CSTA

China Solar Thermal Alliance

Blue Book of China's Concentrating Solar Power Industry 2021

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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 2021 was completed on Jan., 2022 in order to provide the reference for the industry and policy-makers.

The Chinese report was prepared by Mrs. Fengli Du and Prof. Zhifeng Wang, with review of expert committee of CSTA and approval by Academician and 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 is insufficient due to the limited time. Thanks for the contributions of Mr. Cheng Zhang, Dr. Li Xu and Mrs. Fengli Du in translation, terminology checking and pictures and tables editing in English.

The report summary was written by Mrs. Fengli Du, the secretary-general of China Solar Thermal Alliance.

This report should be cited: CSTA (2022), Blue Book of China's Concentrating Solar Power Industry 2021, China Solar Thermal Alliance (CSTA), Beijing

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Summary

China's Concentrating solar power (CSP) installation capacity reached 538MW (including the full systems of 1MW level with a steam turbine) by the end of 2021. No new CSP plants that was connected to the grid since the last September. Among the installed CSP capacity in China, solar tower technology accounted for about 60%, parabolic trough about 28%, and the linear Fresnel about 12%.

The worldwide CSP installation capacity was 6.8GW by the end of 2021 according to the statistics of CSTA. The parabolic trough technology accounts for about 76% of the installed CSP capacity in major countries and regions around the world, while the solar tower route accounts for about 20% and the linear Fresnel route for about 4%.

The annual production capacity in China can support the 2~3GW CSP projects. The stakeholders on the China's industry chain reaches nearly 550, about 320 enterprises engaged in solar concentration, heat collection/transfer/thermal storage, of which the number of enterprises engaged in the solar concentration field is the largest, about 170.

They're 7 CSP demonstration plants put into operation in the first batch list. As China's first large-scale commercial solar thermal demonstration power plant, the generation of CGN Delingha 50MW parabolic trough power plant in 2021 increased by 31.6% over 2020. From September 19, 2021, to Feb.12, 2022, CGN Delingha 50MW parabolic trough power plant kept continuous operation for 146 days, securing a leading position at home and abroad by breaking the previously longest 32.2-day record of continuous operation in 2020.

Inner Mongolia Urat 100MW parabolic trough plant realized the generation of 220GWh from Jan. to Oct. 2021, with the daily highest generation of 2,128MWh. The molten salt thermal storage system put into operation since July 2021. For the first year of operation, the utilization hours was 2107.9h. The expected generation in 2021 would be about 318GWh provided the thermal storage system put in use in January.

Qinghai Supcon Solar Tower Plant constructed by Cosin solar reached or exceed the design value of generation in most of the months since the 2020. The accumulated electricity generated from Sep. to Dec.2021 reached 61GWh. The power generation of Shouhang 100MW solar tower plant was increased by 39.7% in 2021 over 2020. PowerChina Gonghe 50MW solar tower plant had 16 hours and 43 minutes no-stop operation on May 7, 2021, with daily generation to the grid of 539MWh. The electricity sold to the grid in 2021 was increased 260% over that of 2020. The annual utilization hours of Hami 50MW solar tower plant was 186h. From January to July 2021, the plant was basically no operation (affected by an international coronavirus and solar field technology provider cannot be onsite), and it began gradually commissioning in August, and realized the full-capacity generation from Sep. 2021 and 5 days of non-stop operation for national approval. Another factor was steam turbine maintenance. From Jan. to April, 2021, DCTC 50MW molten salt LFC plant shut down because of the steam generator and steam turbine repair. The generation in May, July, August of 2021 was higher than 80% compared with the design value, and realized the first year generation goal. In 2021, it had more than 8000MWh output in multiple months.

Luneng Golmud 50MW solar tower plant of multi-energy complementary project also are in operation, with the highest daily generation was 1096.2MWh in June, 2021. The monthly generation reached 10.674GWh in November of

2021.

In 2021, China launched several large-scale wind and solar PV power base in Gnasu, Qinghai, Jilin provinces, with new CSP projects capacity of 1.01GW.

In terms of R&D projects, the project of *Basic Fundamental Problems Research on Supercritical CO_2 CSP Technology* made great progresses. Three types of receivers: quartz tube particle receiver, solid ball receiver and cylindrical receiver were developed. The team developed a high temperature particle hoist, which had been working more than 100 hours at 550℃ . A MWth level particle/sCO_2 heat transfer experimental system was established. China's first 5MW sCO_2 turbine completed 72h trial operation and put into operation on Dec. 18. 2021 in Xi'an Thermal Power Research Institute of China Huaneng Group.

As an revolutionary technology research project, *Wide Wave Plane Super Surface Solar Concentrator and its Collector System* was launched, with Wuhan University of Technology, IEECAS, Fudan University, Xiamen University, China University of Science and Technology, Changchun Institute optics, fine mechanics physics, Chinese Academy Sciences as research parties. It will study the key scientific issues of wide-wave, wide-angle flat super surface solar concentrator and solar thermal collection system design and manufacture, with the help of the plane super surface electromagnetic coupling effect to develop free tracking, low-cost wide-angle broadband segment sun radiation plane concentration.

The project of Research on *Key Technical Standards for CSP and Solar Thermal Utilization* completed all the work in 2021, with execution period was from July 2017- December 2020. The project has two subtasks, "CSP key technical standards research" and "solar thermal utilization standard system", including procedures and standards of technical conditions, detection methods, evaluation methods, performance test, design specifications.

The project of *Development and Application of Special Alloys for High Temperature Molten Salt System for CSP Plants* got the funds from Ministry of Science and Technology (MOST) under "Advanced Structure and Composites" of National Key R & D Plan in 2022, with the leading of Metal Research Institute, Chinese Academy of Sciences.

The report also made analysis on the investment and cost reduction paths of parabolic trough and solar tower plants under Chinese conditions.

Table of Contents

1. Development Opportunities and Positioning of Concentrating Solar Power

1.1 The needs and challenges of new power systems

The ninth meeting of the Central Finance and Economics Committee held on March 15, 2021 proposed to build a clean, low-carbon, safe and efficient energy system, to control the total consumption amount of fossil energy, focus on improving the efficiency of utilization, implement the action of renewable energy substitution, deepen the reform of the power system, and build a new-energy dominated new power system. This is the first time that the central level has clarified the status of the new energy in the future power system. The construction of a new power system with new energy as the main body means that the wind and solar photovoltaic power with strong random and volatility will become the main body of the future power system, while the current dominant coal power will become auxiliary energy [1].According to the forecast, under the "carbon peaking and carbon neutrality" goals, China's total primary energy consumption will reach 4.6 billion tons of standard coal by 2060, of which the proportion of non-fossil energy will reach more than 80%, with wind and solar as the main energy source and mainly converted into electricity for use. The electricity proportion of terminal energy consumption will reach 79%~92% in 2060 [2].

Academician Jianbo Guo of the Chinese Academy of Engineering said: the new power system is still mainly operated by AC synchronous mechanism, facing the challenges of adequacy, safety, economy, market mechanism and other aspects. Among them, the characteristics of new energy resources bring challenges to the adequacy of the power system: high power fluctuations, difficult to predict, and higher requirements for the system regulation capacity; long time high power, bringing challenges to system safety and energy storage technology; long time low power, bringing challenges to power supply guarantee; power uncertainty, increasing the difficulty of system planning; peak power, large power, small power, the cost of full consumption. The cost of full consumption is high. New energy equipment characteristics bring security challenges: system inertia is reduced, power supply support capacity is weak, system stability problems are prominent; stability characteristics are complex, uncertainty increases, safety control strategy configuration difficulties, mismatch risk increases; broadband oscillation phenomenon appears one after another, endangering equipment safety and grid operation safety; small single capacity, large number, regulation and control operation is complex[2]. Academician Jizhen Liu of the Chinese Academy of Engineering pointed out that the construction of a new power system requires the support of key technologies, and requires a breakthrough from the power side, grid side and load side. Among them, the power side vigorously develop grid-friendly advanced power generation technology, multi -energy complementary system and flexible power generation technology [3].

On August 10, 2021, the National Development and Reform Commission and the National Energy Administration issued the Notice on Encouraging Renewable Energy Power Generation Enterprises to Build their own or Purchase Peaking Capacity to Increase the Scale of Grid Connection , clearly put forward: with the rapid development of renewable energy in China, the shortcomings and problems such as insufficient flexibility of the power system and insufficient regulation capacity are prominent, which restrict the development of higher proportion and larger scale renewable energy. In the future, China will achieve the peak carbon dioxide emissions by 2030. The task of achieving the goal of peak carbon dioxide emissions by 2030 and carbon neutrality by 2060 is arduous and requires strenuous efforts. The key to achieving the peak carbon dioxide emissions is in promoting renewable energy development, the key to promoting renewable energy development lies in consumption, and the key to securing renewable energy consumption lies in grid access, peaking and energy storage. At the same time, the document encourages multiple channels to increase the peaking resources. Undertake renewable energy consumption corresponding to the peaking resources, including pumped storage power plants, chemical energy storage and other new energy storage, gas-fired power, concentrated solar thermal power plants (CSP), flexibility manufacturing transformation of coal power.

1.2 New opportunities for solar thermal power development

Dr. Tao Kon, Deputy Director of the New Energy Division of the Department of New and Renewable Energy of the National Energy Administration, said at the "2021 China Solar Thermal Power Conference" organized by CSTA that, with the goal of peak carbon dioxide emissions, carbon neutrality and the construction of a new power system dominated by new energy, China's wind power and photovoltaic will develop at a faster pace in a longer period of time, which also brings new opportunities for the development of the solar thermal industry.[4]

First, there is a demand for solar thermal power generation as a peaking power source in some areas around China. Some regions with large-scale development and utilization of new energy do not have the construction conditions for flexible power sources such as pumped-storage power and gas-fired power, while it is difficult to add new coal power installations due to ecological protection and other reasons, lacking solutions to provide peaking capability for new energy. Therefore, the construction of solar thermal power plants as peaking power in these areas is conducive to improving the consumption problems arising from the rapid development of new energy.

Second, participation in the electricity market is conducive to ensuring the sustainable development of the solar thermal industry after the withdrawal of state subsidies. At present, the construction cost of solar thermal power plant is relatively high, and the economy of construction as an ordinary power source is insufficient. At present, the construction of power spot market and auxiliary service market in some places is progressing in an orderly manner, and the advantages of using solar thermal power generation as a peaking power source, with its flexible and adjustable power output and long-time energy storage, will be able to win more revenue for the project through market-oriented ways, thus effectively supporting the sustainable development of domestic solar thermal industry.

Third, it is beneficial to participate in international market competition by accumulating experience in project construction and operation. In recent years, the Middle East, North Africa and other regions with abundant solar energy resources have started to use solar thermal power generation as a solution for sustainable renewable energy generation, using solar thermal power generation at night and peaking for PV during the day. The continuous accumulation of experience in peaking construction and operation through domestic solar thermal projects will give China's solar thermal industry a competitive advantage in the international market.

The National Energy Administration has been actively supporting the development of the solar thermal power generation industry. During the "14th Five-Year Plan" period, it will continue to support the construction of solar thermal power generation projects of a certain scale in areas with high quality resources by integrating with wind power and photovoltaic power generation bases, so as to give full play to the regulating role and system support capability of solar thermal power generation and ensure the successive development of the solar thermal power generation industry.

on June 7, 2021, the National Development and Reform Commission issued the Notice on Matters Relating to the New Energy Feed-in Tariff Policy in 2021, which proposed that: to encourage localities to introduce targeted support policies to support the sustainable and healthy development of new energy industries such as solar photovoltaic power generation, onshore wind power, offshore wind power and solar thermal power generation. The State Council's "Action Plan to Achieve peak carbon dioxide emissions by 2030" clearly states: to actively develop solar thermal power generation, and promote the establishment of solar thermal power generation with solar photovoltaic power generation and wind power complementary regulation of the landscape thermal integrated renewable energy power generation base. Accelerate the construction of new power systems. Build a new power system in which the proportion of new energy gradually increases, and promote the optimal allocation of clean power resources on a large scale. Vigorously enhance the comprehensive regulation capacity of the power system, accelerate the construction of flexible regulation power supply; accelerate the promotion and application of new energy storage demonstration.

