trade Co., Ltd.
Molten salt
Beijing University of Technology
Enesoon
SQM (Shanghai)
Shanxi Wojin New Material Co., Ltd.
Jiangxi Jinlida Potassium Industry Co., Ltd.
Sinkiang Nitrate Minerals Co., Ltd. (SNM)
Stainless steel/nickel-base alloy pipe
Wuxi Xinchang Steel PIPE Co., Ltd.
Zhejiang Jiuli Hi-Tech Metals Co., Ltd.
Jiuquan Iron and Steel (Group) Co., Ltd.
Baowu Special Metallurgy Co., Ltd.
Thermal storage/heat exchange
Molten salt storage tank
Xizi Clean Energy Equipment Manufacturing Co., Ltd.
East China Engineering Science and Technology Co., Ltd.

Shanghai Lanbin Petrochemical Equipment Co., Ltd.
Dongfang Boiler Co., Ltd. (DBC)
Shanghai Electric Group
Cosin Solar Technology Co., Ltd.
Shouhang Hi-tech
China Energy Equipment
Lanzhou Dacheng Technology Co., Ltd.
Zhejiang Zhongguang New Energy Technology Co., Ltd.
POWERCHINA (Xi'an) Ganghang
Molten salt pump
Jiangsu FEIYUE Machine and Pumps Group Co., Ltd.
POWERCHINA SPEM
Shandong Huawei Pump Co., Ltd.
Molten salt valve
SHANGHAI YAHE VALVE COMPLETION CO.,LTD
China Energy Equipment
Beijing Jiajie New Energy Saving Technology Co., Ltd.
Salt melting equipment
Shouhang Hi-tech
Enesoon
Liantes Energy Co., Ltd.
Heat transfer oil furnace
Beijing Aerospace Petrochemical Technology & Equipment Engineering Corporation Limited
Molten salt flowmeter
TOPFM (Shanghai) Automation
Heat exchanger
Xizi Clean Energy Equipment Manufacturing Co., Ltd.
Dongfang Boiler Co., Ltd. (DBC)
Shanghai Electric Group
Shanghai Lanbin Petrochemical Equipment Co., Ltd.
Power generation
Steam generator
Xizi Clean Energy Equipment Manufacturing Co., Ltd.

Dongfang Boiler Co., Ltd. (DBC)
Shanghai Electric Group
Shanghai Lanbin Petrochemical Equipment Co., Ltd.
Steam turbine
Shanghai Electric Group
Dongfang Turbine Co. Ltd.
Generator
Shanghai Generator Works
Jinan Power Facilities Plant
Air cooling system
Shouhang Hi-tech
Shanghai Electric Group
UPS
Shenyang Vycon New Energy Technology Co., Ltd.
CHP
SOLETKS
Meixinda Xinwang Energy Co., Ltd.
Terasolar
Lanzhou Dacheng Technology Co., Ltd.
Royal Tech CSP Ltd.
Jiayu Group
Gansu Building Materials Research and Design Institute Co., Ltd.
Hebei Daorong New Energy Technology Co., Ltd.
Service
Scientific research
Zhejiang University
Tianjin University
Nanjing University of Aeronautics and Astronautics
Beijing University Of Technology
Nanjing Tech University
Huazhong University of Science and Technology
China Renewable Energy Engineering Institute (CREEI)
China Electric Power Planning and Engineering Institute (EPPEI)

Shanghai Jiao Tong University
North China Electric Power University
Xi'an Jiaotong University
Wuhan University of Technology
North University of China
Changsha University of Science and Technology
Huadian Electric Power Research Institute
Inner Mongolia University of Technology
Institute of Electrical Engineering, Chinese Academy of Sciences
Shanghai Institute of Applied Physics (SINAP)
State Power Investment Group Science and Technology Research Institute Co., Ltd.
Test and evaluation
Huadian Electric Power Research Institute
China Special Equipment Inspection and Research Institute
Institute of Electrical Engineering, Chinese Academy of Sciences
Construction services
China Sinogy Electric Engineering Co., Ltd (CSEEC)
Shanghai Electric Group
Dongfang Electric Corporation
East China Engineering Science and Technology Co., Ltd.
Shanghai Lanbin Petrochemical Equipment Co., Ltd.
CGN New Energy Holdings Co., Ltd.
Gansu Installation and Construction Group
SEPCO1 Electric Power Construction Corporation
SEPCO3 Electric Power Construction Corporation
Northwest Electric Power Design Institute Co., Ltd. (NWEPDI) of China Power Engineering Consulting Group
Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Southeast Engineering Corporation Limited (POWERCHINA SOUTHEAST)

References

[1] Vocabulary of Concentrating Solar Thermal Power (GBT 26972--2011)

