Capacity Configuration of Hybrid CSP/PV Plant for Economical Application of Solar Energy*

Fei Li[1, 2], *Canbing Li*[3], *Kai Sun*[4*], *Jiamei Zhang*[2] *and Hua Li*[5]

(1. State Grid Henan Electric Power Company Economic Research Institute, Zhengzhou 450000, China;
2. College of Electrical and Information Engineering, Hunan University, Changsha 410082, China;
3. Department of Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China;
4. State Key Lab of Control and Simulation of Power Systems and Generation Equipment, Tsinghua University, Beijing 100084, China;
5. Zhangjiakou Power Supply Company, Zhangjiakou 075000, China)

Abstract: Concentrating solar power (CSP) technology has received increasing attention in recent years because of its distinct advantage for dispatchable power generation from solar energy. However, owing to its highly levelized costs of electricity, CSP plants are less competitive than photovoltaic (PV) power plants. To overcome this drawback and suppress PV power fluctuations, the concept of a hybrid CSP/PV power plant is proposed and developed. A capacity configuration method based on filtering and checking is proposed to seek a relationship between the capacity configuration of a hybrid CSP/PV system and the cost of solar energy. Co-content hybrid systems with different ratios of CSP capacity and PV capacity are modeled, and their comprehensive performance is investigated. Simulations and comparisons with a standalone CSP system focused on annual energy generation, capacity factor, levelized cost of electricity, and possibility for loss of power supply show that the hybrid CSP/PV systems possess different features depending on their capacity configurations. The results indicate that the proposed method can supply a convenient and simple operation pattern that favors engineering utilization and extension.

Keywords: Concentrating solar power, photovoltaic, capacity configuration, levelized cost of electricity

1 Introduction

Transformation of existing electric power systems from fossil fuels to renewable energy sources is gaining momentum because electricity production accounts for approximately 29% of global greenhouse gas emissions [1-2]. With nearly three-quarters of electricity produced from coal-fired power stations [3], China has announced ambitious plans for reforming its energy structure in the coming decades [4]. Solar power-generation technology is a promising direction for development in China owing to the enormous solar potential in its northwest region [5-6].

Solar power technology includes both photovoltaic (PV) and solar thermal-power technologies, with the latter usually called concentrating solar power (CSP). This refers to a technology that uses mirrors or lenses to concentrate sunlight and then collects heat to generate electricity via steam turbines [6]. Compared to the intermittent and variable nature of PV power generation, a CSP system has the distinct advantage of delivering energy like a conventional and dispatchable power plant because of its internal thermal energy storage (TES) capacity [7]. Compared with battery energy storage, it has no degradation cost and can serve thermal demand, which are favorable characteristics in the construction of multi-energy systems [6-7]. In 2017, the global installed CSP capacity totaled 5 133 MW, an increase of 2.3% over 2016, according to statistics from the CSPPLAZA Research Center. China's installed CSP capacity increased by 1 MWe through projects such as Badaling's 1 MW parabolic trough project, which achieved a trial run in May 2017 [8].

However, one of the main obstacles to commercial application of CSP technology is the high levelized cost of electricity (LCOE) incurred by the huge capital investment in construction [9]. Hybrid

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* Corresponding Author, Email: sun-kai@mail.tsinghua.edu.cn

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CSP/PV power systems have been proposed by researchers in recent years to cope with this problem, and they are expected to combine the characteristics of dispatchable power generation and lower LCOE [10-15]. A pointed assessment of the integration of PV and CSP technologies in Chile has been provided using the modular structure of TRNSYS [11]. The possibility of maximizing the operation time of hybrid power systems in California has been introduced by combining a PV unit and a CSP of a certain storage capacity [12], and the daily operation time of a hybrid power system has been extended to 24 h in the excellent weather conditions of South Africa [13-14]. Nevertheless, others argue that the LCOE of a hybrid power system is related to the duration of daily operation and that a standalone PV system coupled with proper storage may be the most cost-effective solution when the daily operation period is less than 8 h [15]. Three pilot hybrid CSP/PV plants are under construction in Copiapó (Atacama Desert, Chile)[13], and another in Ottana (Sardinia, Italy) comprising a 600 kWe CSP plant and a 400 kWe PV plant [16-19].

The focus of this study is to establish a convenient and simple capacity configuration method to investigate the relationship between the capacity configuration of a hybrid CSP/PV system and its effectiveness based on actual engineering. The alternative scheme involves scanning with the proposed configuration scheme filter, and the co-content hybrid systems with different CSP capacity and PV capacity ratios are modeled by the system advisor model (SAM). An assessment framework comprising annual energy generation, capacity factor, LCOE, and the possibility for loss of power supply is established to evaluate the performance of these schemes.

This paper is organized as follows: Section 2 proposes the hybrid CSP/PV plant model method and control strategy. Section 3 illustrates the proposed capacity configuration method based on filtering and checking. Analyses and discussions of the simulation results are presented in Section 4. Finally, a summary of this paper and a conclusion are given in Section 5.

2 Hybrid CSP/PV plant configuration

2.1 Hybrid CSP/PV plant model

The hybrid CSP/PV plant discussed in this paper belongs to the class of medium-sized units, including a CSP system and a PV system. The two systems cooperate to maintain a continuous power supply to satisfy the load demand. The solar power plant was chosen as the CSP type in this paper, and it comprises four sections: heliostat field (HF), tower and receiver (T&R), TES, and power cycle (PC), with the respective functions of solar concentration, heat collection, thermal storage, and conversion of thermal energy to electrical energy, as shown in Fig. 1.

