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EDITED BY
Yuanxing Xia,
Hohai University, China

REVIEWED BY
Qin Wang,
Electric Power Research Institute (EPRI),
United States
Manyun Huang,
Hohai University, China

*CORRESPONDENCE
Xiang Gao,
✉ gaoxiang@szpu.edu.cn

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Optimal revenue sharing model of a wind–solar-storage hybrid energy plant under the green power trading market

Zhuo Zeng[1], Xiang Gao[2]*, Baling Fang[3], Tao Zhang[1] and Ying Zhu[1]

[1]College of Electrical and Information Engineering, Hunan University, Changsha, China, [2]Industrial Training Centre, Shenzhen Polytechnic University, Shenzhen, China, [3]College of Electrical and Information Engineering, Hunan University of Technology, Zhuzhou, China

In the current model, the unclear and unreasonable method of revenue sharing among wind-solar-storage hybrid energy plants may a lso hinder the effective measurement of energy storage power station costs. This lack of clarity discourages energy storage from effectively collaborating with renewable energy stations for greenpower trading and spot trading.Therefore, this study proposes an optimal revenue sharing model of wind-solar-storage hybrid energy plant under medium and long-term green power trading market to facilitate the coordinated operation and equitable revenue allocation. Firstly, a method for decomposing transaction volume of green power is introduced by considering the uncertainty of spot market prices and physical delivery characteristics of green power trading. Then, a coordinated scheduling strategy of hybrid renewable energy plant is proposed to maximize revenues generated from both the green power and spot markets. Consequently, a cost-benefit contribution index system is developed to quantify the contribution of energy storage in the wind-solar-storage hybrid power plant. The revenue sharing model based on the minimum cost-remaining savings (MCRS) method can significantly increase overall revenue for renewable energy plants by reducing deviation penalties. It also enhances the operating revenue of energy storage power stations by considering the contributions of both energy storage and renewable energy plant in the green power market. The superiority of the proposed cooperation revenue sharing m odel for profitability enhancement of energy storage is v alidated through comparative case studies.

KEYWORDS

renewable energy, energy storage, electricity market, green power trading, hybrid energy plant

1 Introduction

As a flexible resource with rapid response ability, an energy storage system can assist a renewable energy power plant to complete its power trading by tracking the scheduling plan (Guo et al., 2023) and power time shift (Abdelrazek and Kamalasadan, 2016; Castro and Espinoza-Trejo, 2023). Since green power trading also delivers the environmental values of renewable energy compared with conventional electricity trading, the particularity of the green electricity market and its coupling relationship with the spot market should be considered further in formulating the operational strategy of energy storage for renewable energy (Li et al., 2024; Yang et al., 2024). With the determination of the independent dominant position of energy storage in the electricity market, the existing research focuses on the mechanism design of the energy market (Akhavan-Hejazi and Mohsenian-Rad, 2014; Krishnamurthy et al., 2018; Xu et al., 2018) and the auxiliary market that adapt to the physical characteristics of energy storage (He et al., 2017; Yang et al., 2023). However, few studies considered the impact of green electricity trading on wind–solar-storage hybrid power plants (Ju et al., 2024). Furthermore, the revenue sharing method in existing research cannot guarantee that the energy storage would be fully able to obtain the return in promoting the realization of the green values of renewable energy (González-Garrido et al., 2020). Therefore, it is necessary to study a scheduling strategy coordinated by an energy storage power station for participating in multiple power markets at the same time and establishing a revenue sharing model for wind–solar-storage hybrid power plants by considering green power trading.

The main contributions of this work are two-fold: (1) a green power trading volume decomposition method considering the uncertainty of spot electricity prices is proposed. Furthermore, a coordinated scheduling strategy of a hybrid renewable energy plant is established with the goal of maximizing revenue from the green power and spot market, and (2) a cost–benefit contribution index system is developed to quantify the contribution of energy storage in the wind–solar-storage hybrid energy plant. Furthermore, a revenue sharing model with contribution degree correction based on the minimum cost-remaining saving (MCRS) method is proposed to enhance the competitive vitality of energy storage in the electricity market.

2 Coordinated scheduling of the hybrid renewable energy plant under the green power market

Although the revenue from a portion of renewable energy can be determined through the green power trading contract, the overall revenue in the green power and spot markets can be improved by adjusting the decomposition curve of the green power transaction volume (Wu et al., 2019). Since it is difficult to predict the electricity price in the spot market, a multi-scenario approach is usually used to describe the uncertainty associated with the day-ahead clearing electricity prices. In view of the day-ahead market clearing price uncertainty, a series of electricity price scenarios are generated by the Latin hypercube sampling (LHS) method. Subsequently, a fast scene reduction method based on Kantorovich probability distance is used to reduce the initial scene to obtain a suitable number of representative day-ahead clearing price scenarios (Roustaee and Kazemi, 2021; Yang et al., 2023), aiming to retain scenarios with the smallest probability distance from the initial scene. Then, a green power trading volume decomposition model is constructed by considering the uncertainty of spot electricity price, the objective function is presented as Equations 1–4:

$$\max\ R^{\mathrm{fc}} = \rho_k \sum_{k=1}^{N_\pi}\sum_{t=1}^{T}\left[\beta^{\mathrm{g}}P_t^{\mathrm{g}} + \beta_{t,k}^{\mathrm{da}}\left(P_{\mathrm{un},t}^{\mathrm{da}} - P_t^{\mathrm{g}}\right)\right]\Delta t - C_{\mathrm{ESS}}^{\mathrm{da,oper}}, \tag{1}$$

$$P_{\mathrm{PW},t}^{\mathrm{pr}} = P_{\mathrm{PV},t}^{\mathrm{pr}} + P_{\mathrm{W},t}^{\mathrm{pr}}, \tag{2}$$