1.3 Positioning and the role of solar thermal power[5]

Wind power and photovoltaic power generation has the characteristics of instability and intermittentity. With the promotion of the "carbon peaking and carbon neutrality" goals , the proportion of high, intermittent and fluctuating wind power and photovoltaic in the power system is increasing, which brings greater peak regulation pressure while meeting the power demand of the power system. In 2020, Mr. Guoping Chen , then former chief engineer of the State Grid Corporation of China, pointed out in his keynote report "Problems, Challenges and Reconfigurations in Modern Power Systems" at the Power System Development Direction and Academic Direction Seminar that power system development needs to be reconfigured; vigorously developing solar thermal power with the characteristics of traditional simultaneous power characteristic sources. In 2019, the Energy Internet Research Institute Tsinghua University pointed out in the article "Value Discovery of Solar Thermal Power Generation in High Percentage Renewable Power Systems" that the flexible and controllable characteristics make solar thermal power generation grid-connected with both renewable energy benefits and flexibility benefits. By leveraging the flexibility of operation, it is possible to realize the smoothing benefits of solar thermal power bundling with wind, PV and other energy sources, and to improve the level of renewable energy consumption in regional consumption and bundled outward transmission. With a high proportion of renewable energy on the grid, solar thermal power generation has significant power support benefits and is expected to become one of the key options for regulating power in some areas; it can play a role in using renewable energy to consume renewable energy.

1.3.1 Thermal storage and continuous power generation with high regulation capacity

According to the operation results of three commercial solar thermal power demonstration projects connected to the grid in 2018 in China, the solar thermal power plants have a maximum peaking depth of According to the operation results of three commercial solar thermal power generation demonstration projects connected to the grid in 2018 in China, solar thermal power units can achieve a maximum peak regulation depth of 80%; fast climbing speed, the rate of lifting and lowering the load can reach 3% to 6% of rated power per minute, cold start time of about 1 hour, hot start time of about 25 minutes, and can partially replace fossil-based conventional power generation units.

It can partially replace fossil-based conventional generating units, which is of great value to ensure the safe and stable operation of high percentage of renewable energy grid. China Electric Power Planning & Engineering Institute has conducted simulations with the current Xinjiang power grids as an example, assuming the construction of 1 million kilowatts ~ 5 million kilowatts of solar thermal power units of different scales, which can reduce the amount of abandoned wind and solar energy by 10.2% ~ 37.6%.

Solar thermal power also has a proven ability to carry base load. It's reported that Spain has 18 solar thermal power plants operating uninterruptedly for 3 weeks, of which the 20MW Gemasolar CSP plant with 15 hours of thermal storage operated 24/7 for 36 days. In China, the CGN Delingha solar thermal power plant with an installed capacity of 50MW kept continuous operation for 146 days from September 19, 2021, to Feb.12, 2022, the Qinghai Supcon Delingha 50MW solar tower power plant operated uninterruptedly for 12 days (292.7 hours), and the Shouhang High-tech Energy Dunhuang 100MW solar tower power plant operates continuously for 9 days (216 hours). Energy Internet Research Institute TsingHua University research results show that if 22GW of photovoltaic and 7GW of wind power are installed, the Qinghai power grid can supply clean energy for 3 consecutive days during the abundant water period (including the provincial load and extra-high voltage outgoing Henan); if 4GW of solar thermal power is installed on this basis, Qinghai Province can supply clean energy for a world record 30 consecutive days during the abundant water period.

1.3.2 High safety, suitable for high-capacity energy storage

Energy storage safety is an important aspect of high-capacity energy storage, and thermal storage with binary nitrate is a kind of thermal storage with high safety. At present, the largest single-capacity Shouhang Hi-Tech Energy solar power tower plant in China has reached 1.7 GWh of electricity storage; the world has reached 1,000 GWh. Since April 1982, when the U.S. SOLAR ONE was installed, 6.69 million kilowatts of solar thermal power generation in the world have not occurred any explosion and other safety accidents, which has been proved a high-safety energy storage method.

1.3.3 Solar thermal power storage system can connect to the grid in both directions

The molten salt storage system for solar thermal power generation can be charged and stored by the solar collection system, or the peak power online can be converted to thermal energy storage for power generation by the electric heating system. On September 23, 2021, the People's Government of Baicheng City, Jilin Province, released the "Announcement of the results of the recommended enterprises selected for the 1.4 million kilowatt outgoing transmission project of the Jixi Base Lugu DC Baicheng", with 800MW of wind power, 400MW of photovoltaic, and 200MW of solar thermal. Among them, the solar thermal power generation system has a molten salt storage tank with an electric heating system that can accept renewable energy power, and the solar thermal power generation system forms a two-way connection to the power grid to achieve the purpose of flexible regulation of renewable energy power.On September 28, 2021, Hainan base Qing Yu DC Phase II 3.4 million kilowatts outgoing project, Haixi base Qing Yu DC Phase II 1.9 million kilowatts outgoing project also made the winning candidate announcement. Among them, the scale of photovoltaic project 3.5GW, wind power project scale 1.5GW, solar thermal power project scale 300MW. The mode of solar thermal power plus other renewable power is taking off.

2. Development of the Market for Solar Thermal Power Generation

2.1 Technology start for megawatt-scale solar thermal power systems in China

In order to promote the technological progress and industrial development of solar thermal power in China, in 2006, the Ministry of Science and Technology launched the "Solar Thermal Power Generation Technology and System Demonstration" key project in the field of advanced energy technology under the National High-tech R&D Program (863 Program). Through the collaborative efforts of 11 consortium led by the Institute of Electrical Engineering of the Chinese Academy of Sciences, and after six years of unremitting efforts, on August 9, 2012, China's own design, development and construction of Asia's first megawatt-class solar power tower experimental power plant successfully generated electricity. The project has achieved a number of technological breakthroughs in core equipment, coordination and control, system integration, etc. It has comprehensively mastered the design technologies of high-precision concentrators, concentrating fields, direct superheat heat absorbers, thermal energy storage and power generation units and systems, as well as the overall, light field, mechanical, instrumentation and control and electrical design technologies, achieved a number of independent innovations represented by the direct superheated steam generation process coupled with light and heat fields, established a solar thermal power technology R&D system and standard specification system, compiled the first national standard for solar thermal power generation, and achieved a 100% equipment localization rate. We have established the R&D system and standard specification system of solar thermal power generation technology, compiled the first national standard for solar thermal power generation, and achieved 100% localization rate of equipment, laying a solid foundation for the development of solar thermal power generation technology in China.[6-7]

In July 2013, the demonstration project of Qinghai Supcon Delingha Solar Power Tower Station Phase I 10MW (5MW each for the east and west) supported by the National High Technology Research and Development Program was connected to the Qinghai power grid.The project developed an intelligent heliostat with a single reflective area of 2 square meters, high-precision intelligent tracking technology for heliostats and a large-scale mirror field control system; realized the overall concentration and heat collection of large-scale heliostat clusters; studied the dynamic modeling and optimal design of tower solar thermal power generation under different geographical and climatic environments; designed a high heat flux receiver based on water mass, steam buffer power generation energy circuit and equipment, and realized the photovoltaic energy conversion technology of the scaled-up solar thermal technology route[8] . In early September 2014, the National Development and Reform Commission approved its feed-in tariff (including tax) at RMB 1.2 per kWh, which is the first time a solar thermal power project has received a state-approved feed-in tariff, marking a solid step towards commercial operation of China's self-developed solar thermal power technology[9].

Supported by the National 863 Program "Research and Demonstration of 10MW Tower Solar Thermal Power Generation Technology Based on Small Area Fixed Helios", the CSC Solar Delingha 10MW Solar Thermal Power Plant was successfully connected to the grid on August 20, 2016 after changing the water/steam heat transfer medium to molten salt, and achieved full load power generation on August 21, 2016, fully demonstrating the level of China's tower solar thermal 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[10].The project has cultivated another group of backbone enterprises including Cosin Solar, Hangzhou Boiler, Hangzhou Steam Turbine, etc., providing technical support and demonstration leadership for the construction and development of large-scale application of commercial solar thermal power plants in China.

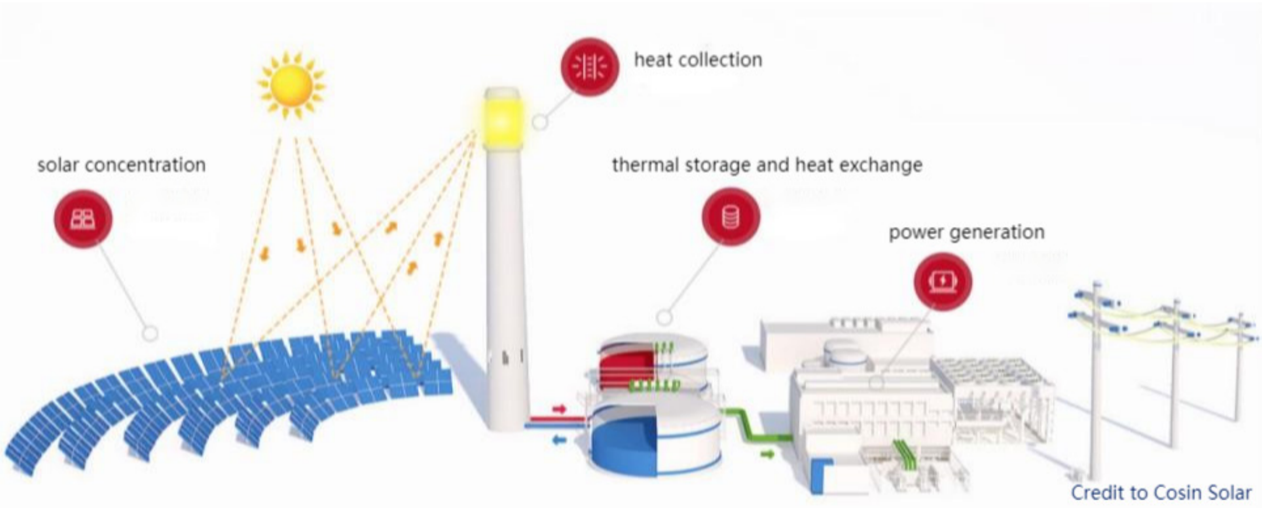

Figure: molten salt solar tower plant diagram

2.2 Installed capacity of solar thermal power generation in China

In the third year after China's first MW-class solar thermal power station completed its test power generation, the National Energy Administration (NEA) launched the construction of solar thermal power demonstration project. In 2016, the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) respectively released the solar thermal power generation benchmark feed-in tariff policy (RMB 1.15 per kWh) and the list of the first batch of solar thermal power demonstration projects. According to the China Solar Thermal Alliance, by the end of 2021, the cumulative installed capacity of solar thermal power in China was 538 MW (including power generation systems of MW scale or above).

