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Study on Operation Strategy of CSP Peak-Regulating Power Station Based on Spot Trading Market in Gansu Province

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Abstract. On March 3, 2022, the National Development and Reform Commission of China and the National Energy Administration of China jointly published the Notice on Accelerating the Construction of the Electricity Spot Market. The notice indicated that the government would support the uninterrupted operation of the power spot pilot project with conditions and form a long-term and stable electricity spot market as soon as possible. These steps will help rapidly improve China's electricity spot market construction. Due to its large-scale energy storage capacity, the Concentrated Solar Power (CSP) station can be used as a peak-regulating power station to provide grid-friendly long-term peak regulating capacity and moment of inertia for the power system. When CSP stations participate in electricity spot market trading, they can optimize their operation strategy to generate more electricity during periods with higher electricity prices, thereby obtaining more profits. In this paper, a 100MW CSP Peak-Regulating Station with an 80.0hm^2 reflecting area of Heliostats Field (HF) is designed in Gansu, China. In the Peak-Regulating operation strategy, the most suitable TES Capacity for this project is determined to be 15h. We take this CSP station as the research objective to optimize the operation strategy of the power station. The research results indicate that optimizing the operation strategy will increase the power station's annual electricity sales revenue by about 19.97% before the strategy was optimized when the power station participated in the real-time trading of the Gansu electricity spot market in 2022.

Keywords: Electricity Spot Market, Concentrated Solar Power, Peak-Regulating

1. Preface

In 2015, China launched a new round of power system reform, focusing on constructing a spot market. In 2018, eight regions were identified as the first batch of pilots, including South China (starting from Guangdong), Western Inner Mongolia, Zhejiang, Shanxi, Shandong, Fujian, Sichuan, and Gansu [1]. On March 3, 2022, the National Development and Reform Commission of China and the National Energy Administration of China jointly published the Notice on Accelerating the Construction of the Electricity Spot Market. The notice indicated that the government would support the uninterrupted operation of the power spot pilot project with conditions and form a long-term and stable electricity spot market as soon as possible. These steps will help rapidly improve the construction of China's electricity spot market [2]. Gansu is one of the first pilot areas in China to build a spot market. At the end of 2018, the GanSu electricity spot market started a trial operation, and two consecutive 7-day settlement trial operations were carried out in 2019. On March 18, 2022, the Gansu electricity spot market took the lead in China to launch the third settlement trial operation [3] and entered the spot continuous long-cycle operation stage in May 2022 [4]. The average feed-in tariff of different periods in the real-time spot market in 2022 has been shown in Figure 1.

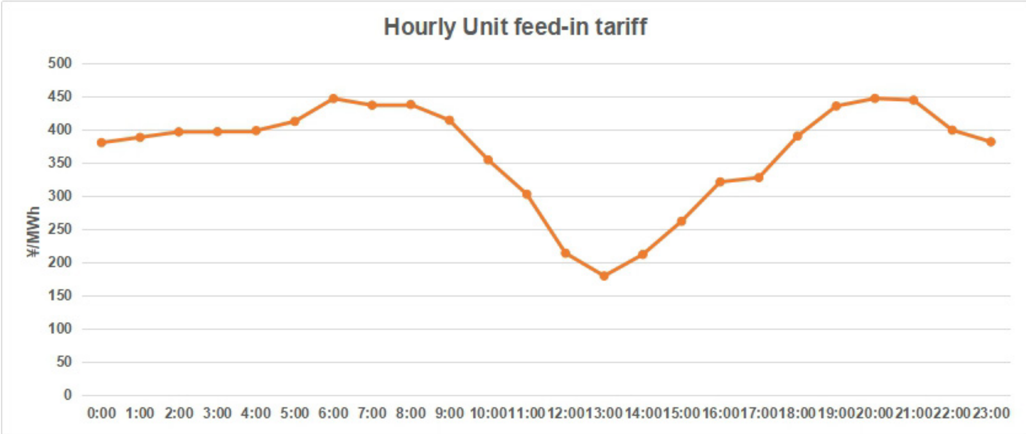

Figure 1. *Hourly unit feed-in tariff.*

2. Introduction

Due to its large-scale energy storage capacity, the Concentrated Solar Power (CSP) station can be used as a peak-regulating power station to provide grid-friendly long-term peak regulating capacity and moment of inertia for the power system. When CSP stations participate in electricity spot market trading, they can optimize their operation strategy to generate more electricity during periods with higher electricity prices, thereby obtaining more profits. In this article, a 100MW CSP Peak-regulating Station with an 80.0hm2 reflecting area of Heliostats Field (HF) is designed in Gansu, China. In the peak-regulating operation strategy, the most suitable TES Capacity for this project is determined to be 15h. We take this CSP station as the research objective to optimize the operation strategy of the power station. The research results indicate that optimizing the operation strategy will increase the power station's annual electricity sales revenue by about 19.97% before the strategy was optimized when the power station participated in the real-time trading of the Gansu electricity spot market in 2022.

