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A Nash-Cournot approach to assessing flexible ramping products☆

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HIGHLIGHTS

- FRPs' impacts on the day-ahead market with unit commitment are studied.
- The co-optimization of energy and FRPs markets are proposed.
- A multi-period Nash-Cournot model is established to study the market equilibrium.
- Energy storage systems are included to reveal their impacts on the equilibrium.

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ABSTRACT

Renewables are increasingly penetrating power systems and impacting electricity markets supported by the stricter energy and environmental policies. To handle the variability and uncertainty of renewable generation and to provide transparent economic incentives for resources to provide flexible services, a bid-based flexible ramping products market is proposed in the CAISO and MISO markets. To investigate the impact of these new products on the market equilibrium, a multi-period Nash-Cournot equilibrium model, formulated as a bi-level optimization problem, was proposed, and the Guass-Seidel iterative method was used to obtain the equilibrium. Moreover, a general framework of co-optimization of energy and flexible ramping products was established, and different types of generators, including thermal units, hydro units, renewable units and energy storage systems, are simultaneously considered to reflect their strategic interactions. Two cases with dominant solar power and wind power, respectively, have been implemented and are compared to demonstrate the impact of flexible ramping products on market prices, unit commitment and renewable integration. Additional energy storage systems are also included in the above case for further analysis. Simulation results show that when introducing the new products: the energy prices will increase slightly under normal conditions, more highly variable renewables can be integrated, the unit commitment will be changed, and more generators should be on line to provide flexible services, etc.

1. Introduction

Renewable energy has never been more favorably received across the world [1,2]. California, for example, recently announced its ambitious goal of a 50% renewable portfolio standard by the year 2030 [3]. Renewable energy contributes to a more sustainable future, but it also poses great challenges to the power system due to its stochastic nature. The unplaced deployment of fast ramping generation resources makes the situation even worse because there may not be sufficient ramping capacity in the system to smooth out the huge fluctuations in renewable energy output, leading to short-term flexibility-induced scarcities [4]. More precisely, by 2020, it is estimated that approximately 4600 MW of flexible ramping capacity will be needed inside the California independent system operator (CAISO) balancing area due to increasing renewables whereas approximately 12,079 MW of traditional generation capacity will be retired over the next eight years [5].

To cope with the short-term flexibility-induced scarcities, the system operators could [6] (1) increase the reserve margins, (2) add a certain offset value to the predicted load, (3) dispatch fast start-up units (mainly hydro units and gas turbines), (4) keep extra units on line in addition to the market-based mechanism, or (5) implement a look-ahead multi-interval dispatch mode in the real-time market. However, these practices are mainly from the system reliability perspective and do not fully consider the market distortions and economic impacts.

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Nomenclature

Indices and Sets

t	time index
Si	energy storage system index
Ti	thermal unit index
Hi	hydro unit index
Ri	renewable unit index.

Parameters and Constants

N	total number of market participants
TP	total number of thermal units
HP	total number of hydro units
RE	total number of renewable units
ES	total number of energy storages
η_{Si}^{dis}	discharging efficiency of storage *Si*
η_{Si}^{cha}	charging efficiency of storage *Si*
$q_{Ti\max}$	maximum generation output of thermal unit *Ti*, MW
$q_{Hi\max}$	maximum generation output of hydro unit *Hi*, MW
$q_{Ti\min}$	minimum generation output of thermal unit *Ti*, MW
$q_{Hi\min}$	minimum generation output of hydro unit *Hi*, MW
q_{Ti}^{RMPU}	Ramp up rate limit of thermal unit *Ti*, MW.
q_{Ti}^{RMPD}	Ramp down rate limit of thermal unit *Ti*, MW.
$E_{Si\max}$	maximum energy the storage *Si* can store, MWh
$E_{Hi\max}$	maximum energy the hydro unit *Hi* can provide, MWh
$q_{Si\max}$	maximum generation output of storage *Si*, MW
$q_{Ri\max}(t)$	maximum generation output of renewable unit *Ri* at time *t*, MW
$q_{Ri\min}(t)$	minimum generation output of renewable unit *Ri* at time *t*, MW
$q_D^E(t)$	energy demand at time *t*, MW
$\alpha^E(t)$	intercept of the inverse demand function of energy, \$/MWh
$\beta^E(t)$	slope of the inverse demand function of energy, \$/(MWh × MW)
$\alpha^{RAMPU}(t)$	intercept of the inverse demand function of upward ramping products, \$/MW
$\beta^{RAMPU}(t)$	slope of the inverse demand function of upward ramping products, \$/MW
$\alpha^{RAMPD}(t)$	intercept of the inverse demand function of downward ramping products, \$/MW
$\beta^{RAMPD}(t)$	slope of the inverse demand function of downward ramping products, \$/MW

Variables

$\pi_{Si}(t)$	profit of energy storage *Si* at time *t*, \$
$\pi_{Ti}(t)$	profit of thermal unit *Ti* at time *t*, \$
$\pi_{Hi}(t)$	profit of hydro unit *Hi* at time *t*, \$
$\pi_{Ri}(t)$	profit of renewable unit *Ri* at time *t*, \$
$\lambda^E(t)$	energy market price at time *t*, \$/MWh
$q_{Si}(t)$	generation output of storage *Si* at time *t*, MW
$q_{Ti}(t)$	output of thermal unit *Ti* at time *t*, MW
$q_{Hi}(t)$	output of hydro unit *Hi* at time *t*, MW
$q_{Ri}(t)$	output of renewable unit *Ri* at time *t*, MW
$q_{Si}^{RAMPU}(t)$	assigned capacity of upward ramping products of storage *Si* at time *t*, MW
$q_{Si}^{RAMPD}(t)$	assigned capacity of downward ramping products of storage *Si* at time *t*, MW
$q_{Ti}^{RAMPU}(t)$	assigned capacity of upward ramping products of thermal unit *Ti* at time *t*, MW
$q_{Ti}^{RAMPD}(t)$	assigned capacity of downward ramping products of thermal unit *Ti* at time *t*, MW
$q_{Hi}^{RAMPU}(t)$	assigned capacity of upward ramping products of hydro unit *Hi* at time *t*, MW
$q_{Hi}^{RAMPD}(t)$	assigned capacity of downward ramping products of hydro unit *Hi* at time *t*, MW
$q_{Ri}^{RAMPU}(t)$	assigned capacity of upward ramping products of renewable unit *Ri* at time *t*, MW
$q_{Ri}^{RAMPD}(t)$	assigned capacity of downward ramping products of renewable unit *Ri* at time *t*, MW
$q_{Si}^{dis}(t)$	discharging power of storage *Si* at time *t*, MW
$q_{Si}^{cha}(t)$	charging power of storage *Si* at time *t*, MW
$b_{Si}^{dis}(t)$	binary variable indicating the discharging status of storage *Si* at time *t*
$b_{Si}^{cha}(t)$	binary variable indicating the charging status of storage *Si* at time *t*
$E_{Si}(t)$	stored energy of storage *Si* at time *t*, MWh

This motivates CAISO [7] and MISO [8] to introduce new products into the electricity markets, i.e., flexible ramping products (FRPs), which include both upward ramping products (URPs) and downward ramping products (DRPs) [7]. The FRPs are designed to relieve the system-wide ramp constraints. The implementation of bid-based FRPs is still under stakeholder consideration, and the FRP market is expected to be fully operated in the near future [9]. FRPs are different from traditional regulation and reserve services in definition, ramping directions and operational time scales (see [4,7–10] for more detailed discussion).