$$P_{\mathrm{un},t}^{\mathrm{da}} = P_{\mathrm{PW},t}^{\mathrm{pr}} + P_{\mathrm{ESS},t}^{\mathrm{da,dis}} - P_{\mathrm{ESS},t}^{\mathrm{da,ch}}, \tag{3}$$

$$C_{\mathrm{ESS}}^{\mathrm{da,oper}} = \sum_{t=1}^{T}\lambda_{\mathrm{ESS}}\left(\frac{P_{\mathrm{ESS},t}^{\mathrm{da,dis}}}{\eta_{\mathrm{dis}}} + \eta_{\mathrm{ch}}P_{\mathrm{ESS},t}^{\mathrm{da,ch}}\right)\Delta t, \tag{4}$$

where R^{fc} is the expected revenue of the hybrid renewable energy plant; ρ_k is the probability of occurrence of day-ahead price scenario k; β^{g} is the contract price of green power trading; P_t^{g} is the output of green power decomposed to time t; $P_{\mathrm{PV},t}^{\mathrm{pr}}$ and $P_{\mathrm{W},t}^{\mathrm{pr}}$ are the predicted output power of wind and solar energies at time t, respectively; $P_{\mathrm{un},t}^{\mathrm{da}}$ denotes the day-ahead planning output power of the hybrid energy plant; $P_{\mathrm{ESS},t}^{\mathrm{da,dis}}$ and $P_{\mathrm{ESS},t}^{\mathrm{da,dis}}$ are the charging and discharging power of the energy storage power station in the day-ahead plan, respectively; $\beta_{t,k}^{\mathrm{da}}$ is the day-ahead spot market clearing price; $C_{\mathrm{ESS}}^{\mathrm{da,oper}}$ is the operating cost of the energy storage power station; λ_{ESS} is the unit charge and discharge cost; and η_{ch} and η_{dis} are the charge efficiency and discharge efficiency, respectively.

In order to ensure the smooth progress of electricity trading in the medium- and long-term markets, it is stipulated that the sum of green power consumption in each period equals the decomposed green power output for the scheduling cycle (Fan et al., 2020). Therefore, the constraints Equations 5–10 of the hybrid renewable energy plant are as follows (Cao et al., 2024a):

$$P_t^{\mathrm{g}} \le P_{\mathrm{un},t}^{\mathrm{da}}, \tag{5}$$

$$\sum_{t=1}^{T} P_t^{\mathrm{g}} = P_T^{\mathrm{g,plan}}, \tag{6}$$

$$\underline{P}_{\mathrm{L},t}^{\mathrm{g}} \le P_t^{\mathrm{g}} \le \bar{P}_{\mathrm{L},t}^{\mathrm{g}}, \tag{7}$$

$$P_{\mathrm{ESS},t}^{\mathrm{da,ch}} = P_{\mathrm{PV},t}^{\mathrm{da,ch}} + P_{\mathrm{W},t}^{\mathrm{da,ch}}, \tag{8}$$

$$0 \le P_{\mathrm{PV},t}^{\mathrm{da,ch}} \le P_{\mathrm{PV},t}^{\mathrm{pr}}, \tag{9}$$

$$0 \le P_{\mathrm{W},t}^{\mathrm{da,ch}} \le P_{\mathrm{W},t}^{\mathrm{pr}}, \tag{10}$$

where $\underline{P}_{\mathrm{L},t}^{\mathrm{g}}$ and $\bar{P}_{\mathrm{L},t}^{\mathrm{g}}$ are the lower and upper limits of the green power decomposition volume in time period t, respectively; $P_T^{\mathrm{g,plan}}$ is the green power output that is planned to be decomposed into the scheduling cycle T; and $P_{\mathrm{PV},t}^{\mathrm{da,ch}}$ and $P_{\mathrm{W},t}^{\mathrm{da,ch}}$ are the charging power of the energy storage power station from the wind farm and photovoltaic power station in day-ahead plan; respectively.

To minimize the operational cost of the energy storage system, it is necessary to consider the physical constraints of the energy storage power station (Cao et al., 2024b), including charging and discharging power constraints and the state of charge constraints (Zhong et al., 2023), as shown below:

$$\begin{cases} P_{\mathrm{ESS},t}^{\mathrm{da,ch}} \le \min\left(P_{\max}^{\mathrm{ESS}}, \dfrac{E_{\mathrm{rat}}soc_{\max} - E_{t-1}}{\eta_{\mathrm{ch}}\Delta t}\right) \\ P_{\mathrm{ESS},t}^{\mathrm{da,dis}} \le \min\left(P_{\max}^{\mathrm{ESS}}, \dfrac{(E_{\mathrm{rat}}soc_{\min} - E_{t-1})\eta_{\mathrm{dis}}}{\Delta t}\right) \end{cases}, \tag{11}$$

$$0 \le P_{\mathrm{ESS},t}^{\mathrm{da,dis}} \le u_{\mathrm{ESS},t}^{\mathrm{ch}} P_{\mathrm{ESS}}^{\mathrm{ch,\,max}}, \tag{12}$$

$$0 \le P_{\mathrm{ESS},t}^{\mathrm{da,dis}} \le \left(1 - u_{\mathrm{ESS},t}^{\mathrm{ch}}\right) P_{\mathrm{ESS}}^{\mathrm{dis,\,max}}, \tag{13}$$

$$E_t = \begin{cases} E_0 & t = T \\ E_{t-1} + \eta_{\mathrm{ch}} P_{\mathrm{ESS},t}^{\mathrm{da,ch}}\Delta t - \dfrac{P_{\mathrm{ESS},t}^{\mathrm{da,dis}}\Delta t}{\eta_{\mathrm{dis}}} & t \ne T \end{cases}, \tag{14}$$

where $P_{\max}^{\mathrm{ESS}}$ is the maximum charging and discharging power of the energy storage power station; $u_{\mathrm{ESS},t}^{\mathrm{ch}}$ means the charging status bits; $soc_{\max}$ and $soc_{\min}$ are the maximum and minimum state of charge, respectively; E_{rat} denotes the rated capacity; E_t is the energy state of the energy storage power station at the end of time period t; and E_0 is the beginning power of energy storage in a dispatch cycle.

