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LCOE analysis of tower CSP plants using different molten salts for TES in China

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Abstract. In recent years, Chinese government is vigorously developing concentrating solar power (CSP) technology. It is one of the most promising renewable-based electricity generation technologies to deal with the increasing demand of electricity consumption and environmental sustainability. For the commercialization of CSP technology, low cost is a precondition. However, studies of electricity generation cost analysis for CSP systems, particularly for the tower systems, in China are quite limited. This paper conducts an economic analysis by applying the levelized cost of electricity (LCOE) model for 100 MW tower CSP plants in various locations in China with four different molten salts for thermal energy storage (TES). The results show that it's inappropriate to build a CSP plant nearby Shenzhen and Shanghai since their LCOEs are higher than 6 RMB kWh⁻¹. There is an optimal capacity of TES resulting in the lowest LCOE for a certain tower CSP plant. And the solar salt has lower LCOE than the other three new molten salts. In order to calculate the time when the grid parity will be reached, four scenarios for CSP development roadmap proposed by International Energy Agency (IEA) are considered in this study. It can be found that the grid parity of tower CSP electricity would be reached in the years of 2038-2041 in the case of no future penalties for the CO₂ emissions, and bring forward about 7-14 years when considering the penalties for the CO₂ emissions. This research can provide support for government to formulate incentive policies for the CSP industry.

Keywords: concentrating solar power (CSP); levelized cost of electricity (LCOE); China; molten salt; tower system

1. Introduction

Concentrating solar power (CSP) technology is one of the most promising renewable-based electricity generation technologies to deal with the increasing demand of electricity consumption and environmental sustainability. It can generate renewable electricity from direct sunlight and produce nearly none of greenhouse gas emissions. In addition, comparing to photovoltaic (PV) solar energy, the CSP systems can delay electricity generation in low or non-solar times by using thermal energy storage (TES). In recent years, Chinese government is vigorously developing CSP technology. The development of CSP in China has increased at a greater rate starting in 2013 [1] and the installed capacity is about 29.3 MWe by the end of 2017 with an increasing rate of 3.53% over 2016 which is higher than the global increasing rate (2.3%) [2]. Moreover, power tower technology is one of the most common technologies of CSP which can achieve higher operating temperature compared to parabolic trough and linear Fresnel technologies. It can yield greater efficiency of thermal-to-electric conversion in the power block and result in lower costs for storage [1].

For the commercialization of CSP technology, low cost of the electricity generation is a precondition. The electricity generation cost of CSP systems in China is approximately triple in comparison with the current grid [3-6]. As a key indicator to evaluate the economic feasibility of CSP systems, the analysis of the electricity generation cost is crucial and affects the development of the CSP generation industry



[7,8]. However, current researches [6,9,10] of electricity generation cost analysis for CSP systems, particularly for the tower systems, in China are quite limited. In addition, considering that no specific policies for CSP industry have been enacted yet in China [6], more data should be put forward for policy makers. Thus, this paper conducts an economic analysis by applying a levelized cost of electricity (LCOE) model for 100 MW tower CSP plants in China with four different molten salts for TES. In view of the geographic conditions, five locations are selected, including Huizhou near Shenzhen, Taicang near Shanghai, Yanqing in Beijing, Linxi in Inner Mongolia and Delingha in Qinghai. Four of them are situated at the eastern of China where the demand of electricity is relative high and near cities with good transportation and sufficient water resource. In order to analyse the economic feasibility of tower CSP plants built at the eastern of China, particularly near the first-tier cities of China, the site of Delingha is taken as reference in this paper, which has annual direct normal irradiance (DNI) near the bottom threshold ($2000 \text{ kWh m}^{-2} \text{ year}^{-1}$) for installing any form of CSP systems to achieve a reasonable economic performance [11]. Then, the calculations of both the present (2017) value of LCOE and its future evolution for the period (2018–2050) under four scenarios proposed by the International Energy Agency (IEA) (i.e. Blue Map [12], Global Outlook Advanced [13], Global Outlook Moderate [12], and Roadmap [14]) are presented. Moreover, this paper also estimates the time when CSP grid parities will be attained.

2. LCOE model for CSP systems

The LCOE is one of the most frequently used models to evaluate the electricity generation technologies which calculates the cost of solar electricity during the whole lifetime of the systems and takes into account the time value of money and the risks. It's equal to the sum of all the discounted costs incurring during the lifetime of the project divided by the units of discounted energy produced over the entire lifetime [15] and can be expressed as follows:

$$LCOE_t = \frac{C_t + L + \sum_{n=1}^N [(V + I)C_t(1+r)^{-n}]}{\sum_{n=1}^N [S \cdot TF \cdot \eta(1-DR)^n(1+r)^{-n}]} \quad (1)$$

where each variables in the equation are summarized on Table 1.

