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Joint energy-frequency regulation electricity market design for the transition towards a renewable-rich power system

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ABSTRACT

Striving to develop renewable energy generation (REG) has become a global trend. Due to high carbon emissions, fossil-fueled generation units (FFGUs) in an electrical energy market such as the day-ahead and real-time electricity markets are facing unprecedented constraints. From the perspective of FFGUs, an effective way is to change their market roles from energy suppliers with high environmental costs to secure and reliable frequency regulation service providers. To help FFGUs successfully complete the transition, a bi-level optimization model for the joint energy and regulation service market is proposed in this paper. Different from existing joint markets, both the environmental cost of FFGUs and the frequency regulation service (FRS) cost of REG units are considered in this research for market operators to determine the scheduling priorities of submitted bids from generation units. In the frequency regulation service market model, a dynamic approach to determining the FRS demand is applied, which not only incentivizes REG units to initiatively manage their outputs, but also derives the price signals through the equilibrium of the FRS demand and supply to ensure the revenue of FFGUs in the FRS market. Meanwhile, the decision-making model of the FFGUs under the proposed market mechanism is also presented. Finally, extensive numerical experiments demonstrate the feasibility and efficiency of the mechanism. Simulation results show that the proposed mechanism can stimulate a smooth transition of FFGUs by adapting to actual situations and policy changes.

1. Introduction

1.1. Background and motivation

As the development of an environment-friendly power system has become the consensus of governments around the world, policies to advance the development of renewable energy generation (REG) has been introduced, and remarkable outcomes have been achieved. In 2021, the global installed capacity of REG increased by 314.5GW and reached 3,146 GW [1]. The increasing outputs of REG are replacing the market share of fossil-fueled generation units (FFGUs) in power systems characterized by the high penetration of REG.

To limit the carbon emissions of FFGUs, many countries have established carbon emission markets. Consequently, FFGUs bear the cost of carbon emissions. Besides, the “energy-only” electricity market with a high share of FFGUs has operational risks. For example, the Australian electricity market was shut down in June 2022, because the rising fuel costs led to the decline in power supply and insufficient provision of ancillary services such as frequency regulation services from FFGUs [2], which made the entire electricity market unable to deal with this extreme situation.

Meanwhile, due to the uncertainty and intermittency of REG outputs, the demand for frequency regulation services in power systems is surging. The incumbent regulation service providers may not be able to provide abundant regulation service to address the expansion of REG units in the energy market. Specially, FFGUs can provide these regulation services, which can not only meet the needs of the REG development, but also stimulate the transition of FFGUs from energy suppliers to regulation service providers.

However, the following challenges are identified in the transition of FFGUs:

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Nomenclature

A. Numbers and Indexes

N^{G} Total number of FFGUs
N^{R} Total number of REG units
N^{up} Total numbers of up FRS providers
N^{dw} Total numbers of down FRS providers
i The index of FFGUs
j The index of REG units
m The index of down FRS providers
n The index of up FRS providers