After determining the output for each time period, the execution of green power and spot trading requires the cooperative control of an energy storage power station to mitigate the adverse effects caused by the stochasticity and volatility of wind power and photovoltaic output (McPherson et al., 2007; He et al., 2017; Krishnamurthy et al., 2018). An energy storage power station scheduling model is constructed for the participation of the wind–solar-storage plant in green power and spot trading. The objective function is presented as Equation 15:

$$\max R_{\mathrm{all}} = R_{\mathrm{sell}} - C_{\mathrm{ab}} - C_{\mathrm{bias}} - C_{\mathrm{ESS}}^{\mathrm{oper}}, \tag{15}$$

where R_{all} is the total revenue of the wind–solar-storage hybrid energy plant during the operating cycle; R_{sell} is the revenue from electricity sales; C_{ab} is the power curtailment loss; C_{bias} is the deviation penalty cost; and $C_{\mathrm{ESS}}^{\mathrm{oper}}$ is the actual operation cost of the energy storage power station. The calculation formula refers to Equation 4. The constraints of the scheduling model are shown in Equations 11–14. The revenue from the hybrid renewable energy plant includes green power trading revenue, day-ahead spot market revenue, and intraday real-time market revenue, and the calculation method is shown as Equations 16–22:

$$R_{\mathrm{sell}} = R_{\mathrm{g},t} + R_{e,t}, \tag{16}$$

$$R_{\mathrm{g},t} = \beta^{\mathrm{g}} P_t^{\mathrm{g}'}, \tag{17}$$

$$P_t^{\mathrm{g}'} = \min\left(P_t^{\mathrm{g}}, P_{\mathrm{un},t}^{*}\right), \tag{18}$$

$$R_{\mathrm{e},t} = \begin{cases} \beta_t^{\mathrm{r}}\left(P_{\mathrm{un},t}^{*} - P_{\mathrm{un},t}^{\mathrm{da}}\right) & P_{\mathrm{un},t}^{*} \le P_t^{\mathrm{g}} \\ \beta_t^{\mathrm{da}}\left(P_{\mathrm{un},t}^{*} - P_t^{\mathrm{g}}\right) + \beta_t^{\mathrm{r}}\left(P_{\mathrm{un},t}^{*} - P_{\mathrm{un},t}^{\mathrm{da}}\right) & P_t^{\mathrm{g}} \le P_{\mathrm{un},t}^{*} \le P_{\mathrm{un},t}^{\mathrm{da}} \\ \beta_t^{\mathrm{da}}\left(P_{\mathrm{un},t}^{\mathrm{da}} - P_t^{\mathrm{g}}\right) + \beta_t^{\mathrm{r}}\left(P_{\mathrm{un},t}^{*} - P_{\mathrm{un},t}^{\mathrm{da}}\right) & P_{\mathrm{un},t}^{\mathrm{da}} \le P_{\mathrm{un},t}^{*} \end{cases}, \tag{19}$$

$$P_{\mathrm{PW},t}^{*} = P_{\mathrm{PV},t}^{*} + P_{\mathrm{W},t}^{*} \tag{20}$$

$$P_{\mathrm{un},t}^{*} = P_{\mathrm{PW},t}^{*} + P_{\mathrm{ESS},t}^{\mathrm{dis}} - P_{\mathrm{ESS},t}^{\mathrm{ch}} - P_{\mathrm{re},t}^{\mathrm{ab}}, \tag{21}$$

$$P_{\mathrm{ESS},t}^{\mathrm{ch}} = P_{\mathrm{PV},t}^{\mathrm{ch}} + P_{\mathrm{W},t}^{\mathrm{ch}}, \tag{22}$$

where $R_{\mathrm{g},t}$ is the revenue from green power trading; $P_t^{\mathrm{g}*}$ is the output of green power at time t; β_t^{da} is the day-ahead spot market clearing price at time t; β_t^{r} is the clearing price in the intraday market; $R_{e,t}$ is the revenue from spot trading; $P_{\mathrm{re},t}^{*}$ denotes the total output of the hybrid energy plant at time t; and $P_{\mathrm{re},t}^{\mathrm{ab}}$ is the curtailed power. Renewable energy power trading will generate green certificate revenue (Gan et al., 2022). Therefore, the revenue from green certificate should be considered in the power curtailment loss, the calculation method is shown as Equation 23:

$$C_{\mathrm{ab}} = \mu^{\mathrm{TGC}} \lambda^{\mathrm{TGC}} P_{\mathrm{re},t}^{\mathrm{ab}} \Delta t, \tag{23}$$

where μ^{TGC} is the green certificate conversion factor and λ^{TGC} is the green certificate price. An additional deviation penalty for green power trading is proposed to improve the forecast accuracy of renewable energy output and prevent the improper arbitrage between day-ahead and intraday markets, the calculation method is shown as Equations 24–27:

$$C_{\mathrm{bias}} = \sum_{t=1}^{T} \left(\lambda^{\mathrm{p}} \Delta P_t^{+} + \lambda^{\mathrm{p}} \Delta P_t^{-} + \lambda^{\mathrm{g}} \Delta P_t^{\mathrm{g}}\right) \Delta t, \tag{24}$$