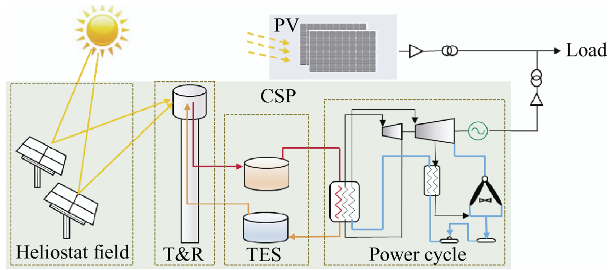


Fig. 1 Structure of the hybrid CSP/PV power plant

With the complex structure of a CSP model, only the key design parameters are listed in Tab. 1 [14, 20]. To compare the influence of different design parameters, the solar multiple (SM) and full load hours of storage (FLHS) range from 2.5 to 4.5 and from 10 to 20 [13-15], respectively. For each set of SM and FLHS, the CSP model optimizes the tower height, receiver height, and receiver diameter of the solar field automatically and determines the most suitable construction parameters, which are not listed here.

Tab. 1 Design parameters of CSP power tower plant

	Parameter	Value
Heliostat field	Design point DNI/(W/m^2)	900
	Solar multiple	2.5–4.5
Tower and receiver	HTF type	Salt (60% $NaNO_3$, 40% KNO_3)
	HTF hot/cold temperature/℃	570/290
Thermal storage	Full load hours of storage/h	10–20
Power cycle	Cycle thermal efficiency	0.4

It should be noted that both the standalone CSP plant and the CSP systems of hybrid power plants adopt the design parameters listed in Tab. 1.

The PV module and inverter of the PV model were chosen from the integrated components listed in Tab. 2[20], whose specific parameters are not listed here in detail. This model is used as the PV system of the hybrid CSP/PV power plant cooperating with the

CSP system to generate electricity. Owing to the controllable and dispatchable power-generation characteristics of the CSP model, the PV model in this paper was set with no energy-storage system, assuming that all energy-scheduling tasks are accomplished by the CSP model. Thus, the LCOE of the hybrid CSP/PV system is further reduced.

Tab. 2 Design parameters of PV power plant

Parameter	Value
PV module	Sunlan solar SLM245P
Inverter	Solar inverter RPI MSOA
DC-to-AC ratio	1.2
Tracking & orientation	2 Axis (ground coverage ratio=0.3)

2.2 The hybrid CSP/PV system control

As mentioned previously, the dispatch of power in the hybrid CSP/PV system entirely relies on the CSP section according to the load demand. When a PV system is producing electricity, the CSP system reduces or ceases electricity output, storing residual heat from the receiver in the TES. When the PV system fails to produce power at night, the PC of the CSP system generates electricity using the heat stored in the TES during the daytime. With coordination of the two systems, the hybrid power plant operates to maintain the desired output and tracks the daily load curves. Fig. 4 shows various output curves of hybrid CSP/PV systems, with different colors for different capacity configurations. Because of the undispatchable characteristic of PV, the output of the CSP system is adjusted to guarantee the demanded power.

The control strategy of the hybrid CSP/PV power plant is realized through the dispatch-control matrix in the PC section of the CSP system. It comprises nine periods and corresponding daily average turbine-output fractions. After calculating the power gap that the CSP system must fill, the production command is translated to the monthly output fractions in the PC section.

3 The proposed capacity configuration method

The production of commercialized large-capacity electricity facilities are standardized and produced by assembly line and thus do not provide accurate localized facility capacity [21-24]. Thus, a capacity configuration method based on filtering and checking is established in this paper.

3.1 The configuration scheme filter

Owing to the uncertainty of PV power generation, the rated power output of a hybrid system is determined by its CSP system, so the capacity of CSP systems must be higher than the base load [6-7]. Thus, the ratios of CSP/PV were set to at least 1 when the base load was set as 5 MW in the case of CSP systems under long-term overload operation. In addition, because of the high investment cost of a CSP system, its capacity cannot greatly exceed the capacity of PV power generation [7]. For large-capacity equipment, power generation is rounded to the nearest integer [23]. According to regularization, the alternative schemes can be filtered.

3.2 The selected configuration scheme checking

To evaluate the performance of power systems in three aspects, an assessment framework was constructed that includes the following four indices.

3.2.1 Productivity performance

The annual energy generation and capacity factor can reflect the productivity performance of power plants most intuitively.

(1) Annual energy generation.

The annual energy generation of a CSP/PV hybrid power plant is the sum of the energy generated by the PV and CSP systems.

(2) Capacity factor.

The capacity factor is used here to evaluate the availability levels for power plants, which are calculated as follows. For a PV power plant, the capacity factor is an AC-to-DC value, whereas for a CSP plant, the capacity is an AC-to-AC value

$$capacity\ \ factor = \frac{\text{Net Annual Energy}}{\text{System Capacity} \times 8\ 760} \tag{1}$$

3.2.2 Economic performance

The LCOE represents the total project lifecycle costs, comprising the investment expenses and operation costs over the lifetime of the plant, which is chosen to evaluate the economic performance of different power plants.

