Optimal Coordinated Bidding Strategy of Wind and Solar System with Energy Storage in Day-ahead Market

Yinping Yang, Chao Qin, Yuan Zeng, and Chengshan Wang

***Abstract*—Although wind and solar power is the major reliable renewable energy sources used in power grids, the fluctuation and unpredictability of these renewable energy sources require the use of ancillary services, thereby increasing the integration cost. This study proposes a wind, solar, and pumped-storage cooperative (WSPC) model that can be applied to large-scale systems connected to dispersed renewable energy sources. This model provides an optimized coordinated bidding strategy in the day-ahead market, along with a method to facilitate revenue distribution among participating members. This model takes advantage of the natural complementary characteristics of wind and solar power while using pumped storage to adjust the total output power. In the coordinated bidding strategy, a proportion of the energies is provided as firm power, which can lower the ancillary service requirement. Moreover, a multi-period firm power-providing mode is adopted to reflect the wind-solar output characteristics of each period accurately. The duration of each period is selected as a variable to accommodate seasonal characteristics. This ensures that the provision of firm power can maintain a high proportion under varied connected ratios of wind-solar, thereby obtaining higher revenue. By using the revenue distribution method, the short-term influencing factors of the cooperative model are considered to provide the economic characteristics of wind farms and photovoltaic stations. In this way, revenue distribution can be fairly realized among the participating members. Finally, the effectiveness and economy of the proposed model are validated based on actual data obtained from the power grid in California, USA.**

***Index Terms*—Wind energy, solar energy, energy storage, energy resources, power system economics.**

Nomenclature

A. System Parameters

d, t, k	Indexes of day, hour, and period of the same firm power
m, n, h	Indexes of wind zones, solar zones, and pumped-storage stations
nD, nT, nK	Number of operation days, operation hours in a day, and operation periods with different firm power
nH	Number of pumped-storage stations contracted by wind, solar, and pumped-storage cooperative (WSPC) model
nM, nN	Number of wind zones and solar zones
t_k	Set of hours during the operation period k
T_k	Total number of hours covered during the operation period k

B. Parameters for WSPC Model

σ_{WSPC}	Standard deviation of aggregate output power of the WSPC model
BV	Bid price for variable power
BF	Bid price for firm power
CT	Cost of transmission
CA	Cost of administration of WSPC model
ET	Total earnings of WSPC model
PCV	Cooperative variable power
PCF	Cooperative firm power
rT	Rental rate of transmission
$RCVP$	Revenue from sale of cooperative variable power for WSPC model in market
$RCVF$	Revenue from sale of cooperative firm power for WSPC model in market
RO	Revenue of entire operation
SF	Smoothing factor of aggregated uncertainty in WSPC model
ZMP	Zonal marginal price

C. Parameters for Pumped-storage Stations

η_1, η_2	Efficiency factors of conversion of water flow to power and power to water flow (release water and pump water)
CSE	Cost of energy storage
CSR	Cost of reserve storage
CST	Total costs of storage

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CWP	Conversion factor of water inflow rate to power
PS	Output power from the pumped-storage station
rWS	Rental rate of reserving one unit of water for the storage
rWC	Rental rate of reserving one unit of water for the capacity of reserve
WFA	Other water inflow rate considering river flow, evaporation, and seepage
WF	Water flow rate
$WF_{\max}$	The maximum water inflow rate
$WF_{\min}$	The minimum water outflow rate
WSR_1	Water storage reserve capacity of release capacity
WSR_2	Water storage reserve capacity of storage capacity
WS	Water storage of pumped-storage station
$WS_{\max}$	The maximum water storage of pumped-storage station

D. Parameters for Wind and Solar Zones

σ_m, σ_n	Standard deviations of output power of a wind zone and a solar zone
PW	Output power from a wind zone
PV	Output power from a solar zone
PWT	Total output power of all wind zones
PVT	Total output power of all solar zones

I. Introduction

CHINA has pledged to reduce its greenhouse gas emissions, aiming to achieve a 60%-65% reduction in emissions by 2050, compared with emission levels in 2005 [1]. To make this commitment a reality, both wind and solar power must be harnessed to the greatest extent possible, to become the major sources of energy within the country. However, while wind and solar power is currently integrated into power grids of China, several problems have become apparent during the actual operation of these renewable energy sources, including the following:

1) The variation and uncertainty of power generation in the power grid increase significantly. The high proportion of connected renewable energy sources has contributed to a sharp increase in the requirement for ancillary services. Although a large number of fast-response generators have been connected to satisfy the ramping and reserve requirements, there still remains a shortage of ancillary services during specific periods, and the penetration of wind and solar power is constrained owing to the lack of ancillary services [2].

2) The output power of the wind farms and photovoltaic stations does not match the load profile. Solar power can meet the demand during the daytime, whereas wind power can satisfy the demand at midnight. However, there is a significant energy supply shortfall during the evening peak period, requiring conventional units to handle a sharply increasing demand.

3) In recent years, the competitiveness of wind and solar power in the market has increased dramatically. However, the costs of integrating these renewable energy sources into the existing power grids have also increased, and these costs increase exponentially with the increase of wind and solar power. These integration costs tend to be borne by wind farms and photovoltaic stations [3]-[5].

As mentioned above, the power grid requires high levels of stability, reasonable provision, and competitive energy.

Despite that wind and solar power have strong natural complementary characteristics, few studies have explored the cooperative operation of these two forms of renewable energy source in the electricity market. Most studies have concentrated on analyzing the relevant characteristics of wind and solar power and the optimization of small-scale independent systems comprising wind farms, photovoltaic stations, and batteries. Reference [6] reviewed the metrics, applications, and future research areas for complementary renewable energy sources. Reference [7] defined a future scenario in Sweden with large-scale solar and wind power and analyzed it over different time scales, demonstrating the existence of a strong correlation. Reference [8] investigated the capacity values of wind and solar power with different integration ratios. Reference [9] calculated the reserve requirement of power grids with the integration of large-scale wind, solar, and ocean wave power, and analyzed the variability and correlation between the multiple forms of renewable energy sources. References [10] and [11] estimated the efficacy of the co-allocation of large-scale wind farms and photovoltaic stations, thereby proving that this deployment clearly improved their benefits. Reference [12] proposed an optimal coordinated bidding strategy for wind farms, photovoltaic stations, and batteries in the day-ahead market. References [13]-[16] have also proposed a method to optimize the planning and operation of small-scale wind/solar/battery hybrid systems.

