Research Article

Day-Ahead Scheduling for Renewable Energy Generation Systems considering Concentrating Solar Power Plants

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With the advent of the new types of electrical systems that attach more importance to the renewability of the energy resource, issues arising out of the randomness and volatility of the renewable energy resource, such as the safety, reliability, and economic operation of the underlying power generation system, are expected to be challenging. Generally speaking, the power generation company can do a reasonable dispatch of each unit according to weather forecast and load demand information. Focusing on concentrating solar power (CSP) plants (wind power, photovoltaic, battery energy storage, and thermal power plants), this paper proposes a day-ahead scheduling model for renewable energy generation systems. The model also considers demand response and related generator set constraints. The problem is described as a mixed-integer nonlinear programming (MINLP) problem, which can be solved by the CPLEX solver to obtain an optimal solution. At the same time, the paper compares and analyzes the impact of concentrating solar power plants on other renewable energy generation and thermal power operation systems. The results show that the renewable energy generation system can lower power generation costs, reduce load fluctuation, and enhance the energy storage rate.

1. Introduction

As the world's largest energy producer and consumer, China has made it clear that it will strive to reach carbon emissions peaks by 2030 and then suppress carbon emissions until complete neutrality is achieved by 2060. With regard to realizing these two “dual-carbon” goals, promoting the construction of high-proportion renewable energy systems is expected to become a trend. New clean energy technologies must replace traditional thermal power systems to undertake peak shaving as well as heat supply tasks. CSP technology is a type of renewable energy generation that uses thermoelectric conversion to generate electricity from solar thermal resources. This technology, which is undoubtedly an ideal clean energy technology choice, has been demonstrated in China and achieved certain results.

The existence of uncertainty is one of the main challenges in the energy scheduling problem of integrating renewable energy. In order to deal with this problem, [1]

describes the uncertainty problem as a multiobjective optimization problem and proposes an optimal day-ahead scheduling method for renewable energy based on the NSGA-II algorithm. However, the effect of energy storage systems has not been considered in renewable energy power generation. Reference [2] uses the dispatchability of CSP plants to integrate CSP plants with wind farms, which reduces output uncertainty, improves overall regulation efficiency, and proves that the addition of CSP plants can increase the reliability of renewable energy power generation systems. Therefore, it is of great significance to analyze the scheduling problems of renewable energy power generation systems including CSP plants and energy storage systems. In addition, the impact of CSP plants on the cost of other renewable energy generation and thermal power generation systems is also worth discussing. From the system structure perspective, [3] proposes a novel robust framework using for day-ahead energy dispatch of residential microgrids, which solved the double uncertainty caused by renewable energy

and user behavior. Therefore, the relationship between power generation and load demands needs to be effectively balanced by grid operators [4, 5]. Solving the reliability problem of the renewable energy generation systems through microgrid technology is an essential means [6]. The types of distributed power generation, generally contained in the power generation side of the microgrid, are wind power, photovoltaics, small gas turbine systems, and battery energy storage systems, as well as other dispatchable resources. The energy management system (EMS) considers system constraints and demand response to perform reasonable dispatch operations on the power generation side, which can effectively increase the profitability of the power generation and the penetration rate of the renewable energy system [7–11]. However, one limitation of microgrid is that it only provides a solution for small distributed power generation systems [12]. Therefore, related studies have proposed using load-side changes to adjust to the uncertainties of renewable energy resources while generating electricity. Reference [13] established a nonlinear model of the demand response programs (DRPs) based on incentives and examined the influence of derivative models on elastic changes, incentives, penalties, and implementation potential and then determined the degree of dependent models. Reference [14] proposed a dispatching optimization model of wind power based on the robust stochastic optimization theory, which considers different demand responses. The simulation results show that the robust stochastic optimization theory can overcome wind power uncertainties and that the two demand response methods have the most substantial effect on wind power absorption. Song et al. [15] showed that, in response to wind power consumption, the demand response and energy storage technology are added to the power generation dispatches. A large-scale wind power dispatch model is constructed with optimization goals such as economic maximization. The simulation results show that the combined effect of the demand response and the energy storage technology has helped improve the system's wind power consumption capacity. The system's coal consumption level of power generation has decreased. Astriani et al. [16] addressed the problem of demand response, with respect to reducing customer comfort, and proposed an incentive scheme feasible for demand-side participants as well as for grid operators. The results show that distributing part of the profits to consumers as an incentive to participate in the program can increase the profits of the grid company. References [17–19] proposed using electric vehicles and battery energy storage to participate in response dispatches; the charging prices for electric cars were optimized; thus, the loads are adjusted, cooperation with the energy storage battery was utilized, and finally, the goal of maximizing profits was achieved. References [20, 21] studied the ability of temperature-controlled loads to adjust the loads. The simulation results show that temperature-controlled load adjustment can reduce system cost and increase system reliability. In addition to general commercial and residential loads participating in the response, [22] suggested that demand-responsive industrial loads with high thermal inertia can participate in the power market frequency

regulation. The simulation results show that an industrial park with a capacity of 500 MW can provide ancillary services with a capacity of up to 40 MW to participate in secondary frequency modulation. Liao et al. [23] proposed using the direct control scheme of the high energy-consuming loads to smooth wind power fluctuations. The above demand response model covers residential electricity, commercial electricity, industrial electricity, and flexible load regulation, which can effectively improve renewable energy generation consumption and grid security. However, the adjustable load-side response capacity is limited and its response is a passive response. Therefore, combining the demand-side response and the renewable energy generation-side dispatch is particularly critical.