B. Parameters

C_i^{carbon} Incurred cost of carbon emissions
c_j^{R} Unit FRS cost caused by the j^{th} REG unit
E_i^{G} Unit carbon emission cost caused by the i^{th} FFGU
e_i^{G} Carbon emission factor of the i^{th} FFGU
H^{cpl}, $H^{cpl,max}$ Auxiliary parameters to characterize the complementarity among REGs
P_l^{max} Transmission capacity of line l
P^{syn} Minimum reserve capacity required
$p_i^{G,bid}$, $p_j^{R,bid}$ Offered power outputs of the i^{th} FFGU and the j^{th} REG unit
$p_n^{bid,cap,up}$ Maximum capacity for up FRS from the n^{th} FRS provider
$p_m^{bid,cap,dw}$ Maximum capacity for down FRS from the m^{th} FRS provider
$p_{j,t}^{R,im}$ Forecasting value of the output extracted from $\mathbf{p_{j,t}^{R}}$
$p_i^{G,min}$, $p_i^{G,max}$ Lower and upper limit of the $p_{i,T}^{G,bid}$
$p_i^{G,rup}$, $p_i^{G,rdw}$ Ramp-up and ramp-down limit of the i^{th} FFGU
C_i^{energy} Incurred cost of the fuel
$p_{i,T-1}^{G,acl}$ Actual power output of the i^{th} FFGU during interval T-1
R_i^{sum}, R_i^{sp}, R_i^{cap}, R_i^{mil} Total revenue, the spot energy market revenue, the FRS market revenue and the actual regulation mileage revenue of the i^{th} FFGU
r_i^{G}, r_j^{R} Offered price of the i^{th} FFGU and the j^{th} REG unit
r^{carbon} Carbon emission price
$r^{cap,up}$, $r^{cap,dw}$ Up and down FRS capacity price
$r_n^{bid,cap,up}$ Bidding capacity price for up FRS from the n^{th} FRS provider
$r_n^{bid,mil,up}$ Bidding mileage price for up FRS from the n^{th} FRS provider
$r_m^{bid,cap,dw}$ Bidding capacity price for down FRS from the m^{th} FRS provider
$r_m^{bid,mil,dw}$ Bidding mileage price for down FRS from the m^{th} FRS provider
r_T^{energy}, $r_T^{frs,cap,up}$, $r_T^{frs,cap,dw}$ Predicted values of the spot energy market price, up-FRS capacity price and down-FRS capacity price in the target dispatch interval T
α, β Weighting factors of the carbon emission cost and the FRS cost
ΔT Time of the target dispatch interval

C. Vector

$\mathbf{p_{j,t}^{R}}$ Vector of forecasted power outputs for the target dispatch interval T submitted by the j^{th} REG unit
$p_{i,T}^{G,bid}$ Decision variable for offered power outputs of the i^{th} FFGU in the target dispatch interval T

D. Variables

η_j Auxiliary variable larger than 0
p_i^{G} Clearing outputs of the i^{th} FFGU
p_j^{R} Clearing outputs of the j^{th} REG unit
$p_n^{cap,up}$ Capacity for up FRS of the n^{th} FRS provider
$p_m^{cap,dw}$ Capacity for down FRS of the m^{th} FRS provider
λ^{up}, λ^{dw}, $\widehat{\mu}_n^{up}$, $\breve{\mu}_n^{up}$, $\widehat{\nu}_m^{dw}$, $\breve{\nu}_m^{dw}$ Auxiliary variables in Karush-Kuhn-Tucker condition
τ_n^{up} Binary variable for the big M method

(1) There is not a widely accepted method to measure the environmental cost of FFGUs participating in electricity markets.
(2) The existing market mechanism for procuring frequency regulation service may not work well in the transition period and a reasonable profit level may not be achieved for FFGUs.
(3) The lack of effective market regulation measures to guide FFGUs through the transition period.

This paper aims to tackle the above challenges through developing an innovative electricity spot market mechanism for power systems with a high REG penetration rate. The solutions presented in this paper will provide suggestions for developing an efficient electricity market mechanism to address the ever-increasing intermittent renewable energy generation.

1.2. Related works

The negative impacts of fossil-fueled generation (FFG) on the environment, especially in terms of carbon emissions, have been well known. In [3], the situation in Ghana is discussed. Quantitative modeling and simulation methods are used to analyze the environmental impacts of generation units and fuel choices, and the technologies for low carbon emission energy conversion such as renewable energy are essential to reduce carbon emissions. An analysis is presented in [4] involving greenhouse gases from small-scale (less than one megawatt) distributed power sources and research results indicate that by 2040, these small-scale fossil-fueled generators could account for around 1%–5% of total carbon emissions from the U.S. electric power sector. The example of Turkey is discussed in [5], which presents the impacts of FFG on Turkish policy and the environment. Some publications investigate how to make FFG reduce carbon emissions. In [6], the technology-economic performance of carbon dioxide capture in FFGUs is examined from an industrial point of view, aiming to reduce the environmental cost of FFG. Besides, the comprehensive impact of carbon tax and demand response on the emission decline of the power system is analyzed in [7]. However, although some advanced technologies and mechanisms can reduce the damage of FFGUs to the environment, it is inevitable that FFGUs will withdraw from the electricity energy market step by step.