An essential way through which an increased penetration of wind and solar power can be realized is the proper utilization of pumped storage. The research associated with pumped storage in cooperation with wind or solar power concentrated on the following aspects: ① using pumped storage to reduce the effect of a shortage of wind or solar power; ② using pumped storage to adjust the energy supply to avoid the uncertainty and variation of wind or solar power; and ③ proposing a coordinated bidding strategy in the market to improve the revenue obtained. Reference [17] proposed a multi-objective optimization model that incorporated the wind curtailment cost, storage revenue, and total social cost to optimize the planning of pumped storage in a power system. Reference [18] used storage to maximize wind power usage over the scheduling period while minimizing its hourly social cost in a power system. Reference [19] considered using storage to overcome the congestion in the power system caused by the variability of wind power. Meanwhile, a tractable adaptive min-max-min model was formulated to achieve robust optimal expansion planning of storage.

In addition, the optimal coordinated bidding strategy of wind farms and pumped storage was also studied [20]-[24]. Reference [20] established a physical connection with a wind farm and a pumped-storage station, selling energy by employing a bilateral contract in the day-ahead market with the objective of risk hedging. Reference [21] proposed a short-term bidding strategy for a pumped-storage station to maximize the profit obtained in the market by reducing the imbalanced cost of wind power. Reference [22] proposed a bidding strategy for the coordination of a wind farm and a pumped-storage station in a power system with high penetration of wind power. The ramping requirement of the power grid was also considered in this model. In another study, a bi-level model was proposed to couple the pumped-storage stations with the wind farms to coordinate the bidding in the day-ahead and ancillary service market, for the purpose of increasing the revenue [23], [24]. However, current studies have mainly focused on the usage of pumped-storage stations in cooperation with only a single uncertain resource such as a wind farm or a photovoltaic station. Studies on the use of pumped storage in cooperation with wind and solar power in the electricity market remain scarce.

In summary, studies on the coordinated operation of wind, solar, and pumped storage in large-scale systems are still limited. Therefore, this study proposes a novel wind, solar, and pumped-storage cooperative (WSPC) model to provide a stable energy supply and enhance the competitiveness of renewable energy sources in the electricity market. The proposed model is based partially on the wind generator cooperative (WGC) model proposed in [25]. To better understand the WSPC model, the WGC model is first explained. In the WGC model, there are three aspects through which the competitiveness and profit are increased.

1) Uncertainty minimization: the forecasting errors of multiple wind farms are highly correlated on a temporal and spatial scale; therefore, the smoothing effect is considered in this model to reduce the total uncertainty of all contracted wind farms together, and in this way reduce the reserve cost caused by the uncertainty.

2) Firm power: a percentage of contracted energies is sold as firm power, and these energies earn more revenue in the market owing to the smaller ancillary service requirement.

3) Energy arbitrage: wind power is mainly provided at night at the lowest price; the pumped-storage stations store energy in the reservoir and release some of the energy at peak hours at a higher price, thus obtaining energy arbitrage.

Then, the WGC model is developed further to implement an improvement that considers the distinctive characteristics of wind and solar power in a cooperative operation. The detailed developments are highlighted as follows.

1) The multi-period firm power-providing mode is adopted to accommodate the different intergration ratios of wind and solar power. In the WGC model, the firm power provided is fixed daily. This may cause the supply of fixed power to be constrained by the solar or wind power supplier during a certain period in a way that is inconsistent with the characteristics of the load profile. In the proposed model, the firm power is provided in multi-period mode, making the supply of firm power consistent with the output characteristics of wind and solar power during each period. This guarantees a high proportion of firm power supply at different intergration ratios of wind and solar power. The three periods (midnight, daytime, and evening) are selected as the optimal number of firm power-providing periods. This makes the supply of firm power consistent with the three-period characteristics of the load profile and reduces the influence of fluctuations in wind and solar power to a great extent.

2) The duration of each firm power-providing period can vary to enhance the flexible energy supply of the proposed model. Wind and solar power outputs are highly uncertain and are influenced by seasonal characteristics and meteorological factors. Therefore, the duration of each firm power-providing period per day can vary. Thus, the energy supply in the model is highly flexible to accommodate the fluctuating outputs of wind and solar power.

3) A new revenue distribution method is proposed to create a reasonable revenue distribution among the participating wind farms and photovoltaic stations. The proposed model gathers all contracted energies and sales as a whole. Consequently, the revenue distribution is an important issue. In the WGC model, all the participating members are wind farms that have similar output characteristics, and the firm power provided in this model is fixed per day. Thus, the revenue could be reasonably distributed according to long-term factors, provided that the differential of the output characteristics of the participating members is ignored for simplicity. Wind and solar power has distinctive output characteristics, and the multi-period firm power-providing mode is adopted, increasing the difficulty of intra-day revenue distribution. Therefore, the new revenue distribution method is proposed to detail the short-term influencing factors and improve the reasonability of the proposed model.

The remainder of this paper is organized as follows. In Section II, the proposed WSPC model is described by detailing the technical and economic aspects. In Section III, the complete mathematics of optimization and the methodology of distribution costs and revenues are provided. In Section IV, a case study is presented based on the actual power grid in California, USA. The results of the base case are provided to validate the proposed model, and a comparison of the proposed and WGC models is conducted to validate the feasibility of the proposed model. A comparison of the proposed model operating over a fixed or variable period is also provided to validate the flexibility of the proposed model under fluctuating wind and solar power. Finally, conclusions are drawn in Section V.

II. WSPC Model

A. WSPC Model and Its Operation

The WSPC model proposed in this study includes multiple wind farms, photovoltaic stations, and pumped-storage stations. This model uses the intrinsic complementary nature of wind and solar power, combined with pumped-storage stations, to adjust the total output power. Therefore, the proposed model aims to decrease the variability and uncertainty of cooperative operations to maximize the total revenue. This model is compatible with both a small-scale system with a single unit or a large-scale system with zonal output from multiple units.

In this model, all wind farms and photovoltaic stations have a contract with it with regard to the energy provided during normal operation. Multiple wind farms and photovoltaic stations in each zonal area are aggregated into wind or solar zones to accommodate the large-scale integration of renewable energy sources. The pumped-storage stations also have a contract with the WSPC model considering the use of water, reserve capacity storage, and operation limits. The contracted pumped-storage stations are assumed to be the reserve suppliers of the WSPC model and are required to retain a portion of the reservoir for reserve capacity. The remainder of the reservoir can be rented to the WSPC model to accomplish energy shifting to optimize the revenue. In addition, we present a detailed model to coordinate the contracted wind farms, photovoltaic stations, and pumped-storage stations. The contracted elements are also assumed to exist in the power grid and the network to be feasible. The network infrastructure cost is considered in the contracts with the WSPC model. The structure of the WSPC model based on the power grid in California is illustrated in Fig. 1.