Zhao et al. [24] considered the uncertainties of wind power and the limitations of the power grid and used the probability method to solve the wind power capacity limit. Reference [25] proposed integrating wind power and energy storage into the power system. The research results show that energy storage devices can reduce the operational risk to an acceptable level. The focus of [26] was on the congestion problem of renewable energy generation channels; utilization of energy storage units was proposed to solve the uncertainties of both wind and solar resources. Using Gaussian probability distribution function modeling and the Monte Carlo simulation, this method effectively alleviates the congestion problem of renewable energy generation lines. Reference [27] proposed solving the PV power prediction error caused by the forecast error; the energy storage system was used to compensate for the uncertain power of the photovoltaic power station and to realize the excellent playability of the photovoltaic resources. However, the battery energy storage currently suffers from such issues as high costs, service life, and safety. The technology of concentrating solar power in accordance with a heat storage system can play an important role in renewable energy generation systems [28].

Unlike other renewable energy generation systems, CSP plants with heat storage systems can make energy use rational. Furthermore, the CSP power generation system is similar to the thermal power unit; therefore, it has more flexible adjustment capabilities [29]. Reference [30] compared the power generation costs of CSP plants and gas turbines. The results show that hybrid solar power plants have proved to be more cost-effective under certain conditions while maintaining significant scheduling and flexibility capabilities. Compared to wind and photovoltaic power generation systems, CSP generation systems also claim higher competitiveness [31]. Reference [32] established a general model framework for an optimal CSP plants supply strategy, under the combined conditions of the energy market, reserve, and supervision. The results show that the provision of ancillary services significantly increases the profits of CSP plants. Reference [33] took wind power plants in the Iberian Peninsula and CSP plants as examples; the short-term coordination of wind farms and CSP plants was studied. The results show that the combined power generation system can increase the profit of power generation enterprises, in addition to increasing the transmission

capacity coefficient. The focus of [34] was on the problem of wind power consumption; a dispatch model based on CSP and price-based demand response participation in the consumption of wind power was proposed. The results show that the application of the price-based demand response and the involvement of the CSP plant in formulating an optimal dispatch can make up for the insufficiency of the wind power antipeak-shaving characteristics, improve wind power consumption, and reduce the overall system costs. Reference [35] proposed a model that considers CSP plants and compressed air energy storage to address the traditional unit combination problem. The simulation results show that adding CSP plants and compressed air energy storage systems can effectively increase the profits of the power generation companies. Based on the above researches and the actual energy situation in Northwest China, this paper proposes a renewable energy generation system dispatch model that considers CSP plants. By comparing four different cases, the paper analyzes the impact the access of the CSP plant has on thermal power, wind power, and battery energy storage, as well as other systems.

The rest of the paper is organized as follows. Section 2 focuses on the system models, including the CSP model, the wind power model, the photovoltaic model, the battery energy storage model, and the demand-side response model. In Section 3, four different cases are given along with their simulation analyzes. Finally, the conclusion of the paper is given in Section 4.

2. System Models

This section alludes to the system mathematical models, which include the CSP plant model, the wind power model, the photovoltaic model, the battery energy storage model, the demand response model, the thermal unit model, and the system's constraints. The objective function of the system is expressed as follows:

$$\min \text{cost} = \sum_{t=1}^T (\text{cost}_t^{\text{CSP}} + \text{cost}_t^{\text{WD}} + \text{cost}_t^{\text{PV}} + \text{cost}_t^{\text{G}}). \quad (1)$$

This paper takes the minimum total power generation cost of the system as the objective function. Thus, the total cost is the sum of the cost concentrating solar power generation, wind power cost, and photovoltaic and thermal power.

2.1. Concentrating Solar Power Plant Model. The cost function of the CSP plant can be described as a linear function of the generation power. The objective function is expressed as follows:

$$\text{cost}_t^{\text{CSP}} = k^{\text{CSP}} P_t^{\text{CSP}}. \quad (2)$$

According to the heat storage characteristics, the CSP plant can be divided into two types: without thermal energy storage (TES) and with TES. The CSP plant without TES has a small area, low initial investment cost, poor dispatch ability, and long gas turbines equipment times. The CSP

plant with TES is generally large-scale. The power generation system can be dispatched reasonably through TES to maximize the use of solar energy and reduce the impact of renewable energy on the power grid. A simplified structure diagram of the CSP plant with a TES is shown in Figure 1.