$$\Delta P_t^{\mathrm{g}} = \max\left(P_t^{\mathrm{g}} - P_{\mathrm{un},t}^{*}, 0\right), \tag{25}$$

$$\Delta P_t^{+} = \max\left[\left(P_{\mathrm{un},t}^{*} - (1+\varepsilon) P_{\mathrm{un},t}^{\mathrm{da}}\right), 0\right], \tag{26}$$

$$\Delta P_t^{-} = \max\left[\left((1-\varepsilon) P_{\mathrm{un},t}^{\mathrm{da}} - P_{\mathrm{un},t}^{*}\right), 0\right], \tag{27}$$

where ε is the allowable deviation margin; ΔP_t^{g} is the deviation assessment output of green power in time period t; λ^{g} is the deviation assessment coefficient of green power output; ΔP_t^{+} and ΔP_t^{-} are the positive and negative deviation output that exceeds the margin of the deviation assessment, respectively; and λ^{p} is the deviation assessment coefficient of the spot market.

3 Revenue sharing model of the wind–solar-storage hybrid renewable energy plant

A shared energy storage power station under the leasing mode obtains fixed funds through its capacity, and it is difficult to give full play to the competitive vitality of energy storage in the electricity market (Tang et al., 2018). In the cooperative alliance mode, the unclear and unreasonable method of revenue sharing among various subjects may also lead to difficulties in effectively measuring the cost of the energy storage power station, which makes energy storage cooperate with renewable energy stations to complete the green power trading and spot trading with insufficient enthusiasm (Liu et al., 2022). In order to develop a scientific and reasonable revenue sharing scheme, this section constructs the energy storage contribution index system from the two levels of cost and benefit in order to comprehensively measure the contribution of energy storage in the wind–solar-storage plant.

The revenue from the storage capacity generated by the peak and valley arbitrage in the intraday real-time electricity market used by wind and solar renewable energy sources is considered the opportunity cost of the energy storage power station (Silva-Monroy and Watson, 2014). The equivalent power generation of the energy storage power station is the amount of electricity that the energy storage power station stores beyond the power generation plant during the period of wind power and photovoltaic curtailment. The marginal revenue contribution degree of each subject in the wind–solar-storage plants is the ratio of the marginal revenue to the total revenue of the hybrid energy plant. The higher marginal revenue contribution degree indicates the higher importance of the participants in the plants. The improvement degree of the green power trading deviation indicates increased transaction cost due to low green power performance under bilateral negotiation transactions. The Equations 28–32 for calculating the above indicators are shown below:

$$\begin{cases} \max\ C_{\mathrm{ESS}}^{\mathrm{opp}} = \sum_{t=1}^{T} \beta_t^{\mathrm{da}} \left(P_{\mathrm{ESS},t}^{\mathrm{dis}} - P_{\mathrm{ESS},t}^{\mathrm{ch}}\right) \Delta t \\ s.t.\ (11) - (14) \end{cases}, \tag{28}$$

$$I_{\mathrm{gen}} = \sum_{t=1}^{T} \left(\hat{P}_{\mathrm{re},t}^{\mathrm{ab}} - P_{\mathrm{re},t}^{\mathrm{ab}} \right) \Delta t, \tag{29}$$

$$I_{\mathrm{ESS}} = \frac{\Delta R_{\mathrm{ESS}}}{F_S}, S = \{\mathrm{ESS}, \mathrm{PV}, \mathrm{W}\}, \tag{30}$$

$$\Delta R_{\mathrm{ESS}} = F_S - F_{S\backslash\{\mathrm{ESS}\}}, \tag{31}$$

$$I_{\mathrm{gre}} = \sum_{t=1}^{T} \left(\Delta \hat{P}_t^{\mathrm{g}} - \Delta P_t^{\mathrm{g}} \right) \Delta t, \tag{32}$$

where $C_{\mathrm{ESS}}^{\mathrm{opp}}$ is the opportunity cost of the energy storage power station; I_{gen} is the equivalent power generation; $\hat{P}_{\mathrm{re},t}^{\mathrm{ab}}$ is the curtailed power of the wind–solar energy plant; I_{ESS} is the marginal contribution degree of the energy storage power station; ΔR_{ESS} denotes the marginal revenue; S denotes the wind–solar-storage hybrid energy plant; ESS, PV, and W represent the energy storage power station, photovoltaic power station, and wind farm, respectively; F_S denotes the total revenue of the hybrid energy plant; $F_{S\backslash\{\mathrm{ESS}\}}$ denotes the revenue of the hybrid energy plant without energy storage; I_{gre} is the green power trading deviation generated by the renewable energy in the scheduling cycle T; and $\Delta \hat{P}_t^{\mathrm{g}}$ is the green power output deviation of the wind–solar energy plant.