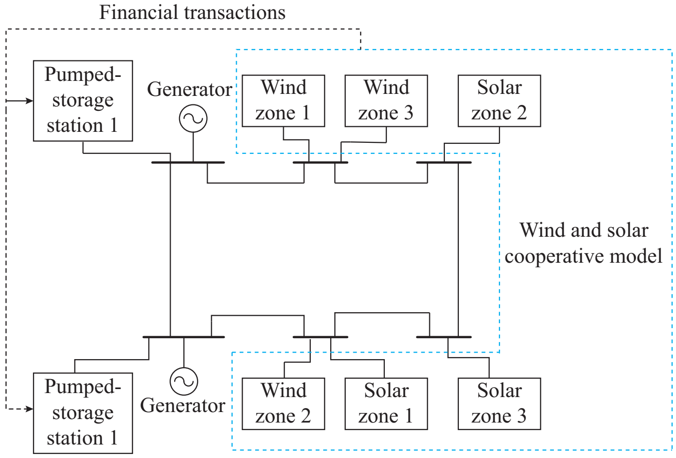

Fig. 1. Structure of WSPC model based on power grid in California.

The operation of the WSPC model is based on the following principle. The energy from all the wind farms and photovoltaic stations is integrated, and a proportion of that energy is sold to the market, whereas the remaining energy is either stored in or released from the pumped-storage stations with optimal schedules. In addition, the errors in forecasting the wind and solar power are also considered, and the contracted pumped-storage stations retain a reservoir to accommodate this uncertainty. The smoothing effect is also considered to reduce the total reserve requirement of all contracted wind farms and photovoltaic stations in the WSPC model. Moreover, the WSPC model optimizes the output of energy with the aim of increasing the revenue, where a portion of the generated energy is sold as firm power in return for firm generation revenue. Another portion of the generated energy is sold as variable power in return for the variable generation revenue. Furthermore, the WSPC model also considers the total cost of storage, cost of administration, and cost of transmission of power generation during optimization. The flow mechanism of the funds for WSPC model is illustrated in Fig. 2, where ISO stands for Independent System Operator.

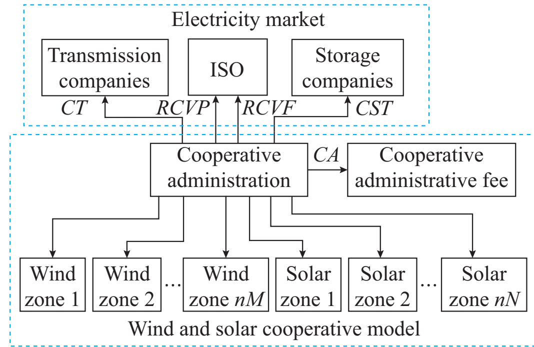

Fig. 2. Flow mechanism of funds for WSPC model.

B. Firm and Variable Power

The WSPC model takes advantage of the natural complementary characteristics of wind and solar power with pumped storage being used to adjust the total required output power. Hence, this model coordinates all contracted members and provides an optimal coordinated bidding strategy in the day-ahead market. In this coordinated bidding strategy, a portion of bidding power is provided as firm power to maintain a stable supply of power, whereas the remaining bidding power is provided as variable power. According to the existing literature [26], [27], the variability of wind and solar power results in higher ancillary service requirements. Furthermore, these requirements increase exponentially when the penetration of wind and solar power into the power grid increases. Apart from conventional ancillary services, the power grid in California specially designed a ramping service to handle the fluctuation of wind and solar power. Hence, all these additional services and facilities that are required due to the fluctuation of wind and solar power result in more expense. As ancillary services are technically public goods, the costs of these services are usually recovered from the beneficiary and users. Moreover, apart from the ancillary service costs, the integration of fluctuating wind and solar power into the existing power grids also leads to additional costs for essential services and facilities such as load following and scheduling of unnecessary thermal units. Currently, wind farms and photovoltaic stations are not required to pay these costs. However, in the current increasingly competitive environment, wind farms and photovoltaic stations will eventually have to reduce the fluctuations in their output to mitigate these costs. In summary, when bidding power is provided as firm power, more revenue can be obtained through the reduction of additional costs.

In addition, to ensure the reasonability of the firm power provided in the WSPC model, the three-period firm power-providing mode is adopted, contributing to ensuring a relatively stable power supply during the midnight, daytime, and evening periods. As each period has similar load demands, the power supply in the WSPC model is consistent with the load demand in each period. This ensures that the impact of the variability of wind and solar power on the system is reduced to a great extent, which effectively reduces the ancillary service requirements. Moreover, the duration of each period is selected as the variable to accommodate the seasonal characteristics of wind and solar power, thus improving the flexibility of the power supply in the WSPC model.

III. Formulation of Mathematical Model

A. Problem Optimization

Formulating the problem as an optimization model is suitable for either short-term or long-term usage based on user requirements, which is compatible with operation in a single day, month, or over a full year.

The optimization time frame consists of nD operation days. Each operation day contains nT operation hours. Furthermore, each operation day is divided into nK operation periods, with each period supplying the same firm power. Additionally, the duration of each period can vary, thereby ensuring the flexibility of the WSPC model.

When optimizing the WSPC model, the variables $PCV_{d,t}$, $PCF_{d,k}$, $WS_{h,d,t}$, $WF_{h,d,t}$, $WSR_{1,h,d,t}$, $WSR_{2,h,d,t}$, $PS_{h,d,t}$, $CSE_{d,t}$, $CSR_{d,t}$, and $T_{d,k}$ are optimized. Most importantly, the variable power in each hour is determined by the duration of each time period and firm power during each period.

This model aims to maximize the market revenue by maximizing returns from selling energy (variable power and fixed power) while minimizing the costs of energy storage as follows:

$$RCVP+RCFP-CST=\sum_{d=1}^{nD}\sum_{t=1}^{nT}PCV_{d,t}\cdot BV_{d,t}+\sum_{d=1}^{nD}\sum_{k=1}^{nK}PCF_{d,k}\cdot\sum_{t\in t_k}BF_{d,t}-\sum_{d=1}^{nD}\sum_{t=1}^{nT}CST_{d,t} \tag{1}$$

s.t.