The following formula is used to calculate the *LCOE* for new projects in the year of installation [21].

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{el,t}}{(1+i)^t}} \tag{2}$$

where $LCOE$, defined above, is in cents (U.S.)/kWh; I_0 is the installed cost in cents (U.S.); A_t is the annual total cost; $M_{el,t}$ is the electricity output in year t in kWh; i is the interest rate (discount rate); n is the analysis period in years; and t is the year of operation $(1,2,\cdots,n)$.

(1) CSP

The total installed cost is the sum of all direct and indirect capital costs of the CSP plant

$$I_{0,CSP} = I_{direct,CSP} + I_{indirect,CSP} \tag{3}$$

The direct and indirect capital costs are

$$I_{direct,CSP} = (C_{HF} + C_{T\&R} + C_{TES} + C_{BOP} + C_{PC}) \times (1 + f_{conti}) \tag{4}$$

$$I_{indirect,CSP} = C_{land} + I_{direct,CSP} \times (f_{EPC} + f_{sale}) \tag{5}$$

where f_{conti}, f_{EPC}, and f_{sale} are factors to account for the expected uncertainties cost, engineering-procurement-construction cost, and total sales tax, respectively, and C_x are the specific plant costs that can be calculated using Tab. 3.

The annual total costs contain the fixed and variable operation costs and the costs for the projects, maintenance, and service replacements, which are calculated as

$$A_{t,CSP} = c_{cap,CSP} \times P_{rated,CSP} + c_{gen,CSP} \times M_{el,t,CSP} \tag{6}$$

where $P_{rated,CSP}$ is the turbine rated capacity, and $c_{cap,CSP}$ and $c_{gen,CSP}$ are the fixed cost by capacity and variable cost by generation of the CSP plant, respectively. The electricity output in year t is

$$M_{el,t,CSP} = M_{el,t-1,CSP} \times (1 - f_{degrad}) \tag{7}$$

where f_{degrad} is the degradation rate to describe the annual reduction in system output.

(2) PV

Similar to the CSP plant, the total installed cost is the sum of all direct and indirect capital costs of the PV plant

$$I_{0,PV} = I_{direct,PV} + I_{indirect,PV} \tag{8}$$

The direct and indirect capital costs are

$$I_{direct,PV} = (C_M + C_I + C_{BOS}) \times (1 + f_{conti}) \tag{9}$$

$$I_{indirect,PV} = C_{land} + I_{direct,PV} \times (f_{EPC} + f_{sale}) \tag{10}$$

where f_{conti}, f_{EPC}, and f_{sale} are the same as in the direct and indirect costs of the CSP plant, and C_x are the specific plant costs that can be calculated using Tab. 3.

The annual total costs of the PV plant are calculated as

$$A_{t,PV} = c_{cap,PV} \times P_{rated,PV} + c_{gen,PV} \times M_{el,t,PV} \tag{11}$$

where $P_{rated,PV}$ is the PV system's rated capacity, and $c_{cap,PV}$ and $c_{gen,PV}$ are the fixed cost by capacity and variable cost by generation of the PV plant, respectively. The electricity output in year t is

$$M_{el,t,PV} = M_{el,t-1,PV} \times (1 - f_{degrad}) \tag{12}$$

where f_{degrad} is the degradation rate.

(3) CSP/PV

Regarding the CSP/PV system, the LCOE formula used here is

$$LCOE_{CSP/PV} = \frac{\sum_{t=1}^{n} A_{el,t,PV} \times LCOE_{PV} + \sum_{t=1}^{n} A_{el,t,CSP} \times LCOE_{CSP}}{\sum_{t=1}^{n} A_{el,t,PV} + \sum_{t=1}^{n} A_{el,t,CSP}} \tag{13}$$

3.2.3 Power supply reliability

Although the CSP plant is a controllable system that can dispatch energy from TES to maintain continuous power generation, it is still possible that a fraction of the total annual electrical load is unserved, considering the limited TES capacity and extreme weather conditions. Thus, LPSP is used here to describe the power-supply reliability of power plants, and it is defined as the probability that an insufficient power supply results when the hybrid system is unable to satisfy the load demand and is calculated according to Ref. [22].

$$LPSP = \frac{\sum_{t=1}^{n} T_{un,t} (P_{available} < P_{demand})}{\sum_{t=1}^{n} T_{o,t}} \tag{14}$$

where $T_{un,t}$ ($P_{available}$<P_{demand}) and $T_{o,t}$ are the annual time under power failure when the available electricity is unable to satisfy the load demand and the total operation time in year t, respectively.

4 Simulation results and discussion

4.1 Financial parameter settings

Most performance and financial parameter settings in PV and CSP systems are listed in Tab. 3 [12, 14, 20].