The CSP plant comprises three systems: the solar field (SF), TES, and the power block (PB). The three systems transfer heat through the heat transfer fluid (HTF). The SF transfers heat to HTF by absorbing the solar heat. HTF transfers heat to the PB through flows to generate a high-temperature and high-pressure steam to drive steam turbines and generate electricity or flow into the thermal energy storage (TES) to the heat directly. The TES can also transfer stored heat to the PB through HTF for power generation. The energy conversion relationship of the CSP plant is shown in Figure 2 [33].

When considering the CSP plant model, most of the losses, incurred during the energy conversion process, happen during the light-to-heat and thermoelectric conversion processes. In contrast, the HTF and TES heat losses are relatively small. Therefore, we simplified the heat loss model.

The CSP plant mathematical model can be described as formulas (3)–(16) [31]. Equations (3)–(5) represent the output power balance of the CSP plant. Equation (6) represents the lowest and highest acceptable heat of the generator. Equation (7) expresses the constraint of the SF heat output to the generator. Equation (8) represents the SF input and output constraints. Equation (9) represents the TES balance constraint. Equation (10) represents the TES capacity constraint. Equation (11) expresses the generator output capacity constraint. Equations (12) and (13) represent the charging and discharging climbing power constraints of the TES. Equations (14) and (15) represent the upper and lower limits of the charge and discharge of the TES; the TES cannot be charged and discharged at the same time.

$$P_t^{\text{CSP}} = P_t^{\text{SP}} + P_t^{\text{TP}}, \quad (3)$$

$$P_t^{\text{SP}} = \eta_1 q_t^{\text{SP}}, \quad (4)$$

$$P_t^{\text{TP}} = \eta_2 q_t^{\text{TP}}, \quad (5)$$

$$q^{\text{PB min}} \leq q_t^{\text{SP}} + q_t^{\text{TP}} \leq q^{\text{PB max}}, \quad (6)$$

$$q^{\text{SP min}} \leq q_t^{\text{SP}} \leq q^{\text{SP max}}, \quad (7)$$

$$q_t^{\text{SP}} + q_t^{\text{SE}} \leq q_t^{\text{SF}}, \quad (8)$$

$$q_t^{\text{TES}} = q_{t-1}^{\text{TES}} + q_t^{\text{ST}} - q_t^{\text{TP}}, \quad (9)$$

$$q^{\text{TES min}} \leq q_t^{\text{TES}} \leq q^{\text{TES max}}, \quad (10)$$

$$P^{\text{CSP min}} \leq P_t^{\text{CSP}} \leq P^{\text{CSP max}}, \quad (11)$$

$$RD^{\text{TP}} \leq q_t^{\text{TP}} - q_{t-1}^{\text{TP}} \leq RU^{\text{TP}}, \quad (12)$$

FIGURE 1: Simplified structure diagram of a CSP plant with TES.

FIGURE 2: Simplified energy flow in CSP plant with TES.

$$RD^{ST} \leq q_t^{ST} - q_{t-1}^{ST} \leq RU^{ST}, \quad (13)$$

$$0 \leq q_t^{ST} \leq MZ_t, \quad (14)$$

$$0 \leq q_t^{TP} \leq M(1 - Z_t), \quad (15)$$

$$P_t^{SP}, P_t^{TP}, q_t^{TP}, q_t^{SP}, q_t^{ST} \geq 0. \quad (16)$$

2.2. Wind Power Model. The cost function of wind power is expressed as follows:

$$\text{cost}_t^{WD} = k^{WD} P_t^{WD}. \quad (17)$$

The power output by the wind turbines is related to the speed of wind; there is a nonlinear relationship. This relationship can be expressed by a piecewise function [22]. The equation shows the relationship between the power output by a single wind turbine and the speed of wind. When the same model is selected for the wind power generator of the wind farm, the wind farm output can be expressed by equation (19).

$$P_{\text{var}}(v) = \begin{cases} 0 & 0 \leq v < v_i \\ a + bv^3 & v_i \leq v < v_r \\ P_r & v_r \leq v \leq v_o \\ 0 & v > v_o \end{cases}, \quad (18)$$

$$P_t^{WD} = P_{\text{var}}(v_t)N_L, \quad (19)$$

where

$$a = \frac{P_r v_i^3}{v_r^3 - v_i^3}, \quad (20)$$

$$b = \frac{P_r}{v_r^3 - v_i^3}.$$

2.3. Photovoltaic Model. The cost function of wind power is expressed as follows:

$$\text{cost}_t^{PV} = k^{PV} P_t^{PV}. \quad (21)$$

The photovoltaic power generation model is shown in equations (22) and (23) [5]. Equation (22) expresses that the output power of the photovoltaic power generation is mainly related to the environmental radiation intensity and temperature; equation (23) represents the output power constraint of the photovoltaic power generation.

