Joint Optimal Scheduling of Renewable Energy Regional Power Grid With Energy Storage System and Concentrated Solar Power Plant

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Under the path of global low-carbon development, increasing the proportion of renewable energy in the power grid will become the main goal in the future. But, it will also aggravate the problem of wind and solar curtailment. A joint optimal scheduling model of a renewable energy regional power grid with an energy storage system and concentrated solar power plant is proposed in this study. The proposed model takes the lowest comprehensive operation cost of the power grid as the optimization goal and considers various constraints of concentrated solar power plants, energy storage systems, thermal power units, wind power, and photovoltaic power generation. Finally, a modified IEEE 9-bus system is used to verify the validity. The results show that the model can effectively improve the system node voltage, promote the accommodation of wind and solar power, and alleviate the peak shaving of thermal power units under the premise of optimal economy pressure.

Keywords: renewable energy, joint optimal scheduling strategy, energy storage system, concentrated solar power plant, wind and solar curtailment

1 INTRODUCTION

Due to depletion of fossil fuels and their negative impact on the environment, the installed capacity of wind power (WP) and photovoltaic (PV) has also increased yearly. In the future, the use of renewable energy to gradually replace carbon-containing fossil energy will become the primary trend of power development (Mehigan et al., 2018; Li, Wang and Li, 2020; Li, Li and Wang, 2022). Restricted by the natural attributes of wind and solar power, WP and PV power generation has the characteristics of volatility and intermittency (Dong et al., 2020). When necessary, we have to curtail wind and solar power to ensure the safe operation of the power grid. The renewable energy regional power grid only relies on thermal power units to participate in peak shaving of the regional power grid. With the high proportion of the renewable energy regional power grid, it is difficult to absorb wind and solar power, resulting in waste of resources (Lv et al., 2020; Heptonstall et al., 2021). In addition, at the peak time of electricity consumption, the node voltage of the regional power grid is low, which increased the line loss and affects the power quality of the distribution network system (Wang, Gu and Liang, 2021). The abovementioned problems restrict the development of the renewable energy regional power grid. Therefore, in this study, we focus on considering the battery energy storage system (ESS) and concentrated solar power (CSP) plants as new flexible resources to participate in renewable energy regional power grid regulation.

In addition to PV, the CSP plant is another technology that uses solar power to generate electricity. Solar energy is concentrated through a concentrating device, and high-pressure steam is used to drive a steam turbine to generate electricity or heat. It is equipped with a heat storage device, which can store heat during low load periods and use solar energy and stored thermal energy to generate electricity during peak load periods. Also, it can not only promote the utilization of solar energy but also participate in system regulation as a flexible resource (Xu and Zhang, 2017; Jelley and Smith, 2015). Du et al. (2016) summarized the research progress of CSP technology; analyzed its characteristics from the perspectives of technology, principle, and benefit; and put forward suggestions for the development of CSP plants in China. Zhang, Dong, and Li (2021) discussed the impact of factors on the development of CSP plants in China, such as GDP growth, incentive policies, technological advances, grid absorptive capacity, and emission regulation schemes and then provided theoretical support for the future development of CSP in China. Dong, Yun, and Ma (2020) established a comprehensive energy system consisting of a CSP plant, a power-to-gas device, and a gas-fired unit and simulated the system with the minimum operating cost as the objective function. The results show that the proposed model can meet various load requirements. However, it is highly dependent on the external market and has certain uncertainties. Compared with WP and PV with output uncertainty, the output of the CSP plant is adjustable and controllable, and the adjustment speed is faster. It can be combined with renewable energy power generation to reduce wind and solar curtailment and improve renewable energy consumption capacity.

The ESS has the characteristics of fast response and flexible configuration (Deng et al., 2021). Adding an ESS to the regional power grid in conjunction with the CSP plant can effectively improve the flexibility of the regional power grid. Li and Wang (2021) pointed out that energy storage systems can improve the flexibility, economy, and safety of power systems; reviewed the research status of ESS and energy management systems in recent years; and studied their control methods and application scenarios. Li, Hui, and Lai (2013) proposed an output power control strategy based on fuzzy logic control for the energy storage system to manage the SOC of the energy storage system and smooth the WP/PV power for the problem of unstable WP/PV output power caused by intermittent characteristics.

Scholars have carried out much research on the optimal scheduling of renewable energy regional power grids. Chang et al. (2019) applied the CSP plant to the coal-based power system. Through the flexibility brought by the CSP plant for the system, the influence of the duck curve caused by high PV permeability is alleviated. The results showed that under the same PV permeability, the proposed control strategy reduces the total cost, abandoned solar power, and load loss power. Du et al. (2019) proposed a forward-looking stochastic unit commitment model for operating power systems with the CSP plant under high penetration of renewable energy and also analyzed the advantages of the CSP plant in the renewable energy system. Chen et al. (2019) combined the CSP plant and WP generation, proposed the

joint dispatch model, and discussed the influence of time scale and energy storage parameters on the dispatch model. Zhao, Fang, and Wei (2019) utilized the schedulability of CSP to integrate it with WP, reduced the output uncertainty, improved the overall regulation efficiency, and proved that the addition of a CSP plant increases the reliability of the renewable energy power generation system. Pousinho et al. (2014) took WP and CSP plants in the Iberian Peninsula as a study case and then studied the short-term coordination of it. The results show that the co-generation system can increase power transmission and increase the profit of power generation enterprises. Li and Wang (2022) and Li et al. (2022) studied the microgrid scheduling method considering demand response and introduced a heuristic algorithm into the application of renewable energy optimal scheduling. Yao et al. (2012) proposed a short-term dispatch model for WP energy storage units in a new energy system, in which the two ESSs alternately use WP to curtail power for energy storage and discharge to the grid so as to maximize the use of wind energy. Li et al. (2021) considered the uncertainty and demand response of renewable energy and proposed a bi-level optimal scheduling method for an integrated energy system. Ma et al. (2021) proposed a regional power grid dispatching model using energy storage to coordinate renewable energy dispatching. The optimization goal is to maximize renewable energy consumption and power delivery and convert this problem into a mixed-integer programing problem to solve. Li et al. (2022) proposed a distributed BESS optimal dispatch model considering peak load transfer, which improves the voltage distribution in the distribution network and significantly improves the system voltage qualification rate. Luo et al. (2018) studied the power and voltage control strategy of the regional power grid with an energy storage system and large-scale new energy access and reduced the bus voltage fluctuation at the new energy access point discrete reactive power compensation strategy. However, few scholars have studied the combined model and CSP plant and energy storage constraints. Lu and Cheng (2021) focused on CSP plants (wind, photovoltaic, battery energy storage, and thermal power plants) and proposed a day-ahead scheduling model for renewable energy power generation systems. It is proved by simulation that the proposed model can reduce the load fluctuation of the renewable energy system and improve the energy storage rate of the system.