$$PCV_{d,t}+PCF_{d,k}=PS_{d,t}+PWT_{d,t}+PVT_{d,t}\quad \forall d,\forall t\in t_k \tag{2}$$

$$\sum_{k=1}^{nK}T_{d,k}=nT\quad \forall d \tag{3}$$

$$PWT_{d,t}=\sum_{m=1}^{nM}PW_{m,d,t}\quad \forall t,\forall d \tag{4}$$

$$PVT_{d,t}=\sum_{n=1}^{nN}PV_{n,d,t}\quad \forall t,\forall d \tag{5}$$

$$PS_{d,t}=\sum_{h=1}^{nH}PS_{h,d,t}\quad \forall t,\forall d \tag{6}$$

$$PS_{h,d,t}=CWP_h\cdot\eta_{1,h}\cdot WF_{h,d,t}\quad \forall t,\forall d,\forall h,\forall WF_{h,d,t}\geq 0 \tag{7}$$

$$PS_{h,d,t}\cdot\eta_{2,h}=CWP_h\cdot WF_{h,d,t}\quad \forall t,\forall d,\forall h,\forall WF_{h,d,t}\leq 0 \tag{8}$$

$$WS_{h,d,t}=WS_{h,d,t-1}+WFA_{h,d,t}-WF_{h,d,t}\quad \forall t,\forall d,\forall h \tag{9}$$

$$WSR_{1,h,d,t}\leq WS_{h,d,t}\leq WS_{h,\max}-WSR_{2,h,d,t}\quad \forall t,\forall d,\forall h \tag{10}$$

$$WF_{h,\min}\leq WF_{h,d,t}-WSR_{1,h,d,t}\leq WF_{h,\max}\quad \forall t,\forall d,\forall h \tag{11}$$

$$WF_{h,\min}\leq WF_{h,d,t}+WSR_{2,h,d,t}\leq WF_{h,\max}\quad \forall t,\forall d,\forall h \tag{12}$$

$$WS_{h,d,0}=WS_{h,d,24}\quad \forall d,\forall h \tag{13}$$

$$\sum_{h=1}^{nH}WSR_{1,h,d,t}\cdot CWP_h\cdot\eta_{1,h}\geq\sigma_{WSPC,d,t}\quad \forall t,\forall d,\forall h \tag{14}$$

$$\sum_{h=1}^{nH}\frac{WSR_{2,h,d,t}\cdot CWP_h}{\eta_{2,h}}\geq\sigma_{WSPC,d,t}\quad \forall t,\forall d,\forall h \tag{15}$$

$$\sigma_{WSPC,d,t}=(1-SF)\left(\sum_{m=1}^{nM}\sigma_{m,d,t}+\sum_{n=1}^{nN}\sigma_{n,d,t}\right)\quad \forall t,\forall d \tag{16}$$

$$CST_{d,t}=CSE_{d,t}+CSR_{d,t}\quad \forall t,\forall d \tag{17}$$

Equation (2) represents the power balance constraint of the WSPC model; (3) represents the constraint of assigning hours to the optimized operation period with the same firm power; (4) represents the constraint of the total wind power forecasting; (5) represents the constraint of the total solar power forecasting; (6) represents the constraint of the total power from multiple pumped-storage stations; (7) and (8) represent the constraints of power from pumped-storage stations; (9) represents the water balance constraint of the storage reservoir; (10) represents the reservoir limit constraint of pumped-storage stations; (11) and (12) represent the water inflow limit constraints of pumped-storage stations; (13) represents the reservoir balancing constraint of pumped-storage stations; (14) and (15) represent the constraints of storage reserve capacity requirements for the uncertainty of wind and solar power; (16) represents the aggregate uncertainty constraint of the WSPC model; and (17) represents the storage cost constraint.

The storage cost consists of two components: the cost of reserve storage and the cost of energy storage, which are shown in (18) and (19), respectively. The cost of reserve storage is the cost used to maintain reserve capacity to avoid uncertainties caused by the forecasting errors of wind and solar power, while the cost of energy storage indicates the cost of storing or releasing water from the reservoir to generate energy for adjusting the output power of the WSPC model.

$$CSE_{d,t}=\sum_{h=1}^{nH}rWS_h\cdot WF_{h,d,t}\quad \forall d,WF_{h,d,t}\geq 0 \tag{18}$$

$$CSR_{d,t}=\sum_{h=1}^{nH}rWC_h\cdot(WSR_{1,h,d,t}+WSR_{2,h,d,t})\quad \forall t,\forall d \tag{19}$$

B. Distribution Costs and Benefits

The WSPC model uses pumped storage to realize energy arbitrage. The revenue distribution method based on hourly revenue might cause over-returns during discharging (water releasing) hours or under-returns during charging (water storing) hours. Therefore, the revenue distribution in the WSPC model is based on daily economic returns.

In the WSPC model, the revenue from the sale of variable power to the market is:

$$RCVP_{d,t}=PCV_{d,t}\cdot BV_{d,t}\quad \forall t,\forall d \tag{20}$$

The revenue from the sale of firm power to the market is:

$$RCFP_{d,k}=PCF_{d,k}\cdot\sum_{t\in t_k}BF_{d,t}\quad \forall k,\forall d \tag{21}$$

The revenue and cost can be divided into two parts. One part is the various costs produced by the power operation and sales as a whole, including the revenue from the sale of cooperative firm energy, variable energy, and the cost of energy storage. This part of the power considers the energy arbitrage and sale in the market as an entirety. Hence, these costs are considered altogether and distributed according to the contributions of the participating wind farms and photovoltaic stations. The other part is the cost resulting from individual aspects of the operation such as the cost of reserve storage and the transmission rental cost; these costs are thus distributed according to the actual requirement of the participating members.

The total earnings of the power operation in its entirety during any particular operation day are:

$$RO_d = \sum_{k=1}^{nK} RCFP_{d,k} + \sum_{t=1}^{nT}(RCVP_{d,t} - CSE_{d,t}) \quad \forall d \tag{22}$$

The zonal marginal price directly reflects economic returns during the output period. This paper proposes an earning distribution method based on the contribution of each zone, which is presented as the output power multiplied by the zonal marginal price of each zone. The earnings of each participating wind and solar zone are expressed as:

$$RO_{m,d} = \frac{RO_d \cdot \sum_{t=1}^{nT} ZMP_{h,d,t} \cdot PW_{m,d,t}}{\sum_{t=1}^{nT} ZMP_{h,d,t} \cdot \left(\sum_{m=1}^{nM} PW_{m,d,t} + \sum_{n=1}^{nN} PV_{n,d,t}\right)} \quad \forall m, \forall d \tag{23}$$

$$RO_{n,d} = \frac{RO_d \cdot \sum_{t=1}^{nT} ZMP_{h,d,t} \cdot PV_{n,d,t}}{\sum_{t=1}^{nT} ZMP_{h,d,t} \cdot \left(\sum_{m=1}^{nM} PW_{m,d,t} + \sum_{n=1}^{nN} PV_{n,d,t}\right)} \quad \forall n, \forall d \tag{24}$$

