Electricity generation costs of concentrated solar power technologies in China based on operational plants

Zhao Zhu, Da Zhang, Peggy Mischke and Xiliang Zhang

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Postal Address:
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 (USA)

Location:
Building E19, Room 411
400 Main Street, Cambridge

Access:
Tel: (617) 253-7492
Fax: (617) 253-9845
Email: ***globalchange@mit.edu***
Website: ***http://globalchange.mit.edu/***

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Zhao Zhu [a], Da Zhang [b, c, *], Peggy Mischke [d], Xiliang Zhang [c]

[a] Corpus Christi College, University of Cambridge, UK
[b] MIT Joint Program on the Science and Policy of Global Change, United States
[c] Institute of Energy, Environment and Economy, Tsinghua University, China
[d] Energy Systems Analysis Group, Technical University of Denmark, Denmark

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ABSTRACT

Recent years witnessed a sharp increase of CSP (concentrated solar power) plants around the world. CSP is currently at its early stage in China, with several demonstration and utility-scale plants underway. China's rising electricity demand, the severe environmental pollution from coal-fired power plants, and favorable renewable energy policies are expected to result in a large-scale CSP deployment in the next years. Detailed CSP studies for China are however hardly available. To fill this knowledge gap, this study collects plant-specific data in a national CSP database in collaboration with local CSP experts. On this basis, this study analyzes and benchmarks the costs of parabolic trough CSP, tower CSP, and dish CSP technologies in China by applying an LCOE (levelized cost of electricity) model. The current LCOE for the different CSP plants falls in a range of 1.2–2.7 RMB/kWh (0.19–0.43 US$/kWh). Among the three CSP technology variants discussed, our sensitivity analysis indicates that the tower CSP variant might have the greatest potential in China. We expect a future cost reduction potential of more than 50% in 2020 and a high share of local content manufacturing for tower CSP.

1. Introduction

China's government is increasingly promoting the deployment of renewable energy technologies in order to cope with the country's rising electricity demand and the increasing air pollution and greenhouse gas emissions from fossil-fueled power plants. CSP (Concentrated solar power) plants are considered as one promising renewable-based electricity generation alternative. China's current Twelfth Five-Year Plan for Solar Energy, which was published by the NEA (National Energy Administration) in 2012, includes a 1 GW capacity target for national CSP installations by the end of 2015 [1]. Demonstration projects for all major CSP technologies have been set up in China's provinces and the commercialization of utility-scale CSP plants is starting.

Many studies have evaluated the technical and economic feasibility of different CSP technology variants in various countries worldwide. Electricity generation cost projections for CSP tower and parabolic trough plants in the United States were carried out by NREL (National Renewable Energy Laboratory), Sargent and Lundy Consulting and Sandia National Laboratories during 2003–2010 [12–14]. The IEA (International Energy Agency) released a CSP technology roadmap in 2010 [15]. The DLR (German Aerospace Center) issued a research report on the potential European technical innovations and research activities for CSP cost reduction in 2005 as part of the EU (European Union)-funded ECOSTAR (European Concentrated Solar Thermal Road-Mapping) project [16]. The electricity prices and potentials for CSP deployment in Australia [17] and Thailand [18] were also recently discussed in the scientific literature. The IRENA (International Renewable Energy Agency) published a global CSP analysis in 2012 [19], accounting for the most recent CSP research reports and consulting studies published since 2010 [20–24].

To the best of our knowledge, a country-wide technical, economic and financial assessment of different CSP technology variants in China is currently not available. A few plant-specific CSP studies for China were recently published. Li et al. [25] assessed the cost of CSP in China based on a hypothetical CSP parabolic trough plant in 2014. A more realistic study for a 50 MW utility-scale CSP parabolic trough plant in Inner Mongolia, China, was published by

* Corresponding author. Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, United States.
E-mail address: zhangda@mit.edu (D. Zhang).

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Abbreviations

ADB	Asian Development Bank
BIPV	building integrated photovoltaics
BNEF	Bloomberg New Energy Finance
CAS IEE	Chinese Academy of Sciences, Institute of Electrical Engineering
CDB	China Development Bank
CGNPG	China Guangdong Nuclear Power Group
CF	capacity factor
CSP	concentrated solar power
CSPPLAZA	a website of the solar thermal power industry, China
DLR	Deutsches Luft-und Raumfahrtzentrum, German Aerospace Center
DNI	direct normal insolation
ECOSTAR	European Concentrated Solar Thermal Roadmap
EIT	enterprise income tax
FIT	feed in tariff
ESTELA	European Solar Thermal Electricity Association
Gemasolar	a CSP tower plant in Spain
Golden Sun	a national solar photovoltaic program in China
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
IRR	internal rate of return
ISEGS	Ivanpah Solar Electric Generating System, a CSP plant in the United States
LCOE	levelized cost of electricity
NDRC	National Development and Reform Commission, China
NEA	National Energy Administration, China
NREL	National Renewable Energy Laboratory, USA
NPV	net present value
O&M	operation and maintenance
PS10	planta solar 10, a CSP tower plant in Spain
RMB	renminbi, Chinese currency, equivalent to Chinese Yuan
US$	US dollar, 2013 average exchange rate for RMB currency conversions
VAT	value added tax

the Clinton Foundation in 2013 [26]. A general CSP cost assessment for China is also available in the global IEA report on the projected costs of generating electricity of 2010 [27].

