Coordinated Operation of Concentrating Solar Power Plant and Wind Farm for Frequency Regulation

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***Abstract*—As a dispatchable renewable energy technology, the fast ramping capability of concentrating solar power (CSP) can be exploited to provide regulation services. However, frequent adjustments in real-time power output of CSP, which stems out of strategies offered by ill-designed market, may affect the durability and the profitability of the CSP plant, especially when it provides fast regulation services in a real-time operation. We propose the coordinated operation of a CSP plant and wind farm by exploiting their complementarity in accuracy and durability for providing frequency regulation. The coordinated operation can respond to regulation signals effectively and achieve a better performance than conventional thermal generators. We further propose an optimal bidding strategy for both energy and frequency regulations for the coordinated operation of CSP plant and wind farm in day-ahead market (DAM). The validity of the coordinated operation model and the proposed bidding strategy is verified by a case study including a base case and sensitivity analyses on several impacting factors in electricity markets.**

***Index Terms*—Concentrating solar power, wind power, frequency regulation, electricity market, bidding strategy.**

NOMENCLATURE

A. Indices and Sets

τ	Time index in real-time operation
$\Delta\tau$	Time resolution in real-time operation (15 min)
Δk	Time resolution for regulation signal (2 s)
Δt	Time resolution in day-ahead market (1 hour)
k	Time index for regulation signal
s	Index for scenario
S	Set of scenarios
t	Time index in day-ahead market
T	Set of time

B. Parameters

α	Ratio of deviation penalty
γ_s	Probability of scenario s
ε_k^{reg}	Frequency control error of wind power at time k
ξ^{IAM}	Correction factor for solar incident angle
η^{con}	Conversion efficiency for concentrator
η^{CSP}	Thermal efficiency for rankine cycle
$\pi_{s,t}^{e}$	Real-time energy market price at time t in scenario s
π_t^{cap}	Regulation market capacity price at time t
π_t^{perf}	Regulation market performance price at time t
λ^{CSP}	Unit investment cost of concentrating solar power (CSP) plant
λ^{w}	Unit investment cost of wind farm
F	Total incomes
F^{cap}	Compensation fee for regulation capacity
F_t^{p}	Penalty cost of real-time deviation at time t
F^{perf}	Compensation fee for regulation performance
G_k^{reg}	Normalized regulation signal at time k
$I_{s,\tau}^{DSI}$	Direct solar irradiation intensity at time τ in scenario s
K^{pref}	Regulation performance score
m	Mileage ratio for regulation resource
$P_{\max}^{CSP}/P_{\min}^{CSP}$	The maximum/minimum output power of CSP
$P_{s,\tau}^{w}$	The maximum available wind power at time τ in scenario s
P^{w}	Rated capacity of wind farm
$Q_{\max}^{TES}/Q_{\min}^{TES}$	The maximum/minimum thermal storage capacity of thermal energy storage (TES)
$Q^{TES,init}$	Initial heat storage level of TES

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$R_{ch}^{TES}/R_{dis}^{TES}$ The maximum charging/discharging rate of TES

$R_{up}^{PB}/R_{down}^{PB}$ Upward/downward ramping capability of power block (PB)

S^{SF} Area of solar mirror field

C. Decision Variables

$D_{s,\tau}^{reg,CSP}$ Reserved regulation-down capacity for CSP plant at time τ in scenario s

$D_{s,\tau}^{reg,w}$ Reserved regulation-down capacity for wind farm at time τ in scenario s

p_t^e Capacity bid in day-ahead energy market at time t

p_t^{reg} Capacity bid in regulation market at time t

$p_{s,\tau}^r$ Aggregate real-time energy base point at time τ in scenario s

$p_{s,\tau}^{r,CSP}$ Real-time energy base point provided by CSP at time τ in scenario s

$p_{s,\tau}^{r,w}$ Real-time energy base point provided by wind power at time τ in scenario s

$p_{s,\tau}^{CSP}$ Output power of CSP plant at time τ in scenario s

$Q_{s,\tau}^{SF}$ Thermal energy absorbed from solar field (SF) at time τ in scenario s

$Q_{s,\tau}^{FE}$ Thermal energy of PB from SF at time τ in scenario s

$Q_{s,\tau}^{FS}$ Thermal energy of TES from SF at time τ in scenario s

$Q_{s,\tau}^{cur}$ Thermal energy curtailed by SF at time τ in scenario s

$Q_{s,\tau}^{TES}$ Heat storage level of TES at time τ in scenario s

$Q_{s,\tau}^{SE}$ Thermal energy of PB from TES at time τ in scenario s

$U_{s,\tau}^{reg,CSP}$ Reserved regulation-up capacity for CSP plant at time τ in scenario s

$U_{s,\tau}^{reg,w}$ Reserved regulation-up capacity for wind farm at time τ in scenario s

I. Introduction

ENVIRONMENTAL aspects of thermal power generation has been the subject of more scrutiny since renewable energy sources such as wind and solar find their way and gain more clout as part of the power generation mix in many countries. The European Union (EU) has proposed a 26%-34% increase by 2030 in the utilization of renewable energy [1]. The US Department of Energy (DOE) has also envisioned a scenario that wind energy can generate 20% of the nation's electricity by 2030 [2]. However, as conventional generators are replaced by large-scale renewable energy sources, there is an increasing level of concern on the adequate provision of ancillary services such as frequency regulation in power grid.