The cost of the reserve capacity is the cost of dealing with the forecasting errors of wind and solar power. Therefore, this cost is apportioned according to the standard deviation of each wind and solar zone, which can be expressed as:

$$CSR_{m,d,t} = \frac{\sigma_{m,d,t}}{\sum_{m=1}^{nM} \sigma_{m,d,t} + \sum_{n=1}^{nN} \sigma_{n,d,t}} \cdot CSR_{d,t} \quad \forall t, \forall d, \forall m \tag{25}$$

$$CSR_{n,d,t} = \frac{\sigma_{n,d,t}}{\sum_{m=1}^{nM} \sigma_{m,d,t} + \sum_{n=1}^{nN} \sigma_{n,d,t}} \cdot CSR_{d,t} \quad \forall t, \forall d, \forall n \tag{26}$$

The energy is sold in its entirety when operating the WSPC model. Thus, the cost of transmission for transmitting power from the wind and solar zones must be considered. The rental rate of the transmission is defined as the difference in the zonal marginal price:

$$rT_{m,d,t} = ZMP_{h,d,t} - ZMP_{m,d,t} \quad \forall t, \forall d, \forall m \tag{27}$$

$$rT_{n,d,t} = ZMP_{h,d,t} - ZMP_{n,d,t} \quad \forall t, \forall d, \forall n \tag{28}$$

$$CT_{m,d,t} = rT_{m,d,t} \cdot PW_{m,d,t} \quad \forall t, \forall d, \forall m \tag{29}$$

$$CT_{n,d,t} = rT_{n,d,t} \cdot PV_{m,d,t} \quad \forall t, \forall d, \forall n \tag{30}$$

Furthermore, the operation of the WSPC model requires the cost of administration to manage the entire model. This cost is represented by the cost of administration.

In summary, the total earnings of each wind and solar zone on any operation day are determined as:

$$ET_{m,d} = RO_{m,d} - \sum_{t=1}^{nT}(CSR_{m,d,t} + CT_{m,d,t}) - CA \quad \forall d \tag{31}$$

$$ET_{n,d} = RO_{n,d} - \sum_{t=1}^{nT}(CSR_{n,d,t} + CT_{n,d,t}) - CA \quad \forall d \tag{32}$$

C. Solving Process of WSPC Model

A flowchart for solving the WSPC model is shown in Fig. 3.

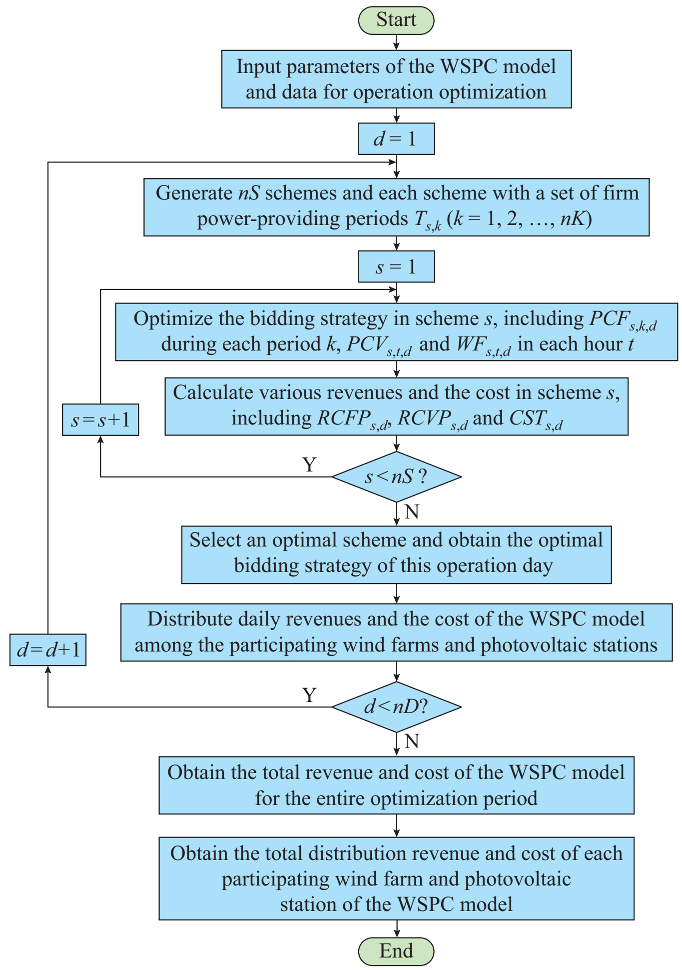

Fig. 3. Flowchart for solving WSPC model.

During the optimization process, the bidding strategy of the WSPC model for each operation day is optimized. The WSPC model provides multi-period firm power per day, and the firm power of each period is equal. Owing to the variability of the duration of each firm power providing period to find the optimal duration of each period, we generate nS firm power-providing schemes, and each scheme possesses a set of firm power-providing periods $T_{s,k}$ (k = 1, 2, ..., nK). In each scheme s, a set of optimal bidding strategies, including the optimal bidding firm power $PCF_{s,k,d}$ during each period k, the optimal bidding variable power $PCV_{s,t,d}$ and water flow rate $WF_{s,t,d}$ of pumped-storage stations in each hour t, is obtained by maximizing the objective function (1) along with constraints in (2)-(19). Additionally, the different revenues and costs of the WSPC model in this scheme can be determined, including the revenue from firm power $RCFP_{s,d}$, revenue from variable power $RCVP_{s,d}$, and total cost of storage $CST_{s,d}$. After obtaining the optimization process of each scheme on this operation day, an optimal firm power-providing scheme can be selected by comparing the total earnings of each scheme. Moreover, the optimal bidding strategy on this operation day can be determined in accordance with the proposed method from (20)-(32). Furthermore, the revenue and acquired cost of each participating member in the WSPC model are calculated.

From the processes described above, we can optimize the bidding strategy of nD operation days during the entire optimization period. Once the optimization is completed, the total revenue and cost derived from the WSPC model during the entire optimization period can be calculated by summing the results of each operation day. The total revenue and costs attained by each participating wind farm and photovoltaic station are also calculated according to their daily distribution results.

IV. Case Study

The effectiveness of the WSPC model is validated by performing a case study based on the power grid in California, which is managed and operated by the California Independent System Operator (CAISO).

A. Data

A large number of wind farms and photovoltaic stations are connected to the power grid in California, and the electricity market is operated via zonal management. Specifically, the entire power grid is divided into three zones: NP15, ZP26, and SP15. The capacities of the wind and solar power connected to the power grid in each zone are summarized in Table I.