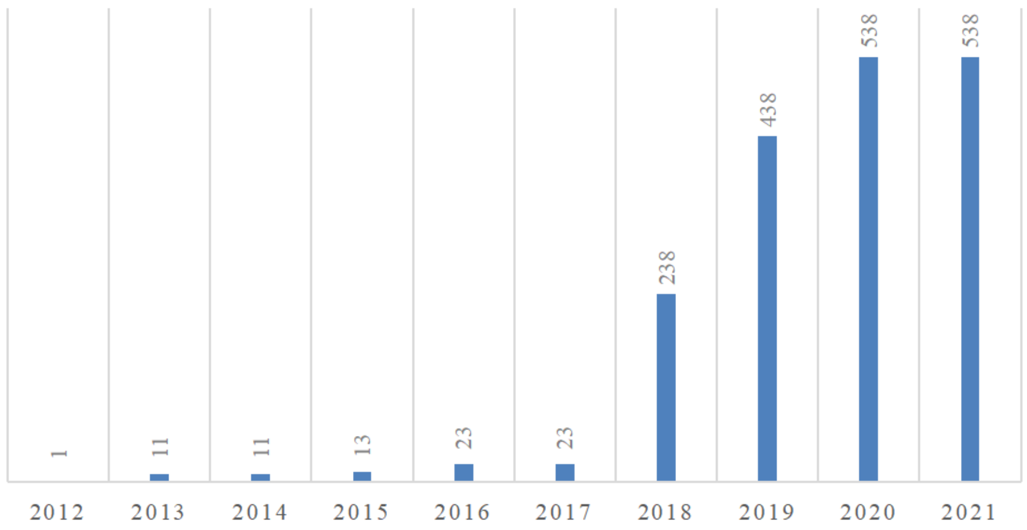

Figure: CSP installed capacity in China (MW)

In China's completed solar thermal power systems, the tower technology route accounts for about 60%, the parabolic trough about 28%, and the compact linear Fresnel reflector (CLFR) technology about 12%.

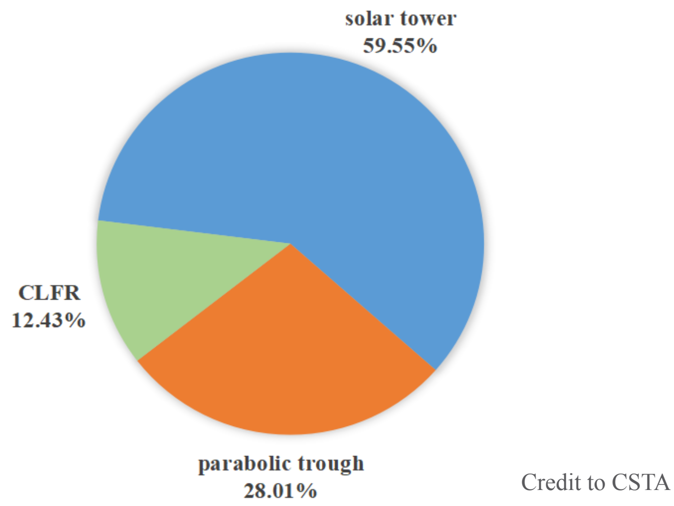

Figure: CSP technology in China's installation capacity

2.3 Global installed solar thermal power capacity

In 2021, the world's new installed solar thermal power capacity of 110MW is a solar thermal power plant in the Chilean solar photovoltaic hybrid project with an installed capacity of 110MW/ 17.5 hours of thermal storage [11]. China has no new solar thermal power projects that was connected to the grid in 2021. Combined with previous statistics from the Solar Thermal Alliance, the cumulative installed global solar thermal power capacity at the end of 2021 is about 6800 MW (including the capacity of retired power plants).

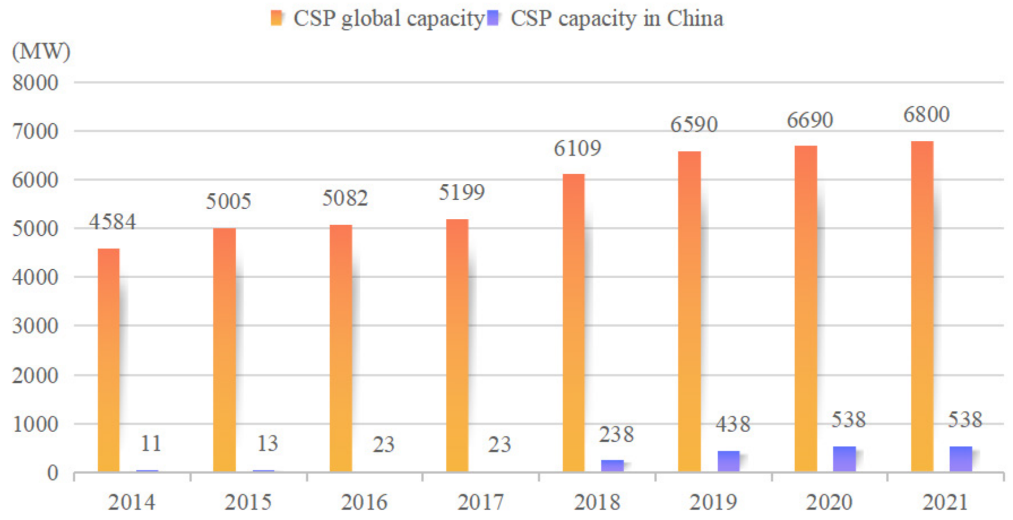

Figure: Worldwide CSP installed capacity (MW)

The development curve of the global cumulative installed solar thermal power capacity shows a high annual growth rate in 2018, mainly due to three solar thermal power demonstration projects with a total capacity of 200 MW were commissioned in China.

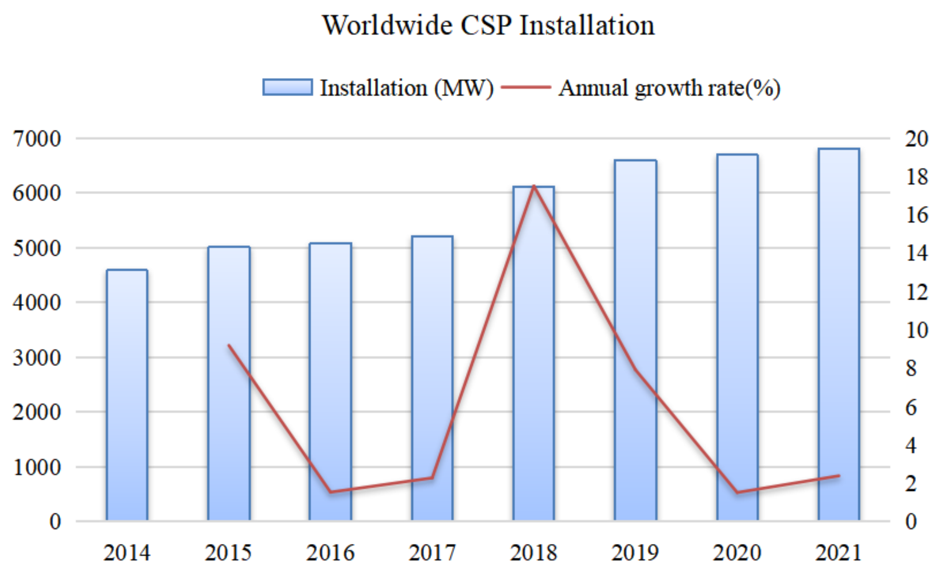

Figure: Worldwide CSP installed capacity development

According to rough statistics from the China Solar Thermal Alliance, the parabolic trough technology route accounts for about 76% of the installed solar thermal power generation in major countries and regions around the world, while the tower route accounts for about 20% and the linear Fresnel route for about 4%. The statistics cover countries and regions such as Spain, the United States, the Middle East, North Africa, South Africa, Israel, India, Chile, France, and China.

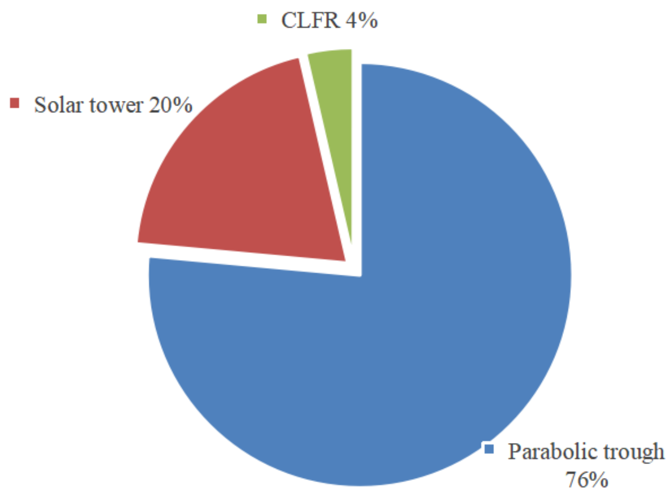

Figure: the proportion of CSP technology in major countries and regions in the world

2.4 New solar thermal power projects in China in 2021

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

On October 12, 2021, President Jinping Xi delivered a keynote speech at the 15th meeting of the Conference of the Parties to the UN Convention on Biological Diversity (COP15), stating that China will continue to promote industrial and energy structure adjustment, vigorously develop renewable energy, and accelerate the planning and construction of large-scale wind power and photovoltaic base projects in Gobi and desert areas. Qinghai and Gansu Province respectively held the new energy project construction ceremony on October 15, 2021, and Jilin Province held a ceremony to start the full construction of the "Three Gorges on Land Landscape" project on October 28. These projects will be completed and connected to the grid by the end of 2023, including a total installed capacity of 1.01 GW of solar thermal power projects.

Table: New projects in Qinghai Province

Location	PV (MW)	CSP (MW)	Parties
Gonghe	900	100	CHINA ENERGY INVESTMENT, Northwest Engineering Corporation Limited (POWERCHINA NORTHWEST)
Gonghe+Golmud	900	100	Huanghe Hydropower Development Co., Ltd of State Power Investment Corporation Limited (SPIC), Cosin Solar, Rongfeng Enegy of SinoseaPetro Group
Gonghe +Golmud	900	100	China Three Gorges Renewables (Group) Co., Ltd. (CTGR) ,Shouhang,
Golmud	200+100	100	China Three Gorges Renewables (Group)

Table: New projects in Gansu Province

Location	PV/Wind(MW)	CSP(MW)	Parties
Dunhuang	600 PV	100	Gansu Electric Power Company of China Energy Investment Corp. (China Energy), DCTC
Yumen	200 Wind +400 PV	100	Yumen Xino New Energy Co., Ltd. of China Nuclear Engineering & Construction Corporation Limited
Guazhou	200 PV+ 400 Wind	100	China Three Gorges Renewables (Group) Co., Ltd. (CTGR)
Akesai	640 PV	110	East China Electric Power Design Institute Co., Ltd. of China Power Engineering Consulting Group (ECEPDI)

Table: New projects in Jilin Province

Location	Project	Wind/PV (MW)	CSP (MW)	Parties
Tongyu County, Baicheng city	No. 1	200+100	100	CHINA ENERGY INVESTMENT, Cosin Solar
	No. 2	200+100		PowerChina
Da’an City	No. 3	200+100	100	CGN,Baicheng Energy Investment Development Co., Ltd.
	No. 4	200+100		China Datang Corporation Renewable Power, China Energy Engineering Investment Coporation Limited

3. Operations of Solar Thermal Power Demonstration Projects in China

Among the first 20 solar thermal power demonstration projects approved by the National Energy Administration, 7 projects were connected to the grid by the end of 2021. According to the National Development and Reform Commission's "Notice on New Energy Feed-in Tariff Policy in 2021", these projects will enjoy a feed-in tariff of 1.15 RMB/kWh. In addition, one solar thermal power plant has been completed and put into operation in the National Energy Administration's multi-energy complementary demonstration project, as detailed in the table below. The performance and power generation capacity of these solar thermal power demonstration projects have been gradually improved through continuous elimination.

Table: CSP demonstration projects in China

Project	Thermal storage hours	Investment (billion yuan)	annual power generation at design point (GWh)
CGN Delingha 50MW parabolic trough power plant	9	1.7	197.5
Shouhang 100MW solar tower plant	11	3.0	390
Qinghai Supcon 50MW solar tower plant	7	1.088	146
PowerChina Gonghe 50MW solar tower plant	6	1.222	156.9
EnergyChina Hami 50MW solar tower plant	13	1.64	198.3
DCTC 50MW molten salt LFC plant	15	1.688	214
Inner Mongolia Urat 100MW parabolic trough plant	10	2.88	392
Luneng Golmud 50MW solar tower plant of multi-energy complementary project	12	1.986	160
Source: China Solar Thermal Alliance			

3.1 CGN Delingha 50MW Parabolic Trough Power Plant

CGN Delingha 50MW Parabolic Trough Power Plant is the first large-scale commercial solar thermal demonstration plant in China. The generation in 2021 was increased by 31.6% over 2020. From September 19, 2021, to Feb.12, 2022, the CSP plant kept continuous operation for 146 days, securing a leading position at home and abroad by breaking the previously longest 32.2-day record of continuous operation in 2020.