Several studies have shown that a wind turbine can control its active power output through rotor inertia [3], overspeed [4], and pitch [5] to provide frequency regulation. A method is proposed in [3] to allow a variable-speed wind turbine to simulate inertia and support frequency regulation. The required power is obtained from the kinetic energy stored in the rotating mass of turbine blades. In [6] and [7], a de-loading control scheme is proposed for combining overspeed and pitch, which enables a wind turbine to provide frequency regulation using pitch angle or frequency droop characteristics. However, when a wind unit reserves some capacity for providing regulation services, the wind turbine needs to be in the de-loading state [8], which may waste some wind energy. Therefore, bidding strategies would have to be carefully designed to maximize the expected payoff when a wind farm participates simultaneously in both energy and regulation markets [9]. The revenue of a frequency regulation provider is directly proportional to its market performance to provide regulation services, which is an important incentive mechanism for encouraging a wind farm to participate in regulation market [10]. However, compared with conventional generators, the frequency regulation performance of a wind unit is not only related to the absolute level of its available power, but also affected by its real-time energy base point and available reserve capacity. So, there is still a performance gap between wind power generation resources and conventional thermal generation resources.

Concentrating solar power (CSP) technology is one of the ways to efficiently harness solar energy. Unlike the photovoltaic (PV) technology, a CSP plant, which is usually equipped with a large-capacity thermal energy storage (TES), offers a valuable energy capacity [11]. By the end of 2018, the global installed CSP capacity had reached 5.5 GW [12]. According to the International Energy Agency (IEA), by 2050, the world's CSP capacity will account for 11.3% of the world's total power generation capacity [13]. A CSP plant can use solar energy without increasing the grid uncertainty, which makes it a dispatchable resource for continuous and stable power generation [14]. More importantly, a CSP plant with a fast ramp rate and short downtime/uptime has better regulation characteristics than a thermal unit [15], [16]. However, the output of CSP plant will have to be adjusted frequently when providing frequency regulation, which will be detrimental to the stable operation of the steam turbine in the power block (PB) of a CSP plant. Therefore, a reasonable operation strategy would have to be formulated when considering the participation of a CSP plant in regulation market.

When CSP and wind power both provide frequency regulation, they can exhibit complementary characteristics in terms of accuracy and durability. The accuracy refers to the regulation signal tracked in a timely and unbiased manner. The durability refers to the regulation signal tracked for a long time. A CSP plant with its inherent dispatchability excels a wind unit in frequency regulation accuracy, although a wind unit provides regulation services which can be adjusted easily without increasing its fatigue loads [17]. Therefore, a wind farm can work in tandem with a CSP plant to provide a bid into the regulation market in which case a reasonable operation strategy will help improve the economics and the frequency regulation accuracy of the joint venture. The coordination of CSP and wind power offers significant potentials [18], especially in places where wind power resources and direct solar irradiation (DSI) are abundant. Reference [18] studies a coordinated operation of wind farm and CSP plant in western Texas, USA, and demonstrates that the coordinated system has a high capacity factor due to the negative correlation of regional wind and solar power. Reference [19] proposes a short-term self-scheduling model for CSP plants and wind farms to partake in day-ahead coordinated energy and spinning reserve markets, but it does not formulate a reasonable bidding strategy for the participation in energy and regulation markets.

Considering the above issues, this paper proposes the coordinated operation of CSP plant and wind farm to provide frequency regulation according to the complementary characteristics of wind power and CSP, and formulates a performance-based optimal bidding model for the frequency regulation strategy of the coordinated system in day-ahead market (DAM). Additionally, the model ensures that the TES of CSP returns to its initial heat storage level at the end of the trading day. The case study results demonstrate the significant benefits of the coordinated system to provide regulation services. The contributions of this paper are summarized as follows.

1) We propose to provide frequency regulation by the cooperation of wind farm and CSP plant, and construct a two-stage stochastic model for the coordinated bidding of wind power and CSP in DAM (in the first stage) with the simulation of real-time operation that considers the variability of wind power in the second stage.

2) We propose a coordinated strategy which prioritizes the wind power durability to respond to regulation signals and exploits the accurate CSP regulation capability to compensate any inefficiencies in the coordinated offer.

3) We propose an optimal bidding model for a coordinated system with performance-based regulation and deviation penalty mechanism in the proposed real-time frequency regulation strategy.

The rest of the paper is organized as follows. The technical benefit of coordinated system for frequency regulation is introduced in Section II. The framework of the market and the optimal bidding model for the coordinated system is established in Section III. In Section IV, the validity of the model is verified by the study case. Conclusions are given in Section V.

II. Technical Benefit of Coordinated System for Frequency Regulation

In this section, we present the proposed coordinated operation of the CSP plant and wind farm and maximize its revenue by properly bidding in the energy and regulation markets based on corresponding market prices and the available wind energy. This is based on the observation that CSP plant and wind farm are highly complementary in terms of accuracy and durability for providing frequency regulation in the regulation market.

A. Frequency Regulation Characteristics of Wind Power

The output of a wind turbine is determined by its pitch angle and rotor speed, as the turbine works in its maximum power point tracking (MPPT) mode. The wind turbine can support frequency regulation through the de-loading control [8], which has to give up its ability to capture the maximum available wind power. Thus, there will be a tradeoff between the lost revenue due to wind power curtailment and the increased revenue for providing frequency regulation.