Table 1. Parameters and their values of the LCOE model.

Symbol	Description	Value	Units
$LCOE_t$	Levelized cost of energy of a tower CSP system installed in the year t between 2017 and 2050	Calculated by Eq. (1)	RMB kWh ⁻¹
C_t	Total cost of the system installed in the year t between 2017 and 2050	Calculated by Eq. (2)	RMB W ⁻¹
L	Land cost	On Table 2	RMB W ⁻¹
V	Operation-maintenance cost	2 [5,16,17]	%
I	Insurance cost	0.5 [18]	%
S	Solar resource (DNI)	On Table 2	kWh m ⁻² year ⁻¹
TF	Tracking factor	100 [16]	%
η	Performance factor	Calculated by SAM	m ² W ⁻¹
DR	Degradation rate	0.2 [19]	%
r	Discount rate	10 [17]	%
N	Lifetime of the system	30 [13,16,17]	years

The total cost of the system installed in a certain year, C_t , can be described as a function of the global cumulative installed capacity expressed as follows [5]:

$$C_t = C_0 \left(\frac{Q_t}{Q_0} \right)^{\frac{\log(1-LR)}{\log 2}} \quad (2)$$

where Q_t is the cumulative installed capacity in a certain year; Q_0 is the cumulative installed capacity in the reference year; LR is the learning rate; C_0 is the total cost of the system installed in the reference year. In this paper, the year of 2017 has been taken as the reference year, and the system cost of the

LCOE present value is only determined by C_0 which is calculated by System Advisor Model (SAM) of NREL [20] in this paper. Besides, its future evolution also relates to the future cumulative installed capacity and the learning rate. The learning rate is used a conservative estimation of 10% recommended by IEA [12,17]. According to CSPPLAZA (a major professional CSP industry website in China), the global cumulative installed capacity by the end of 2017 is reported to be 5.133 GW [2] which is Q_0 in this paper. In order to evaluate the future cumulative installed capacity during the years of 2018-2050, the functions proposed by Li et al. [10] that best fit the objectives of cumulative installed capacity for those four CSP development roadmap scenarios proposed by IEA are used in this paper.

3. Results and discussion

On the basis of the LCOE model described above, the economic analysis of 100 MW tower CSP plants in five locations in China with four different molten salts for TES are estimated in this paper. As a reference, a 100 MW project using solar salt (60% NaNO_3 + 40% KNO_3) with 6 h TES in Delingha is selected in this paper. When assessing the effect of one factor, the other factors are used the same as the reference case. Furthermore, unless otherwise stated, the values for the input parameters of Eq. (1) are used as specified on Table 1.

Table 2. Initial costs and LOCE present values for different locations in China.

Location	DNI ($\text{kWh m}^{-2} \text{ year}^{-1}$)	System cost (RMB W^{-1})	Land cost (RMB W^{-1})	LCOE (RMB kWh^{-1})	Capacity factor (%)
Huizhou	795.7	31.48	18.3	9.28	7.6
Taichang	762.9	31.45	13.97	8.49	7.7
Yanqing	1189.9	31.38	4.05	3.5	15.1
Linxi	1668.1	31.24	4.75	2.33	23
Delingha	2080.5	30.6	1.31	1.45	33.3

Table 2 shows the initial costs and LOCE present values for different locations under reference conditions. Since DNI is the most important energy input data for CSP systems, the specific DNIs for those locations are calculated by the method based on the air mass [21]. It can be seen that the initial costs of Huizhou and Taichang are much higher than that of Delingha which makes the LCOE higher. In addition, the influence of land cost on the LCOE is illustrated in Figure 1. The x-coordinate means the reduction percentage of the initial land cost for each location. It can be found that the land cost affects the LCOE significantly for Huizhou and Taichang as their land costs accounts for 38.8% and 30.8% of the total initial costs. Furthermore, even though their land costs are excluded from the capital cost, the LCOEs would be still higher than 6 RMB kWh^{-1} . It's mainly because their DNIs are less than 800 $\text{kWh m}^{-2} \text{ year}^{-1}$ which makes the capacity factor lower and system cost higher. Thus, it's inappropriate to build a tower CSP plant nearby Shenzhen and Shanghai. It can be also observed from Figure 1 that the land cost has slight influence on the LOCE when it is low such as in Yanqing, Linxi and Delingha. As Yanqing is the location of the pilot project for CSP plants in Beijing, the land cost is relatively low. The LCOE of Linxi has the lowest price of 2.33 RMB kWh^{-1} because of the highest DNI among the selected locations at the eastern of China. So the main factor resulting in low LCOE for different locations is the high DNI, due to more energy produced which increases the capacity factor of a plant and entails to an efficient TES.

