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Chinese CSP for the World?

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Abstract. For three consecutive five-year plans since 2006, China has worked on building up an internationally competitive CSP industry and value chain. One big milestone in commercializing proprietary Chinese CSP technology was the 2016 demonstration program of 20 commercial-scale projects. China sought to increase and demonstrate capacities for domestic CSP technology development and deployment. At the end of the 13th five-year period, we take stock of the demonstrated progress of the Chinese CSP industry towards delivering internationally competitive CSP projects. We find that in January 2021, eight commercial-scale projects, in total 500 MW, have been completed and three others were under construction in China. In addition, Chinese EPC's have participated in three international CSP projects, although proprietary Chinese CSP designs have not been applied outside China. The largest progress has been made in molten-salt tower technology, with several projects by different companies completed and operating successfully: here, the aims were met, and Chinese companies are now at the global forefront of this segment. Further efforts for large-scale demonstration are needed, however, for other CSP technologies, including parabolic trough - with additional demonstration hindered by a lack of further deployment policies. In the near future, Chinese companies seek to employ the demonstrated capabilities in the tower segment abroad and are developing projects using Chinese technology, financing, and components in several overseas markets. If successful, this will likely lead to increasing competition and further cost reductions for the global CSP sector.

INTRODUCTION: THE NEED FOR A CHINESE CSP INDUSTRY

Rising energy prices and increasing concerns about global warming at the beginning of the millennium marked a new dawn for concentrating solar power (CSP). Since the 1980s research in the technology had continued, driven by public policy and entrepreneurs. The first commercial projects since 1991 came online in the US and Spain in 2007, enabled by public support policies [1]. European and American companies dominated the industry by developing and assembling every commercial-scale CSP plant using mostly European or American components [2]. Despite far-reaching plans to expand CSP in several African, and Middle Eastern countries, internationally active Chinese engineering and infrastructure companies found themselves in an uncompetitive situation to deliver CSP plants in the global market. Before 2009 there was no megawatt-scale CSP project in China, and hence no track record for Chinese companies [3]. Consequently, the central government has since enacted a series of policies aimed at commercializing CSP in China leading to a demonstration program for CSP plants in China and engagement of Chinese companies in projects abroad [4]. With the slow growth of worldwide installed CSP capacity in recent years the Chinese industry had a good opportunity to close the gap with their foreign competition [2, 5].

Here, we investigate the success of these policies by examining the track record of the Chinese CSP industry in the last 15 years by asking: Which technological and project development capabilities has the Chinese CSP industry demonstrated?

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BACKGROUND: CSP INDUSTRY AND INNOVATION POLICY IN CHINA

Early Experimentation in the 11th and 12th Five-year Plans Between 2006 and 2015

Chinese energy and innovation policies follow the priorities in the five-year plans (FYP) set up by the central government. First attention to CSP as an emerging energy technology was raised in the 11th five-year plan (2006-2010), which emphasized research and development by devoting 2% of GDP to innovation. Work on a pilot station for research and development – the 1 MW Dahan solar tower *Key Project "863 Solar Thermal Power Generation Technology and System Demonstration"* in Badaling was started [6, 7]. The project was developed by the by the *Institute of Electrical Engineering of the Chinese Academy of Sciences (CAS).* To coordinate industry activities in the emerging Chinese CSP industry, the Ministry of Science and Technology established the *China Solar Thermal Alliance* (CSTA) as one of 36 newly set-up pilot industry alliances in October of 2009 [8].

During the 12th FYP (2011-2015) there were several successful pilot projects. Most notably, the Dahan molten-salt tower project was inaugurated in 2012. Its construction included a broad number of stakeholders, among others the Power Construction Corporation of China (PowerChina) and the China Energy Engineering Group (CEEC), two conglomerates set up in 2011, bundling Chinese competence in conventional power engineering and with international markets in mind [9-11]. The involved parties were later instrumental in building further demonstration projects. As elaborated by Gosens and Binz [12], a post-doc researcher from CAS that was involved in the project was instrumental in founding one of the private pioneer CSP companies, SunCan (that was later acquired by the current Chinese CSP "champion", Shouhang). Shouhang and SunCan built between 2014 and 2016 a 10-MW demonstration power tower in Dunhuang. Similarly, the Northwest Electric Power Design Institute (NWEPDI), a subsidiary of CEEC, has had a linking role between the Dahan project and another successful Chinese CSP developer, Supcon Solar. NWEPDI and Supcon designed and built another 5-MW pilot project with a steam receiver, again supported by the central government [13] and later also explore molten-salt technology at the same plant.