A more comprehensive assessment of CSP technology variants in China is critical for policy makers, energy researchers, and renewable energy industry experts. Therefore this study aims to analyze and benchmark for the first time three different CSP technologies under operation in China. As an expansion of previous studies, this study develops a new national database of seven operational CSP plants in China as of December 2014. First-hand plant-specific data were obtained amongst others through on-site investigations and interviews with local CSP plant operators and domestic energy sector experts. On this basis, this study aims to provide more targeted and detailed insights for future national CSP policies in China, such as a potential CSP-specific feed-in-tariff.

The remaining parts of this study are structured as follows: Section 2 gives an overview of the current deployment of CSP technologies globally and in China. Section 3 describes the methodology and underlying assumptions for the LCOE (levelized cost of electricity) calculations for CSP in China. Section 4 presents the results, including a national database for trough CSP, tower CSP, and dish CSP plants under operation and an LCOE range for CSP in China. Furthermore a sensitivity analysis is carried out to evaluate the future cost reduction potential for CSP. Section 5 concludes the paper and provides targeted CSP policy recommendations for China. Appendix A provides the equations of our LCOE model, and Appendix B lists detailed plant-specific economic and financial data.

2. Current status of CSP technology deployment

2.1. Global status of CSP technology deployment

By 2013 the global cumulative installed CSP capacity reached 3483 MW according to the NREL (US National Renewable Energy Laboratory) [2]. Fig. 1 shows the annual global thermal CSP capacity from 1985 to 2013. While the global CSP capacity remained below 450 MW until 2007, a rapid increase in CSP deployment has been taking place in recent years. From 2007 to 2013 the global average annual growth rate of CSP increased to about 139%. Fig. 2 shows the cumulative installed capacity of global CSP projects under construction in different countries in 2013, as compiled by the authors from NREL [2] and BNEF (Bloomberg New Energy Finance) [3]. BNEF (Bloomberg New Energy Finance) expects a significant deployment of CSP in the short-term future. Based on the current CSP plants under construction globally, the cumulative commissioned global CSP capacity will reach 6146 MW by the end of 2015. This would be equivalent to an almost doubling of the global CSP capacity in 2013 [3].

The cumulative installed CSP capacity in Spain reached 2368 MW in 2013, accounting for 68% of the global CSP capacity. Due to policy changes, no new CSP plants were under construction in Spain by the end of 2013. The parabolic trough CSP technology is the dominant CSP technology in Spain and accounted for about 93% of the country's cumulative installed capacity. Spain is also leading in the CSP tower technology. The first commercial CSP tower plant in Spain started power production in 2007 in Andalucía; it is called PS10 (planta solar 10). The Spanish Gemasolar plant followed in 2011, this CSP tower plant includes a molten salt heat storage system. It is currently the first CSP plant globally that combines a central power receiver with a molten salt heat storage.

Among the CSP plants under operation globally are different CSP technology variants and different project sizes, reaching from small-scale demonstration projects to large-scale utility projects. As shown in Fig. 2 above, the United States is currently leading with 1682 MW of CSP under construction, followed by India with 453 MW under construction. The United States started setting up commercial, utility scale CSP plants since the 1980s. The ISEGS (US Ivanpah Solar Electric Generating System) is currently the world's largest CSP plant. ISEGS has an installed capacity of 392 MW and was put into operation in early 2014 in the Mojave Desert in California [2].

Other countries that have operational utility scale CSP plants include India (104 MW), the United Arab Emirates (101 MW), Algeria (25 MW), Morocco (20 MW), Egypt (20 MW) and Iran (17 MW); all those are parabolic trough CSP plants [2,3].

2.2. Status of CSP technology deployment in China

By the end of 2013 the installed capacity of commercial CSP in China was about 50 MW, equivalent to one utility-scale CSP plant [2,3]. The Twelfth Five-Year Plan for Solar Energy includes a

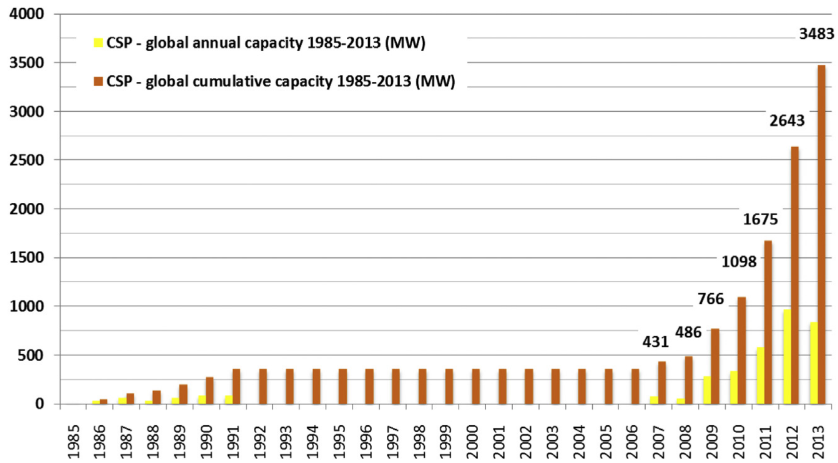

Fig. 1. Global CSP capacity from 1985 to 2013 – compiled by the authors from NREL [2] and BNEF [3].