Investigation of the impact of FRPs on the market operation has appeared only recently. Cornelius used the modified unit commitment (UC) and economic dispatch (ED) models with FRPs to explore the economic, environmental and reliability impacts of the newly proposed FRPs in the MISO electricity market [11]. In [12], Abdul-Rahman et al. presented the mathematical formulation of the FRPs that were actually used in the CAISO market and analyzed the practical benefits observed by introducing the upward flexible ramping constraint in the real-time pre-dispatch process. Navid et al. proposed a modified security constrained economic dispatch model to incorporate the FRPs for a time-coupled multi-interval dispatch [6]. The results of single-interval dispatch and multiple-interval time-coupled dispatch were compared to show the advantages of FRPs. Wang et al. investigated the differences between a deterministic dispatch model with flexible ramping constraints that simulates the ISO operations and a stochastic dispatch model that minimizes the expected operation costs [10]. Apart from the enhancements by introducing flexible ramping constraints, the simulations also show that procuring the FRPs is insufficient to minimize the expected costs and that the FRP market needs further and careful design to avoid potential market inefficiencies. Wu et al. presented a functional analysis based on an ED model with FRPs to study the additional costs that FRPs may incur [13]. The results indicate that the distortional costs could be reduced by carefully choosing the requirements for FRPs [14].

Differing from the previous work, which mostly focused on the intra-day or real-time operation issues of power systems or energy market with FRPs, we strive to answer the following questions: with the new market component, how do FRPs impact the strategic behavior of market participants and thus the overall electricity market equilibrium? Can FRPs effectively improve the integration of renewables and provide various resources with sufficient incentives to provide flexibility? Will the energy price increase significantly, considering the capacity coupling effect of generators when simultaneously providing the energy and FRPs? How can FRPs benefit new technology with high flexibility (e.g., energy storage systems)? How much extra profit could be obtained for various generators when participating in the co-optimized energy and FRP markets? All the above problems need to be clearly addressed to validate the evolving market design. Moreover, it would be more appropriate to consider the combined energy and FRPs in the day-ahead unit commitment process rather than intra-day or real-time because it is usually too late or uneconomical to start additional units to satisfy the ramping requirements close to the real-time operation. Actually, according to [7], the CAISO is considering a plan to "procure some of the ramping capability in the day-ahead market." In their opinion, "modeling flexible ramping products in the day-ahead market could make unit commitment decision for long start units and establish forward financial position for flexible ramping capability."

Therefore, the main contributions of this paper include:

(1) A multi-period Nash-Cournot equilibrium model considering the unit commitment with FRPs in the day-ahead market, where all participants simultaneously submit their strategic offers to maximize their individual profits, are proposed.
(2) To handle the capacity coupling effects of generators and to optimize the utilization of power resources, a quantitative model framework, which can be formulated as a bi-level optimization problem, is established to represent the co-optimization of energy and FRPs markets. And the Guass-Seidel iterative method is employed to determine the market equilibrium [15].
(3) Considering the significant potential of large-scale renewable integrations, two specific cases are analyzed to show the impacts of FRPs on market prices, unit commitment status, renewable integrations and profits of generators, etc. Additional energy storage systems are also included in the previous two cases to present their impacts on the multi-market results and corresponding changes.

The rest of this article is organized as follows. We first introduce the operation of co-optimized energy and FRP markets in Section 2. Section 3 presents the upper-level model, where each participant tries to maximize its own profit. Next, we discuss the lower-level model with all the market clearing conditions in Section 4. Then, we adopt the Guass-Seidel iterative method to better characterize the equilibrium in Section 5. We then conduct several case studies to justify the impact of FRPs in Section 6. Finally, the study's conclusions and future directions are discussed in Section 7.

2. Co-optimization of energy and FRPs

2.1. Energy market

Compared to the complicated supply-function equilibrium model, the generalized Cournot equilibrium model is adopted in this paper because of its computational efficiency, explicit economic meaning and wide application in electricity markets [16]. Therefore, in the pool-based energy market, different types of generators collectively compete in the Cournot manner; that is, each generator is considered as a price-maker and strategically decides its energy production level considering the possible reactions of rivals, and then it submits the offer to the market operator (MO) before the gate closure. The MO then clears the energy market considering the power balance constraint in each period and calculates the time-varying marginal clearing prices (MCPs) to make settlements according to the energy inverse demand function obtained from the demand side.

2.2. FRP markets

In the bid-based FRP market, the participants also behave in the Cournot competition manner to reflect the strategic interactions between them. The thermal units, hydro units and energy storage systems are permitted to provide FRPs and can be compensated with capacity payments. The system-wide requirements for URPs and DRPs are formulated as follows [4,17]: $\forall\, t \in T, T = 1,2,\ldots 96$,

$$\begin{cases} q_D^{RAMPU}(t) = \max\{L_{\text{net}}(t+1) - L_{\text{net}}(t) + q_{Uup}(t+1), 0\} \\ q_D^{RAMPD}(t) = \max\{L_{\text{net}}(t) - L_{\text{net}}(t+1) + q_{Udown}(t+1), 0\} \end{cases} \tag{1}$$

where $q_D^{RAMPU}(t)$ and $q_D^{RAMPD}(t)$ are the requirements for URPs and DRPs in period t, respectively, $L_{\text{net}}(t)$ is the forecast net load (that is, the forecast load minus the forecast renewable generation) in period t, and $q_{Uup}(t+1)$ and $q_{Udown}(t+1)$ are the reserved generation capacities used to handle the forecast errors according to the 95% confidence interval principle.