Based on the abovementioned analysis, it is of theoretical and practical value to study the wind–solar–thermal-storage combined power generation system combining the CSP plant and ESS in the renewable energy regional power grid to improve the wind–solar absorption capacity, but there are still problems that can be further studied. 1) There is still insufficient research on the joint optimal scheduling model of the ESS and CSP plant; 2) there is a lack of scheduling strategies to analyze the overall system economics of abandoning wind and solar power and thermal power output and rarely fully consider the system voltage deviation.

In summary, this study establishes a joint optimal scheduling model for a regional renewable energy power grid with the ESS and CSP plant, considering the various operating constraints of the CSP plant, ESS, thermal power units, WP, and PV. In order to further improve the solution accuracy of the model, the model is

FIGURE 1 | Regional renewable energy grid framework with the ESS and CSP plant.
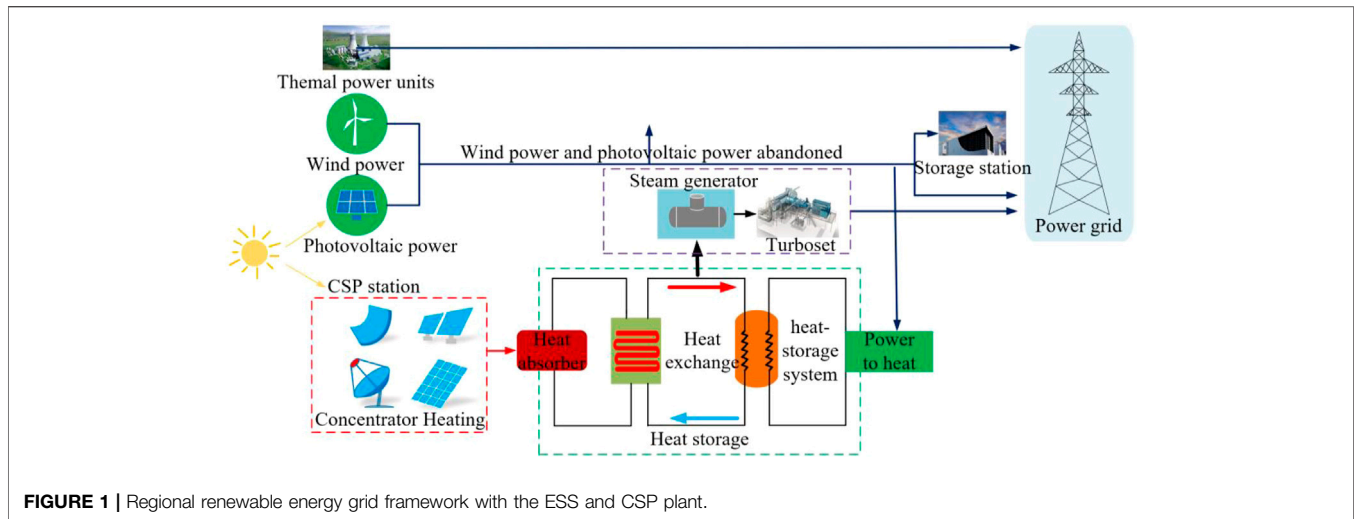
transformed into a mixed-integer linear programming (MLIP) problem to solve. Compared with the traditional scheduling model, the main contributions of our study are

1) We propose a novel optimal scheduling model for the renewable energy regional power grid with the CSP plant and ESS. In the proposed model, the CSP plant and ESS can improve the curtailment of wind and solar power as a flexible resource.
2) Compared with the traditional method, the model proposed in our study increases the WP and PV generation, improves the node voltage of the regional grid system, and reduces the operating cost of the renewable energy regional grid.

The rest of our study is organized as follows. **Section 2** describes the renewable energy district grid architecture with the ESS and CSP plant. **Section 3** describes the model and establishes an optimal dispatch model for renewable energy regional grids, including objective function, power balance, and constraints of the unit, and in **Section 4** we use a numerical study to evaluate the effectiveness of the proposed method, and **Section 5** draws conclusions.

2 RENEWABLE ENERGY REGIONAL GRID STRUCTURE WITH ENERGY STORAGE AND CONCENTRATED SOLAR POWER STATION

The CSP plant mainly comprises the concentrating heat collecting link subsystem, the heat storage link subsystem, and the power generation link subsystem. The solar field absorbs solar energy in the concentrating and heat-collecting link subsystem and further completes the energy transfer in the subsequent links through the heat-conducting working medium and then promotes the heat-conducting medium to enter the power-generating link subsystem and drives the steam turbine to

generate electricity through water vapor. In addition, the thermal storage subsystem of the CSP plant can exchange heat for the thermally conductive working medium to realize heat storage and heat release (Chen et al., 2014). Energy storage is comprehensively considered from multiple dimensions such as efficiency, economy, and power quality. Lithium battery energy storage has obvious advantages and broad application prospects compared with other energy storage. Therefore, the framework structure of the renewable energy regional grid with the ESS and CSP plant established in our study is shown in **Figure 1**.

In **Figure 1**, the renewable energy regional grid scheduling model with the ESS and CSP plant comprises thermal power units, photovoltaic power generation, wind power generation, CSP plant, and lithium battery ESS. The power-to-heat part in the heat storage link subsystem of the CSP plant can consume part of the output of WP and PV in the form of heat energy. The ESS stores the excess WP and PV output in the energy storage system in the form of chemical energy when the renewable energy output is abundant. When the load is at the peak of electricity consumption, the energy storage in the CSP plant and the ESS can bear more peak regulation pressure for the thermal power unit and improve the flexibility of the regional renewable energy grid.

3 JOINT OPTIMAL DISPATCH MODEL OF RENEWABLE ENERGY REGIONAL POWER GRID WITH ENERGY STORAGE AND CONCENTRATED SOLAR POWER STATION

3.1 Objective Function

The objective function of the joint optimal dispatch model proposed in our study is to minimize the cost of power conversion to heat in the CSP plant, the operating cost of thermal power units, and the penalty cost of wind and solar curtailment power. The formula can be expressed in **Eq. 1**.