Tab. 3 Parameter settings of PV and CSP systems

Parameter	Value
CSP system	
Heliostat field cost C_{HF}/(\$/m^2)	145
Tower and receiver cost $C_{T\&R}$/(\$/kWt)	200
Thermal storage cost C_{TES}/(\$/kWht)	24
Balance of plant cost C_{BOP}/(\$/kWe)	340
Power cycle cost C_{PC}/(\$/kWe)	1 100
Fixed cost by capacity $c_{cap,CSP}$/(\$/kW-yr)	66
Variable cost by generation $c_{gen,CSP}$/(\$/MWh)	3.5
PV system	
PV modules C_M /(\$/Wdc)	0.64
Inverters C_I /(\$/Wdc)	0.1
Balance of system equipment C_{BOS}/(\$/Wdc)	0.2
Fixed cost by capacity $c_{cap,PV}$ /(\$/kW-yr)	15
Variable cost by generation $c_{gen,PV}$/(\$/MWh)	0.5
Common	
Total land cost C_{land}/(\$/acre)	10 000
Contingency factor f_{conti}	0.07
Engineering–procurement–constructing factor f_{EPC}	0.13
Sales tax rate f_{sale}	0.04
Degradation rate f_{degrad}	0.01
Discount rate i	0.07
Analysis period n /(years)	25

4.2 Selecting the configuration schemes

Lhasa (latitude 29.43°N, longitude 91.02°E) was selected in this study as the test site owing to its adequate solar radiation for power generation. Fig. 2 shows the average direct normal irradiance (DNI) value of Lhasa in the last decade, with meteorological data from the U.S. National Renewable Energy Laboratory (NREL) website.

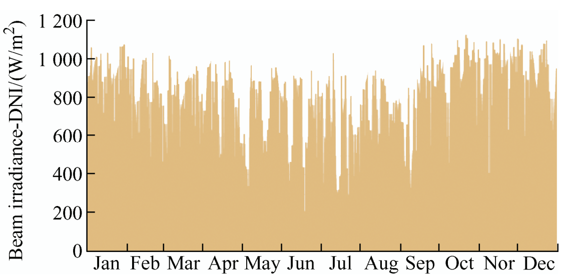


Fig. 2 Annual average DNI of Lhasa

According to the investigation of the annual average daily load of a community in Lhasa, the load of the hybrid CSP/PV plant can be set to 5 MW. Based on the electricity demand and the corresponding solar radiation intensity distribution, and given the PV fluctuation, the hybrid CSP/PV system can be set to 10 MW. The capacity configuration ratios of 4:1, 3:1, 2:1, and 1:1 were selected with the proposed schema illustrated in Section 3, shown as Fig. 3. For each hybrid power plant, the output of the CSP system should be controlled to compensate for the difference between the PV system and the load demand during every dispatch period.

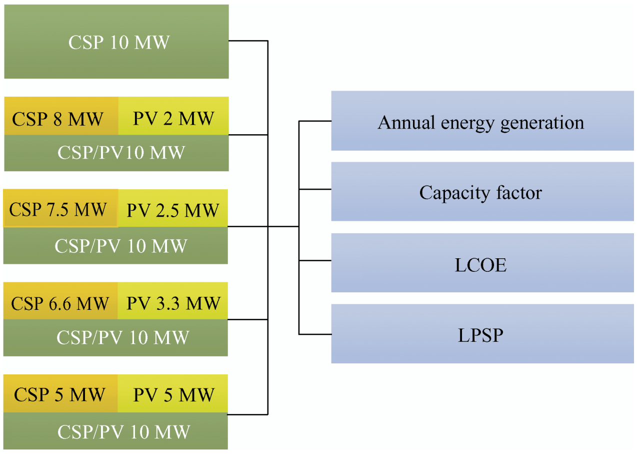


Fig. 3 Research approach diagram

The control strategy of the hybrid CSP/PV power plant is realized through the dispatch-control matrix in the PC section of the CSP system. It comprises nine periods and corresponding daily average turbine-output fractions (Tab. 4). After calculating the power gap that the CSP system must fill, the production command is translated to the monthly output fractions in the PC section, shown as Fig. 4.

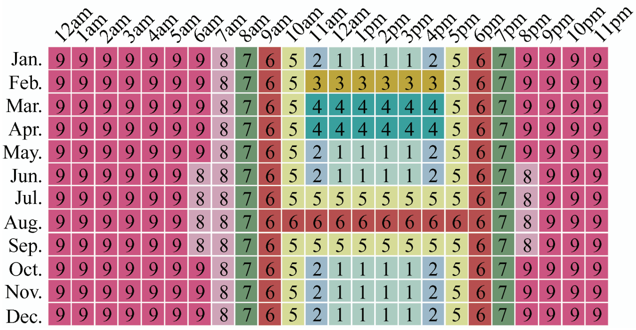


Fig. 4 Dispatch-control matrix in PC section of CSP system

Tab. 4 Design parameters of PV power plant

Fraction number	1	2	3	4	5	6	7	8	9
Fraction	0.20	0.28	0.40	0.30	0.38	0.50	0.85	0.90	0.95

Fig. 5 shows various output curves of hybrid CSP/PV systems, with different colors for different capacity configurations. Because of the undispatchable characteristic of PV, the output of the CSP system is adjusted to guarantee the demanded power.