Therefore, the requirements for FRPs are determined in two parts: one part is used to capture the variabilities of the forecast net load in consecutive periods (that is, the net demand forecast change across intervals), and an additional amount is used to cover their expected uncertainties within a 95% confidence interval [4]. That is, the uncertainties of renewable generation and the load are explicitly considered in the requirement determination of FRPs and thus, the use of the stochastic method is again unnecessary to describe the intermittent

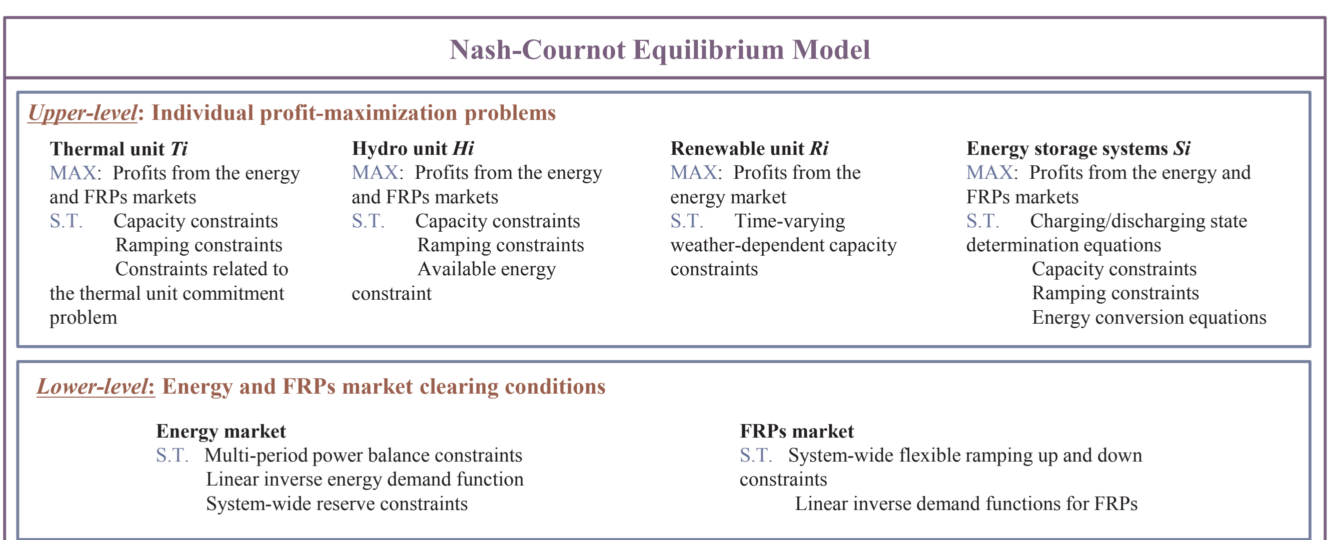

Fig. 1. The chart for the Nash-Cournot equilibrium model.

nature of renewables [10].

2.3. Co-optimization of the energy and FRP markets

Considering the capacity coupling effects of generators when simultaneously providing the energy and FRPs, the co-optimization approach and joint clearing are implemented by extending the objective function to minimize the total production costs of the energy and FRPs [12]. The technical constraints of thermal units, hydro units and energy storage systems, especially their capacity coupling constraints, are explicitly considered to jointly clear the multi-period multi-markets. The traditional ancillary services, such as regulation and reserve services, are not included in the co-optimization so that we can focus on the impact of the FRP on the market equilibrium. Moreover, the co-optimization horizon is the next trading day (24 h), and the time discretization is 15 min.

3. Upper-level model: individual profit-maximization model for each generator

The Nash-Cournot equilibrium model is formulated as a bi-level optimization model, as shown in Fig. 1. The upper-level model indicates an individual profit-maximization problem for each participant, and the lower-level model represents the joint clearing conditions of the energy and FRP markets shared by each participant. Moreover, only the commitment problems of thermal units are formulated in this section, and hydro units and energy storage systems are reasonably regarded as highly flexible and can be started or shut down when necessary.

3.1. Thermal units

3.1.1. Objective function

The objective of the thermal unit Ti is to obtain the maximal profits from providing both the energy and FRPs considering the variable generation costs and the start-up costs. The specific objective function is

$$\max \pi_{Ti} = \sum_{t=1}^{T=96} \lambda^{E}(t)q_{Ti}(t) + \sum_{t=1}^{T=96} \lambda^{RAMPU}(t)q_{Ti}^{RAMPU}(t) + \sum_{t=1}^{T=96} \lambda^{RAMPD}(t)q_{Ti}^{RAMPD}(t) - \sum_{t=1}^{T=96} [C_{Ti}^{FC}(t) + C_{Ti}^{SU}(t)] \tag{2}$$

where $\lambda^{E}(t)$ is the MCP of the 15-min energy market in period t, $\lambda^{RAMPU}(t)$ is the clearing price for resources that provide the URPs in period t, $\lambda^{RAMPD}(t)$ is the clearing price for resources that provide the DRPs in period t, $q_{Ti}(t)$ is the energy production level that the thermal unit Ti decides in period t, $q_{Ti}^{RAMPU}(t)$ is the ramp-up capability that the thermal unit Ti can provide in period t, $q_{Ti}^{RAMPD}(t)$ is the ramp-down capability the thermal unit Ti can provide in period t, $C_{Ti}^{FC}(t)$ is the variable fuel cost of the thermal unit Ti in period t, and $C_{Ti}^{SU}(t)$ is the start-up cost of the thermal unit Ti in period t.

The variable generation cost function is $\forall\, t \in T$,

$$C_{Ti}^{FC}(t) = a_{Ti}q_{Ti}^{2}(t) + b_{Ti}q_{Ti}(t) + Z_{Ti}(t)c_{Ti} \tag{3}$$

where $a_{Ti},b_{Ti},c_{Ti} \geqslant 0$ are the coefficients of the fuel cost function of the thermal unit Ti, and $Z_{Ti}(t)$ is the binary variable indicating the generation status of the thermal unit Ti in period t, that is, $Z_{Ti}(t) = 0$ means that the thermal unit Ti is off-line in period t, and $Z_{Ti}(t) = 1$ implies that the thermal unit Ti is on-line in period t.

The start-up cost of a thermal unit changes with the temperature of the boiler, and the longer the time duration since the previous shutdown, the higher the startup cost. The formulation is [18] $\forall\, t \in T$,

$$\begin{cases} C_{Ti}^{SU}(t) \geqslant C_{Ti}^{cold}Y_{Ti}^{SU}(t) - \sum_{m=1}^{T_{Ti}^{UD}} \Delta C_{Ti}^{W}(m)Y_{Ti}^{SD}(t-m) \\ C_{Ti}^{SU}(t) \geqslant 0 \end{cases} \tag{4}$$

where C_{Ti}^{cold} is the cold start-up cost of the thermal unit Ti, $Y_{Ti}^{SU}(t)$ is the binary variable indicating the start-up status of the thermal unit Ti in period t, $\Delta C_{Ti}^{W}(m)$ is the cost difference between a the cold start-up and a hot/warm start-up, $Y_{Ti}^{SD}(t)$ is the binary variable indicating the shutdown status of the thermal unit Ti in period t, and T_{Ti}^{UD} is the time duration for the thermal unit Ti from operation to full cool down.