FIGURE 2 | Joint optimal scheduling framework of the renewable energy regional grid with the ESS and CSP plant model.
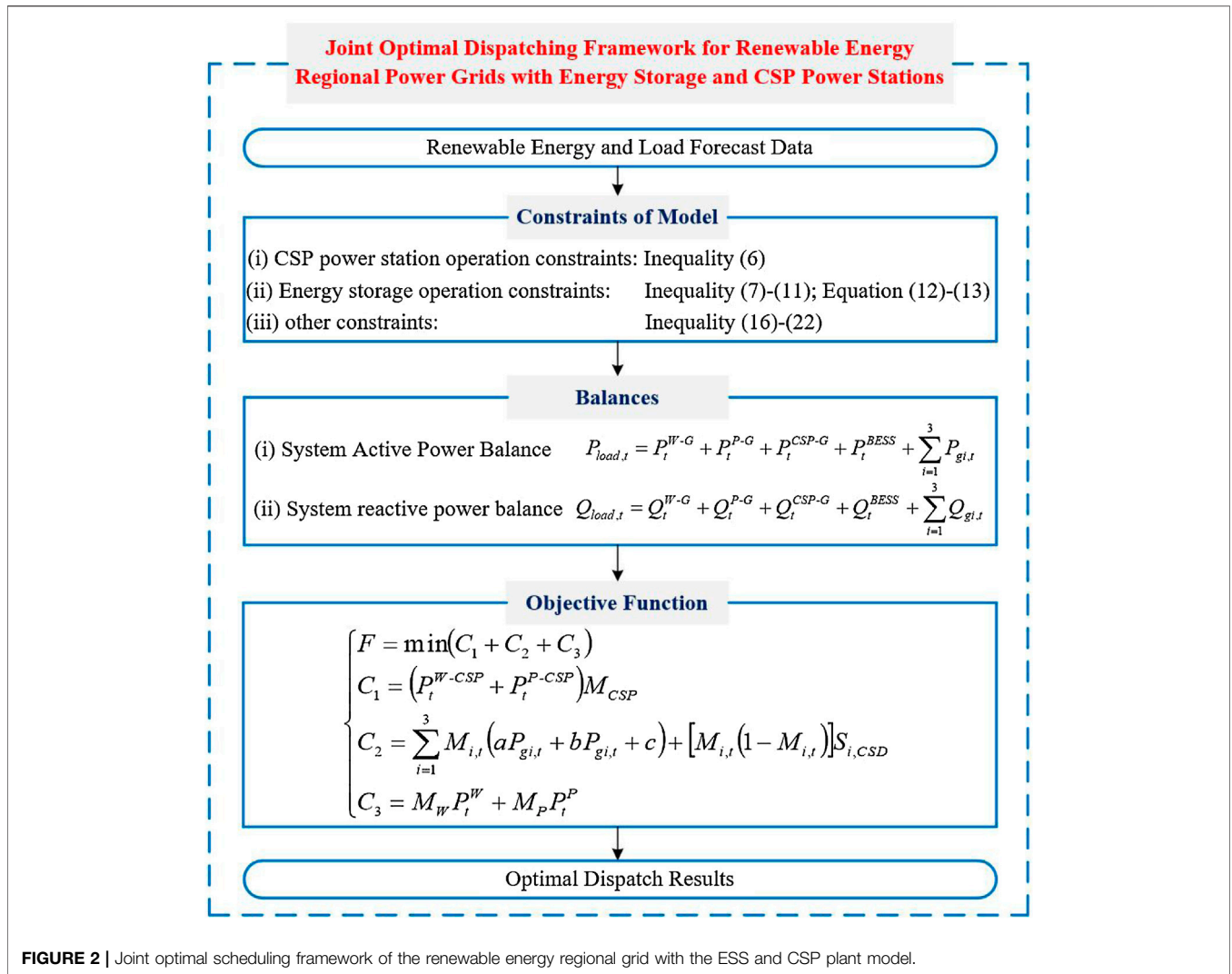
$$\begin{cases} F = \min\left(C_1 + C_2 + C_3\right) \\ C_1 = \left(P_t^{\text{W–CSP}} + P_t^{\text{P–CSP}}\right)M_{\text{CSP}} \\ C_2 = \sum_{i-1}^{3} M_{i,t}\left(aP_{gi,t} + bP_{gi,t} + c\right) + \left[M_{i,t}\left(1 - M_{i,t}\right)\right]S_{i,\text{CSD}} \\ C_3 = M_{\text{W}}P_t^{\text{W}} + M_{\text{P}}P_t^{\text{P}} \end{cases} \quad (1)$$

where C_1 is the power to heat cost of the CSP plant; $P_t^{\text{W–CSP}}$ and $P_t^{\text{P–CSP}}$ are the WP and PV powers to the heat of the CSP plant, respectively; M_{CSP} is the cost coefficient of power to heat; C_2 is the operating cost of the grid thermal power unit; $M_{i,t}$ is the start and stop variables of the i-th thermal power unit; a, b, and c are the coal consumption cost coefficients of thermal power units; $P_{gi,t}$ is the output power of the thermal power unit at time t; $S_{i,\text{CSD}}$ is the start–stop cost of the i-th thermal power unit; C_3 is the penalty cost of abandoning power; and M_W and M_P are the penalty cost coefficients of abandoning WP and PV powers, respectively.

The wind and solar curtailment power are expressed in **Eq. 2.**

$$\begin{cases} P_t^{\text{W–D}} = P_t^{\text{Pre–W}} - P_t^{\text{W}} \\ P_t^{\text{P–D}} = P_t^{\text{Pre–P}} - P_t^{\text{P}} \end{cases}, \quad (2)$$

where $P_t^{\text{W–D}}$ and $P_t^{\text{P–D}}$ are the curtailment power powers of WP and PV at time t, $P_t^{\text{Pre–W}}$ and $P_t^{\text{Pre–P}}$ are the forecast powers of WP and PV, respectively, and P_t^{W} and P_t^{P} are the WP and PV powers, respectively.