The frequency regulation accuracy of a wind turbine is affected by its available energy, reserved capacity for providing regulation service, and a performance score reflecting the frequency regulation accuracy which can reach 0.7 to 0.8 [20]. Although this performance score can meet the basic requirements of frequency regulation, there is still more room for improvement. In addition, the regulation revenue is directly proportional to the performance score, which provides a strong incentive for a wind farm to improve its frequency regulation accuracy by increasing its performance score.

B. Frequency Regulation Characteristics of CSP

CSP is one of the non-fossil fuel technologies with promising applications. It does not increase the uncertainty of the system. Instead, it exploits the energy storage characteristics of TES to make solar energy a dispatchable resource [21]. As a dispatchable renewable energy resource, a CSP plant has a similar ramping capability to that of a gas-fired generator which can reach a maximum 20% of the installed capacity per minute [15]. This is better than the allowable ramping rate of most conventional non-gas generators [22], which enables a CSP plant to track the regulation signal accurately.

C. Coordinated System for Frequency Regulation

Designing a reasonable frequency regulation operation strategy not only maintains frequency stability, but also brings potential benefits to the coordinated system. Based on this idea, a cooperation strategy of wind power and CSP for participating in the energy and regulation markets is proposed. Figure 1 presents the real-time coordinated bidding strategy of a coordinated system for providing energy and regulation service in DAM, where wind farm and CSP plant jointly provide energy and regulation services to DAM. In the energy part, the coordinated system submits an aggregate energy base point to the independent system operator (ISO) for every time period τ, which is equal to the sum of the CSP energy base point and wind power energy base point. For the regulation part, the coordinated system would track the normalized regulation signal G_k^{reg}, where wind power has a higher regulation durability for responding to the regulation signal. When the regulation power is insufficient or inaccurate, there will be a deviation between the reserved capacity and the regulation command, or a deviation due to the control error of the wind power, in which case the CSP compensates with a higher regulation accuracy. Finally, the aggregate frequency regulation output submitted by the coordinated system is equal to the sum of the reserved capacity provided by the wind power and the adjusted capacity provided by the CSP.

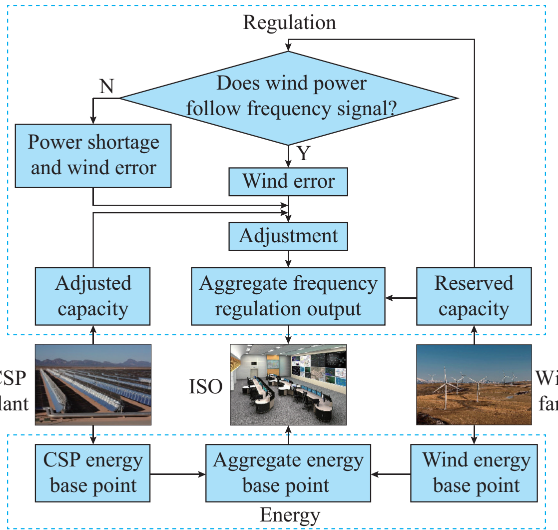

Fig. 1. Coordinated strategy of a coordinated system.

The frequency control error of the wind power in real-time operation ε_k^{reg} is due to the intermittent or insufficient output of wind power, which is assumed and simulated as a random variable. The actual output of the CSP plant will be varied in real-time operation to compensate the control error of the wind, and the deficiency, if any, of the committed regulation capacity of the wind in DAM as compared with the required regulation capacity in real-time operation. The frequency regulation output of the CSP plant, denoted by $p_k^{reg,CSP}$, is shown in (1), in which the regulation-up/regulation-down capacity is considered half of the committed regulation capacity p_t^{reg}.

$$p_k^{reg,CSP}=\begin{cases} 0.5p_t^{reg}G_k^{reg}-U_\tau^{reg,w}+\varepsilon_k^{reg} & U_\tau^{reg,w}<0.5p_t^{reg}G_k^{reg} \\ 0.5p_t^{reg}G_k^{reg}-D_\tau^{reg,w}+\varepsilon_k^{reg} & D_\tau^{reg,w}<0.5p_t^{reg}G_k^{reg} \\ \varepsilon_k^{reg} & \text{otherwise} \end{cases}$$
$$k\in[\tau,\tau+\Delta\tau],\tau\in[t,t+\Delta t] \tag{1}$$

The coordinated strategy takes advantage of the accuracy of CSP plant and the durability of wind turbine in providing regulation services, which can provide more regulation capacities, and accordingly higher profits as compared with the independent operations of the CSP plant and wind farm.

Note that the level of control for the cooperation strategy of the coordinated system in (1) is for the real-time operation in time resolution of k. Thus, k will not show up explicitly in the bidding model of the coordinated system in DAM (hourly) and real-time operation (15 min) as will be discussed in the next section. However, the improved performance score will indirectly affect the bids and the profitability of the joint system in DAM and real-time operation, which will be demonstrated in case study.

III. Economic Benefit of Coordinated System for Frequency Regulation

A. Market Framework

1) Market Mechanism

We assume that the coordinated system is treated like other market participants which submits hourly energy and regulation bids to the ISO in DAM. The DAM time index is t and its time resolution Δt is 1 hour. The time index for the real-time operation is τ and its time resolution $\Delta\tau$ is 15 min. The regulation signal is a normalized signal which is updated every 2 s [23]. The time index for the regulation signal is k and its time resolution Δk is 2 s. The coordinated system with a relatively small capacity is considered as a price-taker in this paper, which means its bidding behavior has less influence on the market clearing prices of the markets. Furthermore, the markets are cleared according to the bids of all market participants.