In addition, several test and pilot plants were set up by private and state-owned companies, for research in parabolic trough and other CSP technologies - including a 1-MW parabolic trough demonstration facility also supported in the *863 Hi-Tech program* that was completed much later in 2017, five years after the Dahan molten-salt tower demonstration project [14, 15]. During this time, private companies and entrepreneurs started experimenting with manufacturing and assembly of CSP components. This work eventually formed the seed for a Chinese CSP innovation system, with a large variety of new entrants into the CSP industry and demonstrating their designs and products at small scales [12].

Finally, with almost 10 years of building foundations for CSP innovation and industry, in the National Energy Administration (NEA) started working together with CSTA and the *China Renewable Energy Engineering Institute* (CREEI), a subsidiary of PowerChina, and the *China Electric Power Planning & Engineering Institute* (EPPEI), a subsidiary of CEEC [9], to develop a commercial-scale CSP demonstration program [16, 17].

The 2015 Demonstration Program for CSP in China in the 13th Five-year Plan

The successful pilot plants fueled optimism that large-scale CSP development was achievable in China [3] and a goal of 5 GW CSP by 2020 was set for the 13th five-year plan [4]. To reach this goal, the NEA implemented the commercial-scale CSP demonstration program in 2015. It announced support for a batch of twenty CSP stations totaling 1.35 GW, to be completed by 31st December 2018 at a rate of 1.15 yuan/kWh ($170/MWh). This would have amounted to about 25% of the existing global CSP capacity at the time [18]. At least one further batch of projects were planned to follow later. The demonstration program had two main objectives [19]:

- Continue building the industrial base for CSP in China, i.e., expand and strengthen the supply chain and intellectual property for CSP-specific components and equipment and prove it in commercial-scale projects of 50 MW or larger.
- Train "system integrators", i.e., engineers able to develop and execute CSP plants in China and abroad.

To further this goal the program aimed at opening the program to a large variety of developers, technologies and regions [20]. China is not known to have particularly good solar resource, although some regions offer decent irradiance, albeit at high altitudes in some cases [6]. The five provinces of Gansu, Hebei, Inner Mongolia, Qinghai, and the Xinjiang Uygur Autonomous Region were chosen to host the demonstration projects.

TABLE 1. CSP plants planned for the first batch of the demonstration program for CSP in China [21, 22]

CSP technology	Planned projects	Planned capacity	Heat Transfer fluid (number of projects)	Novel technologies (number of projects)
Solar tower	8	645 MW	Molten salt (6), steam (2)	-
Parabolic trough	7	464 MW	Thermal oil (5), molten salt (2)	Silicon oil (1)
Fresnel	4	200 MW	Steam (2), Thermal oil (1), Molten salt (1)	Formulated concrete Storage (2)
Beam-down tower	1	50 MW	Molten salt (1)	First in the world
Sum	20	1,359 MW		

Along with aim of supporting actor diversity, every project was developed by a different company – nine state-owned and eleven private companies. Four CSP technology types were supported, with a focus on towers and parabolic trough, with both molten salt and steam (tower) or oil (trough) as heat transfer fluids. (see Table 1). Another policy scheme investigating the combination of different renewable power sources also enabled a commercial-scale CSP tower project [23]. However, the goals set in the five-year plan in the demonstration program for successfully developing, financing, and building commercial-scale CSP projects has proven to be harder than expected. Many of the projects have been delayed and the support policy including the deadline for connection was expanded multiple times and was at the time of writing moved to the end of 2021 [24].