3. System model of CSP

The CSP station is mainly composed of a Heliostats Field (HF), Molten Salt Receiver (MSR), Thermal Energy Storage System (TESS), Steam Generation System (SGS), and Steam Turbine Generator (STG). The simplified model of the heat flow is shown in Figure 2 [5], [6].

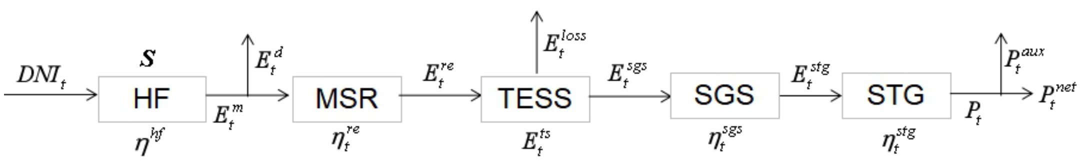

Figure 2. *Simplified Model of the heat flow.*

The heat constraint equation of HF is as follows:

$$E_t^m = DNI_t \bullet S \bullet \eta_t^{hf} \tag{1}$$

Where, E_t^m refers to the heat that can be collected from the HF within t period; DNI_t refers to the solar direct normal Irradiance; S refers to the reflecting area of HF; η_t^{hf} refers to the efficiency of HF within t period.

The heat constraint equation of MSR is as follows:

$$E_t^{re} = \left(E_t^m - E_t^d\right) \bullet \eta_t^{re} \tag{2}$$

$$0 \le E_t^{re} \le E_{re}^{\max} \tag{3}$$

Where, E_t^{re} refers to the heat from the MSR into the TESS within t period; E_t^d refers to the discarded heat of MSR within t period; η_t^{re} refers to the efficiency of MSR within t period; $E_{re}^{\max}$ refers to the upper limit value of heat from MSR.

The heat constraint equation of TESS is as follows:

$$\begin{cases} \Delta_t^{ts} = E_t^{re} - E_t^{loss} - E_t^{sgs} \\ E_t^{ts} = E_{t-1}^{ts} + \Delta_t^{ts} \end{cases} \tag{4}$$

$$0 \le E_t^{ts} \le E_{ts}^{\max} \tag{5}$$

Where, Δ_t^{ts} refers to the change of heat stored in the TESS within t period; E_t^{loss} refers to the heat loss of the TESS from t-1 to t; E_t^{sgs} refers to the heat entering the SGS within t period; $E_{ts}^{\max}$ refers to the upper limit value of heat storage in the TESS.

The heat constraint equation of SGS is as follows:

$$E_t^{sgs} \bullet \eta_t^{sgs} = E_t^{stg} \tag{6}$$

Where, η_t^{sgs} refers to the efficiency of the SGS within t period; E_t^{stg} refers to the heat entering the STG within t period.

The heat constraint equation of STG is as follows:

$$E_t^{stg} \bullet \eta_t^{stg} = P_t = P_t^{aux} + P_t^{net} \tag{7}$$

$$\begin{cases} P^{\min} \le P_t \le P^{\max} \\ P_t - P_{t-1} \le P_{up} \\ P_{t-1} - P_t \le P_{down} \end{cases} \tag{8}$$

Where, E_t^{stg} refers to the efficiency of the STG within t period; P_t refers to the gross electrical generation of STG within t period; P_t^{aux} refers to the auxiliary consumption within t period; P_t^{net} refers to the net electrical generation within t period; $P^{\max}$ and $P^{\min}$ refer to the upper and lower limits of generating capacity of STG; P_{up} and P_{down} refer to the limits for uphill and downhill climbing of STG.