TES is an important feature of CSP systems which makes for continuous electricity generation for solar energy. In this paper, four molten salts are selected to estimate the LCOE for tower CSP systems under reference conditions. These salts show the potential to be used in commercial CSP plants and have excellent thermodynamic properties which have been indicated in previous studies [22-26]. Their thermal properties and TES costs are displayed on Table 3. It can be seen that the chloride salt (8.1% NaCl + 31.3% KCl + 60.6% ZnCl_2) has the lowest TES cost due to the lowest salt price and largest density. And the TES costs of the fluoride salt (29.3% LiF + 11.7% NaF + 59% KF) and carbonate salt (32.1% Li_2CO_3 + 33.4% Na_2CO_3 + 34.5% K_2CO_3) are much higher since their salt prices are more than three times of the solar salt and chloride salt.

As the value of performance factor is relevant to the amount of TES, Figure 2 presents the effect of TES capacity on the LCOE present value for those four salts. It can be found that the chloride salt with

the lowest performance factor has the highest LCOE when the CSP systems have no TES. Since a higher amount of TES improves the performance factor of CSP systems which has been confirmed by other studies [27,28], the LCOE of all molten salts decreases firstly as the capacity of TES increases. However, when the performance factor no longer improves with the increasing TES capacity, the LCOE goes up as the cost of the TES rises. Thus, there is an optimal capacity of TES resulting in the lowest LCOE for a certain tower CSP plant. The LCOE of the chloride salt reduces obviously at the lower range of TES capacity because of its lowest salt price. And the increasing of the LCOEs of the fluoride salt and carbonate salt become more distinct at the higher range of TES capacity due to their much higher costs of TES. The solar salt has the lowest LCOE among those four molten salts for different capacity of TES.

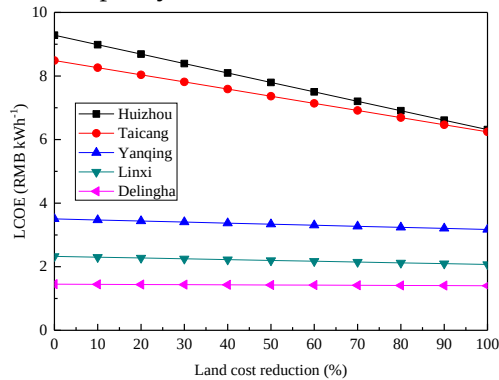


Figure 1. Effect of land cost on the LCOE for five different sites.

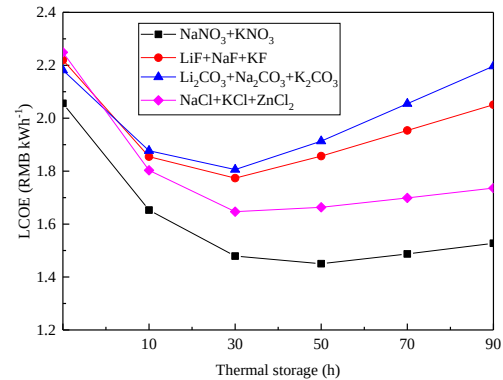


Figure 2. Influence of TES capacity on the LCOE for four different molten salts.

Table 3. Thermal properties and TES costs of selected molten salts.

Molten salt	NaNO ₃ , KNO ₃	LiF, NaF, KF	Li ₂ CO ₃ , Na ₂ CO ₃ , K ₂ CO ₃	NaCl, KCl, ZnCl ₂
Composition by wt.%	60, 40	29.3, 11.7, 59.0	32.1, 33.4, 34.5	8.1, 31.3, 60.6
Melting point (°C)	220	454	400	229
Thermal stability (°C)	600	850	715	850
Density (kg m ⁻³)	1708.4-1950.1	1851.6-2116.5	1959.7-2069.4	1946.2-2275.5
Heat capacity (kJ kg ⁻¹ K ⁻¹)	1.48-1.55	1.28-1.82	1.61	0.9-0.92
Viscosity (mPa s)	0.99-5.78	1.64-12.38	6.11-45.09	3.48-29.63
Thermal conductivity (W m ⁻¹ K ⁻¹)	0.33-0.40	0.05-0.27	0.45-0.49	0.30-0.38
Salt price (RMB kg ⁻¹)	5.80	16.66	15.02	4.68
TES cost (RMB kWh _t ⁻¹)	156.00	316.79	490.15	111.69