2) Compensation Mechanism in Regulation Market

The compensation mechanism in regulation market is assumed to follow a two-part payment for regulation resources: capacity payment and performance payment [24]. The capacity payment is compensated according to the committed regulation capacity p^{reg}, which is expressed as:

$$F^{cap}=\pi^{cap}p^{reg}K^{perf} \tag{2}$$

In the electricity market such as PJM, the performance score will be calculated by the ISO through a performance score calculation engine (PSCE) for each regulation resource after the operational hour and the score is reported to resource owners [23].

F^{perf} is compensated according to m and committed regulation capacity, which is expressed as:

$$F^{perf}=\pi^{perf}mp^{reg}K^{perf} \tag{3}$$

3) Deviation Penalty Mechanism in Energy Market

A penalty mechanism is assumed to settle the energy deviations between day-ahead bidding and real-time operation [25], which is expressed as:

$$F_t^p=\alpha\pi_t^e\sum_{\tau\in[t,t+\Delta t]}\left|p_t^e-p_\tau^r\right|\Delta\tau \tag{4}$$

B. Bidding Coordination Strategy for Frequency Regulation

In this paper, the proposed operation of the coordinated system maximizes its revenue by properly bidding in the energy and regulation markets based on the corresponding market prices and the available wind energy.

The DAM is cleared according to hourly market bids. However, the available wind power can fluctuate drastically in real-time operation. Furthermore, the regulation performance of wind power is calculated using its real-time energy base point, which can also be set to be 1 hour. Accordingly, the wind power frequency regulation capability will be limited by its minimum available output within 1 hour. Otherwise, its frequency performance will be reduced significantly due to insufficient wind power. As shown in Fig. 2, when the bidding time resolution is smaller than 1 hour, the real-time energy bid or the energy base point provided by wind power in real-time operation is more flexible, and the shaded zones demonstrate the difference for the two time resolutions. In this paper, we assume the real-time resolution is 15 min, and a wind farm submits the real-time energy base point of the bid to the ISO. The submitted base points will be accepted by ISO because the coordinated system is a price taker.

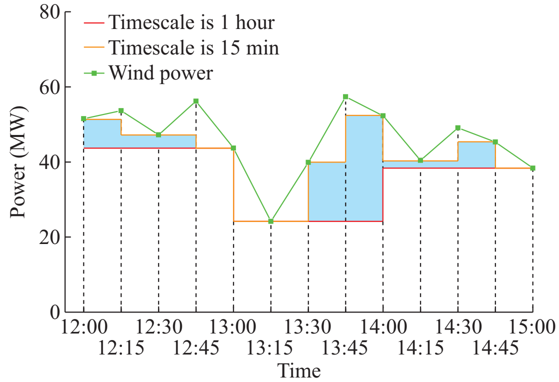

Fig. 2. Illustration of bidding capacity in different time resolutions.

1) Objective Function

In this paper, the objective function is to maximize the income F of the coordinated system, which is equal to the income of each market minus the penalty cost. Note that real-time decision will vary in each real-time scenario, but the day-ahead decision will be the same.

$$\max F=\sum_{s\in S}\gamma_s\left[\sum_{t\in T}\left(F_t^e+F_t^{reg}+F_{s,t}^r-F_{s,t}^p\right)\right] \tag{5}$$

$$F_t^e=\pi_t^e p_t^e\Delta t \tag{6}$$

$$F_t^{reg}=\left(\pi_t^{cap}+\pi_t^{perf}m_t\right)K^{perf}p_t^{reg}\Delta t \tag{7}$$

$$F_{s,t}^r=\pi_{s,t}^e\sum_{\tau\in[t,t+\Delta t]}\left(p_{s,\tau}^r-p_t^e\right)\Delta\tau \tag{8}$$

$$F_{s,t}^p=\alpha\pi_{s,t}^e\sum_{\tau\in[t,t+\Delta t]}\left|p_{s,\tau}^r-p_t^e\right|\Delta\tau \tag{9}$$

2) Constraints

1) Operational constraints of CSP plant [21], [26]: the CSP plant consists of SF, TES, and PB. The energy is transferred between the different modules by heat-transfer fluid (HTF). The operational constraints of CPS are stated in (10) and (20), where the thermal energy received by SF is defined in (10)-(11). Constraints (12)-(17) keep track of the TES storage level and enforce the limits, where $z_{s,\tau}^{TES}$ indicates the TES status with 1 for discharging and 0 for charging. The operational constraints of PB are defined in (18)-(20).