The root mean square error and maximum tracking planned output error (Wei et al., 2023) are utilized as tracking performance evaluation indicators to compare the accuracy rate of renewable energy output with and without energy storage participation (Zhang et al., 2023). The calculation Equations 34, 35 of the accuracy improvement indicator of power output prediction are shown as follows:

$$I_{\mathrm{corr}} = 0.5\left(\kappa_{\mathrm{RMSE}} - \hat{\kappa}_{\mathrm{RMSE}}\right) + 0.5\left(\kappa_{\max} - \hat{\kappa}_{\max}\right), \tag{33}$$

$$\kappa_{\mathrm{RMSE}} = \sqrt{\frac{1}{T} \sum_{t=1}^{T} \left(P_{\mathrm{PV},t}^{*} + P_{\mathrm{W},t}^{*} + P_{\mathrm{ESS},t}^{\mathrm{dis}} - P_{\mathrm{ESS},t}^{\mathrm{ch}} - P_{\mathrm{PV},t}^{\mathrm{fc}} - P_{\mathrm{W},t}^{\mathrm{fc}} \right)^2}, \tag{34}$$

$$\kappa_{\max} = \max_{t} \left| P_{\mathrm{PV},t}^{*} + P_{\mathrm{W},t}^{*} + P_{\mathrm{ESS},t}^{\mathrm{dis}} - P_{\mathrm{ESS},t}^{\mathrm{ch}} - P_{\mathrm{PV},t}^{\mathrm{fc}} - P_{\mathrm{W},t}^{\mathrm{fc}} \right|, \tag{35}$$

where I_{corr} is the accuracy improvement indicator of power output prediction; κ_{RMSE} and $\hat{\kappa}_{\mathrm{RMSE}}$ are the average relative errors of the hybrid renewable energy plant output with and without the energy storage power station, respectively; and $\kappa_{\max}$ and $\hat{\kappa}_{\max}$ are the maximum tracking planned output errors with and without the energy storage power station, respectively.

In order to ensure the effective cost allocation of the energy storage power station and stimulate active participation of the energy storage power station in a hybrid renewable energy plant, the benefits of energy storage and renewable energy are calculated using the MCRS method based on the cooperative game theory (Zhang et al., 2020), and then, revenues are shared according to the modified contribution degree. The MCRS method will distribute cooperation gains depending on the proportion of the difference between the marginal gain ΔR_i from the cooperation of each entity and the benefit $R_{i,\min}$ from independent operation. When wind power and photovoltaic systems operate independently, they are responsible for bearing the costs of the deviation assessment. The decomposition curve of green power and actual output power is determined based on forecasted values (Yang et al., 2023). After the correction of the contribution degree, the revenue of each subject is shown as Equations 36, 37:

$$R_i^{*} = R_{i,\min} + \frac{\theta_i}{\sum\limits_{i \in S} \theta_i} \cdot \frac{\left(\Delta R_i - R_{i,\min}\right) \Delta F_S}{\sum\limits_{i \in S} \left(\Delta R_i - R_{i,\min}\right)}, \tag{36}$$

$$\theta_{\mathrm{ESS}} = w_1 I_{\mathrm{cost}} + w_2 I_{\mathrm{gen}} + w_3 I_{\mathrm{ESS}} + w_4 I_{\mathrm{gre}} + w_5 I_{\mathrm{corr}}, \tag{37}$$

where $w_1 - w_5$ is the weight of each contribution degree index of the energy storage power station; R_i^{*} is the revenue of each entity after the contribution degree correction; ΔR_i is the marginal gain calculated by Equation 31; ΔF_S is the cooperative gain of the hybrid renewable energy plant; and θ_{ESS}, θ_{PV}, and θ_{W} are the contribution degree of the energy storage, photovoltaic, and wind power, respectively; the accuracy rate of wind power and photovoltaic output is calculated according to Equation 33.

TABLE 1 Parameters of the energy storage power station.

Parameter	Value	Parameter	Value
E_{rat}	20 MWh	P_{max}^{ESS}	10 MW
soc_{max}	0.9	soc_{min}	0.1
E_{t0}	6 MWh	η_{dis}	0.95
λ_{ESS}	96 ¥/MWh	η_{ch}	0.95

4 Case studies

The wind–solar-storage hybrid energy plant in a western province of China is used as an example to validate the effectiveness of the proposed revenue sharing model. The specific operating parameters of the energy storage power station are shown in Table 1. The installed capacity of both the wind farm and photovoltaic power station is 30 MW. Each signed a green power trading contract with consumers stipulating that the output of green electricity will be 280 MWh and 120 MWh on the delivery day, respectively. The permitted power deviation range of the hybrid renewable energy plant is set to be 10%. The deviation assessment coefficient of renewable energy output is set to be 400 ¥/MWh (Jiang and Zhen, 2022). Based on the trading situation in the pilot area of the green power market, the green power price is set at 506.6 ¥/MWh, and the environmental premium is set at 91.3 ¥/MWh (Zhang et al., 2022). According to the historical clearing price data on the day-ahead electricity market, 10 sets of typical day-ahead clearing price scenarios are shown in Figure 1A. The predicted and actual output powers of the wind farm and photovoltaic power station and the clearing price in the electricity market are shown in Figure 1B.

In the intra-day scheduling stage, the wind power and photovoltaic output has a certain deviation from the day-ahead plan. Within the permitted range of deviation, the excess power of renewable energy can be sold in the real-time market, while any shortfall must be procured from that market. When the deviation is outside the permitted range, the wind farm and photovoltaic power