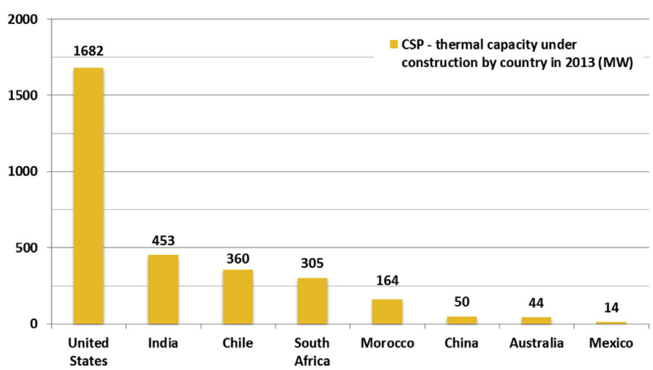

Fig. 2. CSP capacity under construction by country in 2013 – compiled by the authors from NREL [2] and BNEF [3].

planning target of 1 GW of CSP in China [1]. This might seem very ambitious in this context but might also indicate the commitment of the Chinese government to promote CSP in the short-term. No specific policies for CSP were enacted yet in China. Therefore this study mainly is based on renewable and solar PV (photovoltaic) policies currently enacted in China. Those policies are summarized in the following two paragraphs and are considered in our CSP cost calculations in Section 3.

Renewable energy technologies in China fall under the country's Renewable Energy Law enacted in 2005 [4]. In 2009 an amendment to this law was introduced to further specify the funding support and the obligations for the grid companies to purchase renewable energy [5]. In the same year, two national solar PV programs were started, the BIPV (building integrated photovoltaics) program and the Golden Sun program [6,7]. A national solar PV FIT (feed-in-tariff) of 1 RMB/kWh (about US$0.16/kWh) was implemented in 2011 and adjusted in 2013 to a FIT range between 0.9, 0.95 and 1 RMB/kWh depending on the solar radiation level in different locations in China. The current solar PV FIT will be in effect for 20 years [8].

Besides the solar PV FIT, a series of financial incentives have also been implemented by the CDB (China Development Bank) and the Ministry of Finance. The CDB has been offering preferential loans for solar PV installations under the Golden Sun Project. NEA in collaboration with CDB announced financial support for distributed solar PV electricity generation in China in August 2013, in particular a 5–10 % discount on interest rates for loan payments. The favorable solar PV loan term has been set at 15 years with an option for extension for another 3–5 years after project-specific evaluation [9]. One month later, the Ministry of Finance issued the Notice for VAT (Value Added Tax) of solar PV electricity generation which guaranteed a reduced VAT rate of 8.5% for solar PV in China, half of the normal VAT [10]. In addition the EIT (Enterprise Income Tax) Law of China entitles new renewable energy companies in China to receive a two-year EIT exemption for their first two profitable years followed by a three-year 50% reduced EIT rate of 12.5% [11].

3. Methodology: LCOE calculations for CSP technology variants in China

This study develops and applies an LCOE model to analyze and benchmark the electricity generation costs of different operational CSP plants in China. We first identify and classify all operational CSP plants in China as of December 2014 in a national CSP database. In the next step, a commonly financial model is set up to calculate the costs of generating electricity from the various CSP plants we identified. This is followed by a sensitivity analysis that discusses changes in future cost and technology aspects for CSP in China.

3.1. Identification and classification of operational CSP plants in China

CSP technologies are commonly classified in the following four technology variants: (i) parabolic trough CSP, (ii) tower CSP, (iii) dish CSP and (iv) Fresnel reflector CSP [28]. This study analyses and discusses the first three technology variants for China. Considering the relative small-scale application and lack of data for Fresnel reflector CSP plants, this study excludes this CSP technology variant. Since CSP just entered a demonstration phase in China, the plant-specific technical, financial and economic data are difficult to obtain from the literature. This study therefore uses on-site expert interviews to collect data for each operational CSP plant in China and to review those with available CSP data reported in the literature.

We develop and apply a project-specific code for each analyzed CSP plant in China to set up a new national CSP database. This code is constructed as follows: we first classify the plant operator, followed by the plant location and subsequently by the specific CSP technology variant. For example the code “CGNPG-Delingha-Parabolic plant” refers to a parabolic trough CSP plant that is operated by the CGNPG (China Guangdong Nuclear Power Group) in Delingha, Qinghai province.

3.2. LCOE (Levelized costs of electricity) model and underlying default assumptions

LCOE models are widely used to evaluate and compare the cost of energy resources. LCOE is commonly defined as “…the constant electricity price that would be required over the life of the plant to cover all operating expenses, payment of debt and accrued interest on initial project expenses, and the payment of an acceptable return to investors” [29]. IRENA used LCOE as an indicator to evaluate the global cost of CSP and compare CSP costs between countries [19]. Similarly the IEA frequently uses an LCOE model to compare fossil and renewable-based electricity generation costs among countries [28].

This study develops and applies a simple LCOE model to calculate the cost of electricity from different CSP plants in China, accounting for all lifetime costs adjusted for inflation and discounted. The LCOE result for each plant is equivalent to an NPV (net present value) of zero. The detailed equations for the developed LCOE model are provided in Appendix A. We use the following necessary economic, financial and technical default assumptions for key parameters in the LCOE model (see Table 1 and explanation below). To improve the accuracy and the reliability of the underlying LCOE calculations, this study includes only CSP projects in the LCOE calculations that are already operational and generating electricity as of December 2014.