3.1.2. Constraints

The capacity constraints considering the FRPs are $\forall\, t \in T$,

$$\begin{cases} q_{Ti}(t) + q_{Ti}^{RAMPU}(t) - Z_{Ti}(t)q_{Ti\max} \leqslant 0 \\ q_{Ti}(t) - q_{Ti}^{RAMPD}(t) - Z_{Ti}(t)q_{Ti\min} \geqslant 0 \\ q_{Ti}(t), q_{Ti}^{RAMPU}(t), q_{Ti}^{RAMPD}(t) \geqslant 0 \end{cases} \tag{5}$$

where $q_{Ti\min}$ and $q_{Ti\max}$ are the minimum and maximum generation output limits of the thermal unit Ti, respectively.

The ramping constraints considering the FRPs are $\forall\, t \in T$,

$$\begin{cases} [q_{Ti}(t+1) - q_{Ti}(t)] + [q_{Ti}^{RAMPU}(t+1) + q_{Ti}^{RAMPD}(t)] \leqslant q_{Ti\max}^{RMPU} \\ [q_{Ti}(t) - q_{Ti}(t+1)] + [q_{Ti}^{RAMPD}(t+1) + q_{Ti}^{RAMPU}(t)] \leqslant q_{Ti\max}^{RMPD} \\ q_{Ti}^{RAMPU}(t) \leqslant q_{Ti\max}^{RMPU}, q_{Ti}^{RAMPD}(t) \leqslant q_{Ti\max}^{RMPD} \end{cases} \tag{6}$$

where $q_{Ti\max}^{RMPU}$ and $q_{Ti\max}^{RMPD}$ are the maximum ramp-up and ramp-down rates of the thermal unit Ti, respectively. The ramp rate of the coal-fired thermal unit is approximately 1–2% of the maximum capacity per minute. For gas-fired units, the ramp rate can be taken as the maximum capacity during 15 min because of their high flexibility.

The logical relationship constraints of the unit status are [19]: $\forall\, t \in T$,

$$\begin{cases} Z_{Ti}(t) = Z_{Ti}(t-1) + Y_{Ti}^{SU}(t) - Y_{Ti}^{SD}(t) \\ Y_{Ti}^{SU}(t) + Y_{Ti}^{SD}(t) \leqslant 1 \end{cases} \tag{7}$$

The maximum number of the unit start-up constraints during an entire day is

$$\sum_{t=1}^{T=96} Y_{Ti}^{SU}(t) \leqslant N_{Ti}^{SU} \tag{8}$$

where N_{Ti}^{SU} is the maximum start-up time of the thermal unit Ti. For coal-fired units, the number of possible start-ups in a day is at most one, whereas for gas-fired units, the start-ups in a day could be two.

The minimum on-line period of the thermal unit Ti is: $\forall\, t \in T$,

$$Y_{Ti}^{SU}(t) + \sum_{\tau=t+1}^{t+T_{Ti}^{on}-1} Y_{Ti}^{SD}(\tau) \leqslant 1 \tag{9}$$

where T_{Ti}^{on} is the minimum duration for which a thermal unit should be on-line when it starts up.

The minimum off-line period of the thermal unit Ti is: $\forall\, t \in T$,

$$Y_{Ti}^{SD}(t) + \sum_{\tau=t+1}^{t+T_{Ti}^{off}-1} Y_{Ti}^{SU}(\tau) \leqslant 1 \tag{10}$$

where T_{Ti}^{off} is the minimum duration for which a thermal unit should be off-line when it shuts down.

3.2. Hydro units

The objective of the hydro unit Hi is to obtain the maximal profits by simultaneously participating in both the energy and FRP markets. The variable generation costs of the hydro unit Hi are reasonably assumed to be zero [20].

Table 1
Basic data of the generators.

Type	Nominal power (MW)	Minimum Output (MW)	Number
Coal-fired Units	300	150	5
	100	25	7
	350	100	1
	250	50	2
	200	50	2
	420	100	2
	80	30	1
	30	10	3
Gas-fired Units	30	8	11
Hydro Units	70	9	2
	115	17	1
	194	30	1
	80	9	1
Solar Units	100	0	30
Wind Units	100	0	30
Energy Storages	80	-80	8

$$\max \pi_{Hi} = \sum_{t=1}^{T=96} \lambda^{E}(t) q_{Hi}(t) + \sum_{t=1}^{T=96} \lambda^{RAMPU}(t) q_{Hi}^{RAMPU}(t) + \sum_{t=1}^{T=96} \lambda^{RAMPD}(t) q_{Hi}^{RAMPD}(t) \quad (11)$$

where $q_{Hi}(t)$ is the energy production level set by the hydro unit *Hi* in period *t*, $q_{Hi}^{RAMPU}(t)$ is the ramp-up capability that the hydro unit *Hi* can provide in period *t*, and $q_{Hi}^{RAMPD}(t)$ is the ramp-down capability that the hydro unit *Hi* can provide in period *t*.

The capacity constraints considering the FRPs are $\forall\ t \in T$,

$$\begin{cases} q_{Hi}(t) + q_{Hi}^{RAMPU}(t) - q_{Hi\max} \leqslant 0 \\ q_{Hi}(t) - q_{Hi}^{RAMPD}(t) - q_{Hi\min} \geqslant 0 \\ q_{Hi}(t), q_{Hi}^{RAMPU}(t), q_{Hi}^{RAMPD}(t) \geqslant 0 \end{cases} \quad (12)$$

where $q_{Hi\min}$ and $q_{Hi\max}$ are power output limits of the hydro unit *Hi*.

The ramping constraints considering FRPs are $\forall\ t \in T$,

$$\begin{cases} [q_{Hi}(t+1) - q_{Hi}(t)] + [q_{Hi}^{RAMPU}(t+1) + q_{Hi}^{RAMPD}(t)] \leqslant q_{Hi\max}^{RMPU} \\ [q_{Hi}(t) - q_{Hi}(t+1)] + [q_{Hi}^{RAMPD}(t+1) + q_{Hi}^{RAMPU}(t)] \leqslant q_{Hi\max}^{RMPD} \\ q_{Hi}^{RAMPU}(t) \leqslant q_{Hi\max}^{RMPU}, q_{Hi}^{RAMPD}(t) \leqslant q_{Hi\max}^{RMPD} \end{cases} \quad (13)$$

where $q_{Hi\max}^{RMPU}$ and $q_{Hi\max}^{RMPD}$ are the maximum ramp-up and ramp-down rates of the hydro unit *Hi*, respectively. Considering the fast response capability and high flexibility of the hydro units, the maximum ramp rate (up or down) during one period (15 min) can be regarded as the maximum generation capacity $q_{Hi\max}$.