According to the heat constraint equation, the total daily relevant parameters of CSP are calculated according to the following formula:

$$\begin{cases} E_D^{re} = \int_D E_{D_t}^{re} \bullet dt \\ E_D^{loss} = \int_D E_{D_t}^{loss} dt \\ E_D^{use} = \int_D \frac{P_{D_t}}{\eta_{D_t}^{stg} \bullet \eta_{D_t}^{sgs}} dt \\ E_{D_{ed}}^{ts} = E_{D_0}^{ts} + E_D^{re} - E_D^{loss} - E_D^{use} \end{cases} \tag{9}$$

Where, D refers to the simulated day; E_D^{re} refers to the total amount of heat entering the TESS from MSR on the simulated day; E_D^{loss} refers to the heat loss of the TESS on the simulated day; E_D^{use} refers to the heat entering the SGS on the simulated day; $E_{D_0}^{ts}$ and $E_{D_{ed}}^{ts}$ refer to the heat stored of the TESS during the starting and ending periods on the simulated day.

The electricity sales revenue of CSP stations is calculated according to the following formula:

$$Q_{D_{in}} = \int_D \Pr_{D_t} \bullet P_{D_t}^{net} dt \tag{10}$$

Where, $Q_{D_{in}}$ refers to the electricity sales revenue on the simulated day; $\Pr_{D_t}$ refers to the feed-in tariff during the period of t on the simulated day.

4. Optimizing Operation Strategy

Concerning the division of peak-flat-valley periods in Gansu Province (see Table 1), the CSP station operates in the peak-regulating operation strategy before optimization. It does not operate from 9:00 to 17:00 and operates at full load at other times.

Table 1. Peak-Flat-Valley period.

Parameter	Periods
Peak period	07:00~09:00,17:00~23:00
Flat period	00:00~07:00,23:00~24:00
Valley period	09:00~17:00

Three assumptions:

1. The weather conditions at the site of the CSP station are known;
2. The feed-in tariff in the real-time spot market of Gansu Province is known;
3. The CSP station's net electrical generation can be cleared in the real-time spot market.

Based on the feed-in tariff in the real-time spot market, the optimal operation strategy is established by using the mode of day D and the day after day D centralized competition for heat consumption. The steps are as follows:

Step 1:Use the model of the CSP station to calculate the $E_{D_0}^{ts}$, E_D^{re} , E_D^{loss} , E_{D+1}^{re} on the simulated day and the day after the simulated day, specifically define the reference system model section;

Step 2: Use the dichotomy to determine the appropriate price limit value Pr_{bd} , which meets the following constraints:

$$P_t = \begin{cases} P^{cap} & \mathrm{Pr}_t \geq \mathrm{Pr}_{bd} \\ 0 & \mathrm{Pr}_t < \mathrm{Pr}_{bd} \end{cases} \tag{11}$$

$$\begin{cases} E_D^{use} = \int_D \frac{P_t}{\eta_{cap}^{stg} \bullet \eta_{cap}^{sgs}} dt \\ E_{D+1}^{use} = \int_{D+1} \frac{P_t}{\eta_{cap}^{stg} \bullet \eta_{cap}^{sgs}} dt \end{cases} \tag{12}$$

$$\left(E_{D_0}^{ts} + E_D^{re} + E_{D+1}^{re} - E_D^{loss} - E_{D+1}^{loss}\right) \bullet \beta = E_D^{use} + E_{D+1}^{use} \tag{13}$$

Where, P^{cap} refers to the rated output power of STG; Pr_t refers to the feed-in tariff within t period; η_{cap}^{stg} refers to the rated efficiency of the STG; η_{cap}^{sgs} refers to the rated efficiency of the SGS; To avoid frequent start-up and shutdown of STG, it is necessary to reserve part of the heat for maintaining the low-load operation of STG, and the parameter β is introduced, β refers to the proportion of heat used to participate in the competition. In this model, the value β is the same throughout the year, and the optimal value β is determined by iteration. When determined β , the value Pr_{bd} can be determined according to the formula (11), (12), (13).

Step 3: Constraint judgment of heat consumption on day D, i.e:

$$\left(E_{D_0}^{ts} + E_D^{re} - E_D^{loss}\right) \bullet \beta \geq E_D^{use} \tag{14}$$

If the condition of equation (14) cannot be satisfied, the dichotomy would be used to adjust the limit value of the feed-in tariff on day D (Pr_{bd}) so that the formula (14) is valid.

Step 4: Adjust the generation output on day D according to Equations (15) and (16) as the generation output requirements of the STG on day D, as follows:

$$P_t = \begin{cases} P^{\min} & n-m-2 < T_{shutdown} \\ 0 & n-m-2 \geq T_{shutdown} \end{cases} \quad m+1 \leq t \leq n-1 \tag{15}$$

$$\begin{cases} \sum_{t=m+1}^{n-1} P_t = 0 \\ P_m > 0 \\ P_n > 0 \end{cases} \tag{16}$$

Where, $T_{shutdown}$ refers to the limit value of the continuous non-output time of STG.