In order to evaluate the impacts of carbon emission from FFGUs, more and more publications take carbon emissions as a target or constraint condition in developing power system planning and operation optimization models. In [8], the power system expansion planning problem is investigating with the financial costs and revenues of emissions trading in the carbon emission market considered. According to the cap-and-trade principle of the carbon emission market, carbon emissions are expressed as a constraint in [9]. In [10], the targets of carbon emission and REG penetration, as two unconventional economic goals, are included in the optimal planning formulation of the power system. In [11], a two-layer expansion planning model for multi-energy systems with carbon emission constraints under the decentralized methodological framework is presented. To measure the environmental cost of FFGUs, carbon emissions are considered in the proposed joint electricity market mechanism.

Meanwhile, the uncertainty of REG outputs brings additional risks to power system operation. A literature review on system reserves and flexibility is given in [12], which stresses the necessity of revising the existing electricity market mechanism so as to realize its full potential on providing flexibility. Since the integration of REG brings new problems or even challenges to power system operation, if there is not adequate regulation capacity, the intermittency of REGs may lead to significant excursions in power generation, and threaten the security of the power system [13]. Therefore, in [14,15], a stochastic programming and a multi-level stochastic optimization method are adopted to study the coordinated planning and operation of power systems. In [14], a multi-cooperative microgrid energy management strategy is proposed to minimize the total daily operation cost of the microgrid, with the time-varying and intermittent properties of REG considered.

On the other hand, the impact of growing REG integration on the flexibility of power systems is reflected in the increasing demand for regulation services. In [15], a comprehensive review of the demand for ancillary services caused by REG penetration in power systems is conducted. In practice, because of insufficient ancillary services in real-time operation of a power system, the high penetration of REGs has resulted in tremendous economic loss as a result of more frequent power outages. In addition, the frequency regulation service (FRS) capacity in practical power systems, such as ISOs in North America, is pre-statically determined and may not be able to meet future power system operation requirements. If the ancillary service demand of a power system cannot be accurately determined, the actual value of ancillary services provided by FFGUs or other suppliers cannot be attained with the supply–demand relationship. In [16], a method is proposed to dynamically determine the demand for ancillary services in a power system, and could be expanded to discover the actual supply–demand relationship of ancillary services in the system.

Up to now, the research work regarding the role transformation of FFGUs in intermittent renewable energy rich power systems is preliminary. It is shown in [17–19] that energy systems are in a major transformation process and take different approaches such as power electronic devices or flexibility options to help accomplish this process. In [20], the main issues of energy transformation are discussed and analyzed. After investigating multiple paths, one of the conclusions is that market policymakers need to take measures to ensure a rapid transition to REG in power systems. In [21], the difficulties and problems associated with FFGUs are examined during the transition period from the perspective of social relationship. However, the above studies did not propose specific plans of the transformation for FFGUs.

It is worth noting that in the transition path of FFGUs, the design of a joint energy-frequency regulation electricity market is critical. Some joint market mechanisms have been proposed [22–28], and played roles in different application scenarios. For the scenario described in this paper, the proposed method can not only accurately estimate the demanded frequency regulation capability, but also motivate the RESs to initiatively manage the uncertainty of their own power outputs. Comparisons among several existing joint market mechanisms and the proposed one are shown in Table 1.

Table 1
Comparisons among existing joint market mechanisms and the proposed model.

Method	Application scenario	Highlight
Sequential dispatch or deterministic dispatch [22,23]	Traditional power system where the frequency regulation demand is relatively prefixed	• Intuitive • Easy to implement
Adjustable robust co-optimization model [24–26]	Real-time electricity market considering wind power uncertainties	• Capable of obtaining the optimal and feasible solutions • Immunizing against the uncertain wind power output
Versatile distribution model based on a chance-constrained optimization approach [27,28]	Peer-to-peer (P2P) market for distributed energy resource management	• Compensating for the uncertainty originating from RES • Allocating the reserve cost induced by uncertainty fairly
Proposed model in this paper	Guiding FFGUs to complete role transformation in a renewable-rich power system	• Obtaining the frequency regulation requirements of the system based on different unit scheduling schemes • Motivating the RES to manage their own output uncertainty