$$P_t^{PV} = \eta^{PV} S^{PV} \text{DNI}_t (1 - 0.005(T_t - 25)), \quad (22)$$

$$P_t^{PV \min} \leq P_t^{PV} \leq P_t^{PV \max}. \quad (23)$$

2.4. Thermal Unit Model. The thermal power generator is composed of two parts: operation cost and start-up cost. The operation cost is often described as a quadratic function of the power [33]. Equation (24) represents the total cost of the thermal power units.

$$\text{cost}_t^G = \sum_{i=1}^N (f_i(P_{t,i}^G) + S_i(1 - U_{t-1,i}))U_t, \quad (24)$$

where

$$f_i = a_i P_{t,i}^2 + b_i P_{t,i} + c_i. \quad (25)$$

Of course, thermal power units must meet relevant constraints during operation. Equation (26) expresses the unit capacity constraint, which dictates that the generator output must be within the maximum and minimum boundaries. Equations (27) and (28) express the unit's start and stop constraints, which dictates that the unit's runs and stops have minimum times. Equation (29) expresses the unit's climbing constraint, which needs to be met by the generator's output power change within the climbing range for each period of time.

$$P_i^{G \min} \leq P_{t,i}^G \leq P_i^{G \max}, \quad (26)$$

$$(T_{t-1,i}^{\text{on}} - T_i^{\text{on}})(U_{t-1,i} - U_{t,i}) \geq 0, \quad (27)$$

$$(T_{t-1,i}^{\text{off}} - T_i^{\text{off}})(U_{t,i} - U_{t-1,i}) \geq 0, \quad (28)$$

$$P_i^{G \text{down}} \leq P_{t,i}^G - P_{t-1,i}^G \leq P_i^{G \text{up}}. \quad (29)$$

2.5. Battery Energy Storage Model. The battery energy storage system model is described as follows [5]. Equations (30) and (31) represent the BES charge and discharge power constraints. Equation (32) expresses the BES state-of-charge constraint. Equation (33) represents the BES dynamic state of charge. The constraint described by equation (34) dictates that the BES cannot be charged and discharged simultaneously.

$$0 \leq P_t^{\text{ch}} \leq z_t^{\text{ch}} P^{\text{ch max}}, \quad (30)$$

$$0 \leq P_t^{\text{disch}} \leq z_t^{\text{disch}} P^{\text{disch max}}, \quad (31)$$

$$\text{SOC}^{\min} \leq \text{SOC}_t \leq \text{SOC}^{\max}, \quad (32)$$

$$\text{SOC}_t = \text{SOC}_{t-1} + \Delta t \left(\frac{\eta^{\text{ch}} P_t^{\text{ch}}}{E_m} - \frac{P_t^{\text{disch}}}{\eta^{\text{disch}} E_m} \right), \quad (33)$$

$$z_t^{\text{ch}} + z_t^{\text{disch}} \leq 1. \quad (34)$$

2.6. Demand Response Model. Applying the demand response method can make the user-side elastic load a participant in the power market dispatch. This paper adopts the price-based demand response (PBDR) [13]. PBDR achieves the purpose of smoothing the load curve by using the time-of-use electricity price method. The load demand after applying PBDR is calculated as follows.

Define the electricity price elasticity e_{st} according to the demand principle of economics,

$$\begin{cases} e_{st} = \frac{\Delta L_s / L_s^0}{\Delta P_t / P_t^0}, \\ e_{st} \leq 0, \quad s = t, \\ e_{st} \leq 0, \quad s \neq t, \end{cases} \quad (35)$$

where e_{st} represents the price elasticity from time s to time t . L_s^0, P_t^0 are the electricity load at time s and the electricity price at time t , before PBDR. $\Delta L_s, \Delta P_t$ are the load and price fluctuations at times s and t , after PBDR.

Define the value of consumption L_t as $V(L_t)$ and the net profit of the users' consumption of electricity as π^P ,

$$\pi^P = V(L_t) - L_t P_t. \quad (36)$$

Find the first and second derivatives of formula (36) with respect to P_t , and perform Taylor expansion of $V(L_t)$,

$$\begin{aligned} V(L_t) &= V(L_t^0) + \frac{\partial V(L_t)}{\partial L_t} [L_t - L_t^0] + \frac{1}{2} \frac{\partial^2 V(L_t)}{\partial (L_t)^2} [L_t - L_t^0]^2 \\ &= V(L_t^0) + P^0 [L_t - L_t^0] \left\{ 1 + \frac{1}{2} \frac{[L_t - L_t^0]}{e_{tt} L_t^0} \right\}. \end{aligned} \quad (37)$$

Substituting formula (37) into formula (36), the initial model of PBDR can be obtained,

$$L_t = L_t^0 \times \left\{ 1 + e_{tt} \frac{L_t - L_t^0}{L_t^0} \right\}. \quad (38)$$