[2] Zhang Yuqiong, Zhao Qiang, Zhou Xiaoxin. Development Prospect and Key Technologies of China's Energy and Power System Under the Goal of "Carbon Peaking and Carbon Neutrality" [J]. China Power Enterprise Management, November 2021: 14-17

[3] China Energy Information Platform; Guo Jianbo, SGCC: Challenges Faced by New Power System with New Energy as the Main Body [EB/OL]. (2021-09-13). https://www.163.com/dy/article/GJOVHPD105509P99.html

[4] Thermal Power Generation Network. How to Build a New Power System with New Energy as the Main Body [EB/OL]. (2021-09-09). http://www.chinatpg.com/home/news/pages/n_id/124937.html

[5] Du Fengli et al. Blue Book of China's Concentrating Solar Power Industry 2021[R]. Beijing: China Solar Thermal Alliance (CSTA), 2022.

[6] He Yaling. Important Role of Thermal Energy Storage Technology in Energy Revolution [J]. Science & Technology Review, 2022,40 (4): 1-2

[7] Academician Li Can: Concentrating Solar Power Technology is the Most Promising Large-scale Energy Storage Technology and One of the Important Technologies to Replace Thermal Power [EB/OL]. (2022-05-12) https://www.sohu.com/a/546079600_120099883

[8] Academician He Zuoxiu, Chinese Academy of Sciences: I am Most Optimistic About Concentrating Solar Power among New Energy Storage Technologies [EB/OL].(November 2, 2022) http://de.escn.com.cn/news/show-1494782.html

[9] Kang Chongqing, Tsinghua University: Value Discovery of Concentrating Solar Power in High-proportion Renewable Energy Power System [EB/OL]. (August 12, 2019) http://www.cnste.org/html/jishu/2019/0812/5306.html

[10] Liu Yujing, Liu Ziyi, Zhou Qin, et al. Exploration on Low-carbon Transformation of Power System in Northwest China - Building Demonstration Zero-carbon Power System in Qinghai [R], Rocky Mountain Institute, 2022

[11] Sun Rui, China Electric Power Planning and Engineering Institute: Assumption of Large-scale Development of Concentrating Solar Power [EB/OL]. (September 04, 2019) http://www.cnste.org/html/jishu/2019/0904/5406.html

[12] Wang Zhifeng, He Yaling, Kang Chongqing, Wang Weisheng, Du Fengli. Defining the Strategic Positioning of Concentrating Solar Power To Promote Technological Development [J]. Huadian Technology, 2021,43 (11): 1-4.

[13] China Science & Technology Network. China Concentrating Solar Power Conference 2021 was Held in Huzhou, Zhejiang [EB/OL]. (September 30, 2021) http://www.stdaily.com/index/kejixinwen/2021-09/30/content_1223345.shtml

[14] China Datang Corporation Won the Bid for the First 50MW Parabolic Trough CSP Plant Project in China [EB/OL]. (May 10, 2011) https://news.solarbe.com/201105/10/17323.html

[15] China Huaneng Fresnel 1.5MW Photothermal Hybrid Combined Cycle Power Plant was Built in Sanya, Hainan [EB/OL]. (October 31, 2012).http://www.pv-tech.cn/news/huaneng_1.5mw_fresnel_csp_project_built_in_sanya

[16] China Science & Technology Network. China's Concentrating Solar Power Technology is Moving

Toward Commercial Operation [EB/OL]. (December 10, 2013).http://science.china.com.cn/2013-12/10/content_30851823.htm

[17] Ministry of Science and Technology. Important Progress Has Been Made In Theme Project “Research and Demonstration of 10MW Tower Concentrating Solar Power Technology Based On Small-area Heliostat” in the Field of Advanced Energy Technology Under the National 863 Program [EB/OL]. (February 09, 2017). http://www.most.gov.cn/kjbgz/201702/t20170208_130821.htm

[18] 1 MWe Concentrating Solar Power Distributed Cogeneration Power Plant in Liuwu New District, Lhasa http://www.lzdcsolar.com/Success%20Stories/Generating/2015/0819/231.html

[19] Grid Connection of Trough Unit No. 1 of Photothermal Project in Duba of Shanghai Electric Group [EB/OL]. (November 30, 2022). https://finance.sina.cn/2022-11-30/detail-imqmmthc6493662.d.html

China Solar Thermal Alliance 国家太阳能光热产业技术创新战略联盟

Address: No. 6, Beiertiao, Zhongguancun, Haidian District, Beijing, China (zip code: 100190)
(Institute of Electrical Engineering, Chinese Academy of Sciences)
Tel: 0086-10-82547214
Website: cnste.org
Email: cnste@vip.126.com