1.3. Novelty and contributions

To sum up, the challenges of a workable market mechanism design to support the transformation of FFGUs are still not well addressed. The transformation of FFGUs from energy market suppliers to regulation service providers can not only reduce carbon emissions, but also help REGs better integrate into the electricity spot market. Given this background, an electricity market mechanism for joint energy and regulation service clearing is proposed in this work. In the proposed mechanism, carbon emission cost is embedded into the electricity spot market. On the other hand, the cost of regulation services caused by REGs is also incorporated into the spot market clearing, which helps to determine the actual value of regulation services in power systems and motivates REGs to actively manage their power outputs. Besides, the proposed market mechanism employs adjustable weighting factors as a measure of policy regulation to ensure the smooth role transition for FFGUs. The decision-making model for FFGUs is also given to evaluate the feasibility of the proposed market mechanism. The main contributions of this paper are summarized below:

First, the transition path of FFGUs is determined and their transformation from energy suppliers to regulation service providers is guided by a joint energy-regulation electricity market mechanism.

Second, a joint energy and regulation service bi-level market model is proposed, in which its Karush-Kuhn-Tucker (KKT) condition ensures this model solvable. The market clearing model can accurately determine the regulation service demand of the power system and discover the regulation service price according to the actual supply-demand relationship, so as to guarantee the profits of FFGUs during the transition period.

Third, the quantified environmental cost of FFGUs is incorporated into the electricity market mechanism, and the decision-making model of FFGUs under the proposed mechanism is developed. Through simulation results of short-term, medium and long-term data, the effectiveness of the proposed mechanism for guiding the role transformation of FFGUs is demonstrated.

The structure of the remaining parts of this paper is arranged as follows. Section 2 introduces the proposed electricity spot market clearing mechanism. Then, the decision-making model of FFGUs is expounded in Section 3. Case studies are presented in Section 4. Finally, the paper is concluded in Section 5.

2. Proposed market mechanism

To address the challenges that restrict the role transformation of FFGUs, a path is given in Fig. 1. This path serves as a guide regarding the decision-making of FFGUs through the design of a joint energy-frequency regulation electricity market mechanism, and it is expected that the transition of FFGUs from energy suppliers to FRS providers over time would be finally completed. The market design is detailed below and the decision-making procedure of generation units will be described in Section 3.

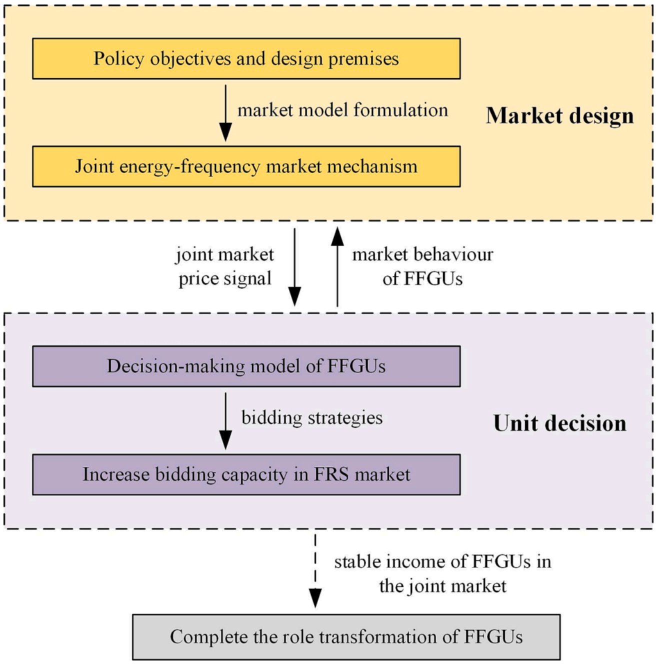

Fig. 1. A flowchart of the role transformation path for FFGUs.

2.1. Assumptions

Prior to the development of the proposed mechanism, some basic assumptions are given below.