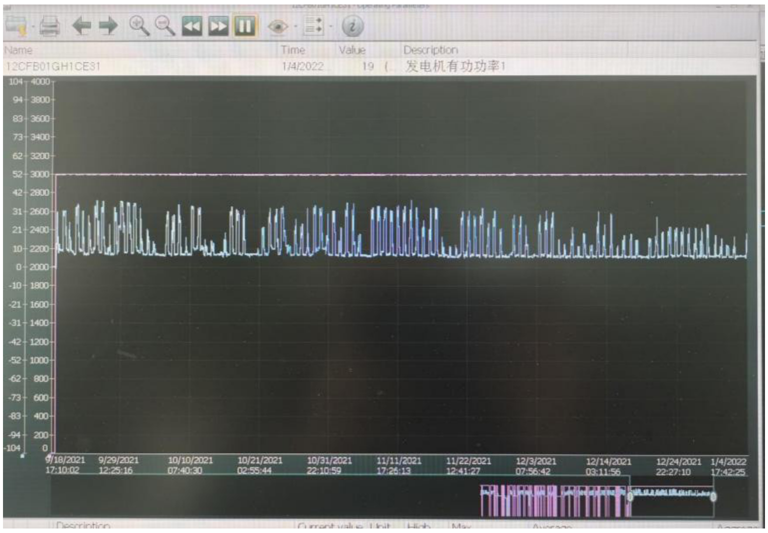

Figure: Steam turbine speed and load curve chart of CGN Delingha 50MW Parabolic Trough Power Plant

3.2 Shouhang Dunhuang 100MW Solar Power Tower Plant

Shouhang Dunhuang 100MW Molten Salt Tower Solar Thermal Demonstration Plant to achieve full load operation in June 2019 [12].Since its commissioning, Shougang has continued to improve the performance of the system in terms of hardware and software, with significant improvements in mirror field efficiency and a steady improvement in the overall performance of the unit. Under the condition that the DNI of Dunhuang area in 2021 was slightly lower than that of the same period in 2020 and the weather was windy and sandy (the cleanliness of the heliostat was seriously affected), the weather at the power station location in the third quarter of 2021 (out of 92 natural days from July to September, there were 40 days of sunny and less cloudy weather, 38 days of cloudy weather and 14 days of cloudy weather).

The total power generation capacity of the power plant is 78.38million kWh, which is an increase of 39.7% in the same period of 2021, on top of the 31.3% increase in power generation capacity in the same period of 2020 compared to 2019, thus achieving an orderly increase in power generation capacity as planned. The project has entered the third year of the 4-year "learning curve" (performance improvement period), and the performance indicators of the power plant are still improving significantly [13].

3.3 Qinghai Supcon Delingha 50MW Solar Power Tower Plant

Qinghai Supcon Delingha 50MW solar thermal power plant was connected to the grid on December 30, 2018 and achieved full load operation on April 17, 2019. Later, through continuous elimination of defects, the problems of vibration of coolant-salt pump, high failure rate of electric tracing, blockage of heat-absorbing screen and thermal stress failure of turbine unit were gradually solved and returned to the factory for refurbishment. Among them, it took one year to solve the problems of vibration of coolant-salt pump and blocked pipes of heat-absorbing screen, and achieved very good results, which had little impact on power generation during the period. The thermal stress problem of the turbine and the connected pipeline has been repeatedly rectified for nearly one year, and finally achieved a more satisfactory result, which had a serious impact on power generation for more than three months during the period. Since October 2019, the actual power generation of the power plant has reached or exceeded the design value in most months, except for the individual months when the turbine failed.

Since the beginning of autumn in September until December 2021, the power station has been in good operation, and the total power generation for four months reached 60,991,200 kWh. The monthly power generation is shown in the table below.

Table: Power Generation Data of Qinghai Supcon Delingha 50MW Solar Power Tower Plant [14]

Month	Designed value (10MWh)	Real value (10MWh)	DNI (kWh/m^2)
Sep. 2021	1457.43	1457.08	193.77
Oct. 2021	1337.08	1367.13	169.81
Nov. 2021	1715.73	1790.68	217.23
Dec. 2021	1451.51	1484.23	186.13

3.4 PowerChina Gonghe 50MW Solar Power Tower Plant

PowerChina Qinghai Gonghe 50MW Solar Thermal Power Project is located in the ecological solar power park of Hainan Prefecture, Qinghai Province, covering a total area of 2.12 square kilometers, with 30,016 heliostats of 20 square meters each, a tower height of 193 meters, and a receiver center elevation of 210 meters. It adopts ultra-high pressure, single reheat, double-cylinder, double-speed, direct air-cooled condensing turbine.

PowerChina Gonghe 50MW solar power tower plant achieved full load operation on November 6, 2020, and passed the national solar thermal power project demonstration acceptance in April 2021. According to the data provided by Gonghe of Northwest Hydropower Solar Thermal Power Generation Co.ltd on May 7, 2021, the plant ran for a total of 16 hours and 43 minutes, and the daily online power reached 539,000 kWh, the highest record since its commissioning; the molten salt temperature at the outlet of the receiver reached a maximum of 568℃ (design value 565℃).

3.5 EnergyChina Hami 50MW Solar Power Tower Plant

EnergyChina Hami 50MW solar power tower plant is located in Hami City, with a total investment of 1.58 billion RMB. A total of 14,500 heliostats are installed in the solar field, with a single heliostat area of 48.5 square meters, and thermal energy storage is 13 hours. For the first time, it adopts the design of double heat tank + single cooling tank and the first domestic direct air cooling turbine with ultra-high temperature, ultra-high pressure, single reheat, double cylinders, axial exhaust and 8-stage regeneration for solar thermal power generation.

The project officially started construction on October 19, 2017, and was first connected to the grid on December 29, 2019. From August 26 to September 27, 2021, the system operated continuously for more than 240 hours; from September 15 to 19, the unit operated continuously for 5 days, with 4.16~24 hours of uninterrupted operation per day, with an average value of 8.674 hours; under the design meteorological conditions, the unit 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.

3.6 DCTC Dunhuang 50MW linear Fresnel solar power plant

DCTC Dunhuang 50MW solar thermal power plant is the world's first linear Fresnel reflector solar power plant that uses molten salt as the heat transfer and storage medium to achieve commercial operation. The project connected to the grid on December 31, 2019, and finished commissioning in early June 2020. On June 18, 2020, the solar collection system was connected to the grid and put into operation. [15] The plant maintains continuous power generation operation of the molten salt collection field throughout the winter low temperature environment in 2020.

Figure: DCTC 50MW molten salt LFC plant

On May 5, 2021, with only 50% of the solar field in operation, the power station reached full capacity, generating 517,700 kWh of electricity on a single day, and since early May 2021, the power station has been generating record power; the cumulative power generation for the whole month of May was 8,633,500 kWh, and the cumulative grid power for the month was 8,558,000 kWh. At present, the concentrating collection system of the power station has been put into operation in batches, and there is still much room for improvement in the power generation capacity of the project.

3.7 Inner Mongolia Urat 100MW parabolic trough plant

The 100MW parabolic trough plant project in Inner Mongolia Urat, officially started construction in June 2018, first achieved grid-connected power generation on January 8, 2020, and realized the full-load power generation on December 16, 2020, and passed the national demonstration acceptance on October 20, 2021. Since the full commissioning of the molten salt energy storage system on July 13, 2021, the plant has achieved continuous 24-hour uninterrupted, stable, high-load power generation operation, with various indicators meeting or exceeding the design value; among them, the optical indicator - interception rate has been tested by a third-party authoritative laboratory in Europe, reaching 98%, which is 1 percentage point higher than the current international level [16].

According to the data provided by CSIC New Energy Co.ltd, from April to October 2021, there were 54 cloudy and rainy days in Urad Middle Banner, where the project is located; during July to August, the accumulated actual direct light radiation is only 68% of a typical year; from August to October, there are more than 10 cloudy days per month, which is rare in history. As of October 2021, the power plant has generated 220 million kWh of electricity, of which the cumulative power generation exceeds 10 million kWh on five consecutive days, with the highest power generation of 2.128 million kWh on a single day[17-18].The power generation of Inner Mongolia Urat 100MW parabolic trough power plant from April to October of 2021. The molten salt thermal storage system put into operation since July 2021. For the first year of operation, the utilization hours is 2107.9h. From Jan. to Oct. 2021, it realized the generation of 220GWh , with the daily highest generation of 2,128MWh. If the thermal storage system put in use in Jan., the expected generation in 2021 was about 318GWh.

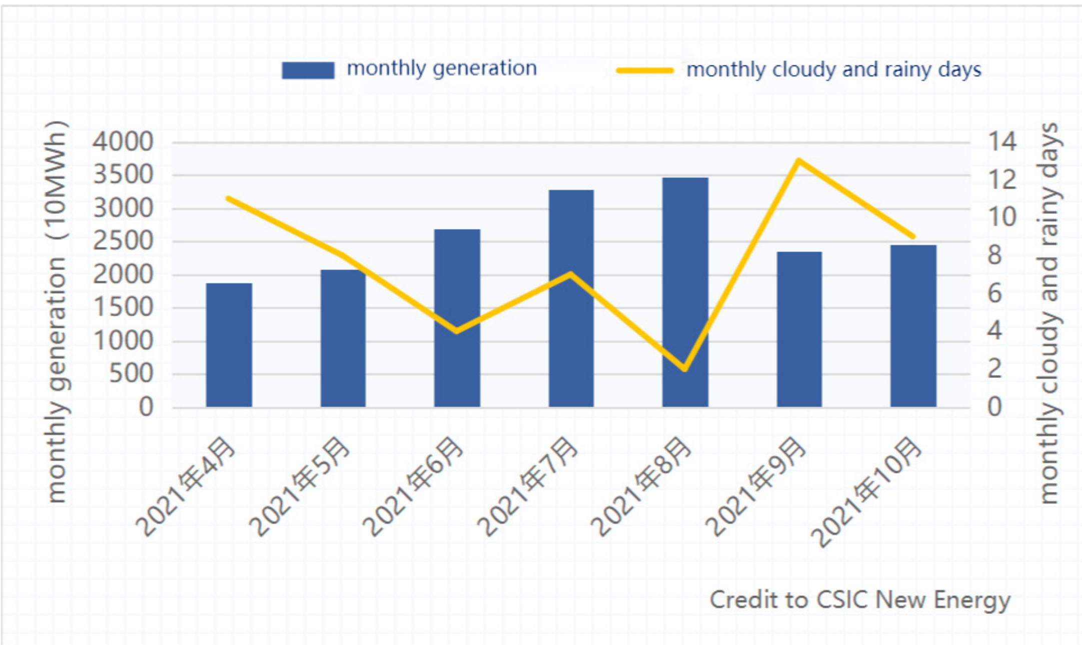

Figure: Power generation of Inner Mongolia Urat 100MW parabolic trough plant from April to October, 2021

At present, the power plant has achieved the record of 24-hour continuous high load power generation for 5 days. Through actual operation data, the parabolic trough solar thermal plant has verified the performance of continuous operation as base load, stable operation at low load and fast load regulation to participate in peak regulation. The details are shown in the figure below.