TABLE I
Capacities of Wind and Solar Power Connected to Power Grid in California in Different Zones

Zone	Capacity of wind power (MW)	Capacity of solar power (MW)
NP15	1508	1609
ZP26	0	1563
SP15	4818	9626

The hourly aggregated power output data of wind and solar power in each zone in 2018 are provided on the CAISO website [28] and are assumed to be wind and solar power forecasts. The forecasting error of the wind and solar power can be represented as a percentage of the output power and is defined as the standard deviation. It was proposed that standard deviations of 18% and 12% for wind and solar power, respectively, should be used with a confidence level of 90% [29], [30]. Therefore, the uncertainties of wind and solar power are assumed to be 21% and 15% in this study, respectively. By using a smoothing factor to combine the operation of the wind farms and photovoltaic stations, the total forecasting error is likely to be significantly reduced. Thus, a 30% reduction in the forecasting error is assumed. This implies that the standard deviation in the WSPC model is 70% of the sum of the standard deviations of wind and solar power in independent operations.

California has a high hydropower capacity within its power grid. However, most of this capacity is provided by runoff hydropower stations, as opposed to pumped-storage stations. The current storage capacity is insufficient for implementing the WSPC model. However, considering that California is bounded by the Pacific Ocean to the west, sufficient hydro resources can be provided to build pumped-storage stations. Thus, two additional pumped-storage stations are assumed to exist in this study. These two pumped-storage stations are assumed to have a storage capacity of 2000 MW (station 1) and 1600 MW (station 2) and are installed in zone NP15. In these pumped-storage stations, a reserve capacity is maintained to store or release water to counter the overproduction or underproduction of wind farms and photovoltaic stations. Any additional capacity can then be rented to adjust the output power to increase the revenue. The relevant parameters of the pumped-storage stations are adopted using the assumption in [25], and the rental rate of pumped-storage stations is assumed to increase due to inflation. Detailed parameters are listed in Table II.

TABLE II
Parameters of Pumped-storage Stations

Parameter	Pumped-storage station 1	Pumped-storage station 2
WS_{max} (m^3)	7.5×10^8	5.0×10^8
$WS_{d,0}$ (m^3)	2.5×10^8	1.5×10^8
rWS (\$/(m^3·h))	0.016	0.016
rWC (\$/(m^3·h))	0.016	0.016
WF_{min} (m^3/s)	−867	−694
WF_{max} (m^3/s)	867	694
WFA (m^3)	0	0
CWP (kW/m^3)	0.64	0.64
η_1	0.93	0.93
η_2	0.88	0.88

Wind farms, photovoltaic stations, and pumped-storage stations are distributed across different zones, and each of these zones has its own zonal marginal price. The zonal marginal price recorded by CAISO [28] in 2018 is used as the forecasting price in this study. In the case of extreme price variations caused by system contingencies, such prices are replaced by the average zonal marginal prices during the same period. The cost of transmission caused by the differences of zonal marginal price is assumed to be the expenses incurred for transmitting power from wind or solar zones to pumped-storage stations. Since the WSPC model combines all generated energies and bids or sales as a single entity, it is assumed that energy sales will occur in only one zone. Hence, in the WSPC model, it is also assumed that the sale price of firm power is the zonal marginal price with the addition of pumped storage (NP15). The sale of variable power attracts additional costs owing to intense fluctuations in wind and solar power. Based on existing descriptions [26], [27], these costs account for 10% of the selling price. Therefore, the bid price for the variable power is considered to be 90% of that for the firm power.

B. Comparisons of WSPC Model and Independent Operations

The proposed WSPC model is coded using MATLAB software and solved using the CPLEX solver. One year is selected as the operation period to validate the effectiveness of the WSPC model. The results of the WSPC model and the independent operations are summarized in Table III.

TABLE III
RESULTS OF WSPC MODEL AND INDEPENDENT OPERATIONS

Condition	Parameter	Value
WSPC model	*RCVP* ($)	292347259
	RCFP ($)	1198750012
	CSE ($)	108881914
	CSR ($)	116220941
	CT ($)	16339741
	CA ($)	3650000
	ET ($)	1246004675
Independent operation of wind zones	*RCVP* ($)	479436634
	CSR ($)	71912890
	ET ($)	407523744
Independent operation of solar zones	*RCVP* ($)	678257194
	CSR ($)	94117024
	ET ($)	584140170

The results show that the WSPC model has higher economic returns than the independent operations, with a 25.6% increase in the final earnings from the market. The increase of the revenue is mainly attributed to three factors. First, the revenue can be obtained by providing the firm power. Second, the smoothing effect of multiple zones can also decrease reserve capacity requirements, thereby reducing the costs of reservoir rental. Finally, the contracted pumped-storage stations can shift the energy from the low-price period to the high-price period, thus acquiring revenue via energy arbitrage.

When the wind and solar zones are operated independently, they only provide variable energy owing to their variability. In contrast, the WSPC model combines all sources of wind and solar power to create firm power, which can increase revenue. Indeed, Table III indicates that 80.4% of the total revenue is derived from the sale of firm power, accounting for a large proportion of the total revenue. This demonstrates that wind and solar power complements each other naturally, providing a stable power supply. Additionally, wind and solar zones have to make reserve payments conservatively in an independent operation, whereas the WSPC operation can avoid 30% of the reserve cost owing to the smoothing effect. The total revenue increases by 4.0% due to the reserve cost reduction.

However, the costs of energy storages, cost of transmission, and cost of administration may be introduced when implementing the WSPC model. The costs of energy storage reflect the expense of using pumped-storage stations to either release or store water to adjust the overall output power, while the cost of transmission considers the rental cost incurred while transmitting power between different zones. However, in the case study in California, local marginal prices do not vary significantly, therefore, the cost of transmission accounts for only a small portion of the total cost. The cost of administration refers to the fixed cost incurred for managing the entire process, as depicted by the WSPC model.

Figure 4 illustrates the earnings of all the wind and solar zones in the WSPC model and the independent operation. It can be observed that each of the wind and solar zones is able to attain a substantially greater amount of earnings by participating in the WSPC model compared with operating independently, with the increases of 26.1% and 25.3% for the wind and solar zones, respectively. As the output power of the solar zones is more stable, a high level of firm power can be maintained to ensure increased earnings in the WSPC model. However, owing to large-scale integration of solar power in California, the bid price of the output period of solar power is lower, resulting in a decrease in the obtained revenue. As the output power of the wind zones tends to fluctuate significantly, the proportion of firm power provision is relatively lower, constraining the obtained revenue. However, the higher sale price still ensures that the wind zones could obtain good earnings from the revenue distribution.

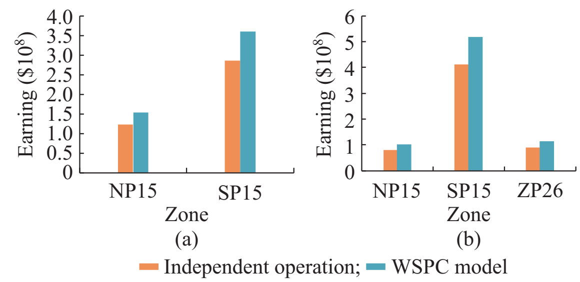

Fig. 4. Earnings of wind and solar zones in WSPC model and independent operation. (a) Earnings of wind zones. (b) Earnings of solar zones.