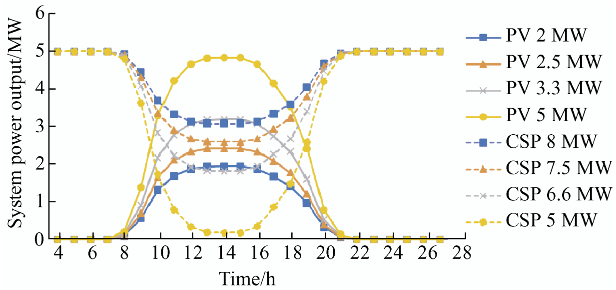


Fig. 5 Energy-dispatch scheme of the CSP/PV power plant

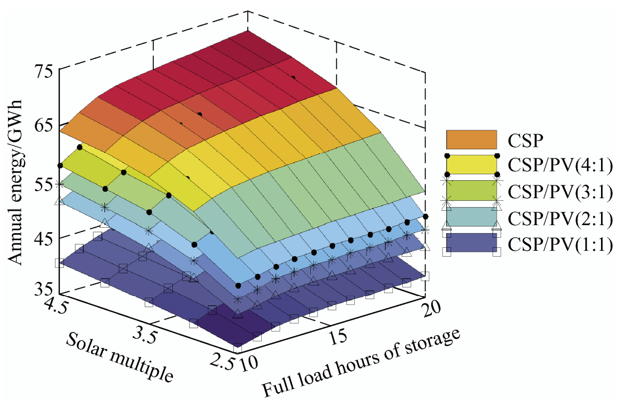
4.3 Checking the selected configuration scheme

SAM was used in this paper to model the hybrid system because it is specialized simulation software aimed at providing basic models that calculate performance and financial metrics of renewable energy, including PV, concentration of solar power, wind, geothermal, biomass, etc. With the flexibility to support the adjustment of models and parameters, SAM simplifies the modeling process of complex power plants, and it can be obtained from the NREL website for free [19].

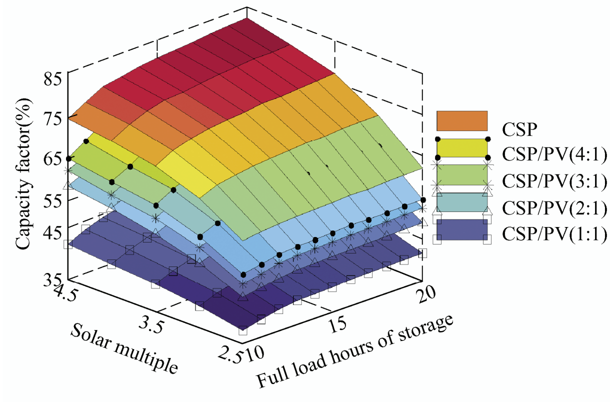
4.3.1 Productivity performance analysis

Fig. 6 shows the simulation results of power-generation performance from the standalone CSP plant and hybrid CSP/PV power plant, with various values of SM and FLHS.

According to Fig. 6a, with increasing SM and FLHS, the annual energy generation of both the standalone CSP plant and hybrid CSP/PV power plant increases, and the increment decreases gradually owing to the declining marginal contribution brought



(a) Annual energy generation of different systems



(b) Capacity factors of different systems

Fig. 6 Productivity performance of different systems

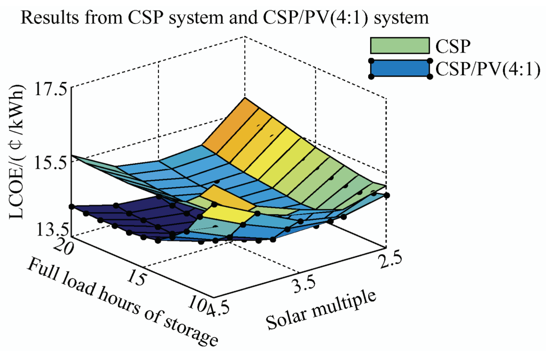
by these two parameters to electricity production. However, the standalone CSP plant has the highest annual energy, whereas the hybrid CSP/PV power plants have diminishing generation as the proportion of the CSP system decreases, with the lowest electricity generation appearing with a capacity ratio of 1:1. Therefore, the addition of a PV system will result in a certain reduction in the annual output of the CSP power plant because the power-generation efficiency of the PV system without energy storage is lower than that of the CSP system.

According to Fig. 6b, the variation trends of the capacity factor under the influence of SM and FLHS are almost the same as the annual energy generation and will not be covered here.

4.3.2 Economic performance analysis

To show the LCOE of these power plants in different configurations, the hybrid CSP/PV power plant in each configuration is compared with the standalone CSP plant, as shown in Fig. 7.

As seen in Fig. 7, with increasing SM and FLHS, the LCOE of both the standalone CSP plant and hybrid CSP/PV power plants decrease first to minimum



(a)