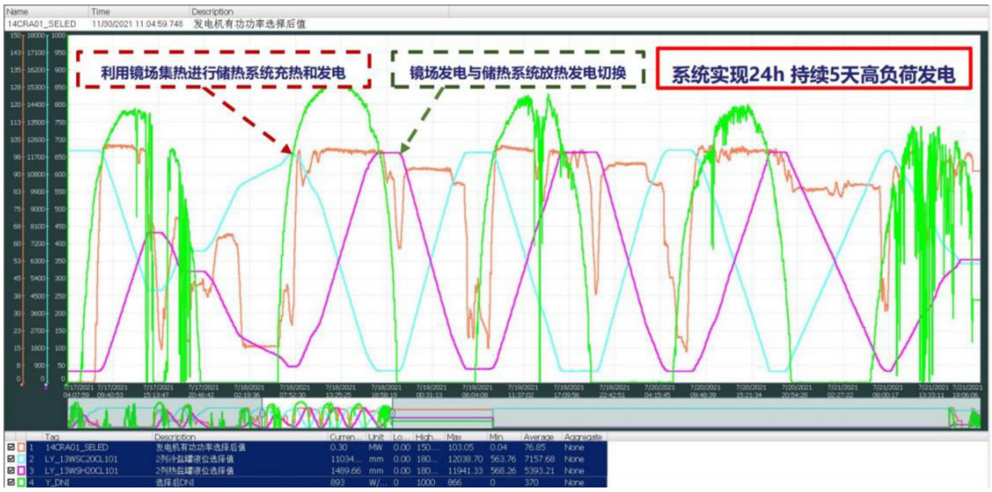

Figure: From July 17 to 21 2021, the power station realized 24h/5 consecutive days of high load power generation

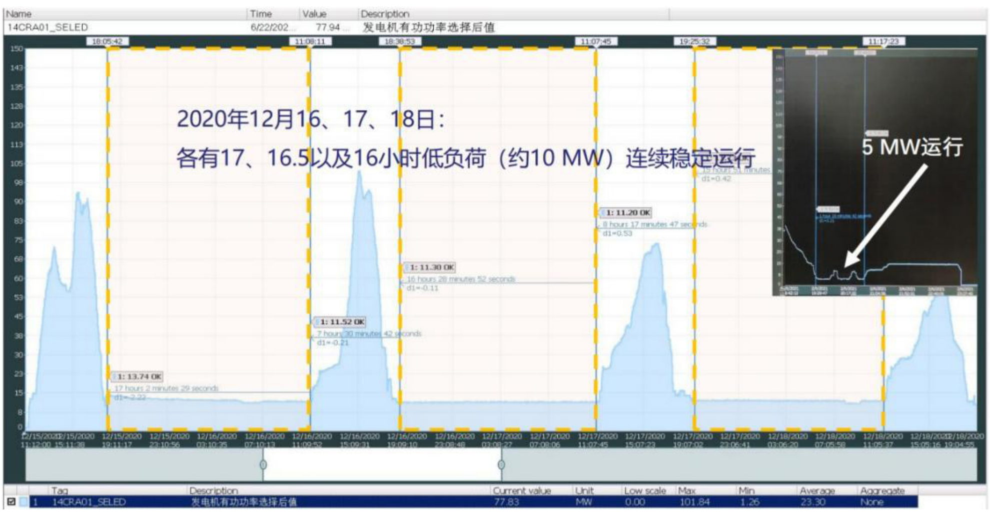

Figure: The minimum load of the steam turbine can reach 5 MW (20%~ 40% of the conventional thermal power), and help peak-shaving with the stable operation in low load runs

3.8 Qinghai Golmud Luneng Multi-energy complementary solar thermal power plant

Luneng Haixi Prefecture Multi-energy Complementary Integration and Optimization National Demonstration Project has a total installed capacity of 700MW, including 200MW of photovoltaic power generation, 400MW of wind power, 50MW of solar thermal power generation, 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, thermal storage and load regulation.

Solar thermal power generation with 12-hour molten salt thermal storage system is an important part of the multi-energy complementary project, which is responsible for peaking for intermittent power sources such as wind power and photovoltaic. The solar thermal power plant was first connected to the grid on September 19, 2019 [19] and completed the

120-hour reliability run on August 27, 2020.

On May 14, 2021, the solar thermal power plant completed the grid-connected joint test. During the grid test, the unit operated continuously for 5 days, with a total of 120.57 hours of operation and a total power generation of 3,093,500 kWh, with an average load factor of 62%, a maximum load of 51MW and a maximum power generation of 764,970,000 kWh in a single day[20]. On June 4, 2021, the single-day power generation of 1,096,200 kWh was the highest in history. In November 2021, the monthly power generation of the plant reached 10,673,775kWh, and the power generation of the Luneng Haixi Prefecture Multi-energy Complementary Solar Thermal Power Plant from May to November of 2021 is shown in the figure below.

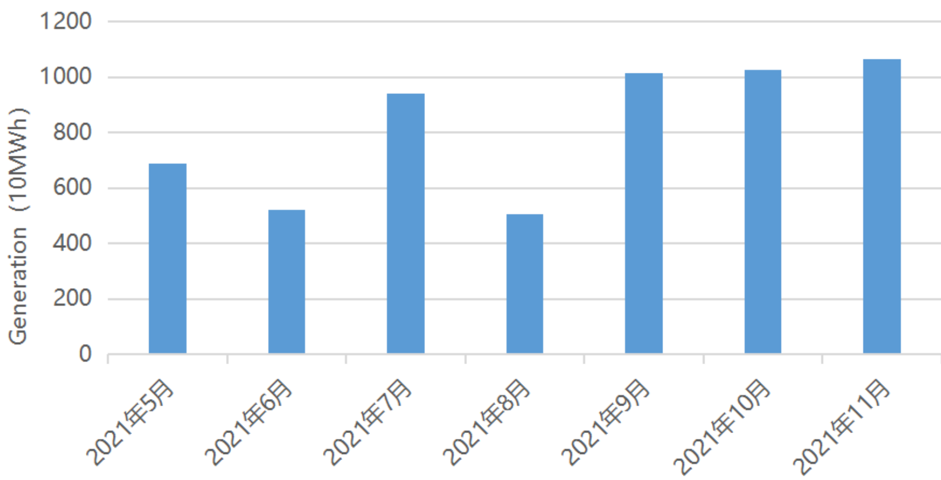

Figure: Generation of Luneng Haixi 50MW solar tower plant from May to November, 2021

4. The Solar Thermal Power Industry Chain in China

4.1 The system and characteristics of solar thermal power industry chain

Solar thermal power is a system that converts solar energy into thermal energy and generates electricity through the process of thermal power conversion. The solar thermal power industry chain system can be divided into research and development, 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, design units with corresponding qualifications; the manufacturing system mainly includes major manufacturing enterprises (state-owned enterprises, private enterprises, joint ventures), production units of universities and colleges, research institutes, etc.; the installation system mainly includes professional power installation units and industrial construction installation units[21].

The main feature of China's solar thermal power industry chain is 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 heat absorption and heat transfer and storage materials (thermal oil, molten salt), insulation materials, etc., which drive the development of core equipment of the industry chain with independent intellectual property rights, such as reflective mirror, heliostat, tower receiver, parabolic trough concentrator, parabolic trough receiver tube, high-precision transmission box, bracket, in-situ controller, thermal energy storage device/system, sliding steam turbine, etc. In the first batch of national solar thermal power demonstration projects, the localization rate of equipment and materials exceeds 90%, and the reliability and advancement of technology and equipment have been effectively verified after the power plant has been put into operation[22]. In Qinghai Supcon Delingha 50MW solar tower power project, the localization rate of equipment and materials has reached over 95%[23].

4.2 The main representative enterprises and institutions of China's CSP field

According to the incomplete statistics of the China Solar Thermal Alliance, in 2021, the number of enterprises and institutions engaged in products and services related to the solar thermal power industry chain in China is nearly 550; among them, the number of enterprises engaged in concentrating, heat collection and thermal energy transfer and storage systems unique to the solar thermal power generation industry is about 320, accounting for about 60% of the total number of enterprises related to the solar thermal power generation industry, with the largest number of enterprises engaged in the field of concentrating, about 170.[24]

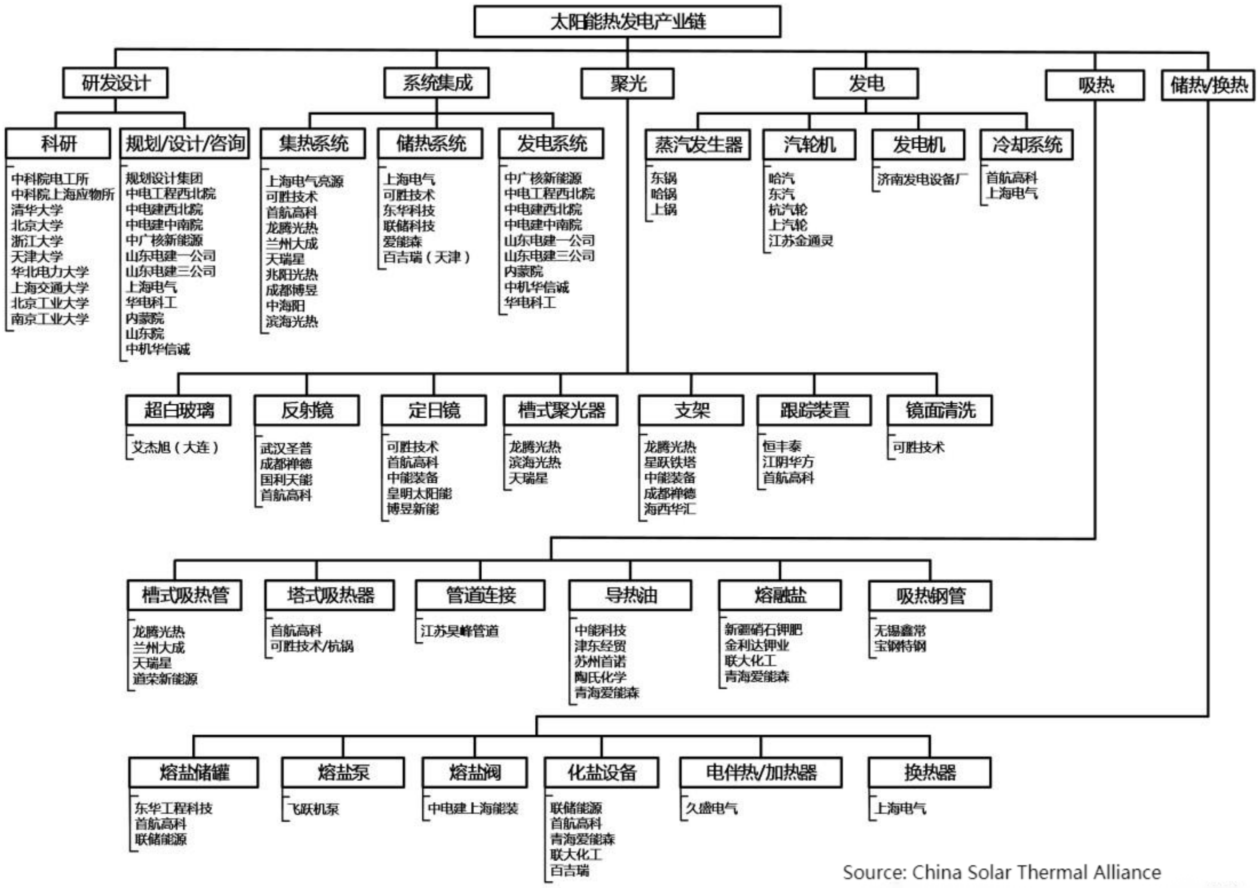

Figure: main representative enterprises and institutions on China's CSP industry chain

4.3 Key components and equipment/materials manufacturing capacity of China's CSP industry

In 2021, the equipment manufacturing and production capacity situation is basically the same as that of the year 2020, as there are no new solar thermal power projects started construction. According to the "China Solar Thermal Power and Heating Industry Blue Book 2020" published by the China Solar Thermal Alliance, China has established several production lines of components and equipment dedicated to solar thermal power generation, and has the supply capacity to support the large-scale development of solar thermal power generation, and the annual supply can meet the installed capacity of 2~3GW solar thermal power projects.