(1) The electricity spot market is usually referred to an ex-ante market such as the day-ahead, hour-ahead, and real-time (for example 15 min-ahead) ones. In this work, the electricity mechanism is developed based on the hour-ahead market.

(2) Due to the power output uncertainty of REGs, there will be an inevitable imbalance between the scheduled and actual power outputs, which will be covered by regulation services. The regulation service in the proposed electricity market mechanism refers to the FRS, which is consistent mainstream regulation service markets in various countries.

(3) The electricity spot market is a wholesale one and generators are required to schedule generation outputs according to the market clearing outcomes. Otherwise, the unindicated deviation of the actual output from the cleared one will be penalized if outside a given tolerance range.

2.2. Model of proposed market clearing mechanism

In the proposed market mechanism, the energy market and the FRS market are jointly cleared, which is described by a bi-level model, as shown in Fig. 2. FFGUs not only participate in the energy market with REGs, but also bid for provision in the FRS market with other regulation service providers.

From the perspective of establishing a market operational organization, the bi-level model is more conducive to its division of market responsibilities. Some market entities do not participate in the energy market and the FRS market at the same time, for example, energy storage systems may only participate in the FRS market. The bi-level model helps the market operator distinguish between these market participants, which is beneficial to define responsibilities within the market organization.

2.2.1. Upper-Level: Energy market clearing model

In the energy market clearing model, FFGUs and REG units provide offers to the electricity spot market, which are represented by $\left(r_i^{\mathrm{G}}, p_i^{\mathrm{G,bid}}\right)(i \in N^{\mathrm{G}})$ for the i^{th} FFGU and $\left(r_j^{\mathrm{R}}, p_j^{\mathrm{R,bid}}\right)(j \in N^{\mathrm{R}})$ for the j^{th} REG unit. r_i^{G}, $r_j^{\mathrm{R}}/p_i^{\mathrm{G,bid}}$ and $p_j^{\mathrm{R,bid}}$ denote the offered price /power outputs of the i^{th} FFGU and the j^{th} REG unit, respectively.N^{G} and N^{R} represent the number of FFGUs and REG units, respectively. After receiving energy