Equation (38) is the load demand after ignoring the influence of elasticity e_{tt} at time t . Add the load demand of the cross-heterogeneity e_{st} to get the final model,

$$L_t = L_t^0 \times \left\{ 1 + e_{tt} \frac{L_t - L_t^0}{L_t^0} + \sum_{\substack{t=1 \\ s \neq t}}^{24} e_{st} \frac{P_t - P_t^0}{P_t^0} \right\}. \quad (39)$$

2.7. Power Balance Constraint. The output of all the generation sides in the model should meet the load requirements. The constraint relationship is shown in equation (36).

$$P_t^{\text{CSP}} + P_t^{\text{WD}} + P_t^{\text{PV}} + P_t^{\text{BES}} + \sum_{i=1}^N P_{t,i}^G \geq P_t^D. \quad (40)$$

3. Case Study and Simulation

This paper provides a mathematical model of the system in Section 2. The simulation system in this paper includes a CSP station with a heat storage system, a wind farm, a photovoltaic power station, and ten thermal power units. The load and environmental parameters are taken from an area in Gansu Province and the wind and DNI data are taken from China Meteorological Station. The parameters of the units come from relevant references. The simulation running time of the system is from 0 o'clock to 24 o'clock, and hour is taken as the scheduling unit. The design of the following 4 cases will be simulated and analyzed in this section; among those cases, wind power and photovoltaic are defined as nonschedulable renewable energy generating units:

- (i) Case 1: equipped with conventional thermal power generating sets and nonschedulable renewable energy generating units
- (ii) Case 2: considering the demand response to be equipped with conventional thermal power generating units and nonschedulable renewable energy generating units
- (iii) Case 3: considering the demand response to be equipped with conventional thermal power units, nonschedulable renewable energy generating units, and battery energy storage
- (iv) Case 4: considering the demand response to be equipped with conventional thermal power units, nonschedulable renewable energy generating units, battery energy storage, and concentrating solar power plants

The proposed model can be described as an MINLP model, which is solved by calling the CPLEX solver, through

FIGURE 3: Schematic of the solution process.

the YALMIP platform in MATLAB. The solution process is shown in Figure 3.

3.1. Parameter Setting. Table 1 shows the parameters of conventional thermal power units [33]. Table 2 shows the parameters of the CSP plant. Table 3 shows the parameters of a single wind turbine. Table 4 shows the parameters of the photovoltaic power units [9]. Table 5 shows the parameters of the battery energy storage station [15]. For the demand response parameters, refer to [32]. Figure 4 shows the original load demand curve. Figure 5 shows the predicted wind power generation and the predicted photovoltaic power.

3.2. Results and Analysis. This section presents the simulation results of the four cases in addition to an analysis of the results based on the comparison results.

3.2.1. Four Cases of Unit Output. This section presents four cases of the arrangements and costs output by the unit. Figure 6 shows the output of Case 1. Figure 7 shows the output arrangement of Case 2. Figure 8 shows the output arrangement of Case 3. Figure 9 shows the output arrangement of Case 4. Finally, Table 6 shows the cost of the system's power generation.

It can be seen from Table 6 that the addition of a nonenergy storage renewable energy generation system not only increases the cost of thermal power generation but also increases the total power generation cost. However, after joining the BES and the CSP plant, the cost of the system's power generation has been reduced. In particular, the addition of the CSP plant has significantly reduced the total cost, the unit cost of the thermal power generation, and the total power generation cost of the system. By analyzing Figures 6–9, first, with PBDR and the addition of BES and the CSP plants to the power system, there is a gradual increase in wind power consumption. Still, it has little impact on the photovoltaic power system. Second, BES is not sensitive to the renewable energy generation system by itself,

but the BES becomes more active after the addition of the CSP plant. Third, from the output of thermal power generation, it can be seen that the renewable energy generation system can effectively assume the role of peak regulation after the addition of the CSP plant. Therefore, the following text will conduct a more specific analysis of the thermal power generation and other renewable energy generation systems, especially wind power generated from the CSP plant.

3.2.2. The Impact of the CSP Plant on the Thermal Power Generation. In this paper, the total load of the system minus the surplus of the renewable energy generation is called the equivalent load. Figure 10 shows identical load conditions in the four cases.

It can be seen from Figure 10 that the application of PBDR to the original load can effectively cut the peak of the original load, but the effect of the valley filling is not obvious. From comparing Cases 1–3 and after applying PBDR, the daytime peak of the equivalent load is significantly weakened, but it shows no sensitivity to the evening peak. The equivalent load has undergone almost no change after BES is put into operation. It can be seen from the curve of Case 4 that the addition of the CSP plant has a more significant impact on the fluctuation of the equivalent load, and the peak of equivalent load is reduced significantly; at the same time, the trough is reduced. Table 7 shows the specific relevant parameters of the equivalent load in different cases.