The available energy constraint considering the reservoir water resource limit is

Table 2
Comparison of day-ahead market prices between BCS, BCS + FRPs and BCSE + FRPs.

Cases	Average Energy Price ($/MWh)	Average URP Price ($/MW)	Average DRP Price ($/MW)
BCS	28.35	–	–
BCS + FRPs	28.50	16.88	10.33
BCSE + FRPs	27.68	9.67	4.93

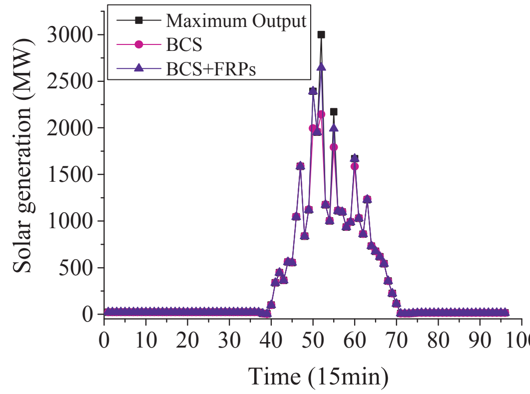

Fig. 3. Comparison of solar integration between BCS and BCS + FRPs.

$$\frac{1}{4} \sum_{t=1}^{T=96} [q_{Hi}(t)] \leqslant E_{Hi\max} \quad (14)$$

where $E_{Hi\max}$ is the maximum energy that the hydro unit *Hi* can provide during an entire day.

3.3. Renewable units

Considering the variabilities and uncertainties of the renewable generation, we assume that the wind units and solar units could not provide the flexibility needed in the system. Thus, the objective function of the individual profit-maximization model of renewable unit *Ri* is to maximize the payments only from the energy market:

$$\max \pi_{Ri} = \sum_{t=1}^{T=96} [\lambda^{E}(t) q_{Ri}(t)] \quad (15)$$

where $q_{Ri}(t)$ is the production level determined by renewable unit *Ri* in period *t*.

The time-varying weather-dependent capacity constraints of the renewable units are $\forall\ t \in T$,

$$q_{Ri\min}(t) \leqslant q_{Ri}(t) \leqslant q_{Ri\max}(t) \quad (16)$$

where $q_{Ri\min}(t)$ and $q_{Ri\max}(t)$ are the forecast minimum and maximum

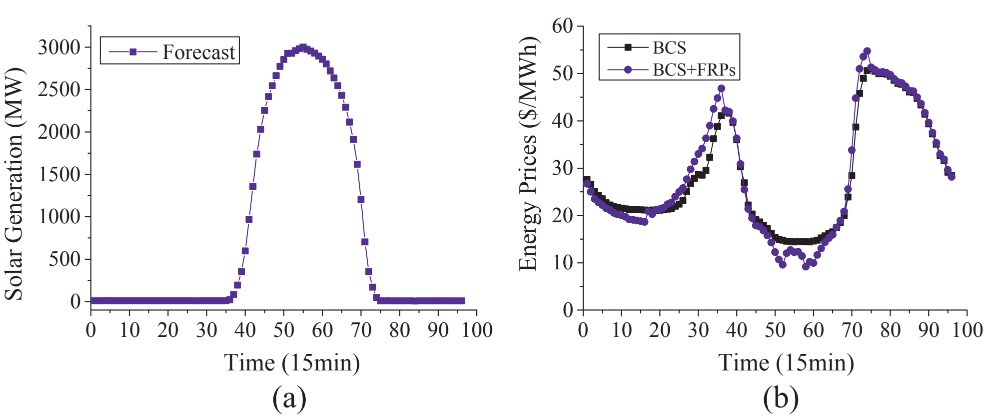

Fig. 2. The forecast solar generation and day-ahead energy prices.

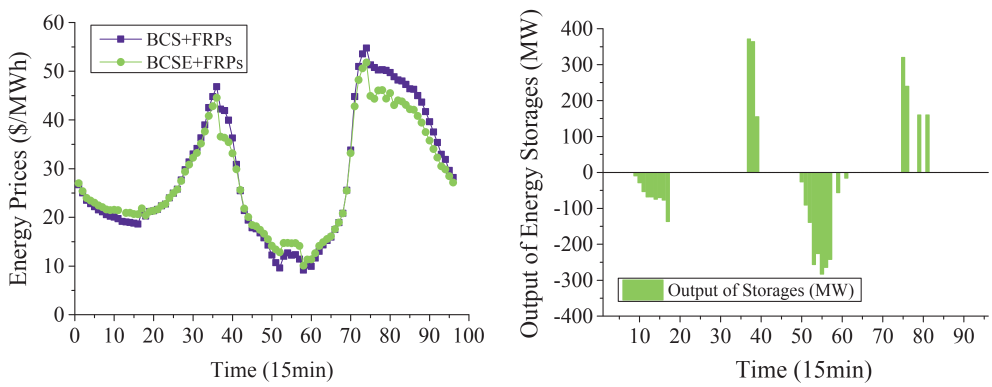

Fig. 4. Day-ahead energy prices and strategic behavior of storage of the BCSE + FRPs.

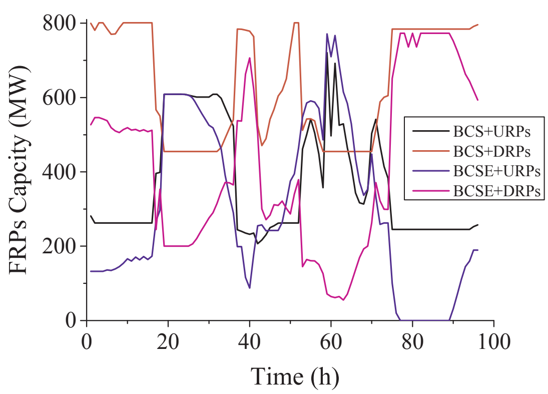

Fig. 5. The changes in the assigned URPs and DRPs of the thermal units of the solar doninated case.

generation output limits in period t based on the time-varying wind speed or the solar irradiation.

3.4. Energy storage systems

Considering the highly flexible capabilities and very low variable costs of the energy storage systems, the objective is to maximize the income from both the energy and FRP markets:

$$\max \pi_{Si} = \sum_{t=1}^{T=96} \lambda^{E}(t) q_{Si}(t) + \sum_{t=1}^{T=96} \lambda^{RAMPU}(t) q_{Si}^{RAMPU}(t) + \sum_{t=1}^{T=96} \lambda^{RAMPD}(t) q_{Si}^{RAMPD}(t) \tag{17}$$

where $q_{Si}(t)$ is the charging or discharging power decided by the energy storage system Si in period t, $q_{Si}^{RAMPU}(t)$ is the ramp-up capability that the energy storage system Si can provide in period t, and $q_{Si}^{RAMPD}(t)$ is the ramp-down capability that the energy storage system Si can provide in period t. Moreover, the variable costs of energy storage systems are implicitly considered in the form of round-trip efficiencies.