Step 5: The power output requirements of STG on day D are substituted into the system model of the CSP station, and then the heat stored in SGS at the beginning time of day D+1 can be calculated.

Repeat steps 1 to 5 to simulate the plant's power generation throughout the year.

5. Overall Scheme Design

The installed capacity of the CSP Peak-regulating station is 100MW, with an HF reflecting area of 80.0hm2. The main configuration parameters are shown in Table 2.

Table 2. Main parameters of CSP peak-regulating power station.

Parameter	**Unit**	**Jinta, Gansu, China**
Total Global Horizontal Irradiance (GHI)	$kW{\cdot}h/m^2$	1695.3
Annual Direct Normal Irradiation (DNI)	$kW{\cdot}h/m^2$	1894.7
CSP Rated Capacity	MW	100
Heliostats field reflecting Area	hm^2	80.0
MSR Capacity	MWt	404

The operation strategy of the peak-regulating power station before optimization is used to simulate power generation under different TES Capacities. Taking the maximum annual net electricity as the optimization goal, the best TES Capacity for this project is determined to be 15h by optimization. The simulation results are shown in Figure 3.

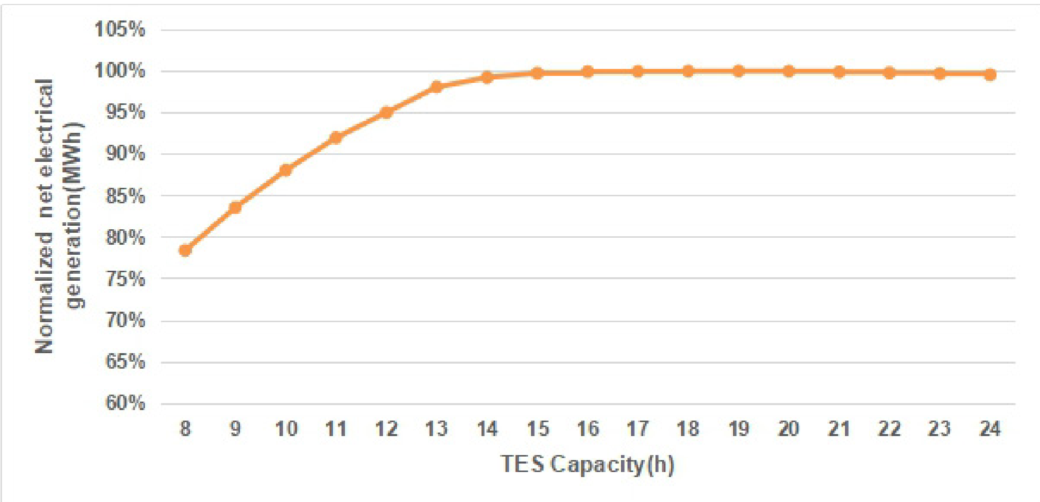

***Figure 3**. Annual net electricity under different TES Capacity.*

6. Result

The optimized operation strategy is adopted to simulate the participation of the CSP Peak-regulating station in the real-time spot market of electricity in Gansu Province in 2022. Compared with the operation strategy before optimization, the increase in power stations' annual electricity sales revenue under different β is shown in Figure 4.