It can be seen from the data in Table 7 that the addition of the CSP plant greatly weakens the peaks and the valleys, while the renewable energy generation system without the CSP plant has no significant difference in the maximum peak-valley difference of the equivalent load. The equivalent load variance can represent the fluctuation of the load. Due to the uncertainty of its output, the renewable energy generation system without CSP increases the equivalent load fluctuation. The addition of the CSP plant can effectively reduce the fluctuation of the equivalent load. The above problems will directly affect the related costs of thermal

TABLE 1: The parameters of the thermal power units.

Unit	$P_{\max}$ (MW)	$P_{\min}$ (MW)	a (\$/MW ² h)	b (\$/MW/h)	c (\$/h)	T_{off} (h)	T_{on} (h)	S (\$/h)	RU (MW/h)	RD (MW/h)
1	130	20	0.00200	16.60	700	5	5	1100	130	130
2	130	20	0.00211	16.50	680	5	5	1120	130	130
3	85	25	0.00790	22.74	480	3	3	520	80	80
4	80	20	0.00712	22.26	370	3	3	340	80	80
5	55	10	0.00413	25.92	660	1	1	60	55	55
6	55	10	0.00222	27.27	665	1	1	60	55	55
7	55	10	0.00173	27.29	670	1	1	60	55	55

TABLE 2: The parameters of the CSP plant.

Parameter	Value
P_{CSPmax} (MW)	100
P_{CSPmin} (MW)	10
q_{TESmax} (MWh)	1000
q_{TESmin} (MWh)	100
P_{climax} (MW/h)	70
P_{charmax} (MW/h)	300
η_1	0.45
η_2	0.51

TABLE 3: The parameters of a single wind turbine.

P_r (MW)	V_i (m/s)	V_r (m/s)	V_o (m/s)	k^{WD} (\$/MWh)
2400	2	14	25	24

TABLE 4: The parameters of the photovoltaic units.

P_{PVmax} (MW)	η^{PV}	S^{PV} (m ²)	k^{PV} (\$/MWh)
100	15.7	21000	21

TABLE 5: The parameters of the battery energy storage station.

$E_{\max}$ (MWh)	P_{chmax} (MW)	P_{dischmax} (MW)	η^{ch}	η^{disch}
50	10	10	0.9	0.9

FIGURE 4: The original load demand.

power generation. Table 8 shows the cost parameters of the thermal power generation in different cases.

FIGURE 5: Day-ahead predicted power.

The original case in Table 8 refers to when the thermal power unit bears all the load. The start-up cost reflects the impact of the uncertainty of the renewable energy system on the dispatch of the thermal power units. The addition of the CSP plant effectively reduces the negative effects of the renewable energy generation systems on the traditional thermal power generation; as the load of the thermal power units decreases, the cost of the peak shaving is transferred to the renewable energy generation system, which effectively reduces the thermal power unit generation cost.

3.2.3. The Impact of the CSP Plant on Wind Power Generation. Among renewable energy generation systems, wind power generation systems suffer the most from randomness. Figure 11 shows the comparison between wind power consumption and abandonment power in the four cases. Table 9 shows the specific wind power consumption and the abandonment data.

The consumption rate of wind power in Case 4 (Figure 11(a)) is significantly higher than that of the other cases. From the curve in Figure 11, it can be seen that the wind power consumption rate of Case 4 is higher than that of other cases almost all day, especially in the time period of 9–13 o'clock; Case 4 in Figure 11(b) has only a partial wind abandonment phenomenon during the early stages. Furthermore, the data in Table 9 show that the addition of the CSP plant reduces the curtailment rate of wind power to

FIGURE 6: The output of Case 1: (a) output of renewable energy generating unit; (b) output of thermal unit.

FIGURE 7: The output of Case 2: (a) output of renewable energy generating unit; (b) output of thermal unit.

7.34%. The addition of the CSP plant has significantly better wind power absorption effects than the other taken measures. For further analyses of the reasons for abandonment and the role the CSP plant plays, Figure 12 shows the output of the thermal power units after all the renewable energy generation power is used in Case 3.

From the comparison between Figures 12 and 8(b), it can be seen that when wind power is absorbed, the mainly affected output is that of unit 3. Figure 13 shows the cost

function of thermal power unit 3, which is related to the output of the unit and the number of unit start-ups.

It can be seen from Figure 13 that the number of start-ups has no noticeable impact on the power generation cost of unit 3 under the condition of the entire load operation. Still, the unit's output has a greater effect on its cost, which increases the power generation cost of the unit when the output is unstable. Therefore, there is a large number of wind abandonment situations in Case 3. The addition of the CSP

FIGURE 8: The output of Case 3: (a) output of renewable energy generating unit; (b) output of thermal unit.

FIGURE 9: The output of Case 4: (a) output of renewable energy generating unit; (b) output of thermal unit.