The charging or discharging state determining equations are: $\forall\, t \in T$,

Table 3
Comparison of day-ahead market prices between BCW, BCW + FRPs and BCWE + FRPs.

Cases	Average Energy Price ($/MWh)	Average URPs Price ($/MW)	Average DRPs Price ($/MW)
BCW	28.80	–	–
BCW + FRPs	29.86	21.04	9.35
BCWE + FRPs	28.93	12.89	5.29

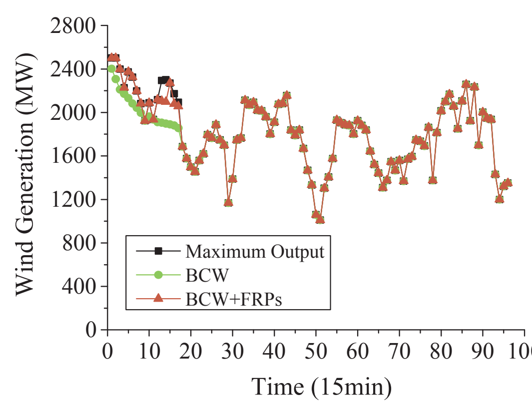

Fig. 7. Comparison of actual wind integration between BCW and BCW + FRPs.

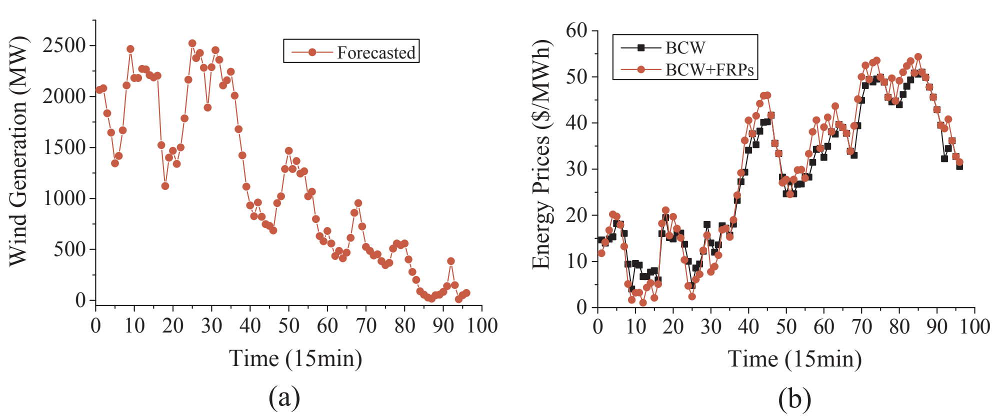

Fig. 6. The forecast wind generation and day-ahead energy prices.

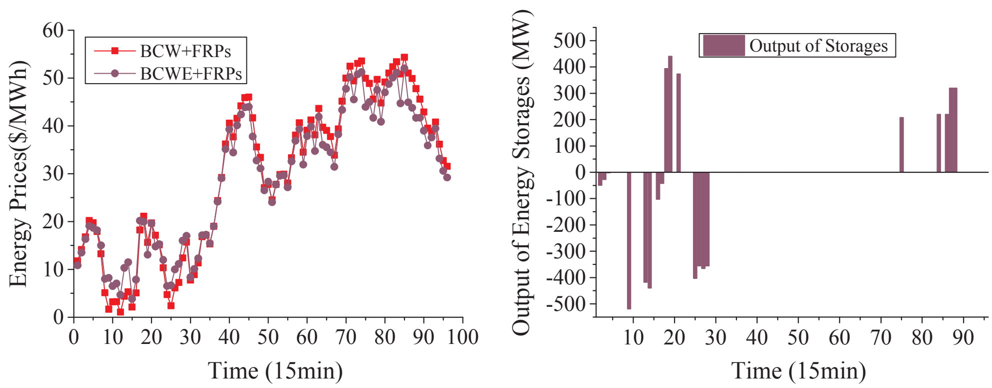

Fig. 8. Day-ahead energy prices and strategic behavior of storage of the BCWE + FRPs.

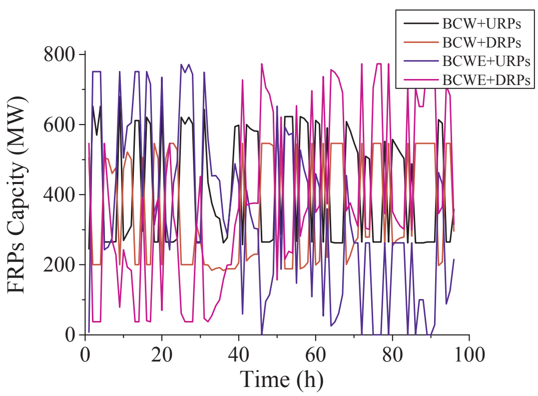

Fig. 9. The changes in the assigned URPs and DRPs of the thermal units of the wind dominated case.

$$\begin{cases} q_{Si}(t) = q_{Si}^{dis}(t) + q_{Si}^{cha}(t) \\ 0 \leqslant q_{Si}^{dis}(t) \leqslant Z_{Si}^{dis}(t) q_{Si\max} \\ -Z_{Si}^{cha}(t) q_{Si\max} \leqslant q_{Si}^{cha}(t) \leqslant 0 \\ Z_{Si}^{dis}(t) + Z_{Si}^{cha}(t) = 1 \\ Z_{Si}^{dis}(t), Z_{Si}^{cha}(t) \in \{0,1\} \end{cases} \tag{18}$$

where $q_{Si}^{dis}(t)$ and $q_{Si}^{cha}(t)$ are, respectively, the discharging and charging power of the energy storage systems *Si* in period *t*, $Z_{Si}^{dis}(t)$ and $Z_{Si}^{cha}(t)$ are the binary variables indicating the working status of *Si* in period *t*, and $q_{Si\max}$ is the maximum capacity of the energy storage systems *Si*.

The capacity constraints considering FRPs are: $\forall\ t \in T$,

$$\begin{cases} q_{Si}(t) + q_{Si}^{RAMPU}(t) - q_{Si\max} \leqslant 0 \\ q_{Si}(t) - q_{Si}^{RAMPD}(t) + q_{Si\min} \geqslant 0 \\ q_{Si}^{RAMPU}(t), q_{Si}^{RAMPD}(t) \geqslant 0 \end{cases} \tag{19}$$

The energy related constraints and the conversion equation are $\forall\ t \in T$,

$$\begin{cases} 0 \leqslant E_{Si}(t) \leqslant E_{Si\max} \\ E_{Si}(t)|_{\text{end}} = E_{Si}(t)|_{\text{ini}} \\ E_{Si}(t+1) = E_{Si}(t) - q_{Si}^{dis}(t)/\eta_{Si}^{dis} - \eta_{Si}^{cha} \cdot q_{Si}^{cha}(t) \end{cases} \tag{20}$$

where $E_{Si}(t)$ is the stored energy of the energy storage system *Si* in period *t*, $E_{Si\max}$ is the maximum energy that the storage *Si* can accommodate, η_{Si}^{dis} and η_{Si}^{cha} are the discharging and charging efficiencies of the energy storage system *Si*. The second equation of (1 s) indicates that the final state of energy equals the initial state of energy on a daily cycle.