3.2.1. Default assumptions of technical parameters

CSP technologies require large quantities of DNI (direct normal insolation) in order to produce electricity and be economically feasible. DNI is a site-specific resource parameter that varies in China. In Delingha, Erdos and Wuhai it is about 1800–2000 kW h/(m^2 year) and about 1900 kWh/(m^2 year) in Yanqing [37].

The average CF (capacity factor) is another key technical parameter to estimate the lifetime electricity generation of a CSP plant. Like DNI, the CF of a CSP plant varies by location. The 1 MW CAS IEE-Yanqing-Tower Plant has a capacity factor of about 0.22 [30–32]. The capacity factors obtained for the Datang-Erdos-Parabolic plant was about 0.32 and the one of the Supcon-Delingha-Tower plant was about 0.29. Those two CF are considered as unlikely to be achieved with the current CSP technology and DNI conditions in China, as the average capacity factor without storage of the ISEGS, a newly installed CSP plant in the US, is 0.3 under an annual solar radiation of 2600 kWh/(m^2 year). Therefore we chose to apply a more conservative capacity factor of 0.22 for all CSP plants in China.

3.2.2. Default assumptions of economic and financial parameters

As stated in Section 2, the economic and financial assessment of CSP will be based on the current solar PV policies in China. We expect in general that the financial expenses for renewable energy projects in China will decrease further in the coming years. With continuing support from the government, more commercial banks are expected to provide loans for renewable energy projects.

We consider that all CSP projects belong to large power companies with financially “strong” balance sheets, allowing for an investment share of 30% in the project's financial structure [38]. The interest rate and the term for loan payments assumed are 5.95% (10% discount rate) and 20 years. This is in line with the current 5-year interest rate set by the People's Bank of China of 6.55% and the 5–10% discounted interest rate for solar PV projects granted by the CDB [9]. We assume different taxes for CSP projects, as follows: With regards to the EIT, the “two-year exemption and three-year half exemption” is applied. The VAT (value-added tax) is set at 8.5%, equivalent to half of the normal VAT level (17%). The VAT paid during the purchase of relevant equipment can be deducted. The study also accounts for a 10% tax surcharge for city construction and education [10].

3.3. Sensitivity analysis to evaluate the future cost reduction potential for CSP

We first carry out two different sensitivity analyses to evaluate the impact of variations in key parameters on the future cost reduction potential for CSP in China, one in a short term perspective and one in a longer term perspective. The future cost reduction potential of the CSP technology variants in the short term assumes an increased average capacity factor and reduced total investment costs. Aligned with IRENA's CSP estimations [19], the short term goal is expected to be achieved by 2020. Then we evaluate the impact of a potentially important cost changer in the longer term: the availability and cost of thermal storage options. This is considered as a future cost reduction potential of mature CSP technology variants in China.

Additionally, the study analyzed the effect of other factors, such as location and financial conditions. The location-based solar performance would have a direct impact on DNI (Direct Normal Insolation) and thus change the capacity factor. Thus, the discussion of location is similar to the sensitivity analysis of the capacity factor in the short term and long term scenario. For a sensitivity analysis

Table 1
Summary of default assumptions of key CSP parameters in this study.

Key parameter	Unit	Default assumption	Reference to Annex A
Technical parameters			
• Capacity factor CF		0.22	Equation (3)
Economic and financial parameters			
• Debt to equity ratio		70/30	Equation (4)
• Interest rate	%	5.95	Equation (6)
• Lifetime	years	25	Equation (3)
• Enterprise income tax EIT	%	0% in the first two years; 12.5% in years 3–5; 25% afterward	Equation (10)
• Value added tax VAT	%	8.5	Equation (10)
• Surcharge tax	%	17	Equation (10)

Table 2
National database of CSP projects under construction and operation in China.

CSP projects in China	1. CAS IEE-Yanqing-Parabolic plant	2. CGNPG-Delingha-Parabolic plant	3. Datang-Erdos-Parabolic plant	4. CAS IEE-Yanqing-Tower plant	5. Supcon-Delingha-Tower plant	6. Sanhua Heli-Wuhai-Dish plant	7. Huaneng-Nanshan-Fresnel plant
General information							
Location, Province	Yanqing, Beijing	Delingha, Qinghai	Erdos, Inner Mongolia	Yanqing, Beijing	Delingha, Qinghai	Wuhai, Inner Mongolia	Nanshan, Hainan
Operator	CAS IEE	CGNPG	Datang	CAS IEE	Supcon	Sanhua Heli	Huaneng
Project status: construction phase	since July 2014	construction completed	since September 2013	construction completed	construction completed	since July 2012	construction completed
Project status: operational phase	expected in 2015	Since July 2014	expected in 2017	Since July 2013	Since July 2013		Since November 2012
Technical information							
CSP technology variant	Parabolic Trough	Parabolic Trough	Parabolic Trough	Tower	Tower	Dish	Fresnel
Installed thermal capacity (MW)	1	1	50	1	50	1	1.5
Project scale	demonstration project	demonstration project	utility-scale project	demonstration project	utility-scale project	demonstration project	demonstration project
Electricity generation (MWh/yr)			138,700	1950	130,000	2000	
Capacity factor			0.3167	0.2226	0.2968	0.2283	
Economic and financial information							
Economic life (years)			25	25	25	25	
Depreciable life (years)			10	10	10	10	
Equipment Costs (RMB/kW)			22422.4	27,160	14035.2	31,000	
Other costs (RMB/kW)			6697.6	10,000	5164.8	10,000	
Total investment cost (RMB/kW)			29,120	37,160	19,200	41,000	
O&M costs (RMB/kW)			104	492	150	492	
Data collection and references							
On-site interviews				X		X	
Press news	X	X			X		X
Research reports, consulting studies, academic literature			X				
References in this study	[41]	[46,47,50]	[26]	[30–32]	[44,45]	[35,36]	[43]

of the financial conditions, the study evaluates how the interest rate influences the future CSP costs.