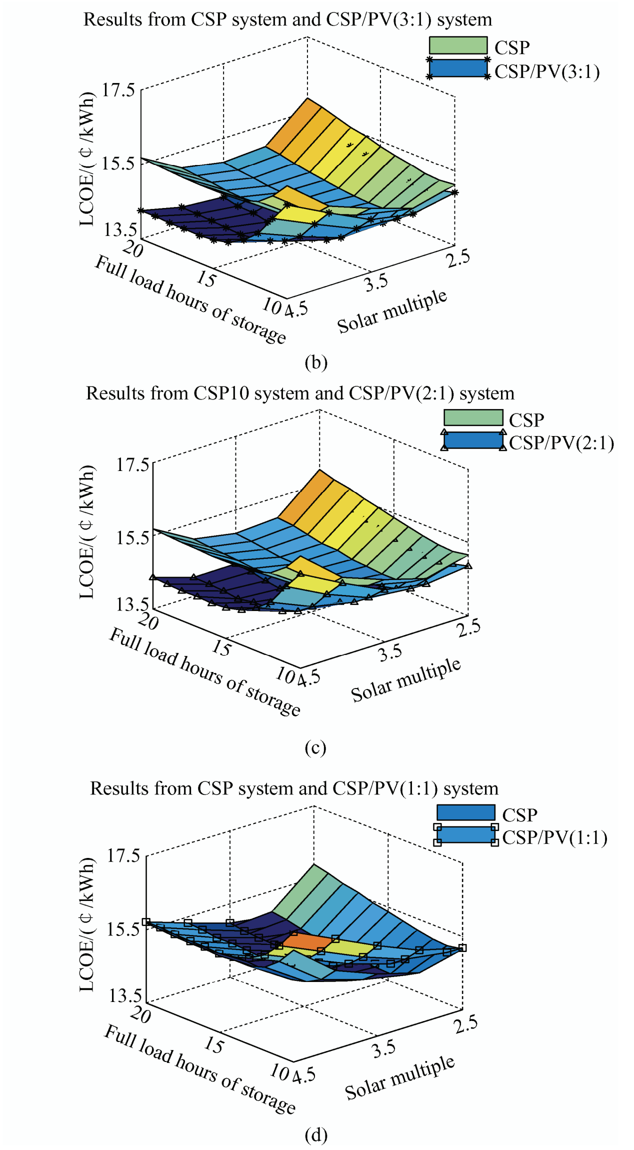


Fig. 7 LCOE comparison between CSP plant and hybrid power plants with different capacity ratios

values and increase later. Because the increase in the two design parameters translates to a larger scale of the power plant, resulting in more capital investment and electricity generation and greater income from the sale of electricity, a certain combination of the two parameters minimizes the LCOE. However, it is clear that the LCOE of the hybrid CSP/PV (1:1) power plant is higher than that of the standalone CSP plant in most parameters, whereas the LCOE of the hybrid power plants in other capacity configurations is lower than that of the standalone CSP plant at different levels with the same design parameters.

To clearly show the differences among the four hybrid power plants, the change curves of their LCOE with SM are given in Fig. 8, selecting FLHS values of 12 h, 16 h, and 20 h for each hybrid system.

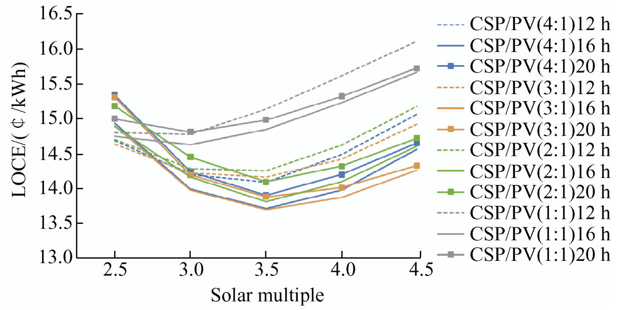


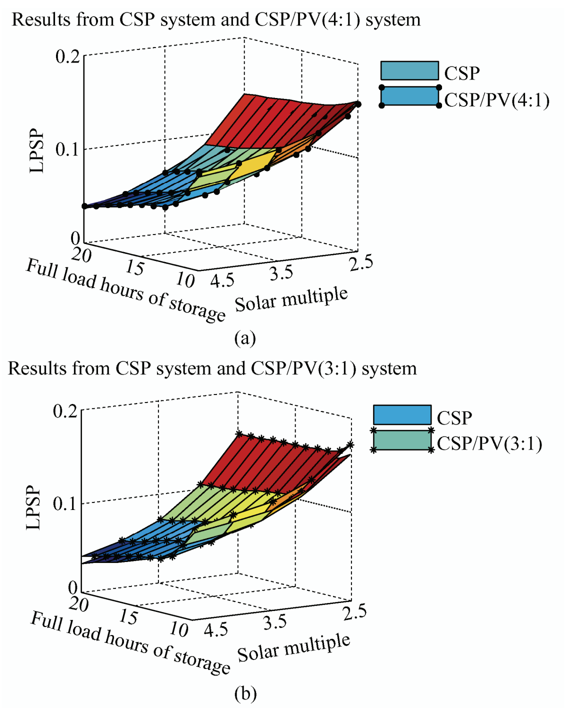
Fig. 8 LCOE curves of hybrid CSP/PV power plants

As seen in Fig. 8, under the same parameters of SM and FLHS, the LCOE of the hybrid CSP/PV (1:1) power plant is much higher than that of the other three hybrid systems when SM is greater than 3. In comparison, the LCOE of the hybrid CSP/PV (2:1) power plant is slightly above that of hybrid systems with 4:1 and 3:1 capacity ratios. The LCOE curve of the hybrid CSP/PV (4:1) power plant almost coincides with that of the CSP/PV (3:1) power plant when SM is smaller than 3.5, and slightly exceeds the latter when SM is greater than 3.5.

4.3.3 Power-supply reliability analysis

To show the LPSP indices of these power plants in different configurations, the hybrid CSP/PV power plant in each configuration is compared with the standalone CSP plant, as shown in Fig. 9.