3.2 Constraints
3.2.1 Concentrated Solar Power Plant Operation Constraints

The charging power of the heat storage system in the CSP plant comprises the heating power, WP, and PV electric heating power. The formula can be expressed by **Eqs. 3, 4.**

$$P_t^{\text{c}} = \left[P_t^{\text{CSP}} + \left(P_t^{\text{W–CSP}} + P_t^{\text{P–CSP}}\right)\eta_{\text{e–h}}\right]\eta_c, \quad (3)$$

$$P_t^{\text{e}} = \frac{P_t^{\text{T–CSP}}}{\eta_{\text{e}}}, \quad (4)$$

where $P_t^{\text{CSP}-T}$ is the solar heating power in the CSP plant, $P_t^{T-\text{CSP}}$ is the heat exchange power between the heat storage system and the heat-conducting medium in the CSP plant, P_t^c is the charging power during the thermal storage process of the CSP plant, P_t^e is the heat release power in the heat storage process of the CSP plant, η_{e-h} is electric to heat efficiency, η_c is the charging efficiency, and η_e is the exothermic efficiency.

Moreover, because the heat storage system of the CSP plant cannot be charged and released simultaneously, the formula can be expressed by **Eq. 5**.

$$P_t^c P_t^e = 0. \tag{5}$$

Capacity constraints of the energy storage system of the CSP plant can be within a limited range as shown in **Eq. 6**.

$$\begin{cases} E_{\text{csp, min}} \le E_{\text{csp,}t} \le E_{\text{csp, max}}, \\ E_{\text{csp,}T} = E_{\text{csp,}0} \end{cases}, \tag{6}$$

where $E_{\text{csp,}t}$ is the heat storage of the heat storage system at time t.

In addition, in order to ensure the response speed in the scheduling process and the life of the heat storage tank, it is necessary to make the heat storage capacity $E_{\text{csp,}T}$ of the heat storage system at the end of the cycle equal to the value of $E_{\text{csp,}0}$ at the beginning of the cycle.

3.2.2 Energy Storage Operation Constraints

The ESS should be continuously charged and discharged during operation. The charge, discharge, and remaining power of ESS must be greater than or equal to 0 and less than or equal to the maximum capacity. Also, the remaining power at the final moment and the starting moment should be equal. Constraints of the ESS are shown in **Eqs. 7–13**.

$$\left\| \begin{matrix} P_{i,t}^{\text{BESS}} \\ Q_{i,t}^{\text{BESS}} \end{matrix} \right\| \le C_{i,\text{max}}^{\text{BESS}}, \tag{7}$$

$$P_{i,t}^{\text{BESS}} = P_{i,t}^{\text{DES}} - P_{i,t}^{\text{CES}}, \tag{8}$$

$$0 \le P_{i,t}^{\text{DES}} \le U_{i,t}^{\text{BESS}} C_{\text{max}}^{\text{BESS}}, \tag{9}$$

$$0 \le P_{i,t}^{\text{CES}} \le U_{i,t}^{\text{BESS}} C_{\text{max}}^{\text{BESS}}, \tag{10}$$

$$0 \le E_{i,t}^{\text{BESS}} \le C_{i,\text{max}}^{\text{BESS}}, \tag{11}$$

$$E_{i,t}^{\text{BESS}} = E_{i,t-1}^{\text{BESS}} + \eta_{\text{cBESS}} P_{i,t}^{\text{CES}} - P_{i,t}^{\text{DES}} / \eta_{\text{dBESS}}, \tag{12}$$

$$E_{i,T}^{\text{BESS}} = E_{i,0}^{\text{BESS}}, \tag{13}$$

where $C_{i,\text{max}}^{bess}$ is the maximum capacity of the ESS i; $P_{i,t}^{bess}$ and $Q_{i,t}^{bess}$ are the active power and reactive power provided by the ESS i at time t, respectively; $P_{i,t}^{Des}$ is the active power discharged by the ESS i at time t; and $P_{i,t}^{Ces}$ is the active power charged by the ESS i at time t.

Same as the heat storage system of the CSP plant, the charging or discharging behaviors of the ESS cannot be performed at the same time. Also, $U_{i,t}^{bess}$ is a binary variable; when $U_{i,t}^{bess} = 1$, the ESS is charged, otherwise, it is discharged. $E_{i,t}^{bees}$ is the remaining power of the ESS i at time t, ηcbess is the charging efficiency of the ESS, and ηdbess is the discharge efficiency of the ESS.

3.2.3 Other Constraints

3.2.3.1 System Power Balancing Constraints

The regional grid of renewable energy should ensure the balance constraints of active and reactive power. In the case of ignoring the line loss, each node power transmission to the power grid must be balanced at each operation period as described in **Eq. 14**.

$$P_{\text{load,}t} = P_t^{\text{W-G}} + P_t^{\text{P-G}} + P_t^{\text{CSP-G}} + P_t^{\text{BESS}} + \sum_{i=1}^{3} P_{gi,t}, \tag{14}$$

where $P_{\text{load,}t}$ is the forecast load demand; $P_t^{\text{W-G}}$ and $P_t^{\text{P-G}}$ are the active powers delivered by WP and PV to the power grid, respectively; $P_t^{\text{CSP-G}}$ is the active power delivered by the CSP plant to the power grid; and P_t^{BESS} is the active power delivered by the ESS to the power grid.

Similarly, the reactive power balance constraint of the system can be expressed in **Eq. 15**.

$$Q_{\text{load,}t} = Q_t^{\text{W-G}} + Q_t^{\text{P-G}} + Q_t^{\text{CSP-G}} + Q_t^{\text{BESS}} + \sum_{i=1}^{3} Q_{gi,t}, \tag{15}$$

where $Q_{\text{load,}t}$ is the forecast load demand; $Q_t^{\text{W-G}}$ and $Q_t^{\text{P-G}}$ are the reactive powers delivered by WP and PV to the power grid; respectively; $Q_t^{\text{CSP-G}}$ is the reactive power delivered by the CSP plant to the power grid; and Q_t^{BESS} is the reactive power output by the ESS to the power grid.

3.2.3.2 Voltage Deviation Constraints

The node voltage limit constraint of the renewable energy system cannot exceed its allowable maximum and minimum voltage values, and the constraint is shown in **Eq. 16**.

$$U_i^{\text{min}} \le U_{i,t} \le U_i^{\text{max}}, \tag{16}$$

where U_i^{max} and U_i^{min} are the maximum and minimum allowable node voltages, respectively.