$$Q_{s,\tau}^{SF}=\eta^{con}I_{s,\tau}^{DSI}S^{SF}\xi^{IAM}\Delta\tau \tag{10}$$

$$Q_{s,\tau}^{SF}=Q_{s,\tau}^{FE}+Q_{s,\tau}^{FS}+Q_{s,\tau}^{cur} \tag{11}$$

$$Q_{s,\tau}^{TES}=Q_{s,\tau-1}^{TES}+Q_{s,\tau}^{FS}-Q_{s,\tau}^{SE} \tag{12}$$

$$Q_{\min}^{TES}\le Q_{s,\tau}^{TES}\le Q_{\max}^{TES} \tag{13}$$

$$-R_{ch}^{TES}\Delta\tau\le Q_{s,\tau+1}^{FS}-Q_{s,\tau}^{FS}\le R_{ch}^{TES}\Delta\tau \tag{14}$$

$$-R_{dis}^{TES}\Delta\tau\le Q_{s,\tau+1}^{SE}-Q_{s,\tau}^{SE}\le R_{dis}^{TES}\Delta\tau \tag{15}$$

$$0\le Q_{s,\tau}^{FS}\le R_{ch}^{TES}(1-z_{s,\tau}^{TES}) \tag{16}$$

$$0\le Q_{s,\tau}^{SE}\le R_{dis}^{TES}z_{s,\tau}^{TES} \tag{17}$$

$$p_{s,\tau}^{CSP}=\eta^{CSP}(Q_{s,\tau}^{FE}+Q_{s,\tau}^{SE}) \tag{18}$$

$$P_{\min}^{CSP}\le p_{s,\tau}^{CSP}\le P_{\max}^{CSP} \tag{19}$$

$$-R_{down}^{PB}\Delta\tau\le p_{s,\tau}^{CSP}-p_{s,\tau-1}^{CSP}\le R_{up}^{PB}\Delta\tau \tag{20}$$

One important CSP parameter for the participation in the electricity market is the TES level at the end of the trading day. We consider that the TES of the CSP plant returns to its initial level at the end of the trading day. The constraints are:

$$Q_{s,\tau}^{TES}=Q^{TES,init}+Q_{s,\tau}^{FS}-Q_{s,\tau}^{SE}\quad \tau=1 \tag{21}$$

$$Q_{s,\tau}^{TES}=Q_{s,\tau-1}^{TES}+Q_{s,\tau}^{FS}-Q_{s,\tau}^{SE}\quad \forall 1<\tau\le N_\tau \tag{22}$$

$$Q_{\min}^{TES}\le Q_{s,\tau}^{TES}\le Q_{\max}^{TES} \tag{23}$$

$$Q_{s,N_\tau}^{TES}=Q^{TES,init} \tag{24}$$

Considering the ramping constraints of CSP plant, its regulation-up/regulation-down capacity should not exceed a percentage $\eta^{reg,CSP}$ of the maximum output, which is expressed as:

$$D_{s,\tau}^{reg,CSP}\le\eta^{reg,CSP}P_{\max}^{CSP} \tag{25}$$

$$U_{s,\tau}^{reg,CSP}\le\eta^{reg,CSP}P_{\max}^{CSP} \tag{26}$$

In addition, the regulation-up for the CSP plant is either half of the total regulation or the available regulation-up, whichever is smaller, as shown in (26). Similarly, the regulation-down for the CSP plant is either half of the total regulation or the real-time energy base point, whichever is smaller, as shown in (27).

$$U_{s,\tau}^{reg,CSP}=\min\left(0.5p_k^{reg,CSP},P_{\max}^{CSP}-p_{s,\tau}^{r,CSP}\right) \tag{27}$$

$$D_{s,\tau}^{reg,CSP}=\min\left(0.5p_k^{reg,CSP},p_{s,\tau}^{r,CSP}\right) \tag{28}$$

2) Operational constraints of wind farm: wind power output cannot exceed its available capacity, which is expressed as:

$$p_{s,\tau}^{r,w}+U_{s,\tau}^{reg,w}\le P_{s,\tau}^{w} \tag{29}$$

$$p_{s,\tau}^{r,w}-D_{s,\tau}^{reg,w}\ge 0 \tag{30}$$

Similarly, considering the wind farm ramping constraints, its regulation-up/regulation-down capacity should not exceed a percentage $\eta^{reg,w}$ of the available capacity, which is expressed as:

$$D_{s,\tau}^{reg,w}\le\eta^{reg,w}P_{s,\tau}^{w} \tag{31}$$

$$U_{s,\tau}^{reg,w}\le\eta^{reg,w}P_{s,\tau}^{w} \tag{32}$$

3) Operational constraints of the coordinated system: CSP plant and wind farm should have sufficient power for the committed regulation capacity in DAM.

$$U_{s,\tau}^{reg,w}+U_{s,\tau}^{reg,CSP}\ge 0.5p_t^{reg} \tag{33}$$

$$D_{s,\tau}^{reg,w}+D_{s,\tau}^{reg,CSP}\ge 0.5p_t^{reg} \tag{34}$$

The aggregate energy base point submitted by the coordinated system is equal to the sum of the respective energy base points:

$$p_{s,\tau}^{r}=p_{s,\tau}^{r,CSP}+p_{s,\tau}^{r,w} \tag{35}$$

3) Solution Methods

The proposed optimization model is solved by CPLEX.

IV. Case Study

A. Case Description

The coordinated system in this case study consists of a wind farm with an installed capacity of 200 MW and a CSP plant with a maximum power output of 50 MW. The parameters of the CSP plant are shown in Table I. It is assumed that m is 5.5 and α is 0.1. Also assume that K^{perf} is 0.95 for the coordinated system, $\eta^{reg,CSP}$ is 50%, and $\eta^{reg,w}$ is 30%.