4. Results

We present the results as follows. First we present the first national CSP database for China, which includes the technical, economic, and financial data we collected for the seven different constructed and operational CSP plants. We also map the locations of all discussed CSP plants in different provinces of China. Subsequently we present the results of the current LCOE for the different CSP technology variants in China under the discussed default assumptions. This is followed by a sensitivity analysis of key parameters that are impacting the future cost reduction potential for CSP in China.

4.1. National database of CSP plants in China

We identified, collected data, and subsequently analyzed data for seven CSP plants in China, which as of December 2014 have completed the construction phase (and therefore are currently operational and producing electricity) or have received full government approvals and are therefore under construction. All CSP data are summarized in the national CSP database (Table 2).

A project-specific summary for each of the seven analyzed CSP plant is given below, using the project classification code described in the methodology section before:

4.1.1. CAS IEE-Yanqing-Tower plant

The 1 MW CAS IEE-Yanqing-Tower plant in Beijing is the first CSP demonstration project in China. Its planning, approval and construction took about six years. The plant started generating electricity in 2012 and is fully operational as of July 2013 [39,40]. The CAS IEE (Institute of Electrical Engineering of the Chinese Academy of Sciences) developed the core tower CSP technology for this plant.

4.1.2. CAS IEE-Yanqing-Parabolic plant

The 1 MW Yanqing Parabolic Trough plant started construction in 2014. It is located near the CAS IEE-Yanqing-Tower plant in Beijing [41]. This demonstration project for parabolic CSP technology was supported by the Chinese 863 R&D project.

4.1.3. Sanhua Heli-Wuhai-Dish plant

The construction of the 1 MW Sanhua Heli-Wuhai-Dish plant, located in Wuhai, Inner Mongolia, was completed in October 2013 [42]. A new feature of this plant is the dish design from HelioFocus, which is different from the traditional stirling-dish. Sanhua Group ambitiously plans to increase the capacity of this plant from currently 1 MW to 200 MW for the second stage in the near future.

4.1.4. Huaneng-Nanshan-Fresnel plant

The 1.5 MW Huaneng-Nanshan-Fresnel plant located in Nanshan, Hainan Province, was put into operation in October 2012. We do not have further plant-specific information at this stage [43].

4.1.5. Supcon-Delingha-Tower plant

The Supcon-Delingha-Tower plant is the first commercial, utility-scale CSP plant in China. The construction of the first phase with a capacity of 10 MW was completed in January 2013 [44], followed by its grid connection in July 2013 [45]. It is located in Delingha, Qinghai Province, in western China and operated by Supcon.

4.1.6. Datang-Erdos-Parabolic plant

Datang Corporation made a 0.94 RMB/kWh bid for the concession of the parabolic trough plant in Erdos, Inner Mongolia, in 2010. According to our information, the construction is currently on hold and full operation is expected in 2017 [46,47].

Fig. 3 shows the locations of the seven CSP plants in China. Most of them are located in the in western and north-eastern regions of China, as the DNI in these areas can reach up to 2200–2300 kWh/(m^2 year) [48,49].

4.2. Current electricity generation costs for different CSP technology variants in China

Table 3 lists the current LCOE of four CSP projects in China with the default assumptions discussed in Section 3. We obtained sufficient data to carry out the LCOE calculation for four of the seven CSP plants. The current LCOE for the four different CSP plants falls in a range of 1.2–2.7 RMB/kWh (0.19–0.43 US$/kWh).

The 50 MW Supcon-Delingha-Tower plant achieved the lowest electricity generation costs in comparison with the other analyzed CSP projects. A major reason is the lower total investment and O&M costs per MW of capacity installed. Preferential government policies and regulations might have contributed to the favorable land, equipment and construction costs of this project.

Table 3
Current LCOE costs of different CSP projects in China.

CSP project	LCOE (RMB/kWh)	LCOE (US$/kWh)
3 Datang-Erdos-Parabolic plant	1.71	0.27
4 CAS IEE-Yanqing-Tower plant	2.51	0.40
5 Supcon-Delingha-Tower plant	1.19	0.19
6 Sanhua Heli-Wuhai-Dish plant	2.71	0.43

4.3. Future CSP costs and sensitivity analysis

The short-term best technology scenario assumes an increase in the capacity factor from 0.22 to 0.3 and an overall investment cost reduction of 20% for the Datang-Erdos-Parabolic plant and 50% for the CAS IEE-Yanqing-Tower plant and the Sanhua Heli-Wuhai-Dish plant. The higher average capacity factor applied is in line with the US ISEGS plant. The decrease of total investment costs are based on the economy of scale from a 1 MW demonstration plants to a 50 MW utility-scale commercial plants. A total investment cost reduction of as high as 67% might be possible under economy of scale when comparing the demonstration project of the CAS IEE-Yanqing-Tower Plant with the commercial project of Supcon-Delingha-Tower plant. The future LCOE in the “short-term best technology scenario” could decline to up to 0.87 RMB/kWh for the Supcon-Delingha-Tower plant; up to 1.03 RMB/kWh for the Datang-Erdos-Parabolic plant; up to 1.12 RMB/kWh for the CAS IEE-Yanqing-Tower plant and up to 1.19 RMB/kWh for the Sanhua Heli-Wuhai-Dish plant.