3.2.3.3 Photovoltaic Constraints

The output power of the PV should be guaranteed to be less than the maximum power it can provide. The constraints are shown in **Eq. 17**.

$$\begin{cases} 0 \le P_{i,t}^{\text{pv}} \le P_{\text{pvs}} \\ 0 \le Q_{i,t}^{\text{pv}} \le Q_{\text{pvs}} \end{cases}, \tag{17}$$

where $P_{i,t}^{\text{pv}}$ is the active power provided by PV i at time t, $Q_{i,t}^{\text{pv}}$ is the reactive power provided by PV i at time t, P_{pvs} is the maximum active power provided by PV i, and Q_{pvs} is the maximum reactive power provided by the PV i.

3.2.3.4 Wind Power Constraints

Wind power should be ensured that the output power must be less than the maximum power it can provide. The constraints are shown in **Eq. 18**.

$$\begin{cases} 0 \le P_{i,t}^{wp} \le P_{\text{wps}} \\ 0 \le Q_{i,t}^{wp} \le Q_{\text{wps}} \end{cases}, \tag{18}$$

where $P_{i,t}^{wp}$ is the active power provided by the WP i at time t, $Q_{i,t}^{wp}$ is the reactive power provided by the WP i at time t, P_{wps} is the maximum active power provided by the WP i, and Q_{wps} is the maximum reactive power provided by the WP i.
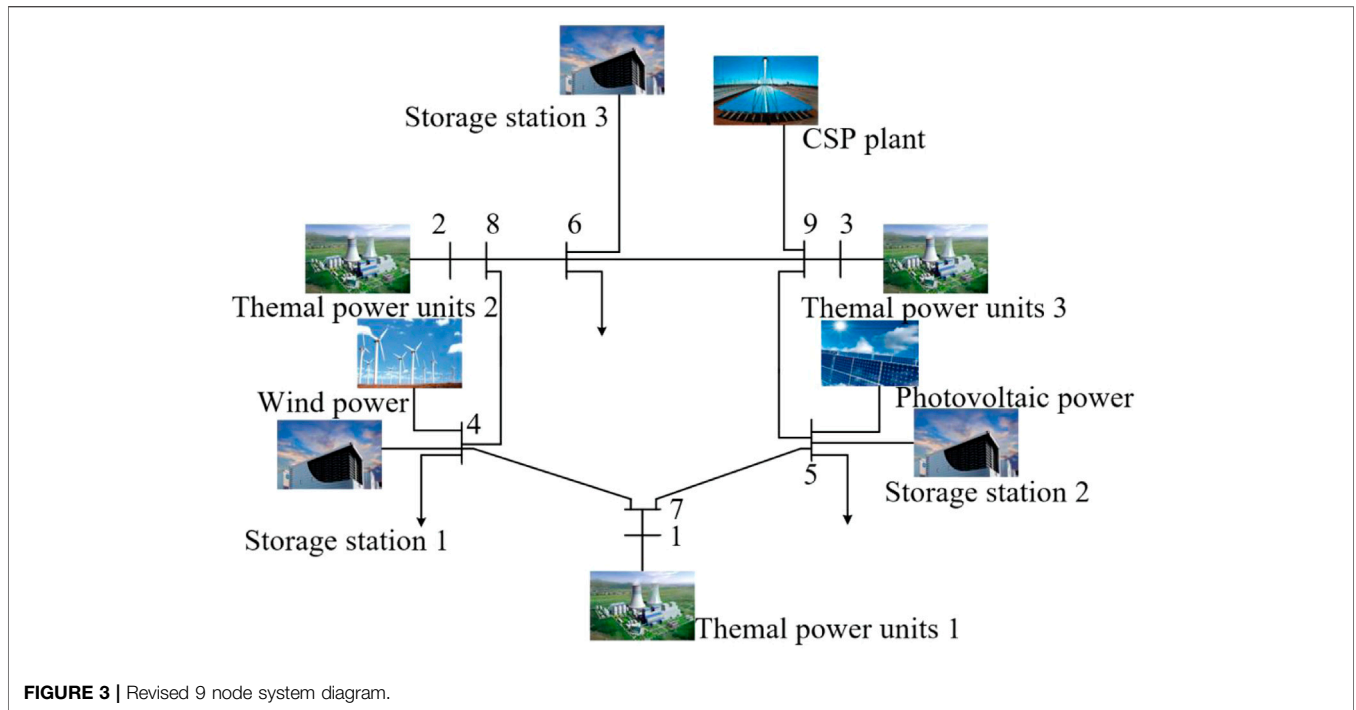
FIGURE 3 | Revised 9 node system diagram.

TABLE 1 | Operation parameters of thermal units.

Nodes position	Output limit/	Output lower limit/	Climb rate/	Cost factor		
	P_{max} (MW)	P_{mim} (MW)	(MW/h)	a/(yuan/MW2)	b/(yuan/MW2)	c/yuan
1	250	45	25	0.25	20	0
3	130	30	15	0.01	20	0
8	190	35	15	0.01	20	0

TABLE 2 | Operation parameters of CSP.

CSP plant operating parameters	Numerical value	CSP plant operating parameters	Numerical value
Rated output power of the CSP plant/MW	50	CSP plant operating cost ks/yuan	50
Minimum output power/kW	12	Maximum daily heat storage capacity/(MW·h)	800
CSP plant ramp rate/(MW/h)	40	Initial value of heat storage capacity of the heat storage system/(MW·h)	400
Heat loss rate of the heat storage system/%	3	Heat storage lower limit of the heat storage system/(MW·h)	100
Thermal-electric conversion efficiency of the CSP plant/%	0.4		

3.2.3.5 Thermal Power Unit Constraints

When the thermal power unit is running, the processing constraints of the thermal power unit are given by **Eqs. 19**, **20**.

$$\begin{cases} P_{Gi,\min} \le P_{Gi,t} \le P_{Gi,\max} \\ U_{i,t} = 1 \end{cases}, \quad (19)$$

where $P_{Gi,\min}$ and $P_{Gi,\max}$ are the minimum and maximum outputs of the thermal power unit during operation, respectively.
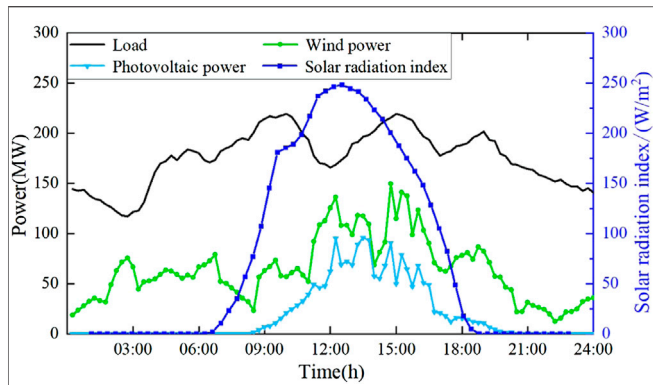
When the thermal power unit is less than the minimum technical output, its output is $U_{i,t} = 0$

$$\begin{cases} P_{Gi,t} = 0, P_{Gi,t} \le P_{Gi,\min} \\ U_{i,t} = 0 \end{cases}. \quad (20)$$