Figure 3 displays the future evolution of the LCOE between 2018 and 2050 for four scenarios under reference conditions. It can be deduced that the future cost of tower CSP electricity decreases as the increase of cumulative installed capacity during the period of 2018-2050. Moreover, the future LCOE in the Blue map scenario presents slower reductions than other three scenarios, particularly at the initial years, owing to the lower objectives. Then, the differences of the LCOE in 2050 for all scenarios become not very large. The LCOE of tower CSP systems are 0.72, 0.64, 0.70 and 0.67 RMB kWh⁻¹ in 2050 and represents 49.88%, 44.02%, 47.94% and 46.14% of its present value in 2017 for Blue map scenario, Global outlook advanced scenario, Global outlook moderate scenario and Roadmap scenario, respectively.

Figure 3 also illustrates the time when the electricity cost of tower CSP plants will reach the grid parity under reference conditions. Since more than three quarters of the electricity are generated in coal-fired power plants in China [17], the cost evolution of coal-fired electricity is used as the grid parity in this study. The cost of electricity produced by coal-fired power plants is 6.26 US cents kWh⁻¹ [29] which is only considered the production costs and would increase linearly in the future with an annual conservative growth rate of 2.7% [10]. In addition, considering the CO₂ emissions by the coal-fired power plants, the carbon emission prices of 25 \$ ton⁻¹ CO₂ [30] and 50 \$ ton⁻¹ CO₂ [11] are added to estimate the grid parities with an emission factor of 0.9 kg CO₂ kWh⁻¹ [17,31,32]. According to

Figure 3, the time when the grid parities of tower CSP systems would be achieved are summarized on Table 4. It can be observed that the cost of tower CSP electricity would reach the grid parity in the years of 2038-2041 in the case of no future penalties for the CO₂ emissions. And the grid parity would bring forward about 7-8 years for the carbon emission price of 25 \$ ton⁻¹ CO₂ and about 13-14 years for the carbon emission price of 50 \$ ton⁻¹ CO₂.

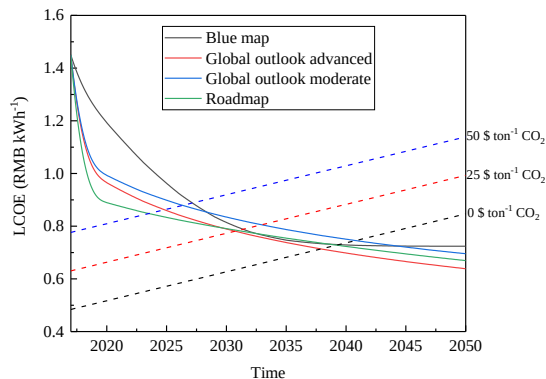


Figure 3. Future evolution of the LCOE for tower CSP systems for four scenarios and grid parities calculations.

Table 4. Time when the grid parities of tower CSP systems would be achieved.

Scenario	Time when LCOE equals to the grid parity		
	0 \$ ton ⁻¹ CO ₂	25 \$ ton ⁻¹ CO ₂	50 \$ ton ⁻¹ CO ₂
Blue map	2040	2032	2028
Global outlook advanced	2038	2031	2025
Global outlook moderate	2041	2033	2027
Roadmap	2040	2031	2024

4. Conclusion

In order to provide support for Chinese government to formulate incentive policies for the CSP industry, we have presented the economic analysis for 100 MW tower CSP plants in five locations in China with four molten salts for TES in this paper based on a model of LCOE. From the results found in this paper, we can summarize the following conclusions:

- (1) It's inappropriate to build a tower CSP plant nearby Shenzhen and Shanghai since even though their land costs are free, their LCOEs would be still higher than 6 RMB kWh⁻¹ mainly owing to the DNIs lower than 800 kWh m⁻² year⁻¹. When the land cost is low, it has slight influence on the LOCE. The main factor resulting in low LCOE for different locations is mainly the high DNI.
- (2) There is an optimal capacity of TES resulting in the lowest LCOE for a certain tower CSP plant as the performance factor firstly increases with the increasing TES capacity, and then no longer rises. The solar salt has the lowest LCOE among those four molten salts for different capacity of TES.
- (3) The cost of tower CSP electricity would reach the grid parity in the years of 2038-2041 in the case of no future penalties for the CO₂ emissions based on four scenarios for CSP development roadmap proposed by IEA. And the grid parity would bring forward about 7-8 years for the carbon emission price of 25 \$ ton⁻¹ CO₂ and about 13-14 years for the carbon emission price of 50 \$ ton⁻¹ CO₂.

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