METHOD

Approach

We built on the rich literature on clean innovation and the lens of technological innovation systems in particular [25]. We start from the observation that the Chinese CSP industry was unexperienced prior to 2006, but that commercial CSP projects were operational in other countries [1]. Thus, any Chinese CSP technology or components needed to be developed and demonstrated to achieve similar performance as comparable foreign plants at commercial scale. Such catching-up and rapid knowledge-driven technology development been shown to be difficult [26]. Yet, building a home market of commercial-scale plants is one key step towards business in foreign markets, although success is not guaranteed [27]. Here we use a simplified analytical perspective and view the creation of a domestic commercial-scale CSP market as a necessary step towards competitive CSP projects relying on Chinese technology and components built by a Chinese company in a foreign energy market. Three conditions need to come together:

1. Intellectual property of the specific CSP technology needs to be developed by Chinese academia and industry stakeholders.
2. Theoretical knowledge needs to be demonstrated in a commercial-scale real-world project.
3. An experienced international project developer capable of bringing that technology to other markets.

For the creation of a CSP market and thus the successful technical demonstration of a commercial-scale project, finance and policy support must be designed to allow not yet demonstrated (and thus risky) technologies or designs to be financed and built in a protected environment. In other words, the policy must create a niche in which the technology and the related industry can grow, away from the pressures of the general market [28]. This is true for all yet immature technologies, and certainly for CSP: no commercial-scale project has been realized without policy support [2]. Therefore, we focus on the plants supported by dedicated policies in China, especially by the 2016 demonstration program and analyze on a project-by-project basis, which technological routes have been realized, and which have not, and if they used Chinese intellectual property. Additionally, we systematically analyze non-Chinese CSP projects for Chinese participation.

Data

We base the analysis on the newly published OpenCSP dataset that bundles information from both the NREL/SolarPACES and the CSP.guru databases [18]. The dataset holds information on all commercial-scale (larger than 10 MW) CSP plants in operation or under construction on 1 January 2021; it also holds data on several smaller pilot and demonstration plants. Additionally, we consulted company websites and other public information to understand connections between companies. We show which company built which plant and cross check participation in pilot plants or other projects.

RESULTS

Demonstrated Capabilities of the Chinese CSP Industry

As of 1 January 2021, eight commercial-scale CSP plants were connected to the grid in China. With a total capacity of 500 MW, they correspond to about 8% of the global CSP capacity. More than half of this fleet, 300 MW in five projects, use molten-salt tower technology, two projects employ parabolic trough designs, and one linear Fresnel. Additionally, 200 MW consisting of one beam-down tower power station, a molten-salt tower and a parabolic trough project were under construction. Overall, about half of the demonstration projects were successful (see Table 2). One reasons why many projects failed is that the promised remuneration was only granted to project coming online before the end of 2018, and although the support was extended in principle, the remuneration of projects that did not meet the 2018 deadline still remains unclear [29] amid a general renewable energy subsidy backlog [30, 31].

Abroad, Chinese EPCs successfully completed two projects in Morocco (Noor II a 200-MW trough and Noor III a 150-MW molten-salt tower) and are leading the 950 MW *Noor Energy 1* project, including 600 MW in parabolic troughs and a 100-MW molten-salt tower, under construction in Dubai working with state-of-the-art international parabolic trough (provided by Abengoa) and molten-salt tower (by BrightSource) technology. All three projects have been developed by Saudi Arabian ACWA Power. However, to our knowledge, none of the solar-specific CSP components, especially the receivers or solar collectors in any foreign project has to date been designed by Chinese companies.

TABLE 2. Demonstrated abilities of the Chinese CSP industry at the end of the 13th Five-year plan.