According to the incomplete statistics of China Solar Thermal Alliance, China has 5 solar ultra-clear glass production lines with an annual capacity of 92 million square meters, 6 trough glass mirror production lines with an annual capacity of 23.5 million square meters, 6 flat mirror production lines with an annual capacity of 33.6 million square meters, 10 parabolic trough tube receiver production lines with an annual capacity of 1 million pieces, 21 tracking drive production lines with an annual capacity of 20,000 sets, 9 thermal oil production lines with an annual capacity of 500,000 tons, 15 molten salt production lines are in operation with an annual capacity of 600,000 tons, and 19 assembly lines for tower-type heliostats and trough-type collectors are in operation.

Table: China's key components / material production lines in CSP industry

Key components	Production lines number	Production capacity
Solar ultra white glass	5	92 million m2
Parabolic trough mirror	6	23.5 million m2
Flat mirror	6	33.6 million m2
PT tube receiver	10	1 million pieces
Tracking device	21	20,000 sets
Thermal oil	9	0.5 million tons
Molten salt	15	0.60 million tons
Statistics by CSTA		

Aijiexu Special Glass (Dalian) Co., Ltd has the largest annual production capacity of solar ultra-clear glass, with a capacity of 700 tons per day and an annual production capacity of 2GW of solar ultra-clear glass for solar thermal power projects. It has supplied 556MW of solar ultra-clear glass for domestic solar thermal power generation and solar thermal utilization projects, and 473MW of solar ultra-clear glass to foreign countries, totaling about 1.03GW.

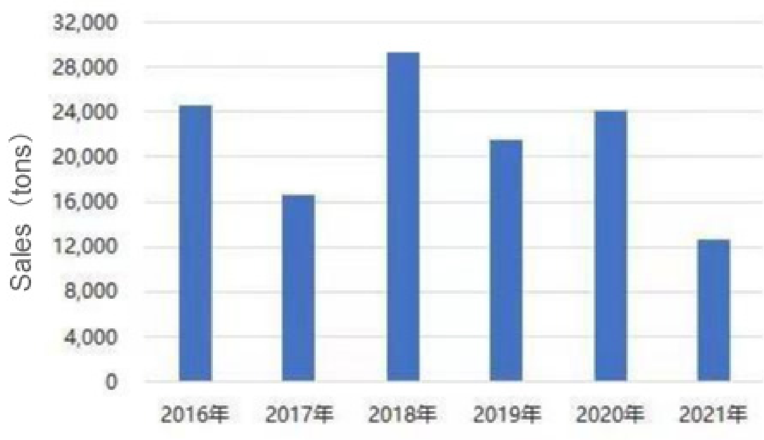

Figure: Aijiexu Special Glass's sales of solar ultra-clear glass in the past 6 years

4.4 Sales and application of key components for solar thermal power in China

The production and sales of key solar thermal power components are closely related to the construction of solar thermal power projects. At present, there are 8 large-scale solar thermal power projects in China that are connected to the grid, and the usage of each project basically coincides with the shipments of equipment component suppliers, so the sales of key components can be seen based on the usage of the projects.

According to the China Solar Thermal Alliance, the eight solar thermal power stations put into operation between 2018 and 2020 used a total of 6,912,922 square meters of reflective mirrors, 214,523 tons of molten salt, 102,300 vacuum tube receivers, and 10,500 tons of thermal oil (sorted by energy storage hours in the table below). The component usage of the Yumen Xineng beam-down solar power tower plant and the Aksai molten salt parabolic trough plant are not included.

Table: key components usage of 8 CSP plants in China

Project	Thermal Storage (h)	Reflector (m^2)	Molten salt (tons)	Tube receiver(pieces)	Thermal oil(tons)
DCTC 50MW molten salt LFC plant	15	1270000	24000	22000	/
EnergyChina Hami 50MW solar tower plant	13	719902	16000	/	/
Luneng Golmud 50MW solar tower plant	12	610000	16000	/	/
Shouhang 100MW solar tower plant	11	1400000	30000	/	/
Inner Mongolia Urat 100MW Parabolic Trough plant	10	1150000	73130	52800	7500
CGN Delingha 50MW Parabolic Trough Power Plant	9	620000	36000	27500	2000
Qinghai Supcon 50MW solar tower plant	7	542700	10093	/	/
PowerChina Gonghe 50MW solar tower plant	6	600320	9300		
Subtotal		6912922	214523	102300	10500
Statistics by China Solar Thermal Alliance					

From a country perspective, the reflective mirrors are mainly China's domestic enterprises, accounting for 91.03% of the total usage of the solar thermal power demonstration projects in operation; the suppliers of molten salt are all domestic enterprises; in the three line-focusing solar thermal power generation projects (trough type and linear Fresnel type), the domestic supply of receiver tube accounts for 73.12%; the domestic supply of thermal oil accounts for 71.43%.

It is important to note that the four foreign supplies of materials and components for solar thermal power generation all took place in the CGN Delingha 50MW Parabolic Trough Power generation project. This project is the first large-capacity solar thermal power generation project built in China, using a low-interest loan of $150 million from the Asian Development Bank (ADB).

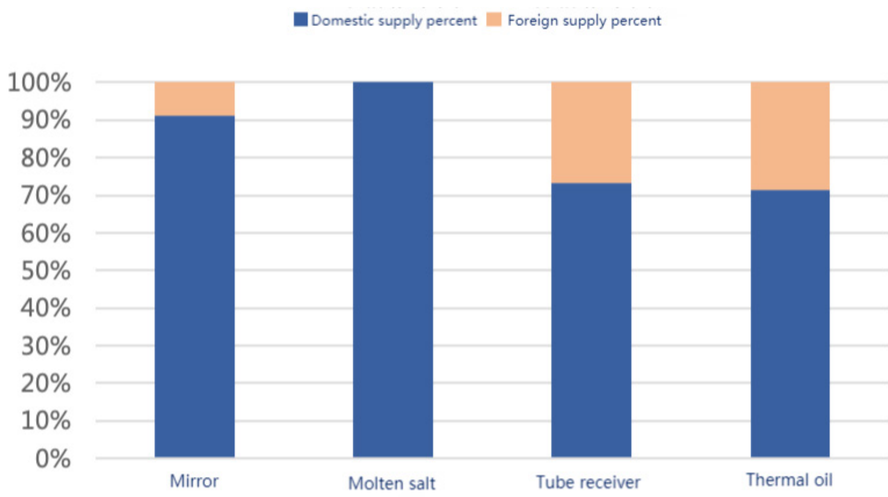

Figure: domestic and foreign supply percent of key components in CSP demonstration plants

In recent years, the shipments of China's parabolic trough tube receivers have gradually increased, achieving large-scale application in commercial trough power plants at home and abroad. For example, up to now, RoyalTech CSP has achieved a total of nearly 60,000 domestic and nearly 10,000 foreign deliveries. Tianruixing Solar Thermal Technology has sold more than 26,800 heat-absorbing tubes in the past three years, as shown in the figure below.

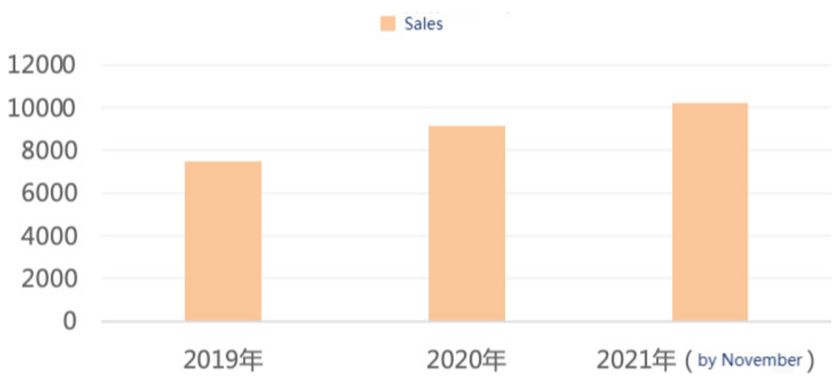

Figure: Tianruixing Solar's tube receiver sales

At present, the metal hose assemblies of rotary joints developed by Chinese enterprises have also achieved engineering verification applications, and the cumulative number of applications has reached more than1040 sets.

5. Overview of China’s R&D Projects on CSP

5.1 "Wide-Band Planar Super-Surface Solar Concentrator and its Heat Collection System" project

In April 2021, the project " wide-wave, wide-angle flat super surface solar concentrator and its solar thermal collection system" was launched under the National Key R&D Program "Key Scientific Problems of Transformative Technologies". The project is led by Wuhan University of Science and Technology, and the participating institutions include Institute of Electrical Engineering, Chinese Academy of Sciences, Fudan University, Xiamen University, University of Science and Technology of China, and Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, with Prof. Jianguo Guan of Wuhan University of Technology as the chief scientist. The project focuses on the key scientific issues of wide-wave, wide-angle flat super surface solar concentrator and solar thermal collection system design and manufacture, with the help of the plane super surface electromagnetic coupling effect to develop free tracking, low-cost wide-angle broadband segment sun radiation plane concentration aiming to solve the problem that the current general curved concentrator requires high-precision bracket and complex solar tracking device, resulting in the high cost. The project has advanced technical specifications, is difficult to complete, focuses on disruptive technology breakthroughs, and is of great significance to promote the development of the solar thermal power generation field.

5.2 "Research on Key Technical Standards for Solar Thermal Power and Thermal Utilization" project

In 2021, the National Key R&D Program "Research on Key Technology Standards for Solar Thermal Power Generation and Thermal Utilization" project completed all the research work. This project is a key special project of the National Key R&D Program "National Quality Infrastructure (NQI) Common Technology Research and Application" in 2017, led by China Energy Engineering Investment Corporation Limited, China National Institute of Standardization, China Electricity Council, China Datang Corporation Renewable Power and other parties. The implementation period was from July 2017 to December 2020. Under the project, there are two sub-topics: "Research on Key Technical Standards for Solar Thermal Power Plants" and "Research on Key Technical Standards for Medium Temperature Solar Thermal Utilization", which aims to establish a standard system for solar thermal power generation and thermal utilization as well as related technical conditions, testing methods, performance tests, and design specifications.

5.3 "Research on High Temperature Solid Particle Receiver for Fourth Generation Solar Thermal Power " project

This project is a new energy frontier technology research project (original innovation category) funded by Beijing Municipal Science and Technology Commission, and the implementation period was from January 2018 to June 2021. The project is undertaken by the Institute of Electrical Engineering, Chinese Academy of Sciences. The main research work of the project includes:

Firstly, three types of solid receiver were studied, including solid particles, spherical flows, and columns. Two aspects of the receiver research were used: indoor cold state experiment and outdoor tower type thermal state experiment. In the theoretical aspect, the factors affecting the thermal efficiency of the receiver were analyzed by establishing the relationship between the heat flux and the heat gain, and the receiver was designed and fabricated. The temperature of spherical flow and columns receiver reaches 1100 ℃ , the maximum temperature of particle receiver reaches 845 ℃ , and the thermal power reaches 415kW. For the particle receiver, the influence of particle thermal physical properties and size on particle flow and heat absorption performance is studied theoretically and experimentally. Some series of cold state and indoor and outdoor hot state experiments were carried out. The developed MW particle receiver worked for up to 9 hours a day and achieved a high performance.

Secondly, The heat gain process of solar particle receiver system is studied. The dynamic model of aggregated energy flow in the heliostat field and the dynamic model of heat absorption and heat transfer in the quartz tube pellet receiver are established, and the simulation platform of the dynamic process of pellet receiver was built based on TRNSYS, which can calculate the effect of solar irradiation, the number and area of heliostats put into operation, the ambient meteorological conditions and the particle flow rate on the dynamic receiver performance, and the corresponding simulation software is prepared. Based on the above model analysis, we designed the receiver system, including the process parameters of receiver , feeding system, thermal energy storage system and transfer mechanism, designed the control system and proposed the operation mode, etc.