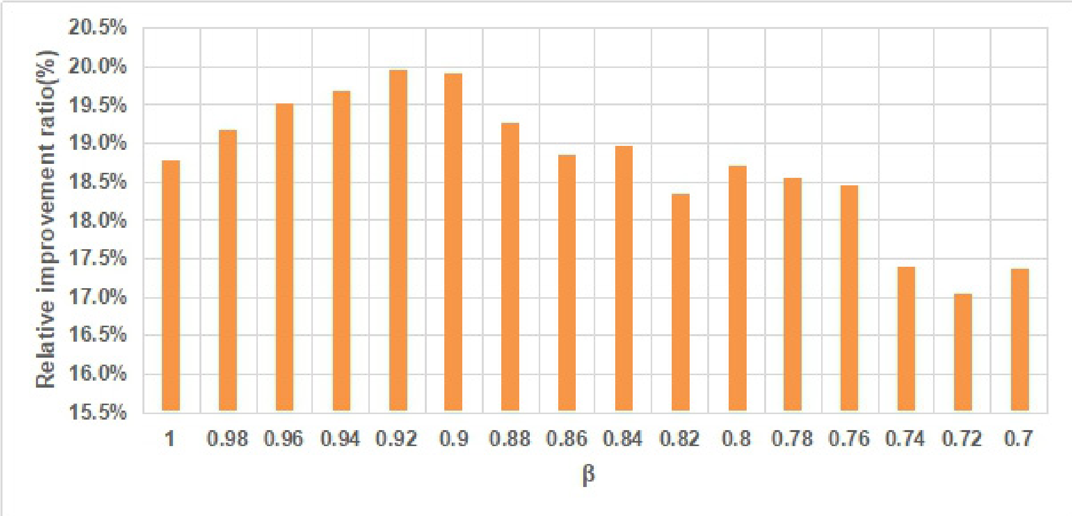

***Figure 4**. The increase situation under different β.*

The above figure shows that the power station's revenue improvement effect reaches its maximum value when β is equal to 0.92. The increase rate is about 19.97%. The corresponding monthly increase in the power station is shown in the figure below.

***Figure 5**. Monthly Increase.*

Figures 6 and 7 show the simulation curves on typical days before and After Operation Strategy optimization.

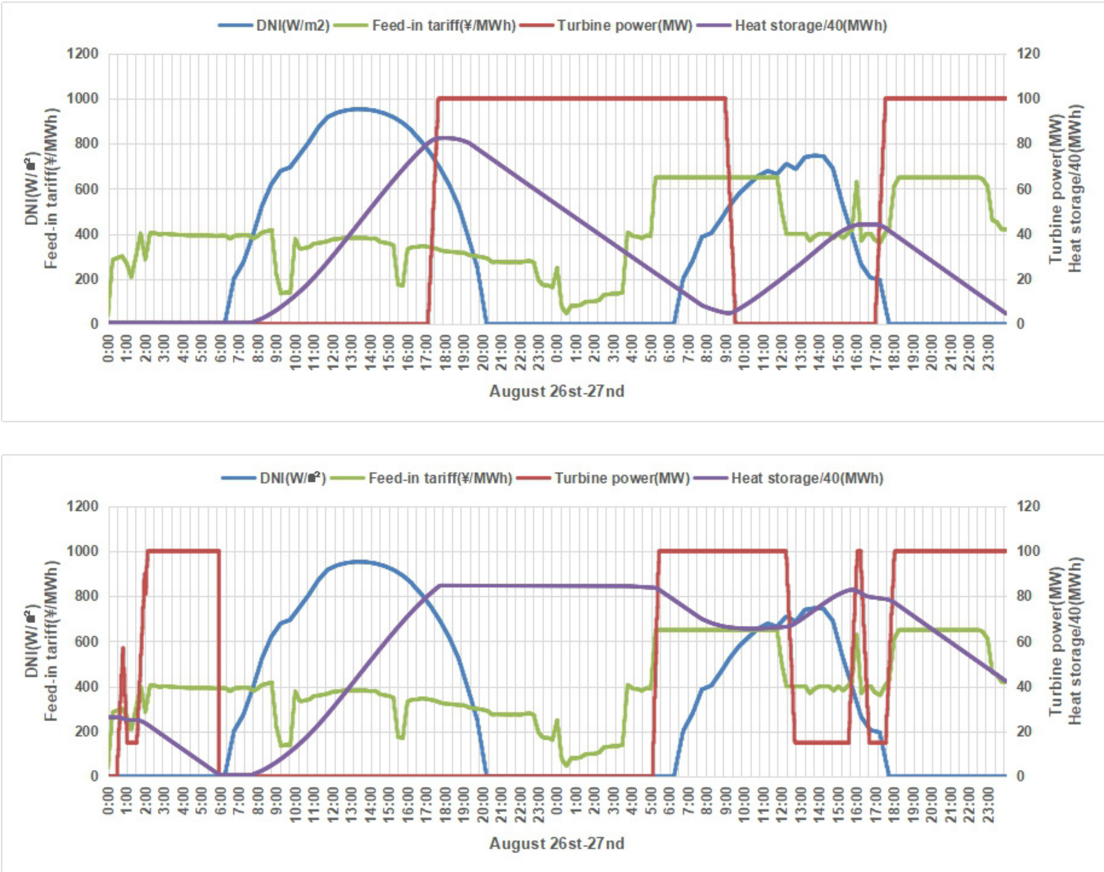

Figure 6. *Simulation curves before optimization (above) and after optimization (below) of* August 26~27.