Thermal power unit climbing constraints are given by **Eq. 21**.

$$\begin{cases} P_{Gi,t} - P_{Gi,t-1} + U_{i,t-1}\left(P_{Gi,\min} - R_i^u\right) + \\ U_{i,t}\left(P_{Gi,\max} - P_{Gi,\min}\right) \le P_{Gi,\max} \\ P_{Gi,t-1} - P_{Gi,t} + U_{i,t}\left(P_{Gi,\min} - R_i^u\right) + \\ U_{i,t-1}\left(P_{Gi,\max} - P_{Gi,\min}\right) \le P_{Gi,\max} \end{cases}, \quad (21)$$

where R_i^u is the ramp rate of the i-th thermal power unit.

FIGURE 4 | Typical daily load, wind power, photovoltaic, and solar radiation index prediction curve. Analysis of the results of the cases

Thermal power unit start and stop time constraints are given by **Eq. 22**

$$\begin{cases} \sum_{k=t}^{t+T_S-1} \left(1 - U_{i,k}\right) \ge T_S \left(U_{i,t-1} - U_{i,t}\right) \\ \sum_{k=t}^{t+T_O-1} U_{i,k} \ge T_O \left(U_{i,t} - U_{i,t-1}\right) \end{cases}, \quad (22)$$

where T_S and T_O are the minimum shutdown and startup times, respectively.

The joint optimal scheduling framework of the renewable energy regional grid with the ESS and CSP plant proposed in our study is shown in **Figure 2**.

4 CASES ANALYSIS

4.1 Overview of the Cases System

In our study, the modified IEEE9 node system is used to analyze the cases. We use Yalmip to build mathematical models of the joint optimal scheduling of the renewable energy regional grid with the ESS and CSP plant model and the CPLEX commercial solver to solve the optimization function in Matlab (R2018B). The case study is carried out on a configuration environment with i7-11700K CPU and 64 GB RAM. The 9-node model diagram is shown in **Figure 3**.

In **Figure 3**, three thermal power units with installed capacities of 250, 190, and 130 MW at nodes 1, 2, and 3, respectively; the ESS with an installed capacity of 10 MW at nodes 4, 5, and 6, respectively; a CSP plant with an installed capacity of 50 MW at node 9; a PV with an installed capacity of 100 MW at node 5; and a WP with an installed capacity of 120 MW at node 4 are shown.

The operating parameters of the thermal power unit are shown in **Table 1**.

The operation and parameters of the CSP plant are shown in **Table 2**.

The load predicted power, WP predicted power, PV predicted power, and solar radiation index of the renewable energy regional grid system of a typical day are shown in **Figure 4**.

4.2 Analysis of the Results of the Cases

In order to verify the effectiveness of the proposed optimal scheduling model for the renewable energy regional power grid with the ESS and CSP plant, we set the following three models for comparison.
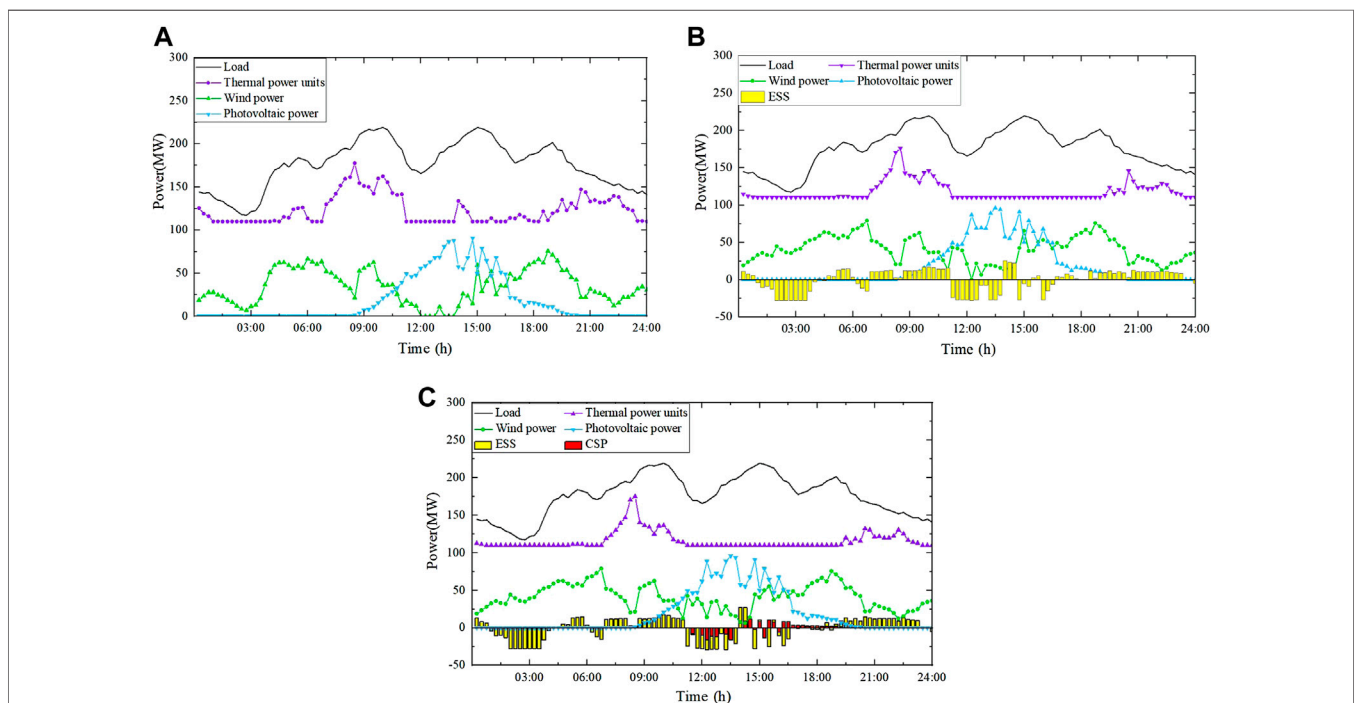