In the two wind zones, the earnings in the WSPC model increase by 25.9% and 26.2% in zones NP15 and SP15, respectively. The zone SP15 obtains a higher increase in earnings because a high percentage of the connected wind farms in the mountainous areas in this zone. Wind farms connected in such areas can provide more consistent wind power, which can improve firm power to attract increased earnings. In the three solar zones, the total earnings in the WSPC model increase by 24.6%, 25.4%, and 25.5% in zones NP15, SP15, and ZP26, respectively. The zone ZP26 experiences stronger irradiation intensity and longer exposure time, thereby enabling more energy to be provided in the afternoon at a higher price. Consequently, the improvement in earnings in zone ZP26 is slightly higher.

C. Comparison of WGC and WSPC Models

The results of the proposed WSPC model, which considers the distinctive characteristics of wind and solar power in cooperative operations, are compared with the results of the WGC model to validate the effectiveness of the enhancement in the model.

Table IV shows a comparison of the results of the wind and solar zones for the independent operation and the WGC model. Several differences are apparent when comparing these results with those for the WSPC model in Table III.

For example, the revenue from the sale of firm power decreases by 56% in the WGC model compared with the WSPC model. There are two reasons for this.

TABLE IV
RESULTS OF INDEPENDENT OPERATION AND WGC MODEL

Condition	Parameter	Value
WGC model	*RCVP* ($)	870025843
	RCFP ($)	527080803
	CSE ($)	103719907
	CSR ($)	323323157
	CT ($)	16339741
	CA ($)	3650000
	ET ($)	950073841
Independent operation of wind zones	*RCVP* ($)	479436634
	CSR ($)	233146448
	ET ($)	246290186
Independent operation of solar zones	*RCVP* ($)	678257194
	CSR ($)	228743777
	ET ($)	449513417

First, the firm power provided in the WGC model is seasonally fixed, implying that the firm power is maintained at the same level during the entire season. Although the power grid can obtain a more stable power supply, the revenue from the sale of firm power still declines owing to the lower energy supply. In contrast, the WSPC model adopts the multi-period firm power-providing mode to be consistent with the characteristics of the load profile during the midnight, daytime, and evening periods. Moreover, the duration of each firm power-providing period is variable to accommodate the fluctuating wind and solar power supply, which ensures that the cooperation of wind and solar power can reasonably satisfy the demand and significantly improve the amount of firm power.

Second, the solar and wind power has distinctive seasonal characteristics. For example, the wind power always provides more energy in winter, whereas the solar power tends to decline in energy supply in winter and increase in summer. Therefore, a fixed seasonal firm power may cause the supply of firm power to be constrained by the output characteristics of any one resource. Moreover, the differentially connected ratios of wind and solar power can also influence a firm power supply. For example, a lower proportion of integrated resources can limit available firm power. In the WGC model, the seasonal firm power is shown to be 1616, 2635, 1306, and 589 MW during spring, summer, autumn, and winter, respectively. The values are constrained by seasonal output characteristics and the integrated ratio of wind power. Notably, a large number of connected wind farms are located in the Tehachapi area in California, where more wind power is available during spring and summer. Thus, the output power from wind farms in California is higher during spring and summer, which may differ from other areas. In contrast, the WSPC model adopts a three-period firm power-providing mode, with the wind power being provided mainly during the midnight and evening periods, and solar power being provided during the daytime; thus, this mode in the WSPC model is able to reflect the stable energy supply power of both wind and solar power accurately in different seasons and with different integrated ratios.

Additionally, the total earning when using the WGC model is $9.50 billion, whereas the total earning using the WSPC model is $1.24 billion. This difference is due to two factors. First, the reserve capacity is assumed to be seasonally fixed in the WGC model, whereas the reserve capacity in the WSPC model is allowed to vary hourly and according to the day-ahead forecasting profile of wind and solar power. The reserve capacity in the WGC model compared with the WSPC model is relatively conservative, at 2.78 times as much in reserve costs. This therefore reduces the total earnings in the WGC model, even though higher revenue can have been obtained by reducing reserve costs. Second, the use of the multi-period firm power-providing mode in the WSPC model clearly increases the amount of supplied firm power, generating more revenue from the sale of firm power.

The WSPC model gathers all the energy of contracted wind farms and photovoltaic stations and sells the energy as an entirety in the day-ahead markets. Thus, fairly distributing the revenue among the participating members is regarded as an important aspect of the WSPC model. In the WGC model, all participating members are wind farms with similar output characteristics. Thus, the distribution method in this model tends to consider long-term factors for simplicity. However, this revenue distribution method may cause unfair revenue distribution between the wind farms and photovoltaic stations. In the WSPC model, a new short-term revenue distribution method is presented. The intra-day revenue influencing factors are considered to accurately reflect the economic characteristics of wind farms and photovoltaic stations.

Figure 5 shows the earnings of all the wind and solar zones in the WGC model and the independent operation. It shows that the revenue of the WGC model in the wind zones increases by 41.2%, whereas that of the solar zones only increases by 33.9% compared with the independent operation. The revenue distribution among the wind and solar zones differs for two reasons. First, the revenue obtained from variable power in the WGC model is distributed according to the hourly revenue, which can result in an over-return during the hours of water release and under-returns during the hours of water storage. For example, the wind power in California is plentiful during the afternoon and evening periods, commanding the highest price along with the water release to realize energy arbitrage. Thus, energy arbitrage in the model is mostly distributed to the wind zones, causing revenue over-returns in those zones. Second, the revenue obtained from the firm power in the WGC model is distributed based on the installed capacity, which cannot reflect the bid price for a distinctive output period of wind and solar power, influencing the fairness of the revenue distribution.

Compared with the results of the WSPC model shown in Fig. 4, the revenue distribution in the WSPC model is relatively fair among different wind and solar zones. The earnings of wind zones increase by 26.1%, whereas those of solar zones increase by 25.3% in the WSPC model compared with the independent operation. These results demonstrate that the proposed distribution method is appropriate and reasonable, even with different integration ratios.

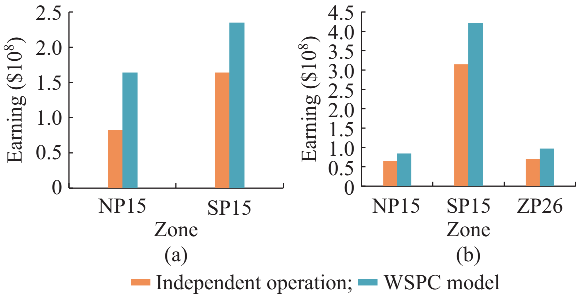

Fig. 5. Earnings of wind and solar zones in WGC model and independent operation. (a) Earnings of wind zones. (b) Earnings of solar zones.