The ramping constraints considering FRPs are: $\forall\ t \in T$,

$$\begin{cases} [q_{Si}(t+1) - q_{Si}(t)] + [q_{Si}^{RAMPU}(t+1) + q_{Si}^{RAMPD}(t)] \leqslant q_{Si\max}^{RMPU} \\ [q_{Si}(t) - q_{Si}(t+1)] + [q_{Si}^{RAMPD}(t+1) + q_{Si}^{RAMPU}(t)] \leqslant q_{Si\max}^{RMPD} \\ q_{Si}^{RAMPD}(t) \leqslant q_{Si\max}^{RMPD}, q_{Si}^{RAMPU}(t) \leqslant q_{Si\max}^{RMPU} \end{cases} \tag{21}$$

where $q_{Si\max}^{RMPU}$ and $q_{Si\max}^{RMPD}$ are the maximum ramp-up and ramp-down rates of the energy storage systems *Si*, respectively. Considering the fast response capability and high flexibility of the energy storage systems, the maximum ramp rate (up or down) during one period (15 min) can be regarded as the maximum regulating capability $2q_{Si\max}$.

4. Lower-level model: market clearing conditions

The market clearing conditions shared by each participant incorporate multi-period power balance constraints, flexible ramping constraints, system reserve constraints, and linear inverse demand functions for both energy and FRPs and network constraints.

The energy supply–demand balance constraints and the inverse demand functions for energy in different periods are: $\forall\ t \in T$,

$$\begin{cases} \sum_{i=1}^{N} q_{Xi}(t) = \sum_{Ti=1}^{TP} q_{Ti}(t) + \sum_{Hi=1}^{HP} q_{Hi}(t) \\ \qquad + \sum_{Ri=1}^{RE} q_{Ri}(t) + \sum_{Si=1}^{ES} q_{Si}(t) \\ \sum_{Xi=1}^{N} q_{Xi}(t) = q_D^E(t) \\ \lambda^E(t) = \alpha^E(t) - \beta^E(t) q_D^E(t) \end{cases} \tag{22}$$

where $N = TP + HP + RE + ES$ is the total number of different types of generators, $q_{Xi}(t)$ represents a certain type of generator that can provide energy in period *t*, $q_D^E(t)$ is the total energy demand in period *t*, and $\alpha^E(t)$ and $\beta^E(t)$ are the coefficients of the energy inverse demand function in period *t*.

The system-wide reserve constraint in each period is: $\forall\ t \in T$,

$$\sum_{Ti=1}^{TP} Z_{Ti}(t) q_{Ti\max}(t) + \sum_{Hi=1}^{HP} q_{Hi\max}(t) + \sum_{Ri=1}^{RE} q_{Ri}(t) + \sum_{Si=1}^{ES} q_{Si\max}(t) \geqslant q_D^E(t) + R(t) \tag{23}$$

where $R(t)$ is the reserve demand in period *t*, which is also regarded as the emergency reserve and usually determined by the capacity of the largest on-line generator.

The system-wide flexible ramp-up and ramp-down constraints are: $\forall\ t \in T$,

$$\begin{cases} \sum_{Ti}^{TP} q_{Ti}^{RAMPU}(t) + \sum_{Hi}^{HP} q_{Hi}^{RAMPU}(t) + \sum_{Si}^{ES} q_{Si}^{RAMPU}(t) \geqslant q_D^{RAMPU}(t) \\ \sum_{Ti}^{TP} q_{Ti}^{RAMPD}(t) + \sum_{Hi}^{HP} q_{Hi}^{RAMPD}(t) + \sum_{Si}^{ES} q_{Si}^{RAMPD}(t) \geqslant q_D^{RAMPD}(t) \end{cases} \tag{24}$$

where $q_D^{RAMPU}(t)$ and $q_D^{RAMPD}(t)$ are the requirements for the upward and downward ramping capacities in period t, respectively, which can be determined by function (1).

The linear inverse demand functions for URPs and DRPs are, respectively, $\forall\ t \in T$,

$$\begin{cases} \lambda^{RAMPU}(t) = \alpha^{RAMPU}(t) - \beta^{RAMPU}(t) q_D^{RAMPU}(t) \\ \lambda^{RAMPD}(t) = \alpha^{RAMPD}(t) - \beta^{RAMPD}(t) q_D^{RAMPD}(t) \end{cases} \tag{25}$$

where $\alpha^{RAMPU}(t)$ and $\beta^{RAMPU}(t)$ are the coefficients of the inverse demand function for URPs in period t, and $\alpha^{RAMPD}(t)$ and $\beta^{RAMPD}(t)$ are the coefficients of the inverse demand function for DRPs in period t. According to [7], the coefficients could be obtained from the demand curve of FRPs calculated by CAISO.

The transmission network constraints are $\forall\ t \in T$,

$$L_k^{\min} \leqslant \sum_{Xi=1}^{N} G_{k-Xi} q_{Xi}(t) - \sum_{l=1}^{L} G_{k-l} q_{D,l}^{E}(t) \leqslant L_k^{\max} \tag{26}$$

where G_{k-Xi} is the shift distribution factor of the generator Xi to transmission line k, G_{k-l} is the shift distribution factor of the node load l to transmission line k, $q_{D,l}^{E}(t)$ is the load of node l, and $L_k^{\min}$ and $L_k^{\max}$ are the minimum and maximum power limits of transmission lines.

Moreover, although there is no objective function in the lower-level model as in the classical bi-level optimization models, the equilibrium problem proposed in this paper is still regarded as a bi-level model with the same structures [16,21,22].

5. Solution method

To obtain the Nash-Cournot equilibrium, the above bi-level optimization model should first be derived by substituting the common lower-level model into the upper-level model of each participant, so that we can obtain the multi-individual optimization problems.

Then, two general ways are to simultaneously solve the multi-individual profit-maximization problems with either the diagonalization methods or nonlinear complementarity problem (NCP) approach [22]. Specifically, the diagonalization methods consist of the Jacobi and Guass-Seidel algorithms, which iteratively solve the profit-maximization model of each generator until a stationary point is obtained. The NCP method collects all the optimal KKT conditions of the individual profit-maximization models of each generator and then solves them together. Considering that the Guass-Seidel iterative method is more computation-efficient and robust [22], we use it to solve the multi-individual optimization problems.