CSP technology	**Installed capacity at the end of 2020**	**Completed of planned demonstra-tion projects**	**Chinese Proprietary Technology for the CSP-specific components**	**Heat-transfer fluid used in completed projects**	**Under construction domestically (number)**	**Foreign projects involving Chinese EPCs (under construction)**
Solar Tower	300 MW	5 of 9*	4 of 5	Molten salt (5)	100 MW (1)	1 (1)
Parabolic Trough	150 MW	2 of 7	0 of 2	Thermal oil (2)	50 MW (1)	1 (1)
Linear Fresnel	50 MW	1 of 4	1 of 1	Molten salt (1)	0	None
Beam-down Tower	0	0 of 1	1 of 1**	Molten salt (1)	50 MW (1)	None
Sum	500 MW	8 of 20+1*	5		200 MW	2 (1)

* the successful LuNeng Haixi project was supported by another policy schema for "*Complementary multi-energy demonstration projects*", ***including project that are under construction in January 2021.*

Solar Tower

All three conditions for successful commercialization are met by the molten-salt solar tower value chain. This is by far the most successful CSP segment in China: more than half of all completed projects are molten-salt towers. The three companies Supcon, NWEPDI and Shouhang have together with some foreign partners designed all five successful commercial-scale and several pilot towers in China. Also abroad, Chinese EPCs Shandong Electric Power Construction Corporation III (SEPCO III, a subsidiary of PowerChina) and Shanghai Electric have been involved in the two tower projects in Noor III in Morocco and Noor Energy 1 in Dubai, both developed by Saudi Arabian ACWA Power. Further, NWEPDI has been working with ACWA Power and experienced Spanish CSP engineering company Empresarios Agrupados International (EAI) [32] and with Brightsource Energy on the overall design optimization of the tower at Noor Energy 1 [33]. In early 2020, CEEC the parent company of NWEPDI has bought EAI thus adding additional international CSP engineering experience to its portfolio [34].

Four of the tower projects have not been realized as originally planned. Especially, none of the originally planned two direct-steam towers was realized. After experimentation in the demonstration towers the technical route seems to have disappeared. One potential explanation could be the smaller potential for energy storage in this technological route. The other two molten-salt tower projects that did not break ground were co-developed by large power companies in cooperation with NWEPDI (CEEC) and SunCan (Shouhang). They would, judging from these participants, likely have used similar technology than the successful molten-salt tower plants, so the reasons for their failure are likely not related to the technology. In 2018, 2019 and 2020 the four unsuccessful tower projects were taken up by Shouhang, NWEPDI (CEEC), Power China and Supcon with the intention of connecting them to the grid by the end of 2021 [5]. However, only one of these is reported to be under construction in early 2021:a100-MW tower project in Yumen developed by Shouhang with engineering from NWEPDI [35].

Parabolic Trough

For parabolic trough projects, we find that there were domestic and international projects involving Chinese companies, but that Chinese technology development is lagging expectations. Only two out of the seven projects planned in the first batch of the demonstration program have been successfully commissioned by the end of 2020. The two plants were developed by state-owned companies, China General Nuclear Power Group (CGN) in one case and China Shipbuilding New Power (CSNP) together with Royal Tech CSP in the other and show strong inclusion of European companies. In fact, the Eurotrough-150 design using thermal-oil as the heat transfer fluid – which had both been widely used in the Spanish CSP expansion between 2006 and 2013 – was used and Spanish consulting firms helped to optimize the design to the high-altitude conditions of Northwestern China [36]. Royal Tech CSP had already in 2016 focused on the manufacturing of European trough designs by setting up a Eurotrough-150 loop licensed from German SBP [37] and developed receiver tubes that work with them. Chinese companies were involved in all stages of project development and most components including proprietary Chinese receiver tubes for one of the projects were sourced from the Chinese industry allowing for capacity building and provide suppliers with references for international projects. Moreover, one distinction from Spanish troughs is remarkable: both stations differ from European stations by including large molten-salt storage of 9 and 10 hours, respectively, in both completed plants that have been constructed and engineered by Chinese companies. This is another component that could be very interesting for international projects. Abroad, similarly to the tower segment, Chinese companies are involved in two parabolic trough plants as EPC's: Sepco III, which is a subsidiary of Power China, was part of the consortium delivering Noor II in Morocco, whereas Shanghai Electric is EPC for the through part of Noor Energy 1 in Dubai, which uses Abengoa's most recent design, the E2 trough.