Thirdly, based on a large number of experimental tests on the particle receiver, the performance testing and evaluation methods including the particle receiver system were studied, the corresponding specifications were prepared, and the corresponding testing instruments and data processing software were designed and produced.

Fourthly, the auxiliary equipment involved in the 800℃ receiver, including high-temperature elevator, high-temperature thermal energy storage tank, and the control operation mode of the upper and lower material system of the receiver were studied, and the corresponding products were developed in conjunction with industry. Through the application, it is proved that the auxiliary equipment works well. The subject developed 800℃ high temperature particle valve, high temperature particle elevator, etc. Which has filled the gaps in China and provided the equipment basis for future high temperature industry, especially high temperature thermal energy storage utilization.

5.4 "Research on Supercritical CO_2 Heat Exchanger for Fourth Generation Solar Thermal Power" Project

The fourth generation solar thermal power generation technol ogy uses particles as the heat absorption medium and supercritical CO_2 as the power generation medium, which has the advantages of high stability, small equipment size, low cost and high efficiency. The efficient heat transfer between high-temperature pellets and supercritical CO_2 is one of the key technologies to realize next-generation solar thermal power generation. Under the funding of Beijing Municipal Science and Technology Commission (New Energy Frontier Technology Research Project - Original Innovation Category), the Institute of Electrical Engineering of Chinese Academy of Sciences and Tsinghua University have solved the design problems of supercritical carbon dioxide - high temperature solar heat-absorbing medium exchanger and developed the exchanger with supercritical carbon dioxide as exchanger medium, which is a solid technology foundation for the realization of supercritical carbon dioxide in the fourth generation of solar thermal power technology. Brayton cycle in the fourth generation of solar thermal power technology. The research indexes reached the world advanced level, filled the domestic technology gaps, and formed the design method and technical conditions of supercritical carbon dioxide - high temperature solar heat-absorbing medium heat exchanger, which is of great significance to the development of the fourth generation solar power technology.

The project implementation period was from January 2018 to June 2021. The main research results are as follows:

1) A 20 kW particle/supercritical CO_2 pilot heat transfer system was designed and built. The experimental study of fluidized bed fluidization characteristics was carried out, and the fluidization characteristics of particles at different bed heights and apparent gas velocities were obtained.

2) A heat exchange system study was conducted to summarize the heat transfer model of the pellet side under the conditions of single tube, tube bundle and different tube arrangement, and a model of the particle/supercritical CO_2 heat transfer system including system heat transfer, particle side heat transfer, supercritical CO_2 side heat transfer and fluidized air heat transfer was established. Specific solutions and countermeasures are proposed for the problems that occur or may occur in the system operation. Simulation studies of fluidized bed flow heat transfer at low gas velocities were carried out. The research results can provide a theoretical basis for improving the particle/supercritical CO_2 fluidized bed heat exchange technology, and are also important for the development of high-efficiency solar thermal power generation technology.

3) Built a 1MW pellet/supercritical CO_2 heat exchanger prototype test system. The commissioning of the fluidized bed heat exchanger was carried out. A method for calculating and predicting the thermal performance of the pellet/supercritical CO_2 heat exchanger was developed, and the performance parameters of the heat exchanger can be obtained more accurately by this method. Under the agreed conditions on the pellet side, the heat exchanger can achieve the targets of supercritical CO_2 outlet temperature above 550°C, system pressure above 10 MPa, and thermal power above 1 MWth.

5.5 "Development and Application of High Temperature Resistant Molten Salt Special Alloy for Solar Thermal Power Generation" project

On December 13, 2021, the project "Development and Application of High Temperature Resistant Molten Salt Special Alloy for Solar Thermal Power Generation" led by Institute of Metal Research, Chinese Academy of Sciences was included in the public announcement list of the key projects to be established in 2021 under the National Key R&D Program "Advanced Structure and Composite Materials".

The project implementation period is 4 years. According to the application guide, the project will make research on the heat-resistant stainless steel, high temperature alloy plate and its welding interface in the high temperature chloride, nitrate corrosion mechanisms and service life prediction technology, so as to meet the chloride and nitrate molten salt power generation system.

6. Investment Costs of Solar Thermal Power Generation

6.1 Construction cost and composition of solar power 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]

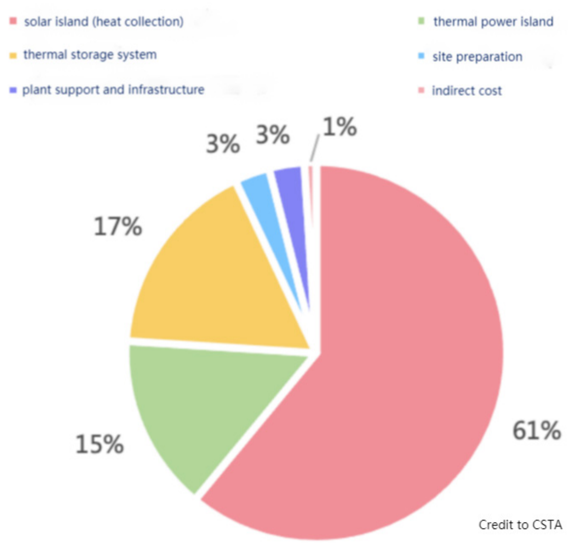

Figure: Investment composition of 50MW solar tower power plant with 7-hour thermal storage

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%.

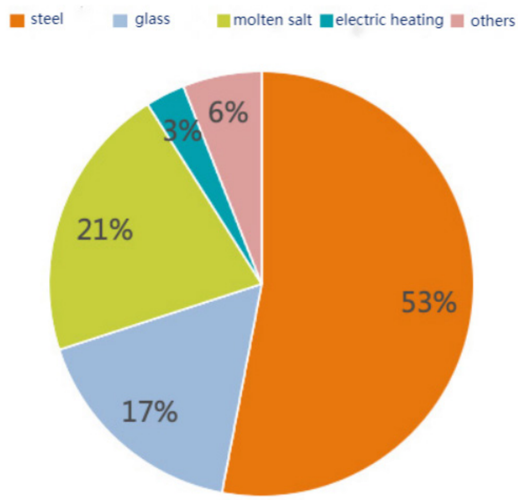

Figure: the cost proportion of raw materials in solar field, heat collection and thermal storage subsystems of Qinghai Supcon Delingha 50MW solar tower plant

6.1.2 Investment of a100MW 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.

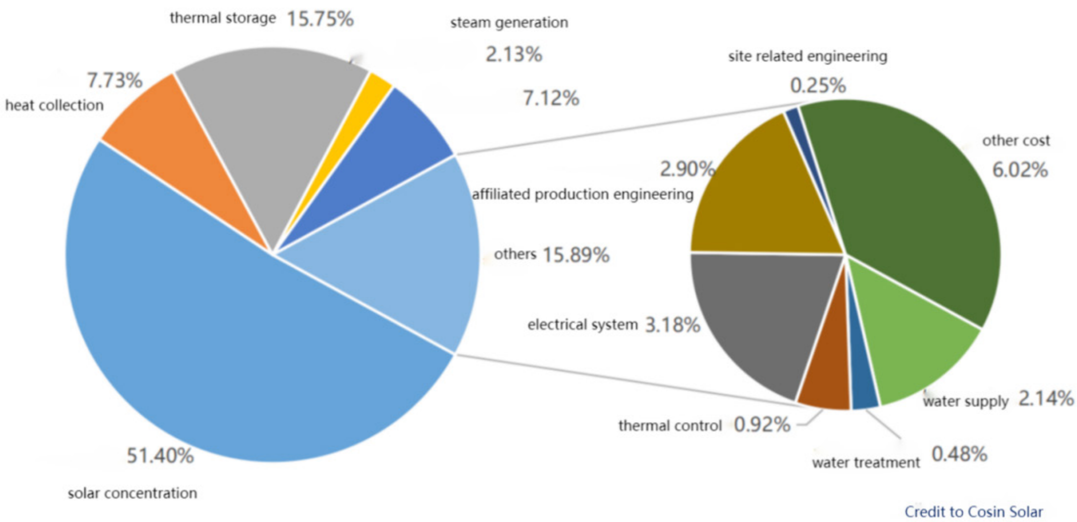

Figure: Investment composition of a100MW solar power tower plant with 12h thermal storage system

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 Parabolic Trough solar thermal power plant construction costs and components

6.2.1 Investment composition of China's a 50MW Parabolic Trough solar thermal 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.

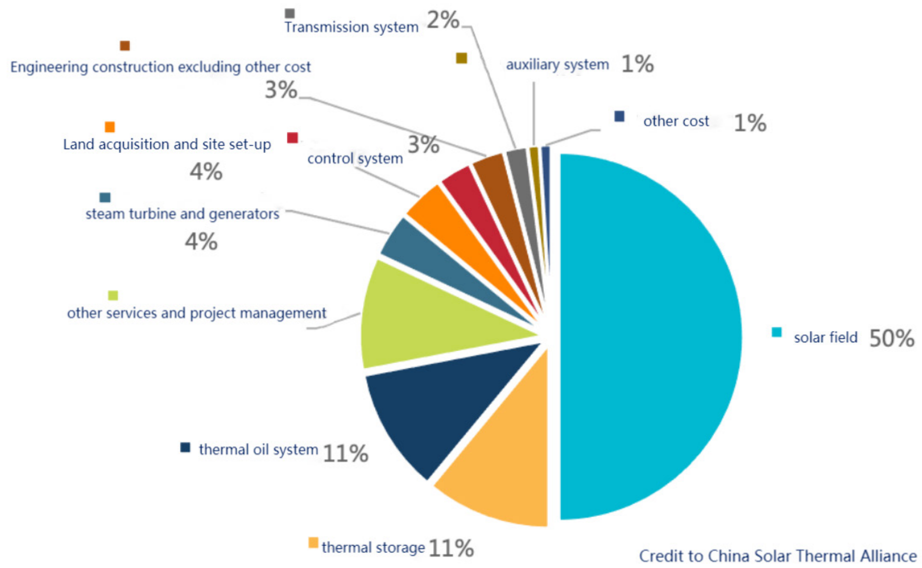

Figure: Investment composition of China's a 50MW parabolic trough plant with 4h thermal storage system

6.2.2 Investment composition of one 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%.

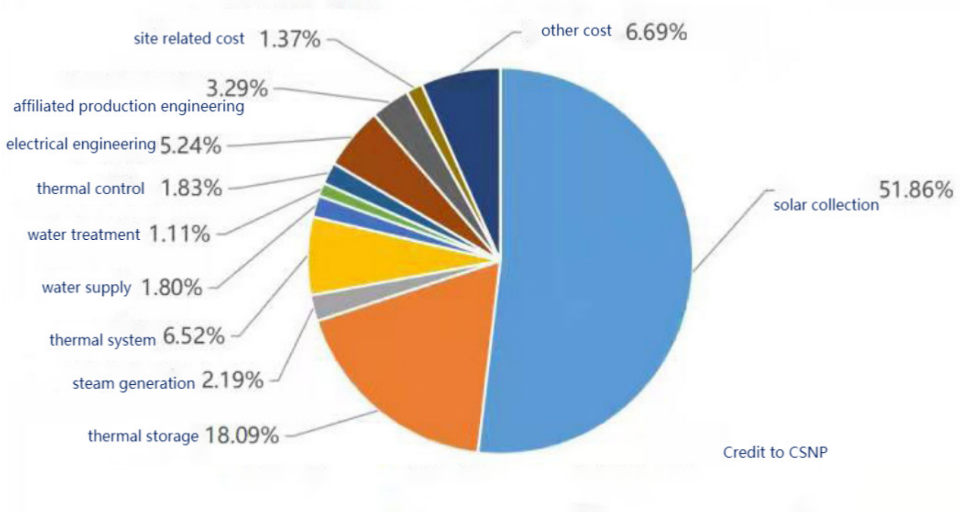

Figure: Investment composition of one 100MW parabolic trough power plant with 10h thermal storage system

7. Challenges and Countermeasures for Solar Thermal Power Development in China

Solar thermal power is easy to configure large-capacity, long-duration, safer and low-carbon thermal storage system, and the use of conventional turbine generator sets, the system has rotation inertia and grid synchronizer feature, is a flexible regulation power. CSP can meet the urgent need for fast peaking power in line with the current high proportion of unstable renewable energy power grid requiring the safe and stable operation of the grid, which can lay a safe and stable foundation for the construction of new energy-based power system.