6. Numerical examples

6.1. Basic data

Numerical tests are performed on a modified power system with 23 coal-fired power units, 11 gas-fired units, 5 hydro units, 30 solar units, 30 wind units and 8 energy storage systems. The basic data of various generators as shown in Table 1.

Six cases are implemented and compared to show the impact of FRPs on the market equilibrium. The base case (BC) includes only traditional thermal units and hydro units, and their total installed capacity is 5319 MW. The generation costs and technical parameters of thermal units are obtained from [23]. The system ramp capability that the thermal and hydro units can provide in 15 min without availability constraint can be as high as 1415.25 MW.

The BC with dominant solar power (BCS), the BC with solar power considering FRPs (BCS + FRPs) and the BC with solar power and energy storage systems considering FRPs (BCSE + FRPs) are included for comparison. The BC with dominant wind power (BCW), the BC with wind power considering FRPs (BCW + FRPs) and the BC with wind power and energy storage systems considering FRPs (BCWE + FRPs) are also compared. The capacity for each solar or wind unit is 100 MW. The requirements for FRPs are set to 500 MW during the morning and evening ramping hours, while the requirements decrease to 200 MW for the remaining periods.

6.2. Comparisons between BCS and BCS + FRPs

The forecast solar generations for the next day are illustrated in Fig. 2(a). Considering the forecast load profile, the system flexibility is most needed during the morning ramp-down hours and the evening ramp-up hours [24]. Therefore, the day-ahead energy prices of BCS + FRPs during these hours will go up because the total energy supply will decrease when the conventional units are providing FRPs considering the capacity coupling effects, as shown in Fig. 2(b). During the daytime, a large part of the load can be satisfied by solar generation, and thus, the thermal and hydro units have more capacity for providing energy and FRPs, leading to the prices becoming slightly lower.

The average energy price of BCS + FRPs is slightly higher than the average energy price of the BCS under normal conditions, as presented in Table 2, indicating that FRPs do not greatly impact the energy market. The average price of URPs is higher than the average price of DRPs because of the relatively higher demands of URPs during the entire day. Moreover, the gas-fired units and hydro units prefer to provide FRPs due to their high flexibility, especially URPs, with higher prices, leading to increased profits by providing energy and FRPs.

In the BCS case, all coal-fired units decide to start and remain online throughout the entire day, whereas gas-fired units with higher generation costs choose to start twice during the morning and evening periods with higher energy prices. For the BCS + FRPs case, all thermal units except one gas-fired unit with too much high variable cost must start and always remain online to provide both energy and FRPs. That is, the impact of introducing FRPs on the unit commitment is that more thermal units should be dispatched and more make-whole payments should be implemented.

The ex-post actual solar generation is shown in Fig. 3, and the production variabilities between adjacent intervals (15-min) are seen to be extremely high [25].

Considering that FRPs are designed to handle the real changes of the load and renewable generation, the solar curtailment due to the ramp shortages can truly be reduced by providing more flexibility. The total reduction can be as much as 1080.4 MWh by providing FRPs. Furthermore, the profit per MW of thermal units can increase from \$591 (BCS) to \$663 (BCS + FRPs) by simultaneously participating in both the energy and FRP markets.

6.3. Comparison between BCS + FRPs and BCSE + FRPs

Considering the load-shifting and price-leveling effects of the arbitrage behavior of strategic energy storage systems [26], the average energy price of the BCSE + FRPs case is lower than the average energy price of the BCS + FRPs case, as presented in Fig. 4 and Table 2. Moreover, the average prices of URPs and DRPs are much lower than the average prices of the BCS + FRPs case because energy storages can provide the increased flexibility needed in the system and relieve the relatively tight FRP market.

Compared to the BCS + FRPs case, six gas-fired units choose to start only from the 19th periods when introducing energy storage systems, which can partly replace the gas-fired units with high generation costs and reduce the corresponding consumer payments, as shown in Fig. 5. In addition, the solar curtailment can be reduced further by 235.3 MWh due to the extra flexible services provided by storage, and the profit per MW of thermal units decreases from $663 (BCS + FRPs) to $614 (BCSE + FRPs).

6.4. Comparison between BCW and BCW+FRPs

For the forecast net load considering wind generation, the system ramping capabilities are always needed because of the high uncertainties of wind production, as shown in Fig. 6. The day-ahead energy market prices of BCW + FRPs are comparatively higher during the peak load and ramping hours, also incurring a higher average energy price than BCW. The average price of URPs is higher than the average price of DRPs in Table 3, providing stronger incentives for resources.

In the BCW case, all coal-fired units strategically choose to be online, and the gas-fired units decide to start from the 40th periods with increasingly high energy prices. For the BCW + FRPs case, all thermal units start at the beginning of the day and are always online, indicating that more generation units should be committed considering the impact of FRPs.

The actual wind generation is shown in Fig. 7. When considering FRPs, the wind curtailments can also be reduced with more system flexibility, and the total reduction can be 2775.3 MWh. Moreover, by providing FRPs, the profit per MW of the thermal units can increase from $599.5 (BCW) to $670.9 (BCW + FRPs).

6.5. Comparison between BCW+FRPs and BCWE+FRPs

The energy storage systems strategically arbitrage to maximize individual profits, that is, they choose to charge during the periods with low energy prices and discharge during the periods with comparatively high prices, leading to a lower average energy price, as given in Table 3 and Fig. 8. In addition, more flexible services provided by energy storage systems lower the average FRP market prices.

Compared to the BCW + FRPs case, one gas-fired unit will not start and another gas-fired unit can generate for fewer periods to reduce the total generation costs in the BCWE + FRPs case. The changes in the assigned URPs and DRPs of the thermal units are shown in Fig. 9. Moreover, the wind curtailment can be further reduced by 122.6 MWh due to the extra flexible services provided by storage, and the profit per MW of thermal units decreases from $670.9 (BCW + FRPs) to $630.2 (BCWE + FRPs).

7. Conclusion

This paper uses a multi-period Nash-Cournot equilibrium model to investigate the impact of FRPs on market prices, unit commitment and renewable integration, considering the framework of co-optimized energy and FRP markets. The results of numerical examples demonstrate that when introducing FRPs into the electricity markets,

(1) The energy prices will increase slightly under normal conditions,
(2) The unit commitment will be changed, and more generators should be on line to provide flexible services,
(3) More highly variable renewables can be integrated,
(4) Gas-fired units and hydro units are given more incentives considering the transparent price signals,
(5) The additional energy storage systems will provide more flexible services, and their arbitrage behavior can lead to lower energy and FRPs prices, fewer online units and more renewable integration. Moreover, the energy storage systems can obtain increased profits and incentivize their further development.

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