As seen in Fig. 9, with increasing SM and FLHS, the LPSP indices of both the standalone CSP plant and



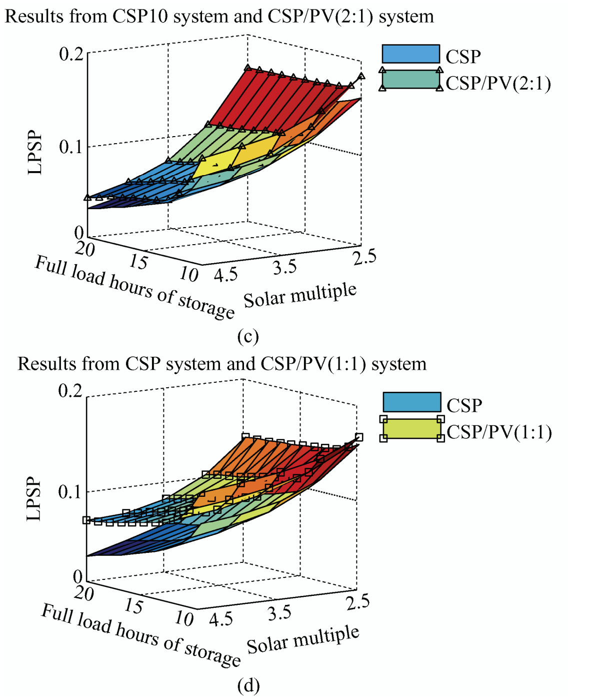


Fig. 9 LPSP comparison between CSP plant and hybrid power plants with different capacity ratios

CSP/PV power plants decrease, but the decrements decrease, which indicates that increasing the design parameters improves the power-supply stability but with a declining marginal contribution. However, it is clear that the LPSP of the standalone CSP plant is lower than that of the hybrid CSP/PV power plants at different levels with the same design parameters. Because the result of the hybrid system with a 4:1 ratio is almost the same as that of a standalone CSP plant, other configurations with 3:1, 2:1, and 1:1 ratios show incrementally increasing LPSP compared with the standalone CSP plant, which means that reliability decreases with increasing capacity portion of the PV system.

To show the difference among the four hybrid power plants clearly, the change curves of their LPSP values with SM are shown in Fig. 10, selecting three FLHSs of 12 h, 16 h, and 20 h for each hybrid system. As seen in Fig. 10, the LPSP value of hybrid systems

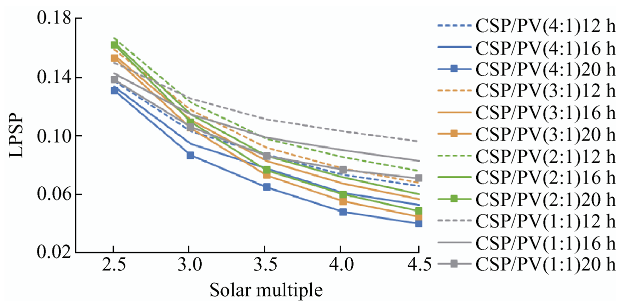


Fig. 10 LPSP curves of hybrid CSP/PV power plants

decreases with increasing capacity portion of the PV system when SM is greater than 3.5. This is because the megawatt-class CSP plant needs a higher SM value to function properly; in this case, the impact of PV's intermittent character on the hybrid system's reliability is relatively stable.

In addition, from Fig. 8 and Fig. 10, it can be seen that the variation trend of the LPSP index is not consistent with LCOE. With increasing SM and FLHS, there is a U-shaped LCOE curve, while the LPSP follows a trend of decline. Therefore, to evaluate the performance of the hybrid CSP/PV power plant and the standalone CSP plant more effectively, these assessments should be analyzed comprehensively.

4.3.4 Comprehensive analysis of system performance

In the four assessments above, annual energy and capacity factors are mainly used to measure the utilization rate of operating power plants, whereas LCOE and LPSP are used to measure the economic efficiency and power-supply reliability of power plants and provide important decision support for investors. Thus, it is necessary to find a reasonable capacity configuration to meet some threshold requirement of reliability with the lowest LCOE. Fig. 11 shows the lowest LCOE of all power plants under different reliability requirements.

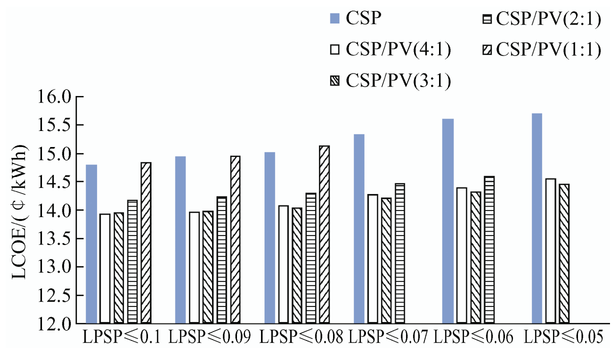


Fig. 11 Lowest LCOE of all power plants under different reliability requirements

It can be clearly seen in Fig. 11 that under the same reliability requirement, the LCOE of the hybrid CSP/PV power plant in the 4:1, 3:1, and 2:1 configurations has different degrees of reduction compared with the standalone CSP plant. Conversely, the hybrid power plant with a 1:1 ratio shows the opposite result when the LPSP value is higher than 0.08. On the other hand, the ability of each power plant to meet the requirements of power-supply reliability is different. The lowest LPSP that the hybrid CSP/PV (1:1) power plant can achieve is approximately 0.08, that of the hybrid CSP/PV (2:1) power plant is approximately 0.06, and those of the standalone CSP plant and hybrid system with 4:1 and 3:1 ratios are less than 0.05. Moreover, it can be seen in Fig. 10 that a lower LPSP value means a higher SM or FLHS value, and when the LPSP value is less than 0.1, the SM value is greater than 3.5. Within the range from 3.5 to 4.5, the LCOE values of all hybrid systems are proportional to the two parameters, based on Fig. 8. Thus, as seen in Fig. 11, the LCOE value of each power plant increases with increasing reliability demands on the power supply.