TABLE 6: The cost of the system's power generation.

Case	Thermal power cost (\$)	PV cost (\$)	Wind power (\$)	CSP cost (\$)	Total cost (\$)
1	235409.65	13461	17976	—	266846.65
2	238732.21	13461	20184	—	272377.21
3	235824.40	13461	20352	—	269637.40
4	196457.15	13461	25400	25536	260894.15

FIGURE 10: Identical load conditions in the different cases.

TABLE 7: The specific relevant parameters of the equivalent load in different cases.

Case	Peak (MW)	Valley (MW)	Maximum peak-valley difference (MW)	Equivalent load mean square error
Original load	590	310	270	5547.526
PBDR load	590	345	245	4279.9427
1	565	310	255	4865
2	542	340	202	4830
3	535	340	195	4651
4	467	260	207	4422

TABLE 8: The cost parameters of the thermal power generation in different cases.

Case	Operating costs (\$)	Start-up cost (\$)	Total cost (\$)	Total power generation (MW)	Unit power generation cost (\$)
Original	280841.44	3380	284221.44	10725	26.50
1	231109.65	4300	235409.65	9335	25.22
2	234772.21	3960	238732.21	9435	25.30
3	231984.40	3840	235824.40	9406	25.07
4	192917.15	3540	196457.15	8141	24.13

FIGURE 11: Wind power output in different cases: (a) wind power consumption; (b) wind power abandonment.

TABLE 9: Wind power consumption and abandonment in different cases.

Case	Total consumption power (MW)	Total abandonment power (MW)	Wind curtailment rate (%)
1	749	395	34.53
2	841	303	26.49
3	848	289	25.42
4	1060	84	7.34

FIGURE 12: The thermal unit output of Case3 in wind power consumption fully.

FIGURE 13: The cost function of thermal power units 1 and 3.

plant ensures the stable operation of the thermal power units in high wind power consumption rate; it transfers the peak-shaving pressure to the CSP unit, thus guaranteeing the wind power consumption rate and reducing the cost of the thermal power generation. At the same time, it can be seen

from the figure that the unit power generation cost is reduced with the increase of the output power, regardless of the number of units. And the unit power generation cost of unit 1 with a large capacity is higher than that of unit 3 when the output power is low. When unit 1 is running at full load,

its cost is less than the minimum power generation cost of unit 3. It can be seen from the relevant data of the thermal power units and the power generation cost function that the large-capacity units are characterized by low full-load operation costs and high start-up costs. In contrast, the small-capacity units have relatively high operating costs but low start-up costs. Therefore, the large-capacity units are often responsible for the base load, while the small-capacity units are responsible for the peak shaving.

4. Conclusions

This paper studies the day-ahead scheduling problems of the CSP plant, the wind power generation system, the photovoltaic system, the battery energy storage system, and the conventional thermal power plants. The system schedule is solved by optimizing the cost target and the CPLEX solver is called in the YALMIP environment to obtain the optimal solution. This paper studies and compares the role of the CSP plant in the renewable energy generation system in four cases. The results show that when the CSP plant is added to the renewable energy generation system, the total system cost is at its lowest, 260,894.15 USD. The unit thermal power cost has also been reduced to 24.13\$/MWh.

Furthermore, when the CSP plant is added, it has a significant peak-shaving effect on the equivalent load and the equivalent load fluctuation is minimal. The phenomenon of wind curtailment has been significantly reduced; the wind curtailment rate has been reduced from 25.42% to 7.34%. The proportion of renewable energy consumption has increased significantly. The results also show that a single addition of a battery energy storage power station on the generation side of a renewable energy generation system, without CSP, has no obvious effect on promoting renewable energy generation and consumption. Compared to the scale of renewable energy generation, the small scale of the battery energy storage power stations cannot meet the requirements of the uncertain large-scale renewable energy generation storage. The large-scale increase in the battery energy storage power stations requires higher costs. When the thermal power unit that bears the basic load does not have to start and stop, its power generation cost is lower. When the renewable energy power access brings the start-up cost, a large amount of wind power abandonment often occurs at this time. The dispatch of a renewable energy cogeneration output through the CSP plant transfers the start-up cost of the thermal power generation. It reduces the impact of uncertain renewable energy generation on thermal power generation. Therefore, the main restrictions on renewable energy generation have been lifted and the consumption rate of renewable energy generation has been increased.

The CSP plant is an indispensable link in future high-proportion renewable energy generation systems. By optimizing the dispatch of the CSP plant and the reasonable configuration of the energy storage system, the stability of the system can be greatly improved; the consumption of renewable energy generation can be promoted. The cost of

the thermal power generation and that of the comprehensive power generation can also be reduced. Future work will try to do a further improvement upon the system's model, taking into consideration both the cogeneration model and the system's profit; the exploration of the potential of solar thermal power generation systems is also a part of our future work.