There is thus no proven application of Chinese IP of the parabolic trough collector technology developed in test loops. Chinese EPCs and even though they may well have supported the plant optimization and the operators training. Hence, other than in the tower segment, the experimentation phase did not yet sufficiently support the build-up of proven Chinese IP in parabolic trough collector technology and additional demonstration will be needed. The same is true for the technological routes of the other demonstration projects proposing to use alternate heat-transfer fluids especially molten-salt parabolic troughs, and troughs using novel silicon oil solutions. At the beginning of 2021, a third parabolic trough project aiming to champion molten-salt troughs has solved its financing problems and resumed construction and is going to use a Chinese trough design [38].

Linear Fresnel and Beam-down tower

Apart from the two worldwide most widely applied CSP technologies parabolic trough and solar towers, two other designs were part of the demonstration program, neither of which has been built by Chinse firms abroad. Of the four planned Fresnel plants only one was commissioned at the end of 2020. The plant is remarkable in employing molten salt as its heat transfer fluid and involved NWEPDI and Southwest Electric Power Design Institute (SWEPDI), another CEEC subsidiary, in the overall engineering [35]. An associated 10-MW demonstration project has been operating since 2016. Its EPC is a subsidiary of PowerChina and PowerChina has also provided the funding [39], thus there is an internationally experience EPC involved. Another 15-MW Fresnel pilot plant using formulated concrete for thermal-storage and has been operational since 2018, but no activity is reported for the other large demonstration projects.

Construction of a 50-MW plant using 15 beam-down towers has been ongoing for several years in the city of Yumen and three of these towers have been assembled. Nevertheless, progress with this novel approach is slow and finalization has been postponed to the end of 2022 [40]. Shanghai Electric, the EPC of the Dubai Noor 1 project, has bought BCP solar the company building the beam-down tower project [41].

DISCUSSION

Chinese CSP for the World?

We set out to answer the question which technological and project development capabilities the emerging Chinese CSP industry has demonstrated in the last 15 years. Our results show that Chinese companies have demonstrated technological capacity in the tower segment: today, five out of seven operating commercial-scale molten-salt towers with multi-hour storage are located in China, and Chinese EPCs were involvement with two out of four tower projects outside China (including two under construction, and one not operating). Chinese companies are at the global forefront of the solar tower segment and are beginning to step outside China. We thus expect that Chinese actors have the potential to play a central role in future molten-salt tower projects. For parabolic trough, Chinese companies have not demonstrated this capacity: the two completed projects rely on foreign intellectual property for critical CSP-specific components, although many of these components were manufactured by Chinese companies. Further, several international projects, using advanced non-Chinese component designs, have been successfully executed or are currently carried out by Chinese EPCs. In sum, this means that Chinese tower technology may be able to compete in international markets, whereas so far, the parabolic trough segment is likely to continue being dominated by European technology.

The link between the domestic demonstration program and international ambition is very strong. The successful domestic Chinese CSP projects show strong ties to CEEC and Power China, two large state-owned internationally active infrastructure conglomerates that have been involved in devising the demonstration program from the beginning. Subsidiaries of Power China have participated in EPC roles in international projects for tower and trough and domestically in tower both with foreign and domestic designs, trough, and Fresnel plants. Now, it has partnered with Shouhang to further bring its tower technology to the domestic and international markets [42]. CEEC through its design institutes (especially NWEPDI) has been instrumental in commercializing molten-salt (tower) technology in China [35] and has by adding international competence and hands-on experience in the overall engineering of the Noor Energy 1 project also maneuvered itself into a promising position in the overall world market. The successful participation in three international projects by Chinese EPCs is linked to the successful Saudi developer ACWA Power, active all over Africa and the Middle East. It is no surprise that the Silk Road fund, one major financing mechanism in the Belt and Road Initiative geared at bringing Chinese infrastructure projects abroad, has recently acquired a 49% share in ACWA's renewable energy business[43]. Going forward, it seems likely that Chinese CSP technology and components could play an increasing role in new foreign projects, with the Noor Energy 1 project already demonstrating Chinse capabilities.