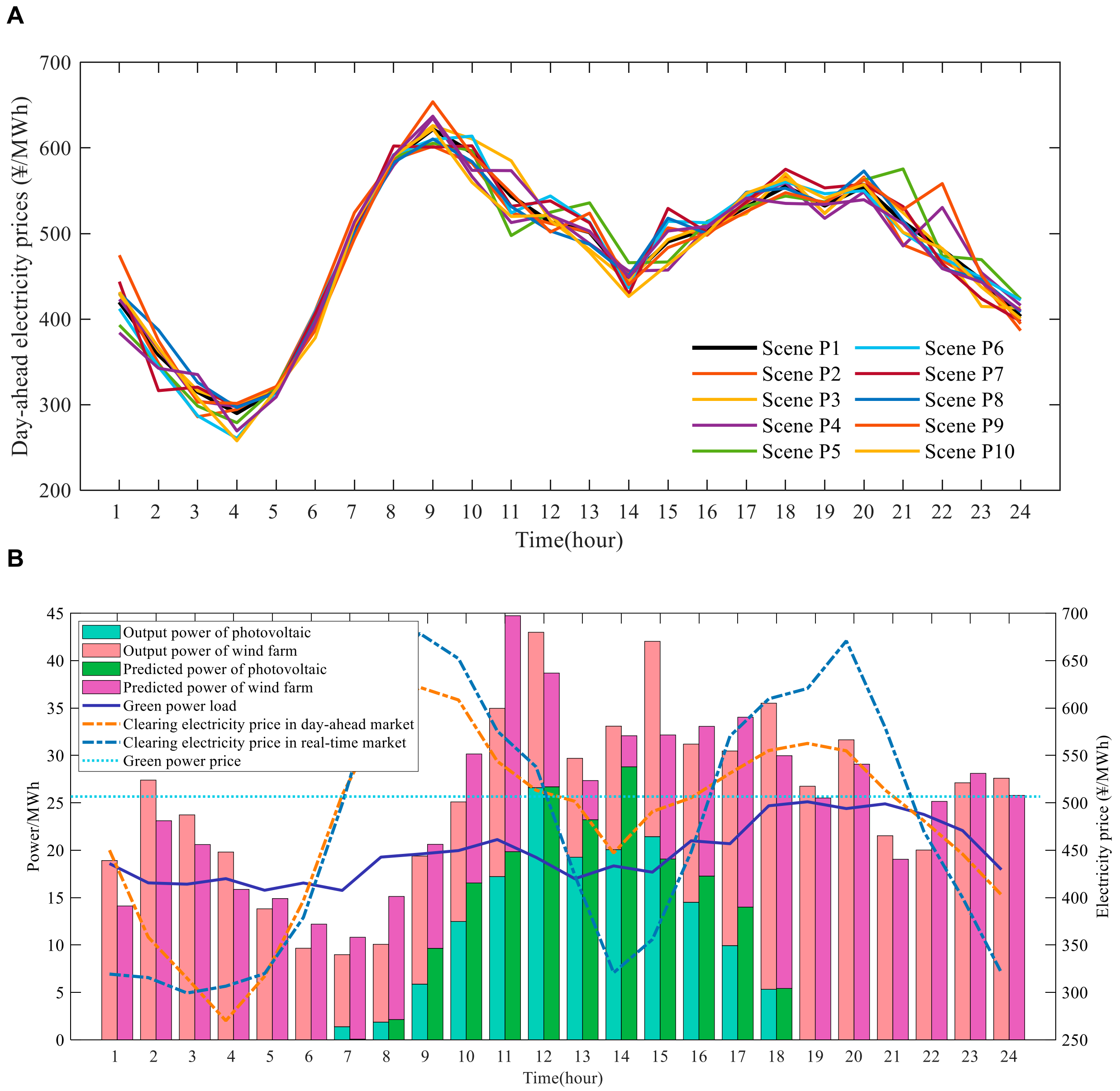

FIGURE 1
(A) Typical scenarios for clearing price in day-ahead electricity market. **(B)** Wind power and photovoltaic output and electricity market price.

station need to pay the deviation fee. The green power trading curve and bidding status of the wind–solar-storage hybrid energy plant in the day-ahead market are shown in Figure 2A, and the actual operation scheduling results of the hybrid renewable energy plant are shown in Figure 2B.

Figure 2 shows that the wind–solar-storage hybrid energy plant will decompose the green power into periods of off-peak price within a limited decomposition area according to day-ahead price prediction, resulting in the final green power decomposition curve being negatively correlated with the predicted day-ahead price. For example, the hybrid renewable energy plant tends to decompose more green power into the off-peak pricing times, such as 2–3 h and 12–16 h. Conversely, during the peak pricing times of 8–11 h and 17–21 h, the decomposed green power falls into the lower limit set by consumers. In addition, the scheduling strategy of the energy storage power station is more conservative, owing to the consideration of the uncertainty of electricity price and loss cost of energy storage during the day-ahead stage. The energy storage system plans to absorb only a portion of the electricity during the off-peak pricing time and resell it during the peak pricing time. Furthermore, the wind–solar-storage hybrid energy plant will release the stored power during the peak pricing times to obtain excess profit, such as in 19–20 h. Although the real-time price is not the highest in 6–7 h and 22 h, the hybrid energy plant still chooses to discharge the stored power to compensate for deviations in the green power output. The energy storage power station can compensate for deviations with its flexible adjustment capacity, thereby reducing deviation assessment cost and increasing profitability in real-time markets. The real-time scheduling result of the energy storage power station is shown in Figure 3.