The “scenario of mature thermal storage” assumes a capacity factor increase to 0.6, slightly below the 0.75 capacity factor of the new Gemasolar plant in Spain. Here we define the long-term scenario by the technically and economically availability of thermal storage. The low cost end of the “mature thermal storage scenario”

Fig. 3. Locations of China's seven operational CSP projects.

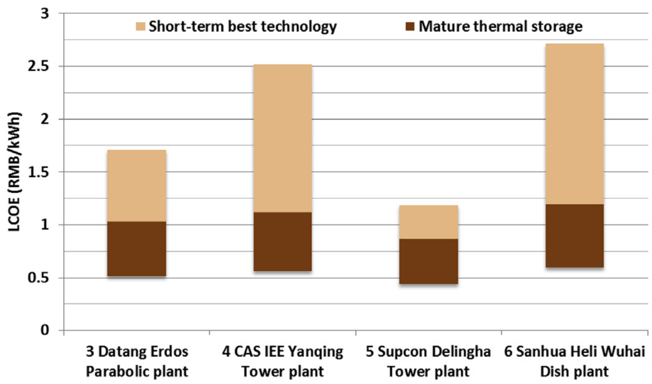

Fig. 4. Sensitivity analysis of Chinese CSP plants.

can be reached when the capacity factor increases to 0.6 on top of the same significant cost reduction as the one expected in the short-term scenario. The low overall investment costs assume the costs will not increase with the addition of the thermal storage. The future LCOE in the "scenario of mature thermal storage" could decline to up to 0.47 RMB/kWh (0.8 US$/kWh) for the Supcon-Delingha-Tower plant; up to 0.51 RMB/kWh for the Datang-Erdos-Parabolic plant; up to 0.56 RMB/kWh for the CAS IEE-Yanqing-Tower plant and up to 0.61 RMB/kWh for the Sanhua Heli-Wuhai-Dish plant.

Fig. 4 below shows the result ranges of our short-term and long-term sensitivity analysis for the four discussed CSP plants.

5. Discussion

5.1. Benchmarking of results for current LCOE costs

The LCOE of CSP varies significantly depending on the location, the size of the thermal storage and other project-specific factors. This study compares the calculated cost-ranges of current Chinese CSP projects with CSP cost studies in other countries [19–24] in Figs. 5 and 6[1]. The estimations are based on the CSP projects that have been commissioned or will come online in the near future in the United States, South Africa, Morocco, and India. The calculated electricity generation costs of the Datang-Erdos-Parabolic plant and the Supcon-Delingha-Tower plant in this study therefore fall in the range of IRENA's recent CSP projections for China. The main reason why the CAS IEE-Yanqing-Tower plant is much more expensive than other analyzed CSP plants is that this plant is still at the 1 MW demonstration stage.

The 50 MW Supcon-Delingha-Tower plant, in comparison, has gained cost advantage over other tower CSP projects. The calculated LCOE of the Supcon-Delingha-Tower plant is close to the FIT of 1.2 RMB/kWh the NDRC (National Development and Reform Commission) issued. A project-specific FIT (Feed-in Tariff) of 1.2 RMB/kWh (US$0.23 in 2013 US dollar) for 50 MW Supcon-Delingha-Tower plant was approved by the NDRC (National Development and Reform Commission) in August 2014 [51]. Though the national FIT of CSP will call for an evaluation of other demonstration projects, the approval of this project-specific FIT has already set a milestone for the CSP development in China.

[1] We use the 2010 USD for currency conversion.

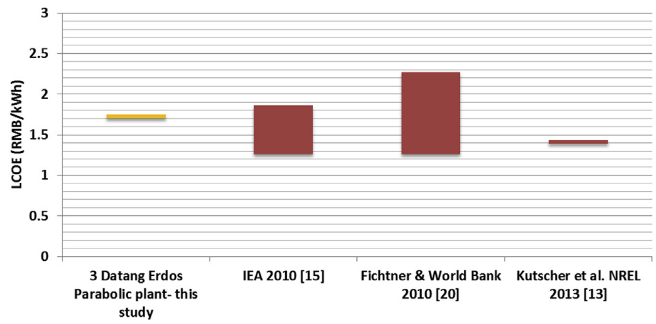

Fig. 5. LCOE benchmarking of parabolic trough CSP plants.

5.2. Drivers of future cost reduction for CSP in China

The CF is the key technical parameter that can be enhanced in the future, for instance by improved performance of receiver optics. Solar collector field, thermal storage system and the power block are the main drivers of total CSP investment costs in the short term. The reduction could occur with technological advancements, economic scaling and volume production. Comparing the demonstration project of the CAS IEE-Yanqing-Tower Plant with the commercial project of Supcon-Delingha-Tower plant, indicates that a total investment cost reduction of above 50% might be possible under economies of scale and a favorable investment conditions in China.