D. Comparison of WSPC Model Operating with Variable and Fixed Periods

The WSPC model proposed in this study adopts a variable operation period to accommodate distinct probable scenarios. This subsection compares the results obtained when variable and fixed periods are used, showing the flexibility and adaptability of the WSPC model when operating with a variable period.

Table V lists the result of WSPC model and independent operation with a fixed period. It can be observed that the total earning of the WSPC model operating with a fixed period increases by 24.5% compared with the independent operation, as compared with an increase of 25.6% when the WSPC model operates with a variable period. Furthermore, the revenue obtained from the firm power decreases by 6.4% for a fixed period because the use of a variable period enables a reasonably allocated and optimized output power regardless of the time of the year. In addition, the total cost of storage is relatively higher for a fixed period, as it reduces the flexibility of the WSPC model, so that pumped-storage processes have to be utilized to a greater extent to adjust the output power.

TABLE V
RESULTS OF INDEPENDENT OPERATIONS AND WSPC MODEL WITH FIXED PERIOD

Condition	Parameter	Value
WSPC model	*RCVP* ($)	366958917
	RCFP ($)	1121844379
	CSE ($)	117967573
	CSR ($)	116220941
	CT ($)	16339741
	CA ($)	3650000
	ET ($)	1234625041
Independent operation of wind zones	*RCVP* ($)	479436634
	CSR ($)	71912890
	ET ($)	407523744
Independent operation of solar zones	*RCVP* ($)	678257194
	CSR ($)	94117024
	ET ($)	584140170

Figure 6 shows the results of WSPC model operating with fixed and variable periods with different values of operation periods. In the case with fixed periods, the time intervals for nK = 1, 2, 3, 4 are assumed to be 24, 12, 8, and 6 hours, respectively. Figure 6 shows that the total earnings of the WSPC model are higher when operating for a variable period for different values of nK. The increments in the earnings in the WSPC model are 19.8%, 23.1%, 25.6%, and 26.6% for the variable period compared with the independent operation, whereas these increments are 19.8%, 21.9%, 24.5%, and 22.7% for the fixed period, respectively. When the value of nK is 1, the results of the WSPC model operating with variable and fixed periods are equal. This confirms that operating the WSPC model for a variable period improves the flexibility and increases the economic return. The increase in the revenue from firm power by 17.8%, 6.9%, and 10.2% for different values of nK, respectively demonstrates that operating the WSPC model for a variable period enables the adjustment of the output power to a more reasonable period.

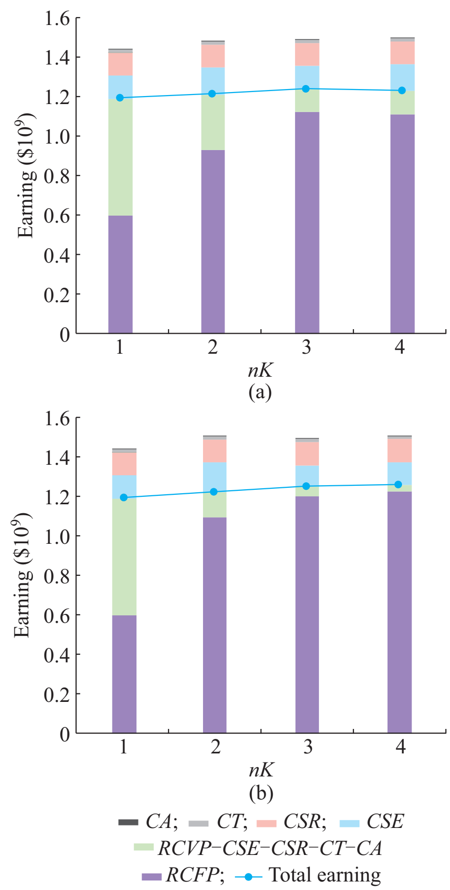

Fig. 6. Results of WSPC model operating with fixed and variable periods with different values of operation periods. (a) Fixed period. (b) Variable period.

V. CONCLUSION

This study proposes a WSPC model that can be applied to large-scale systems with dispersed connected wind farms, photovoltaic stations, and pumped-storage stations. The model provides a coordinated bidding strategy in the day-ahead market, along with a model that distributes the revenue among the participating members. The smoothing effect, ancillary cost reduction, and energy arbitrage are considered in the proposed model to improve the coordinated bidding revenue.

Furthermore, the cooperation characteristics of wind and solar power are considered to further enhance the market competitiveness and reasonability of the proposed model. These characteristics are as follows.

1) The multi-period firm power-providing mode is adopted to accommodate different integration ratios of wind and solar power. In this mode, based on the output characteristics of wind and solar power, the entire operation horizon is divided into several periods in which the same firm power is distributed. This enables the bidding strategy and firm power provided in the WSPC model to be consistent with the power supply characteristics of the period. With different integration ratios of wind and solar power, a high firm power can be provided, thereby reducing the ancillary service cost, and increasing the coordinated bidding revenue. In the power grid in California, approximately 80.4% of the total energy is provided in the WSPC model, which is a relatively high proportion.

2) The duration of each firm power-providing period is selected as a variable to enhance the flexibility of the energy supply of the WSPC model. The proposed model is a bi-level optimization model. At the first level, the duration of each firm power-providing period is determined, while the coordinated bidding strategy is optimized at the second level. This means that the duration of each firm power-providing period is optimized according to the day-ahead zonal marginal price and the forecasted wind and solar power. This ensures that the firm power-providing period is reasonable, which also improves the bidding revenue.

3) A new distribution method is proposed to realize a fair intraday revenue distribution. The proposed distribution method considers short-term influencing factors and divides costs and revenue into two sections. First, the cost resulting from individual operations is distributed according to the actual performance in order to reflect the individual operation characteristics of the participating members. Second, the costs and revenue from the WSPC model as a whole are distributed in accordance with the daily contribution of each participating member, addressing the challenge of fairly distributing the revenue from multi-period firm power and energy arbitrage. Based on the results obtained, it can be confirmed that the proposed distribution method ensures a fair distribution of revenue among participating wind farms and photovoltaic stations.

For ease of calculation, it is assumed that the initial reservoir capacity of the pumped-storage stations on each operation day is fixed. However, in the process of long-term operation optimization, it is preferred that the initial reservoir capacity on each operation day is optimized to enhance the regulating performance of the pumped storage, which will consequently improve the market competitiveness of the proposed model. This aspect deserves further investigation.

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