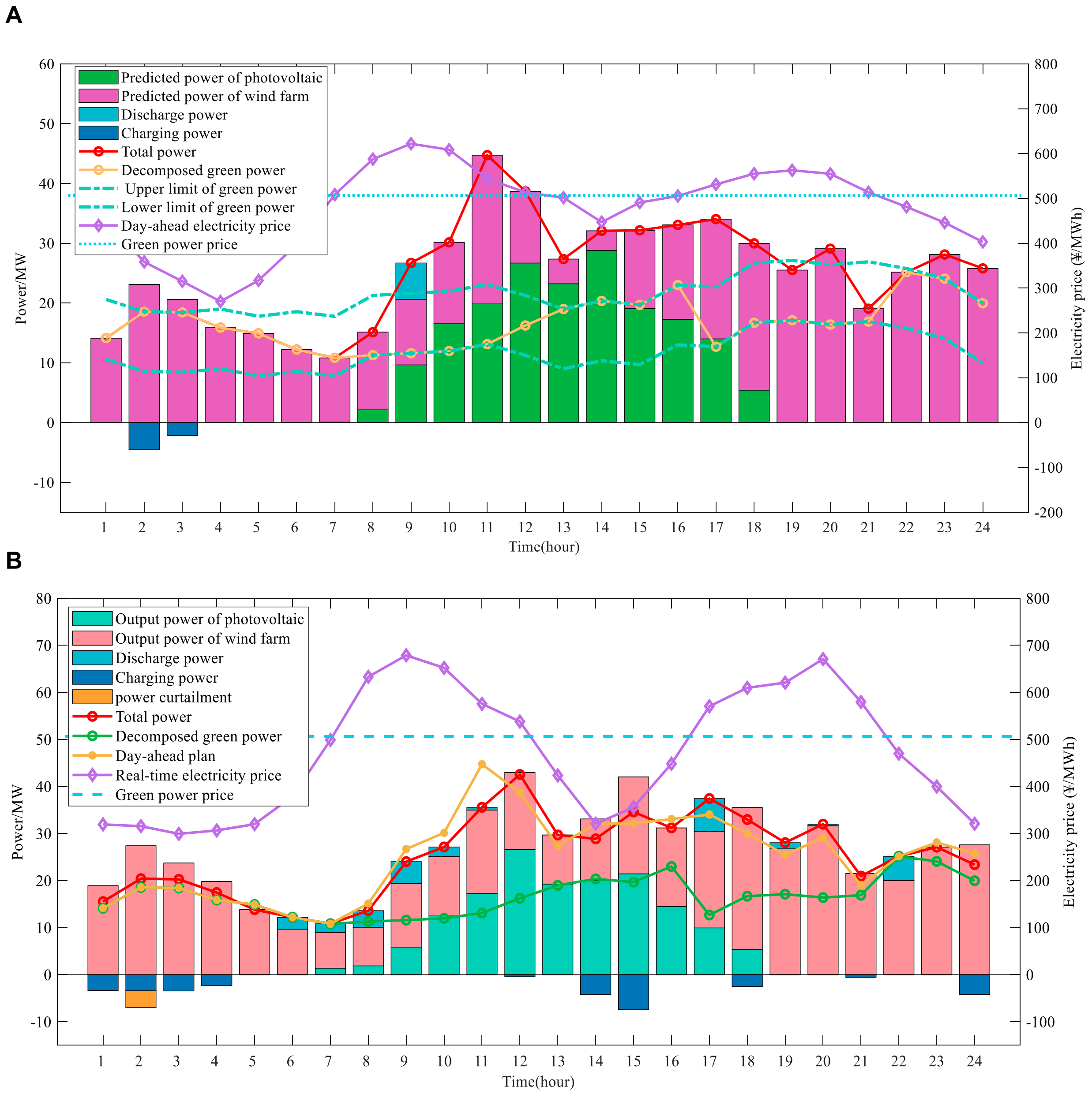

FIGURE 2
(A) Green power decomposition curve and day-ahead outputs. (B) Coordinated scheduling results of the wind-solar-storage hybrid energy plant.

When surplus electricity is available in the combined system, the energy storage power station chooses whether to charge or not based on the real-time electricity price. For example, in 1 h–4 h, the energy storage power station chooses to absorb the surplus power up to its capacity as the night-time price is lower than the deviation penalty cost. In contrast, when the real-time price is higher than the deviation penalty cost, such as in 12 and 20 h, the combined system sells the surplus electricity directly without using the energy storage power station. To further explore the contribution of energy storage power stations in hybrid renewable energy plants, the revenue model proposed in this paper is considered scheme 1, and the revenue model for the hybrid plant without energy storage participating in the green electricity market is considered scheme 2. The simulation results of scheme 2 are shown in Figure 4. The comparison of economic benefits between schemes 1 and 2 is shown in Table 2.

Figure 4 shows that the hybrid renewable energy plant can reduce the power deviation to a certain extent through complementary operation. However, the compensation to deviation under this scheme is stochastic in nature. Excess energy is curtailed proactively to partially mitigate deviation penalties when there is surplus wind and solar power. Passive acceptance of the penalty for deviation is unavoidable to compensate for the shortfall power of wind and solar. The comparison results in Table 2 show that the deviation penalty of scheme 1 is much smaller than that of scheme 2. The deviation penalty in the green power market and spot market of the

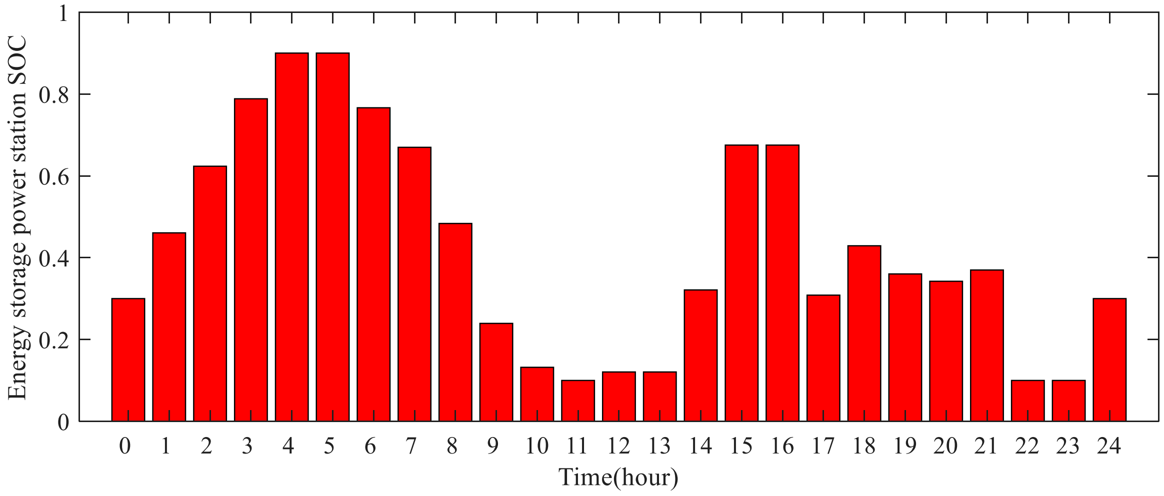

FIGURE 3
Real-time scheduling result of the energy storage power station.