Presently thermal storage is still an expensive technology and most of commercial CSP plants choose to run either with short-term storage or be backed up with a natural gas power station. In the long-term thermal storage might become a future CSP standard, since continuous solar-base electricity generation with a thermal storage option is one of the main advantages that CSP has in comparison with the intermittent solar PV technology. The Gemasolar CSP Tower Plant in Spain is the first operational CSP plant with thermal storage globally. So far it reported a storage capacity of 15 h and a 24 days' non-stop power generation. The overall investment of this 20 MW CSP plant are quite high, about 230 million Euros [53].

There are currently no operational CSP plants with long-term thermal storage systems in China. Several new projects have however been announced recently. In April 2014 a 20 MW molten salt thermal storage system started construction in Jiangsu province, as announced by Jiangsu Sunhome New Energy Company [54]. In August 2014 a 1 million ton molten salt project

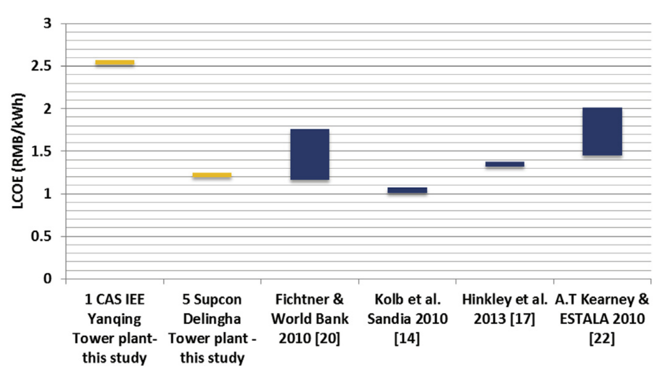

Fig. 6. LCOE benchmarking of tower CSP.

started the construction in Delingha [55]. The future impact of heat storage on LCOE for CSP in China is very uncertain and needs to be recalculated later when data from operational plants become available.

5.3. Future steps of research and limitations

Since all the CSP projects in China are very new, it is difficult to obtain a complete set of technical, economic and financial data for every CSP project. The key data of this study were therefore obtained by personal interviews with different local CSP experts. A few data were also obtained from industry-specific press news, such as CSPPLAZA, a major professional CSP industry website in China (in Chinese) and from previous studies, as discussed in the following paragraphs:

- For parabolic trough CSP technology many key parameters were unavailable for the 1 MW CAS IEE-Yanqing-Parabolic plant, as it only started operation in July 2014. As the Clinton Climate Initiative evaluated the CSP costs of the 50 MW Datang-Erdos-Parabolic plant in Erdos recently [26], we rely on this set of data for the missing parameters.
- For tower CSP technology, there are two major operational projects in China, the 1 MW CAS IEE-Yanqing-Tower Plant and the 50 MW Supcon-Delingha Tower plant. Detailed plant data [30–32] and system simulation data [33] were obtained for the CAS IEE-Yanqing-Power Plant. Data for the Supcon-Delingha-Tower plant were mainly obtained through press news and local CSP expert estimations.
- For dish CSP technology, the study is based on the 1 MW Sanhua Heli-Wuhai-Dish plant. Since the project has not been in full operation yet, the data obtained are partly from simulations [34]. Based on the on-site investigation [35] and the reference data from experts [36] in Sanhua, a specific simulation including dish collector, air receiver, heat exchanger and electricity generation was discussed and agreed upon.

A more precise CSP technology evaluation should be carried out in the future; once more operational data of these CSP plants or new CSP plants are available. Our results would also call for modification when CSP policies in China would change, as we base our results on the currently enacted solar PV and renewable energy policies.

6. Conclusion

Several new 100 MW parabolic trough CSP plants and 50 MW CSP tower plants are currently in the planning phase in China. The LCOE calculations for different CSP technology variants in different locations in China, as carried out in this study, will help to assess and compare the economic profitability of these new projects. Different from previous China-specific analysis that base on many assumptions and the data from other countries, this study assesses the economic feasibility of three CSP technology variants in China. A first benchmarking of CSP plants in China was carried out by calculating the LCOE of four typical CSP projects.

In comparison with CSP cost estimates in other countries, this study found that the utility-scale tower CSP plants in China have currently cost advantage over other CSP technology variants. The cost comparison between demonstration projects and the commercial projects reveals a huge potential of investment cost decline. Our sensitivity analysis on future LCOE for CSP in China indicates that tower CSP would be the short-term best CSP technology with the lowest LCOE of 0.87 RMB/kWh (0.14 US$/kWh). In the longer term tower CSP with mature thermal storage systems could achieve an LCOE decrease of up to 0.47 RMB/kWh (0.08 US$/kWh). This holds if we assume that the total investment costs would be managed well, that CSP technologies installed in China would be in line with the globally best available CSP technologies, and that China continues a favorable set of CSP investment conditions and regulations.

Based on our expert interviews, tower CSP might also be the most promosing CSP technology for China as a high share of local content manufacturing could be achieved. Marked by the successful construction and operation of the self-developed 1 MW CAS IEE-Yanqing-Tower Plant, Chinese CSP experts are confident that the core technology of tower CSP can be manufactured and managed locally. The 50 MW Supcon-Delingha-Tower plant shows the economic potential when the demonstration project is expanded to the commercial scale. However, currently no specific CSP policies have been enacted in China. The only exception is the project-specific FIT (feed-in tariff) of 1.2 RMB/kWh (US$0.23 in 2013 US dollar) for the 50 MW Supcon-Delingha-Tower plant, which was approved by the NDRC (National Development and Reform Commision) in August 2014. Therefore it is expected that national level FIT and financial incentives, such as preferential loans from the CDB (China Development Bank), will contribute to the economy scale of tower CSP and incentivize its deployment in the future.