TABLE I
CSP PLANT PARAMETERS

Parameter	Value	Parameter	Value
η^{con}	35%	$Q_{\min}^{TES}$	50 MWh
$P_{\max}^{CSP}$	50 MW	$Q_{\max}^{TES}$	1000 MWh
P_{up}^{PB}	100 MWh^{-1}	$Q^{TES,init}$	640 MWh
P_{down}^{PB}	100 MWh^{-1}	R_{ch}^{TES}	300 MW
η^{CSP}	30%	R_{dis}^{TES}	300 MW

The price scenarios are generated based on the PJM historical market data in June 2019, and historical wind power and DSI from a certain area of the Northwest China are used to generate the corresponding scenarios for the coordinated system. We implement the K-medoids parallel clustering algorithm to cluster the data into 10 scenarios [27]. The hourly prices in the energy and regulation markets and the available wind power for one specific scenario (scenario 5) are shown in Fig. 3. The normalized regulation signal and the control error of the wind power are shown in Fig. 4, and the time interval is 15 min. The proposed optimization model is solved by CPLEX on a PC with 1.6 GHz processor and 8.00 GB of RAM.

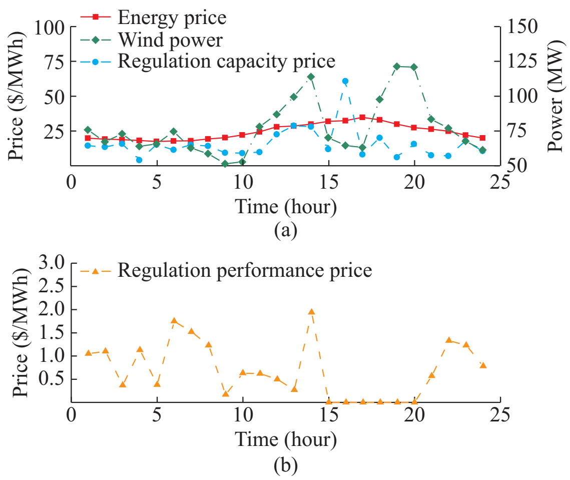

Fig. 3. Energy and regulation market prices, and available wind power for scenario 5. (a) Hourly prices in energy market and available wind power. (b) Hourly prices in regulation market.

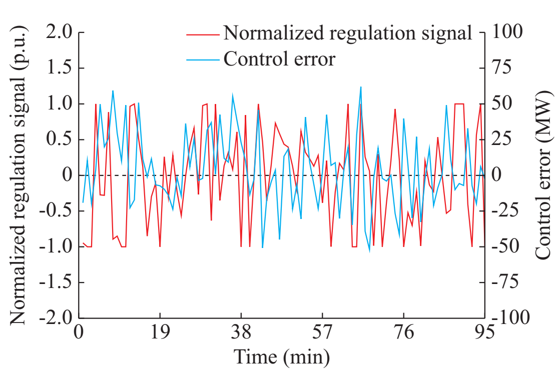

Fig. 4. Normalized regulation signal and wind power control error.

As shown in Fig. 5, the coordinated system has a large energy bid during the periods when the energy prices are relatively high, and its output trend roughly follows the trend of energy price. During the periods when the regulation prices are significantly lower than the energy prices, the coordinated system only participates in the energy market. However, during the periods of high regulation prices, the coordinated system can offer a higher capacity for regulation.

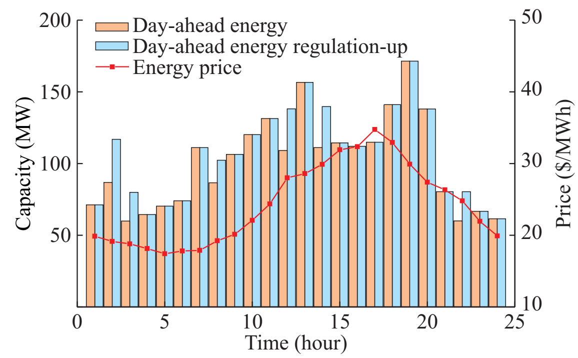

Fig. 5. Day-ahead bidding strategy of coordinated system.

The real-time energy base points provided by the wind farm will change as the available wind power fluctuates, which results in the deviation between the energy base points provided in real-time operation and the energy bids provided in DAM, and accordingly a penalty. However, since the regulation performance of wind power is calculated based on real-time energy base points, the more flexible change of the energy base points compared with day-ahead energy bids enables the wind farm to commit and fulfill more regulation capacities. In Fig. 6, the wind farm provides almost all energy in most time periods, and reserves some regulation capacity in certain time periods. Figure 7 shows that the CSP plant seeks more profit in the energy market while reserving enough regulation capacity to meet the demand for regulation. Figure 8 shows the energy flow inside the CSP plant, in which TES is discharged when the sun is not shining. Also, TES is charged and SF transfers a part of the received energy to PB through HTF when the DSI intensity is gradually increased. At the end of the day, TES returns to its initial heat storage level, which leaves sufficient capacity for the next day and leaves a certain margin for possible unexpected situations. Note that the time interval for Figs. 6-8 is also 15 min.

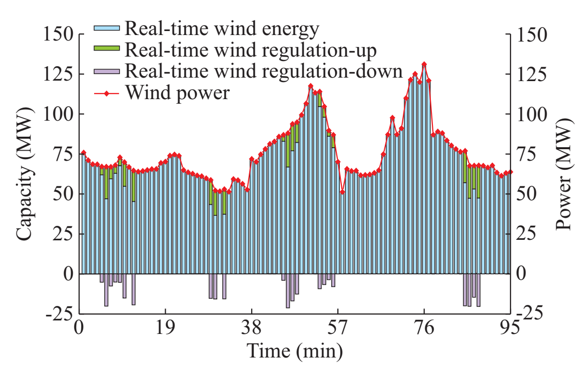

Fig. 6. Real-time bidding strategy of wind farm.