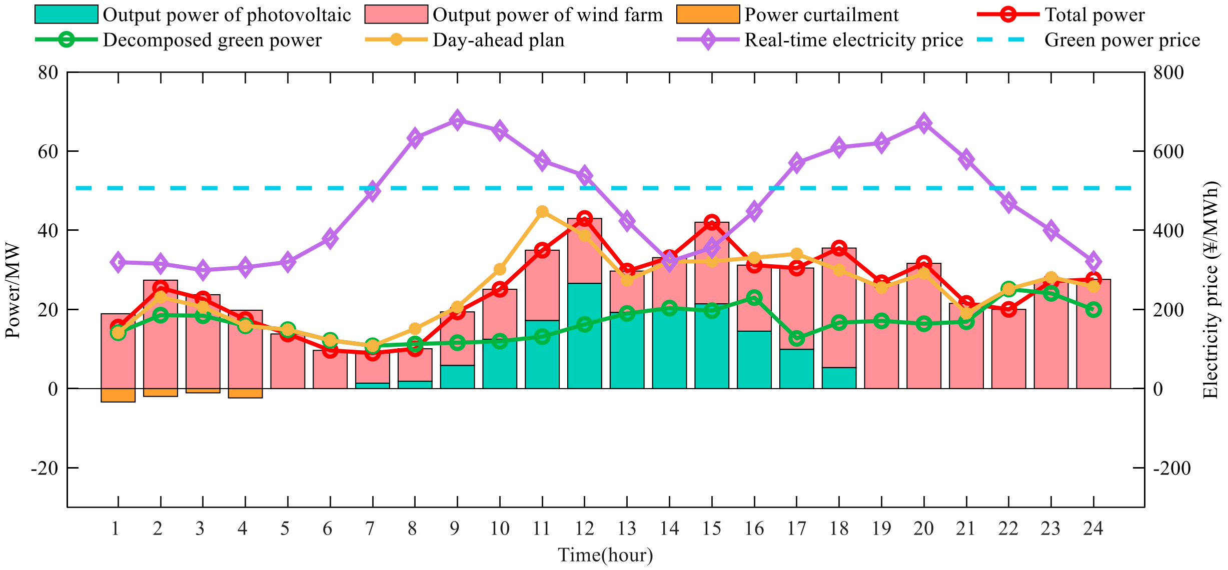

FIGURE 4
Coordinated scheduling results of the wind–solar renewable energy plant.

TABLE 2 Comparison of the economic indicators for schemes 1 and 2.

Scheme	Day-ahead predicted revenue/¥	Spot market deviation penalty/¥	Green power deviation Penalty/¥	Energy storage operating costs/¥	Total market revenue/¥	Net profit/¥
Scheme 1	312,450	−2,850	−669	−5,849	308,931	303,082
Scheme 2	308,990	−23,910	−15,262	--	269,818	269,818

wind–solar-storage hybrid energy plant is only 11.92% and 4.38% of the wind–solar plant, respectively. The market revenue increased by 14.50%, and the completion rate of the green power transaction increased by 5.93%. The net profit exceeds by 12.33%, considering the operational costs of the energy storage power station. Moreover, the incremental revenue of the wind–solar-storage hybrid energy plant is allocated according to the proposed cooperative revenue sharing method and MCRS method, as shown in Table 3.

TABLE 3 Comparison of revenues under different allocation methods.

Entities	Allocation by output		MCRS method		Method of this paper	
	Allocation of proceeds (¥)	Share of proceeds (%)	Allocation of proceeds (¥)	Share of proceeds (%)	Allocation of proceeds (¥)	Share of proceeds (%)
Wind	205,115	66.40	199,729	64.65	198,263	64.18
Solar	90,497	29.29	92,813	30.04	89,659	29.02
Energy storage	13,319	4.31	16,389	5.31	21,009	6.80

Table 3 shows that the revenue sharing method proposed in this paper takes into account the contribution degree of the wind farm, photovoltaic power station, and energy storage power station to the combination system. Energy storage power station participation in renewable energy plants can mitigate their power deviations and enhance competitiveness in the green power market. Therefore, both the wind farm and photovoltaic power station are inclined to provide incentives for the energy storage power station, resulting in a 28.19% increase in energy storage power station revenue after adjusting for the contribution factor.

5 Conclusion

In this paper, a revenue sharing model of the wind–solar-storage hybrid energy plant under medium- and long-term green power trading markets is proposed to facilitate their coordinated scheduling and reasonable revenue allocation. The key findings of this study are as follows: 1) the proposed coordinated scheduling strategy for the hybrid renewable energy plant can significantly reduce the deviation penalty of green power and increase the completion rate of transactions and net income in the green power and spot trading market and 2) the revenue sharing model proposed in this paper effectively enhances the operating revenue of energy storage power stations by considering the contribution of the energy storage power station and renewable energy in the green power market.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

ZZ: writing–original draft and writing–review and editing. XG: conceptualization, data curation, and writing–review and editing. BF: visualization and writing–review and editing. TZ: formal analysis and writing–review and editing. YZ: formal analysis and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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