Nomenclature

Indices

- i : Index of thermal unit
 t : Index of time periods (h).

Parameters and Constants

- k^{CSP} : Cost factor of the CSP unit power generation (\$/MWh)
 k^{WD} : Cost factor of the wind power generation (\$/MWh)
 k^{PV} : Cost factor of the photovoltaic power generation (\$/MWh)
 e_{tt} : Matrix of price elasticity
 η_1 : Efficiency on thermoelectricity conversion coming from the SF (%)
 η_2 : Efficiency on thermoelectricity conversion coming from the SF (%)
 η^{PV} : Efficiency on photoelectric conversion of photovoltaic (%)
 a_i, b_i , and c_i : Cost function coefficients of the i th conventional thermal unit
 η^{ch} and η^{disch} : Efficiency of the BES charge and discharge (%)
 v_t : Wind speed at period t (m/s)
 DNI_t : Radiation intensity at time t (kW/m²)
 E_m : Capacity of the BES (MWh)
 L_t^0 and L_t : Electricity demand of before and after demand response (MW)
 M : Capacity of the TES charge and discharge (MW)
 N_L : Number of wind turbines in wind farm
 P_r : Rated power of a wind turbine
 p_t^D : Electricity demand at period t
 $p^{\text{PV min}}$ and $p^{\text{PV max}}$: Capacity of the PV unit (MW)
 $p_i^{\text{G min}}$ and $p_i^{\text{G max}}$: Lower and upper bound of the electricity produced by the i th thermal unit (MW)
 $p_i^{\text{G down}}$ and $p_i^{\text{G up}}$: Ramp-down and ramp-up of the i th thermal unit (MW/h)
 $p^{\text{ch max}}$ and $p^{\text{disch max}}$: Maximum capacity of the BES charge and discharge (MW)
 $p^{\text{CSP min}}$ and $p^{\text{CSP max}}$: Capacity of the CSP unit (MW)
 P_s^0 and P_s : Electricity price of before and after demand response (\$)
 $p^{\text{clim max}}$: Maximum climbing power (MW/h)
 $p^{\text{char max}}$: The TES maximum charging and discharging power (MW/h)

$q_{PB \min}^{PB}$ and $q_{PB \max}^{PB}$:	Minimum and maximum acceptable capacity of the CSP unit (MWt)
$q_{SP \min}^{SP}$ and $q_{SP \max}^{SP}$:	Minimum and maximum acceptable capacity of the SF to the CSP unit (MWt)
$q_{TES \min}^{TES}$ and $q_{TES \max}^{TES}$:	Minimum and maximum thermal energy level of the TES (MWht)
RD^{TP} and RU^{TP} :	Ramp-down and ramp-up rate of the TES charge (MW/h)
RD^{ST} and RU^{ST} :	Ramp-down and ramp-up rate of the TES discharge (MW/h)
S^{PV} :	Area of photovoltaic mirror field (m ²)
$S_{t,i}$:	Start-up cost of the i th thermal unit (\$)
$SOC^{\min}$ and $SOC^{\max}$:	Lower and upper bound of the BES state of charge
T_t :	Temperature at period t (°C)
T_i^{on} :	Minimum “on” time of the i th thermal unit (h)
T_i^{off} :	Minimum “off” time of the i th thermal unit (h).

Functions and Variables

cost:	Cost of total system (\$)
$cost_t^{CSP}$:	Cost of operating CSP units (\$)
$cost_t^{WD}$:	Cost of the operating wind power units (\$)
$cost_t^{PV}$:	Cost of the operating PV units (\$)
$cost_t^G$:	Cost of the operating thermal units (\$)
P_t^{CSP} :	Power output of the CSP unit at period t (MW)
P_t^{SP} :	Power output of the CSP unit from the SF at period t (MW)
P_t^{TP} :	Power output of the CSP unit from the TES at period t (MW)
P_t^{WD} :	Power output of the wind power unit at period t (MW)
P_t^{PV} :	Power output of the PV unit at period t (MW)
$P_{t,i}^G$:	Power output of the i th thermal unit at period t (MW)
P_t^{ch} :	Power input of the BES unit at period t (MW)
P_t^{disch} :	Power output of the BES unit at period t (MW)
z_t^{disch} :	Binary variable representing commitment state of the BES discharge at period t
q_t^{SP} :	Thermal power from the SF utilized to produce electricity at period t (MW)
q_t^{TP} :	Thermal power from the TES utilized to produce electricity at period t (MW)
q_t^{SF} :	Thermal power of TES utilized to produce electricity (MW)
q_t^{SE} :	Thermal power of the SF absorbs at period t (MW)
q_t^{TES} :	Thermal energy stored in TES at the end of hour t (MWht)
SOC_t :	State of charge of the BES unit at period t
U_t :	Binary variable representing commitment state of thermal unit i at period t
z_t^{ch} :	Binary variable representing commitment state of the BES charge at period t .

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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