Outlook: CSP in the 14th Five-year Plan and Chinese CSP Projects Abroad

At the beginning of 2021, the demonstration program has not seen a second batch, despite a large number of projects under development [44]. Except for projects from the first batch, no technology-specific national support for CSP projects will foreseeably be granted in the 14th five-year period on the national level [30]. Although the government recently increased its climate policy ambitions to become carbon neutral by 2060 [45], the share of renewable electricity is likely going to remain well below 30% in the next decade [46]. Thus, there will be little immediate need for further technologies to balance fluctuating renewables – in the 2030 horizon, that task can still be handled by the fossil fuel power fleet – it is thus unlikely that dispatchable solar power from CSP will continue growing in the absence of policy support. On the other hand, with the considerable planned expansion of the HVDC corridors [47], CSP and its inherent thermal energy storage can play an important role for providing power and utilizing the transmission capacity at night [48] and reducing the curtailment of fluctuating renewables. Grid operators and regions hosting the demonstration projects have indicated that they see CSP as a good solution [49, 50]. Hence, there appears to be a need for dispatchable renewables, such as CSP, in Chinese power system development plans, but the concrete measures to support deployment are missing – a barrier that CSP also faces in other power markets such as Europe [51].

Despite a lack of concrete measures valuing renewable dispatchability, some of the projects from the first demonstration batch remain active for example by changing developer or adapting the plans, including the technology to be used and three were reported to be under construction at the beginning of 2021 [35, 52, 53]. The beam-down tower project and the molten-salt trough project are progressing and could add further abilities in the future. The additional another molten-salt tower could contribute for bringing down cost. Moreover, several follow-up projects to the successful plants have been announced with the support of CSP host provinces and cities close to the power corridors potentially adding a medium-term pipeline in the GW-scale [54-56]. One characteristic of these new projects is that they focus on power storage and may include large capacities of fluctuating renewables along CSP in line with efforts to create a renewables with storage market in China [57-59]. This mirrors international interest in CSP hybridization and could be an asset in the future [48, 60-62].

For the remaining demonstration projects, there are no news on any activity. This corresponds to the global situation: in 2019 and2020, no additional CSP project has broken ground outside China [2]. With the abandonment of national support, China may be following in the footsteps of the US and Spain: after successfully building up CSP industries there, the support cancellation greatly diminished the CSP industries and only a handful of companies managed to step out onto the global market and survive there [2]. Indeed, with their commitment to financing and building the Noor Energy 1 project, Chinese companies have shown that they can play a decisive role in creating and enabling CSP projects in international markets [63]. The financial muscle and risk appetite of Chinese development banks as well as the long-term strategic visions of the Belt and Road initiative to export Chinese technology to African and Asian countries [11] could be instrumental in enabling further CSP markets, including in countries that have not seen any CSP projects before. Several project announcement show that PowerChina and CEEC are both actively developing CSP project abroad, for example in Zambia that has no CSP yet [64] and in Greece [65], where the Minos project includes CEEC as its EPC, Supcon Solar as its technology provider, and expects financing from several Chinese banks. If successful, it could thus feature all Chinese technology, equipment, and engineering[66] and be the first European CSP project in a long time. Chinese tower companies have also set up shop in Spain and if there are new CSP tenders, Chinese companies are likely to enter with projects of their own [67].

This development hints at an emerging competition between European and Chinese CSP companies. Our results suggest that this competition could be characterized by a technological split: while Chinese companies may be very competitive in molten-salt tower technology, the parabolic trough segment is likely to continue being dominated by European companies and their IP. Such competition, while possibly problematic for single companies, could be great news for the CSP sector: real competition between different companies and technologies could enable a virtuous cycle of further cost reduction in CSP technologies, improve the attractiveness of CSP in general, and thus expand the CSP market. For now, however, commercial-scale CSP projects continue to hinge on the emergence of any large market or policy scheme, anywhere in the world: without further support, both the Chinese and European companies, and hence CSP as a whole, will struggle.

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