The main obstacle to the large-scale development of solar thermal power in China is the large primary investment and the relatively high cost of power generation. How to reduce the cost of solar thermal power is a major challenge to the further development of the industry.

According to a simplified formula published by the International Energy Agency (IEA) for calculating the cost of power generation from renewable energy systems (shown below), the total investment, O&M costs and the annual net power production of the plant (annual power production minus plant power consumption) are the key indicators. Reducing the total investment and O&M costs of a solar thermal power plant, while increasing the annual net power production of a solar thermal power plant is an effective way to reduce the cost of solar thermal power. The reduction of the initial investment cost can be achieved by decreasing the cost of the subsystems and key components. The annual power production of a solar thermal power plant is related to the annual average system efficiency and the annual direct solar irradiation projected on the heliostat field, and under the same solar irradiation conditions, the higher the annual average system efficiency, the more the annual power production of the plant. The increase of annual net power generation can be achieved by improving the system efficiency and reducing the plant electricity consumption. [26]

$$LEC = \frac{crf \cdot K_{invest} + K_{OM} + K_{fuel}}{E_{net}}$$

7.1 Initial investment and O&M costs reduction

As mentioned earlier, the costs of solar concentration, heat absorption and thermal energy storage system account for a high percentage of the total investment in solar thermal power plants. According to Cosin Solar, the equipment acquisition costs account for about 73% of the total investment of a solar power tower plant, installation cost accounts for about 12%, construction works account for about 9%, and others account for about 6%. Among them, the main ways to reduce the cost of equipment acquisition part are shown in the following table.

Table: the main paths to reduce the cost of equipment acquisition

Items	Cost reduction paths	Absolute value of cost reduction（≥）
Heliostat field	Heliostat: reduce the steel consumption, improve the production efficiency, use new tracking devices; Competitive effect; Heliostat field control system: reduce the software and hardware cost	10.7~15.4%
Receiver system	Material manufacturing Locally, optimized the production techniques, industrial scale	1.03~1.49%
Thermal storage and exchange	Storage tank design optimization, mature machining, centralized purchasing; Domestically produced molten salt valves and pumps; O&M cost reduction; industrial scale of molten salt	3.59~5.66%
Thermal generation	Design optimization and centralized purchasing	1.4~2.1%

In addition, according to international experience, technological progress contributes about 42% to the cost reduction of solar thermal power, about 37% for scale up and about 21% for mass production. According to calculations by Chinese companies, the overall reduction in total power plant investment due to scale development can reach 18.42~27.56% under ideal conditions.

A study by North China Electric Power University points out that if the O&M cost is reduced by 20%, the IRR of solar power tower, parabolic trough solar power and linear Fresnel reflector solar power plants will increase from 12.33%, 11.72% and 11.43 to 13.41%, 12.79% and 12.49%, respectively. The operating cost of a 50MW solar thermal power plant in China is about RMB 0.05/kWh, which mainly includes labor cost, maintenance cost, spare parts cost, purchased electricity, water cost, material cost, etc.; among which labor cost accounts for the highest percentage. With the improvement of operating experience, the O&M cost is expected to decrease significantly in the next few years; moreover, with the increase of the installed capacity, the increase of labor cost is not significant.

7.2 Efficiency improvement

The basic process of solar thermal power generation involves concentrator, heat transfer and thermal work conversion. The conversion of solar energy into electricity in the form of heat requires multiple energy conversion and transmission processes. In terms of the light-heat-work conversion process, solar thermal power generation mainly consists of the following three processes (as shown in the figure below): 1) light aggregation and conversion process; 2) heat absorption, storage and transfer process; and 3) thermal work conversion process. The higher the annual efficiency of a solar thermal power plant, the stronger the conversion ability of solar energy to electricity. The annual efficiency of a solar thermal power plant is the ratio of the power generated by the solar thermal power plant in a year to the amount of direct solar irradiation projected onto the light harvesting area of the solar field, which is related to many factors such as installed capacity, direct normal irradiation, design point, inlet parameters of steam turbine, thermal energy storage system capacity, annual sunshine hours, and the percentage of auxiliary energy.

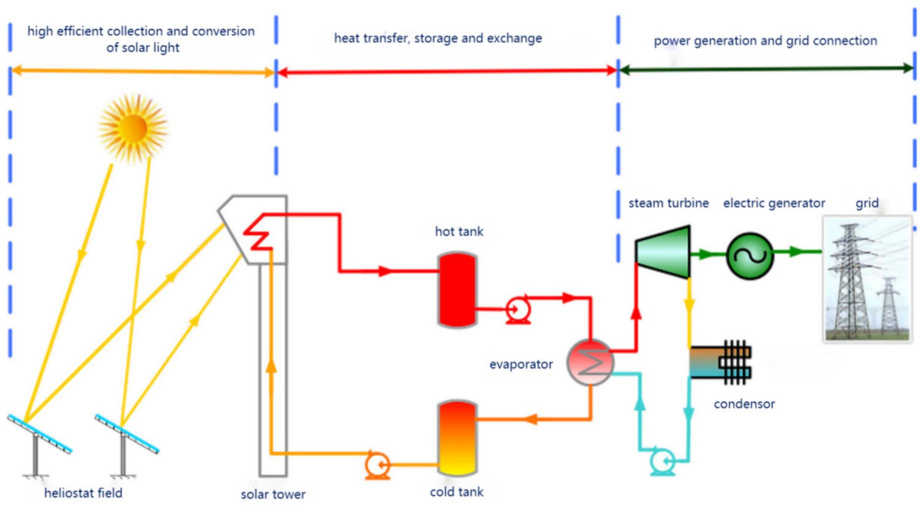

Figure: Schematic of solar tower plant with molten salt as heat transfer fluid

Several disciplines such as thermodynamics, heat transfer, optics, materials science and the intersection of these disciplines are the theoretical basis of solar thermal power technology. The heat transfer mechanism and heat flow characteristics of each energy transfer and conversion link, the integration theory of light-heat-power conversion system, and key materials and technologies are the basic problems that need to be paid attention to and solved in solar thermal power technology.

The figure below shows the energy transfer composition of a typical solar power tower plant. As can be seen from the diagram, the concentrating, heat absorption and thermal power conversion processes are the main parts of the energy and efficiency losses of the system, accounting for about 97% of the total losses. Therefore, the key to improving the efficiency of solar thermal power is to improve the efficiency of the concentrating, heat absorption and thermal power conversion processes. Most of the domestic and international research has focused on these two processes and the thermodynamic cyclic characteristics of the system under non-stationary conditions in order to obtain stable operation technology.

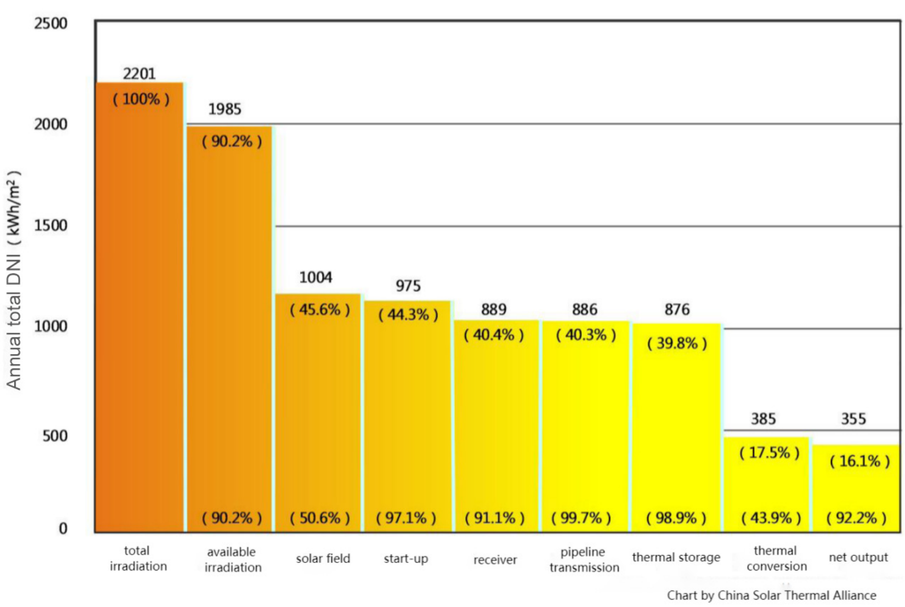

Figure: Efficiency and energy loss of a typical CSP plant

Under the existing molten salt tower technology system, the solar-electricity conversion efficiency can be improved by 12~27% through the optimization of the following parts [24].

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 solar thermal power technology and industry development in China

1) Solar thermal power plant integration: exploring the solar thermal power plant operation process and establishing solar thermal power plant design and operation specifications. Solid work on system operation, system improvement, and system analysis for completed solar thermal power systems. Through improvements, to optimize the safety and reliability of the system, improve the efficiency of the system, and derive operating operation specifications, system design specifications and an outline for accident handling. To conduct detailed analysis of the parameters of each equipment in the system, propose the technical specifications of each equipment, and summarize a number of industry and national standards.

2) High-temperature thermal energy storage and heat exchange: thermal energy storage is an important factor in the continuity of solar thermal power . The thermal energy storage problem involves the coupling of materials and

thermodynamics, and requires research on low-cost thermal energy storage materials and systems, design methods for molten salt heat absorption and thermal energy storage systems with inherent safety, etc.

3) solar concentrator: through the data of the commercial power plants, it is found that the cost of concentrator accounts for about 50% of the investment of the whole solar thermal power plant. In the future, try to reduce the spillover losses, improve the concentration ratio and to explore other new concentrator, as well as the reliability improvement of the current parabolic trough concentrator and heliostat.

4) Receiver: there are many types of receivers, currently commonly used parabolic trough receiver and tower type receiver. The safety of the receiver is the most important indicator of the receiver, which works every day under high temperature, non-uniform and non-stable heat flow boundary conditions, and needs to have a certain fatigue resistance life. There is a need to explore the materials used for receivers and the mechanics and heat transfer characteristics associated with their operation, and to develop solar receivers with inherent safety and long life, with increased efficiency and operating temperature.

5) Solar energy components production line special equipment: solar energy key components production line technology in China has been slow to develop. China's current research results in the production line of glass mirrors, receiver tubes, concentrators, special turbines and so on is not enough to support the needs of large-scale industrialization. Need to improve the quality control technology and process of products in large-scale practice, the establishment of concentrator, heat absorption and heat transfer components of the production line and production process.

6) Core materials, equipment and system performance testing platform: development or development of large-scale high-heat flux measurement system, concentrator concentration accuracy measurement and evaluation, core materials and equipment reliability and thermal performance testing instruments and methods, key system performance testing platform, etc.

7) Technical specifications and standards: Establish specifications and standards for the evaluation of the performance of core materials, equipment and systems for solar thermal power generation. Through continuous research and development and attention to new forms of concentrating light, optimal design of concentrating light system, receiver technology adapted to different forms of thermal power generation technology, different types of working materials and operating temperatures, thermal energy storage materials and thermal energy storage systems, and high-efficiency thermoelectric conversion technology, promote China's solar thermal power generation technology to high parameters- high efficiency -low cost -base load direction.

8) Supercritical CO_2 solar thermal power technology: increase the temperature of the receiver to 800℃, study the method to improve the heat transfer coefficient of the particle and carbon dioxide heat exchanger, use supercritical carbon dioxide as the power generation medium, and generate power efficiently.

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