It should be noted that with the capacity configuration at a 1:1 ratio, rather than effectively reducing the LCOE of the CSP plant, the hybrid CSP/PV power plant has a higher levelized cost under most design parameters and a comparatively lower reliability level of the power supply. In other words, when PV replaces CSP by half of capacity, the effect of the inherent low energy-conversion efficiency and poor reliability of PV by itself has counteracted the advantage of its low LCOE. Therefore, the hybrid CSP/PV(1:1)power plant may be not a good option for Lhasa.

The minimum LCOE and the corresponding parameter settings of the power plants under different reliability requirements, as well as the LCOE reduction of the hybrid power plant compared with that of the standalone CSP plant, are listed in Tab. 5.

Tab. 5 Lowest LCOE and configuration of CSP plant and hybrid power plant under different reliability requirements

Parameter	fun≤ 0.10	fun≤ 0.09	fun≤ 0.08	fun≤ 0.07	fun≤ 0.06	fun≤ 0.05
Minimum LCOE of CSP plant/(¢/kWh)	14.80	14.94	15.06	15.33	15.60	15.83
Minimum LCOE of CSP/PV plant/ (¢/kWh)	13.93	13.98	14.04	14.21	14.33	14.44
Capacity configuration of CSP/PV plant	4:1	4:1	3:1	3:1	3:1	3:1
Design parameters of CSP/PV plant (SM, FLHS)	(3.5,12)	(3.5,13)	(3.5,15)	(3.5,17)	(4,18)	(4.5,18)
LCOE reduction/ (¢/kWh)	0.87	0.96	1.02	1.12	1.27	1.39

According to Tab. 5, under the same power-supply reliability requirements, the largest reduction in LCOE of a hybrid CSP/PV power plant is 1.39 cents (U.S.)/kWh (approximately 0.09 RMB/kWh), compared to the standalone CSP plant, which is a considerable figure in the power market.

5 Conclusions

This paper proposed a capacity configuration method based on filtering and checking. The superiority of the proposed method was shown in terms of convenience and operability, which favors engineering utilization and extension. The results indicated that although the replacement of a certain PV capacity can reduce the capital investment cost (mainly the HF cost) of a hybrid CSP/PV power plant, both the annual energy generation and capacity factor of the hybrid power plant decrease owing to the low efficiency of a PV system. A hybrid CSP/PV model was established using SAM software, and by comparing the simulation results from hybrid CSP/PV power plants in different capacity configurations with a standalone CSP plant, it was shown that the power-supply reliability and economic efficiency of a hybrid power plant are significantly affected by the ratio of PV to total capacity. For the weather conditions of Lhasa, a hybrid CSP/PV power plant in a 1:1 capacity configuration is not a cost-effective option, and the 3:1 ratio achieves better performance than other configurations mentioned in this study.

Admittedly, because SAM supports only discrete sample data, this paper only compared four capacity configurations of hybrid systems, but the impact of the capacity ratio of CSP/PV on the hybrid system was indicated. The accuracy of the capacity configuration was considered sufficiently cogent to provide a technological and economic analysis for a megawatt-class CSP plant. This conclusion may provide some reference on CSP/PV technology development in the Lhasa area, and additional influencing factors, including site topography, land use, and transmission availability, will be investigated in a future study.

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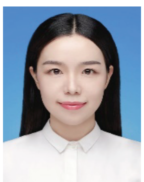
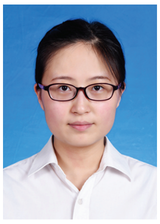


Fei Li received her B.E. degree in electrical engineering from Tianjin Polytechnic University, Tianjin, in 2014, and received her M.E. degree in electrical engineering from Hunan University, Changsha, China, in 2018. She is currently working at the State Grid Henan Electric Power Company Economic Research Institute, Zhengzhou, China. Her major research interest is renewable energy configuration optimization.

Canbing Li (M'06-SM'13) received both his B.E. degree and Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China, in 2001 and 2006, respectively. He is currently a professor with the College of Electrical and Information Engineering, Hunan University, Changsha, China. His research interests include smart grids, energy efficiency, and energy policy.

Kai Sun (M'12-SM'16) received his B.E., M.E., and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 2000, 2002, and 2006, respectively. He joined the faculty of Electrical Engineering, Tsinghua University, in 2006, where he is currently an associate professor. His current research interests include power electronics for renewable generation systems, micro-grids, and the energy internet.



Jiamei Zhang received her B.E. degree at the College of Electrical and Power Engineering, Taiyuan University of Technology, Taiyuan, China, in 2013. She is currently working toward her Ph.D. degree at the College of Electrical and Information Engineering, Hunan University, Changsha, China. Her major research interests include renewable energy generation and optimization.

Hua Li received his B.E. degree in electrical engineering and automation at Hebei Normal University, Shijiazhuang, China, in 2014. He received his M.E. degree in electrical engineering in Hunan University, Changsha, China, in 2017. He is currently working at Zhangjiakou Power Supply Company, Zhangjiakou, China. His research interest is optimal operation of renewable energy.