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Appendix A. LCOE model [38].

Net Present Value (NPV)-based LCOE model

$$\mathrm{NPV} = \sum_{i=1}^{N} \mathrm{Cash}(i) \cdot (1 + \mathrm{IRR})^{-i} \tag{1}$$

where

NPV is the net cash value;
IRR is the internal rate of return, which is equal to the discount rate when the NPV is 0;
N is the total years of the project period;
Cash(i) is the cash flow in year i;

$$\mathrm{Cash(i)} = \mathrm{Revenue(i)} + \mathrm{Debt(i)} - \mathrm{CapitalCost(i)} - \mathrm{O\&}MCost\mathrm{(i)} - \mathrm{Loanpayment(i)} - \mathrm{Tax(i)} \tag{2}$$

Where $\mathrm{Revenue(i)} = \mathrm{Q(i)} \cdot \mathrm{P}$

P is the LCOE price, which is assumed fixed for the whole economic life;
Q(i) is the annual electricity generation;

$$\mathrm{Q(i)} = \begin{cases} 0, \mathrm{i} = 1, 2 \\ 8760 \cdot \mathrm{CF}, \mathrm{i} = 3 - 28 \end{cases} \tag{3}$$

$$\mathrm{Debt(i)} = \begin{cases} 0.7\ \mathrm{CapitalCost}, \mathrm{i} = 2 \\ 0, \mathrm{i} \neq 2 \end{cases} \tag{4}$$

$$\mathrm{CapitalCost(i)} = \begin{cases} 0.3\mathrm{CapitalCost}, \mathrm{i} = 1 \\ 0.7\mathrm{CapitalCost}, \mathrm{i} = 2 \\ 0, \mathrm{i} > 2 \end{cases} \tag{5}$$

$$\mathrm{Loanpayment(i)} = \frac{\mathrm{Debt(2)} \cdot \mathrm{r} \cdot (1+\mathrm{r})^{20}}{(1+\mathrm{r})^{20} - 1}, \mathrm{t} = 3 - 28, \mathrm{r} = 5.95\% \tag{6}$$

$$\mathrm{Principal(i-1)} = \begin{cases} \mathrm{Debt(2)}, \mathrm{i} = 3 \\ \mathrm{Principal(i-2)} \cdot (1+\mathrm{r}) - \mathrm{Loanpayment(i)}, \mathrm{i} = 4 - 28 \end{cases} \tag{13}$$

$$\mathrm{Tax(i)} = \mathrm{VAT(i)} + \mathrm{EIT(i)} + \mathrm{Surtax(i)} \tag{7}$$

where,

the value added tax in year i:

$$\mathrm{VAT(i)} = \frac{\mathrm{Revenue(i)} \cdot 0.17 \cdot 0.5}{1.17} \tag{8}$$

the tax surcharge in year i:

$$\mathrm{Surtax(i)} = 0.1 \cdot \mathrm{VAT(i)} \tag{9}$$

the enterprise income tax in year i:

$$\mathrm{EIT(i)} = \begin{cases} 0, \mathrm{i} = 1 - 4 \\ 0.125\mathrm{IBT(i)}, \mathrm{i} = 5 - 7 \\ 0.25\mathrm{IBT(i)}, \mathrm{i} \geq 8 \end{cases} \tag{10}$$

where

$$\mathrm{IBT(i)} = \mathrm{Revenue(i)} - \mathrm{InterestPayment(i)} - \mathrm{O\&}Mcost(i) - Depreciation(i) \tag{11}$$

where

$$\mathrm{InterestPayment(i)} = \mathrm{Principal(i-1)} \cdot \mathrm{r}, \mathrm{i} = 3 - 28 \tag{12}$$

$$\mathrm{Depreciation(i)} = \frac{\mathrm{CapitalCost}}{10}, \mathrm{i} = 3 - 13 \tag{14}$$

We use the straight-line method to calculate the depreciation. The useful economic life is assumed to be 25 years.

Appendix B. Detailed costs of major CSP projects

Costs (1000 RMB)	Datang-Erdos-parabolic plant	CAS IEE-Yanqing-Tower plant	Supcon-Delingha-Tower plant[a]	Sanhua Heli-Wuhai-Dish plant
Equipment costs	1,121,120	27,160	701,760	31,000
Solar collection system	728,000	20,000		20,000
Thermal storage system	160,160	1810		
Heat collection system	160,160	1850		8000
Power block	72,800	3500		3000
Other costs	334,880	10,000	258,240	10,000
Control system	72,800	1500		C
Land	58,240	500		500
Construction	43,680	5000		5000
Other services and management	160,160	3000		3000
Total investment cost	1,456,000	37,160	960,000	41,000
Labor	2700	720	2700	720
Materials	10,000	200	10,000	200
Unpredictable costs	1800	40	1800	40
Overall O&M costs	14,500	960	14,500	960
References	[26,4]	[30–32]	[45]	[49–51]

[a] Total investment cost of Supcon-Delingha-Tower plant is acquired online. Equipment costs and other costs are calculated by the reference of the 1 MW Yanqing Tower Plant.

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