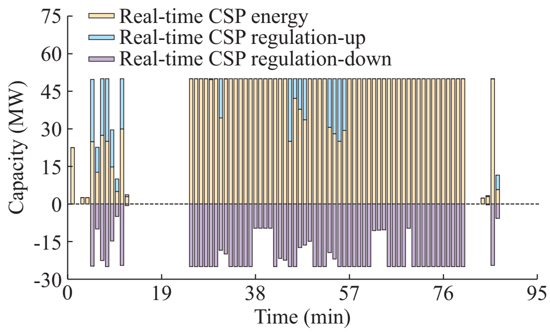

Fig. 7. Real-time bidding strategy of CSP plant.

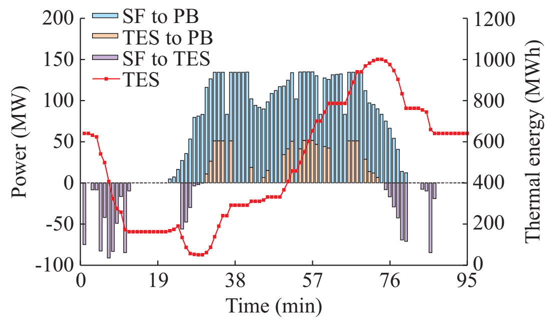

Fig. 8. CSP plant behavior in base mode.

C. Benefit of Coordinated Operation of CSP Plant and Wind Farm

Four different operation modes are compared to demonstrate the benefit of coordinated operation of CSP plant and wind farm based on the proposed model. Mode 1 refers to the proposed coordinated operation of CSP plant and the wind farm; mode 2 refers the coordinated system without applying the coordinated strategy; mode 3 refers to the independent operation of the wind farm without applying the CSP plant; mode 4 refers to the independent operation of the CSP plant without applying the wind farm. We assume the performance score is 0.8 in mode 3 and 0.95 in mode 4, which considers the rapid ramping capability of the CSP plant.

Table II shows a comparison of the hourly average bidding capacity for different operation modes, where the sum of individual regulation capacities of CSP plant and wind farm is 10.2 MW, which is 1.8 MW (or 15.0%) and 7.4 MW (or 42%) less than that of the coordinated system in mode 1 and mode 2, respectively. This shows that the coordinated operation of CSP plant and wind farm can provide more regulation capacity to earn a higher profit in the regulation market. The coordinated CSP plant and the wind farm without applying the coordinated strategy tracks the regulation signal and compensates control errors together. Thus, it provides larger bids to the regulation market than the coordinated system in mode 1. Furthermore, it can be observed that the hourly energy bid of the coordinated system without applying the coordinated strategy is 85.4 MW, and the sum of hourly individual energy bids of CSP plant and wind farm is 90.1 MW, which is 15.4 MW (or 15.3%) and 10.7 MW (or 10.6%) less than the coordinated system with the proposed strategy, respectively. The wind farm tracks the regulation signal alone and compensates the wind power control error in the independent operation. Thus, it provides smaller bids to the energy market. The CSP plant with dispatchable characteristics in the coordinated system can choose to increase the energy bid in appropriate periods. Thus, the coordinated operation of CSP plant and wind farm provides energy bids to the energy market to earn a higher profit as well as regulation capacity in the regulation market while ensuring the regulation accuracy.

TABLE II
COMPARISON OF HOURLY AVERAGE BIDDING CAPACITIES OF OPERATION MODES 1-4

Mode	Day-ahead energy (MW)	Day-ahead regulation capacity (MW)
1	100.8	12.0
2	85.4	17.6
3	59.7	6.8
4	30.4	3.4

Table III compares the incomes of different operation modes. The coordinated operation can generate a higher extra income, which is mainly due to the increase in energy bids and the improvement in the regulation performance score through coordination. If half of this extra income in mode 1 is allocated to the CSP plant and the other half goes to the wind farm, the revenue of the CSP plant will increase by about 20.1% as compared with that of mode 4, and the revenue of the wind farm will increase by about 11.2% as compared with that of mode 3.

TABLE III
ECONOMIC COMPARISON OF OPERATION MODES 1-4

Mode	Energy income ($)	Regulation income ($)	Net deviation income ($)	Total income ($)
1	61507	6486	1142	69135
2	52398	9019	781	62198
3	36068	3384	–707	38745
4	19341	1816	529	21687

D. Impact of Performance Score

Table IV compares the incomes of the coordinated system for different performance scores. It can be observed that the total income of the coordinated system increases with the improvement in the performance score. The regulation market income shows an upward trend, indicating that the performance score improvement provides a strong economic incentive for regulation resources to improve their regulation accuracy. In addition, when the coordinated system has the same performance score as that of mode 3, the total incomes of the coordinated operation of CSP plant and wind power increase by 12.8% as compared with the sum of independent operations of the wind farm (model 3) and the CSP plant (model 4).