FIGURE 5 | The power balance of regional renewable energy grid with models 1,2 and 3 **(A)** the day-ahead scheduling results of model 1; **(B)** the day-ahead scheduling results of model 2; **(C)** the day-ahead scheduling results of model 3.
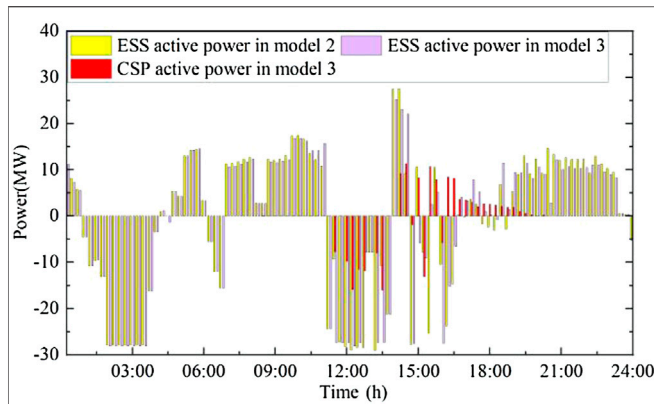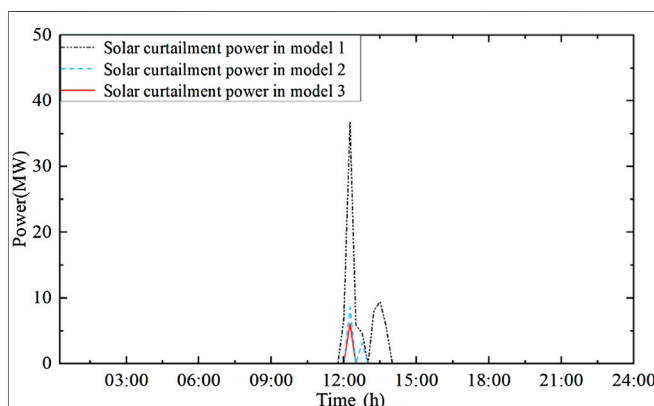
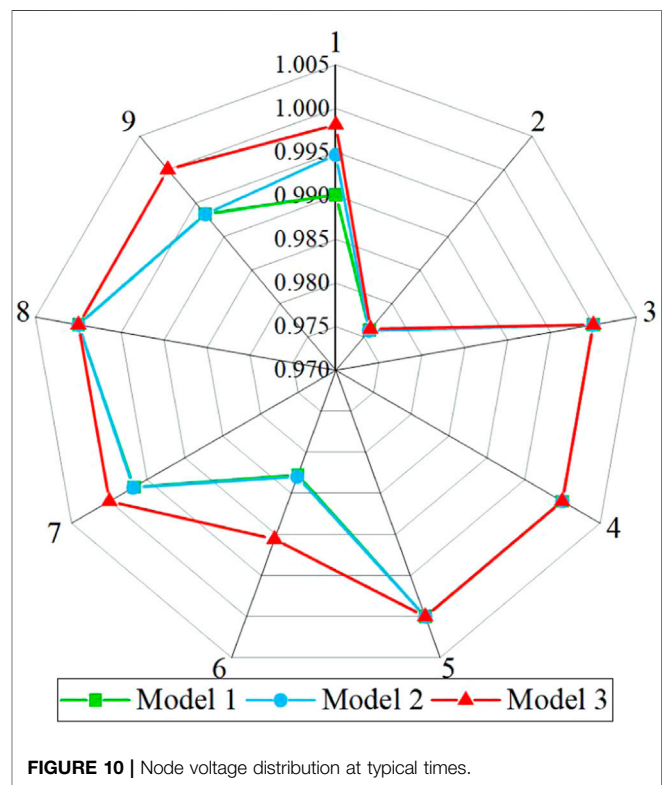FIGURE 6 | Power balance of the ESS and CSP plant active power with model 2 and model 3
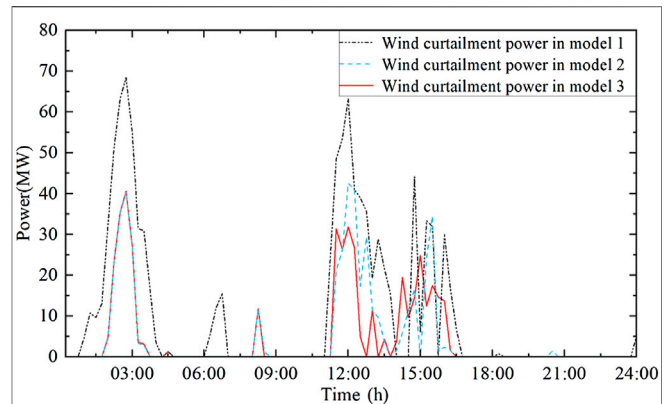
FIGURE 9 | Comparison diagram of wind curtailment power in the scheduling model.
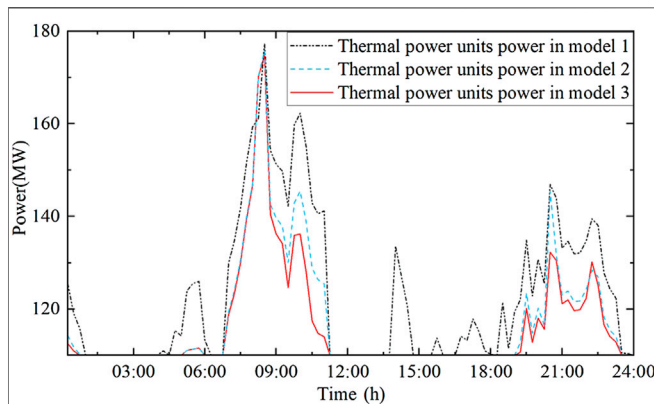
FIGURE 7 | Scheduling model power comparison diagram of thermal power units.

FIGURE 8 | Comparison diagram of solar curtailment power in the scheduling model.

FIGURE 10 | Node voltage distribution at typical times.

Model 2: A day-ahead optimal scheduling model considering the ESS is adopted for the renewable energy regional power grid.

Model 3: The scheduling model proposed in this study is adopted for the renewable energy regional power grids, and the joint optimal scheduling of the ESS and CSP plant is considered.