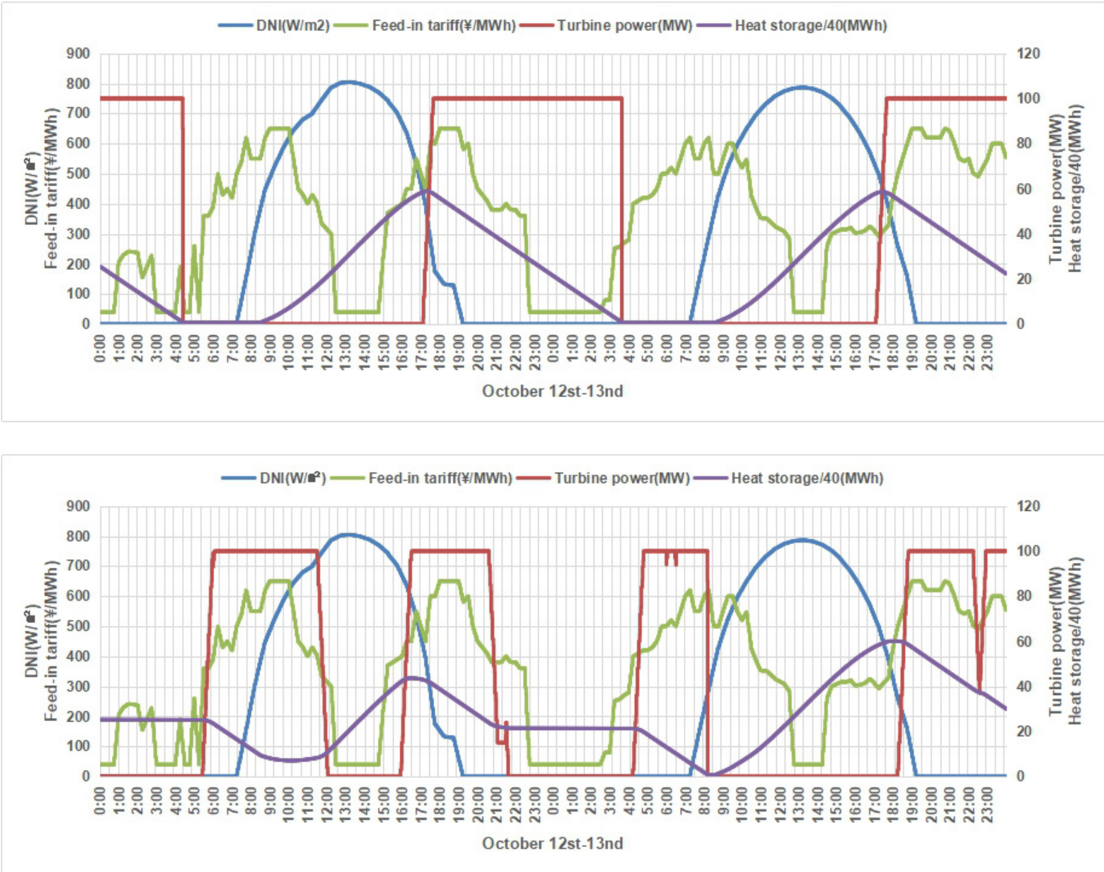

Figure 7. *Simulation curves before optimization (above) and after optimization (below) of October 12~13.*

Figures 6 and 7 show that after optimizing the operation strategy, the CSP Peak-regulating station can capture the price peak of the spot market and adjust the STG's power generation output in time.

7. Conclusion

1. The CSP Peak-regulating stations in different regions all have the best TES Capacity, which needs to be optimized and determined. The best TES Capacity of the CSP Peak-regulating station in Gansu District is 15h.

2. The CSP Peak-regulating station can reap considerable benefits in the electricity spot market by capturing the price peak and optimizing its operation strategy. The results show that optimizing its operation strategy can increase the CSP peak-regulating station's annual electricity sales revenue by about 19.97%.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

Underlying and related material

None.

Author contributions

Xiaobo Li: Formal analysis, Investigation, Data curation, Writing-original draft.

Xiaoling Mi: Conceptualization, Supervision, Writing- review & editing.

Dutang Yang: Investigation, Data curation, Formal analysis.

Yi Yang: Conceptualization, Methodology.

Competing interests

The authors declare no competing interests.

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