TABLE IV
ECONOMIC COMPARISON OF PERFORMANCE SCORES

Score	Energy income ($)	Regulation income ($)	Net deviation income ($)	Total income ($)
0.80	61599	5128	1412	68139
0.85	62087	5448	924	68459
0.90	61731	6145	918	68794
0.95	61507	6486	1142	69135

E. Impact of Installed Capacity of Wind Farm

To study the impact of the installed capacity of the wind farm, we fix the installed capacity of the CSP plant and vary the installed capacity of the wind farm. We define a return on investment (ROI) metric, as shown in (36), which is the ratio of the annual income to the investment [28].

$$ROI=\frac{365F}{P_{\max}^{CSP}\lambda^{CSP}+P^{w}\lambda^{w}} \tag{36}$$

λ^{CSP} and λ^{w} are set to be 1170 \$/kW and 3200 \$/kW, respectively [12]. The ROIs for different ratios of CSP plant capacity to wind farm capacity are shown in Fig. 9. The results show that as the installed capacity of the wind farm increases, the ROI of the coordinated system increases gradually. However, the ROI of 7.0% will remain constant once the ratio reaches 1:17. Thus, for a fixed installed capacity of the CSP plant, the total incomes of the coordinated system gradually increase with an increase in the installed capacity of the wind farm. However, the economic return of the coordinated system from the investment reaches its maximum when the ratio of the CSP plant capacity to the wind farm capacity reaches 1:17.

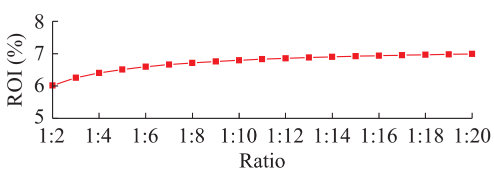

Fig. 9. ROIs for different ratios of CSP plant capacity to wind farm capacity.

F. Impact of Installed Capacity of CSP Plant

Similar to that in Section IV-E, the ROI is analyzed to study the impact of the installed capacity of the CSP plant for a fixed installed capacity of the wind farm. Figure 10 shows that as the installed capacity of the CSP plant increases, the ROI of the coordinated system decreases with a declining trend from fast to slow. When the ratio of wind farm capacity to CSP plant capacity reaches 1:5, the ROI drops to 0.7%. Thus, simply increasing the installed capacity of the CSP plant will not increase the economic return of the coordinated system from the investment perspective.

G. Impact of Maximum Regulation Capacities

The total incomes of the coordinated system are related to the maximum regulation capacities of the CSP plant and the wind farm. We use the ratios λ^{w} and λ^{CSP} to characterize the maximum regulation capacities of the wind farm and the CSP plant.

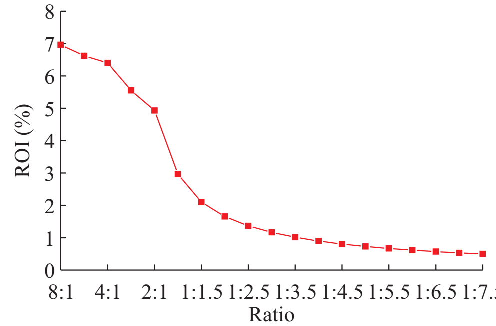

Fig. 10. ROIs for different ratios of wind farm capacity to CSP plant capacity.

Figure 11 show the total incomes of the coordinated system, with λ^{w} and λ^{CSP} gradually changing from 0 to 0.5. It can be observed that the total incomes of the coordinated system increase as the ratio increases. When the regulation capacities of the CSP plant and wind farm reach their maximum, the total incomes of the coordinated system reach their maximum. Thus, increasing the regulation capacities of the CSP plant and the wind farm can increase the total incomes. In addition, the total income increments for a given regulation ratio factor of the wind farm λ^{w} is greater than that for the same regulation ratio factor of the CSP plant λ^{CSP}. Therefore, considering the same regulation ratio factor, the regulation capacity of the CSP plant has a greater impact on the total incomes of the coordinated system than the regulation capacity of the wind farm.

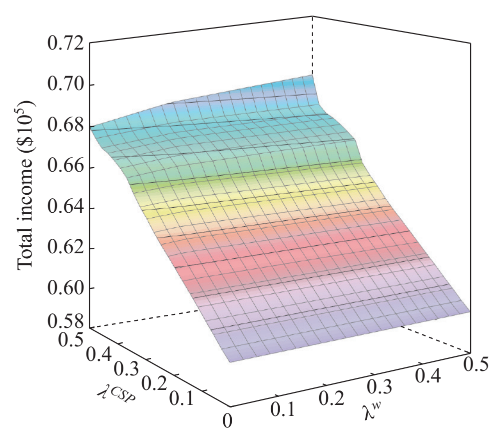

Fig. 11. Total income of coordinated system.

V. CONCLUSION

In this paper, a coordinated strategy for CSP and wind power providing frequency regulation is proposed which is based on the complementary characteristics of CSP plant and wind farm for providing regulation services. We consider the regulation performance score and deviation penalty to establish an optimal bidding model for a coordinated operation of CSP plant and wind farm. The case study results point out that the coordinated system can provide more regulation services, alleviating the regulation pressure of the system while increasing the coordinated system income. Since the regulation error of wind has a strong relationship with the turbulence, it is determined that the gap in regulation accuracy for the wind farm could be filled by the CSP plant. The increased regulation performance score and energy bids, enabled by the CSP plant, will bring extra income, as illustrated in the results. Finally, we conduct sensitivity analysis to study the impact of various parameters such as the installed capacity of wind farm and CSP plant on the total income of the coordinated system, which can provide insights into deciding the configuration of the coordinated system.

Besides, the coordination of CSP and wind power to participate in peak load regulation is also an area of interest, which will be an interesting research area in the future.

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