Figure 5A–C show the day-ahead scheduling results of model 1, model 2, and model 3, respectively.

In **Figure 5A**, the thermal power generator unit in model 1 undertakes the primary load power consumption of the system. Due to the high output of WP during 00:00–05:00, the load

Model 1: The traditional day-ahead scheduling model is adopted for the renewable energy regional power grid, and the joint optimal scheduling of the ESS and CSP plant is not considered.

TABLE 3 | Comparison of costs under three models.

Parameter	Model 1	Model 2	Model 3
Thermal power unit output cost/yuan	8.6506×10^5	8.3104×10^5	8.2333×10^5
Wind and solar curtailment power penalty cost/yuan	1.0671×10^6	4.6444×10^5	4.2604×10^4
Solar curtailment rate/%	0.2294	0.1049	0.0973
Wind curtailment rate/%	0.0421	0.0064	0.0033

demand during this period is limited. The WP exhibits anti-peak shaving characteristics, which makes the WP consumption of the regional grid of renewable energy insufficient. In addition, the solar radiation index is high during 12:00–16:30, and the PV output is mainly concentrated during this time period, which will also lead to serious PV consumption problems. In **Figure 5B**, that is, in model 2, the problem of WP and PV absorption in the above two periods in the system is well-solved due to the access of the ESS. The output power of WP and PV increases significantly during the abovementioned period. Also, the discharge of the ESS alleviates the peak of electricity consumption during 19:00–22:00. In **Figure 5C**, the ESS and CSP plant are used as flexible resources in the regional power grid to further improve the WP and PV consumption problem during the abovementioned period in model 3. Compared with model 1 without the ESS and CSP, model 2 only has the ESS involved in system scheduling. In model 3, due to the coordinated regulation of the ESS and the CPS plant, the power curve of the thermal power unit is smoother, and the primary active power output is maintained during the off-peak period.

Figure 6 shows the active output power curves of the ESS and CSP plant in model 2 and model 3.

In **Figure 6**, the ESS in model 2 and model 3 is charged more and less discharged during 00:00–05:00, absorbing the curtailed wind generated by less load in the renewable energy system. More charging and less discharging during 12:00–14:30 can absorb the solar curtailment power caused by the high solar radiation index and intense solar power, among which the radiation index is high during this period. Also, the CSP plant passes electricity to heat during this period, by converting the wind and solar curtailment power in the regional power grid into heat for storage, consuming more abandoned energy with the ESS, and improving the utilization rate of renewable energy. Furthermore, during 14:30–20:00, the electric energy is provided during the peak load period to cooperate with the ESS and CSP plant to relieve the peak regulation pressure of the thermal power unit. During the rest period, the charging and discharging of the ESS is alternately performed to play its role in the renewable energy regional power grid regulating effect.

Figures 7–9 are the power comparison diagram and the abandoned solar and power wind power comparison diagram of the models 1, 2, and 3 thermal power units, respectively.

In **Figures 7–9**, compared with model 1 and model 2, in model 3, due to the coordinated regulation of the ESS and CPS plant, the thermal power unit has the least output. The proposed scheduling model alleviates the peak load regulation pressure of thermal power units obviously. In addition, the improvement effect of wind and solar curtailment power is most obvious in **Figure 8** and

Figure 9. During 00:00–05:00 and 12:00–17:00, the wind curtailment power decreased significantly, and the absorption effect of solar curtailment power is remarkable during 12:00–14:30.

Further analysis is carried out on node voltage during the peak period of the renewable energy regional power grid. Because during 20:00 is the peak load period, the voltage drop of the system point node is relatively significant, so this time is selected as a typical time. Then, we set three cases to study the role of the ESS and CSP plant in voltage support of the renewable energy regional power grid. **Figure 10** is the node voltage distribution map at typical times.

In the analysis of **Figure 10**, the per-unit value of all node voltages is in the range of 0.95–1 p.u. When the ESS is connected to model 2, due to the voltage regulation effect of the ESS system, the system node voltage is slightly improved. In model 3, because the CSP plant provides both active and reactive power to the system, the voltage at node 6 and node 9 improves obviously. In summary, the proposed model can effectively avoid the voltage drop problem and improve the voltage quality of the renewable energy regional power grid.

Table 3 shows the output cost of thermal power units, the penalty cost of curtailing solar and wind power, and the total rate of wind and solar curtailment under three models.

In **Table 3**, compared with model 1, model 3 reduces the thermal power unit output cost from 8.6506×10^5 (CNY) to 8.2333×10^5 (CNY) and reduces the wind and solar curtailment power penalty cost from 1.0671×10^6 (CNY) to 4.2604×10^4 (CNY). In addition, the wind curtailment rate is reduced from 0.2294% to 0.0973%, and the solar curtailment rate is reduced from 0.0421% to 0.0033%. From the abovementioned cases, we found that the model which we proposed can effectively reduce the operating cost and increase the new energy consumption of the renewable energy regional power grid.

5 CONCLUSION

This study proposes a joint optimal scheduling model for the regional power grid with the ESS and CSP plant, which considers the constraints of renewable energy operation, power balance, voltage deviation, and other constraints in the renewable energy regional power grid. Through the case analysis, the following conclusions are drawn:

1) The proposed scheduling model can fully utilize the energy time-shift characteristics of the ESS and CSP plant and also improves the flexibility of the ESS and CSP plant by absorbing wind and solar power generation and alleviating the peak load regulation pressure of thermal power units. Moreover, this

significantly reduces the operating cost of the regional power grid.

2) The proposed scheduling model reduces the system solar curtailment power rate of the traditional scheduling model from 0.2294% to 0.0973%. The system wind curtailment power rate ranges from 0.0421% to 0.0033%. Also, the unit voltage of the system node is maintained above 0.98 p.u. at the peak period of electricity consumption, which improves the voltage quality of the system.

The construction cost of the electricity-to-heat transfer part in the CSP plant is not considered in our research, so the application value of the model proposed in our study in areas with low wind and solar curtailment power needs further consideration. In future research, we consider further increasing the research on the uncertainty of power supply and load, consider the impact of user demand response on renewable energy systems, and study the specific implementation plan of the CSP plant electric heating part.

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DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

YD: conceptualization, methodology, and writing—review and editing. ZH: investigation, formal analysis, software, and data curation. XL: validation and software. SM: supervision and financial support. FG and WL: writing–review and editing.

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