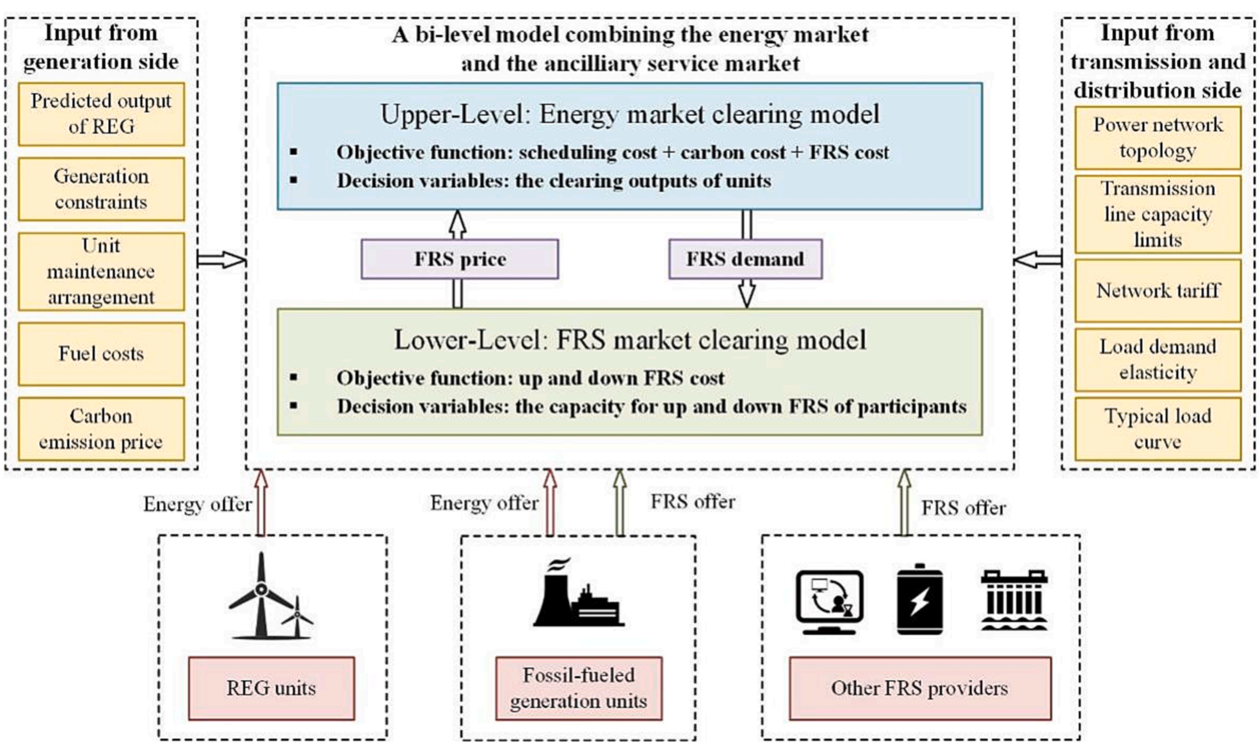

Fig. 2. Illustration of the bi-level clearing model for the joint market.

bids from all participants, the energy market bids will be cleared as follows

$$\min\sum_{i\in N^{\mathrm{G}}}\left(r_i^{\mathrm{G}}+\alpha E_i^{\mathrm{G}}\right)p_i^{\mathrm{G}}+\sum_{j\in N^{\mathrm{R}}}\left(r_j^{\mathrm{R}}+\beta c_j^{\mathrm{R}}\right)p_j^{\mathrm{R}} \quad (1)$$

$$s.t.\quad \sum_{i\in N^{\mathrm{G}}}p_i^{\mathrm{G}}+\sum_{j\in N^{\mathrm{R}}}p_j^{\mathrm{R}}=\sum_{k\in N^{\mathrm{bus}}}p_k^{\mathrm{D}} \quad (2)$$

$$\left|\sum_{k\in N^{bus}}\rho_{l,k}\left[\sum_{i\in k}p_i^{\mathrm{G}}+\sum_{j\in k}p_j^{\mathrm{R}}-p_k^{\mathrm{D}}\right]\right|\leqslant P_l^{\max} \quad (3)$$

$$E_i^{\mathrm{G}}=e_i^{\mathrm{G}}\cdot r^{\mathrm{carbon}}\cdot\Delta T \quad (4)$$

$$c_j^{\mathrm{R}}=\frac{p_j^{\mathrm{R}}\cdot r^{\mathrm{cap,up}}+\left(p_j^{\mathrm{R,bid}}-p_j^{\mathrm{R}}\right)\cdot r^{\mathrm{cap,dw}}}{p_j^{\mathrm{R}}} \quad (5)$$

$$0\leqslant p_i^{\mathrm{G}}\leqslant p_i^{\mathrm{G,bid}} \quad (6)$$

$$0\leqslant p_j^{\mathrm{R}}\leqslant p_j^{\mathrm{R,bid}} \quad (7)$$

where the objective function (1) is to minimize the procurement cost in the given time period including the energy cost, carbon emission cost as well as FRS cost which is obtained via the lower-level market model. E_i^{G} and c_j^{R} denote the unit carbon emission cost caused by the i^{th} FFGU and unit FRS cost caused by the j^{th} REG unit, respectively.α and β are the weighting factors of the carbon emission cost and the FRS cost, which are determined with power system security, environmental benefits, policy support for RES development and other factors considered. Equations (2) -(3) represent the power balance constraint and transmission capacity constraint. p_k^{D} represents the load at the k^{th} bus, $\rho_{l,k}$ denotes the power transfer distribution factor, and P_l^{max} represents the transmission capacity of line l. Equations (4) -(5) represent the calculation formulas of E_i^{G} and c_j^{R}, respectively. r^{carbon} denotes the carbon emission price during the clearing period. e_i^{G} is the carbon emission factor of the i^{th} FFGU. $r^{\mathrm{cap,up}}$ and $r^{\mathrm{cap,dw}}$ are respectively the up and down FRS capacity prices, which are obtained from the lower-level FRS market clearing model. Equations (6) -(7) respectively represent constraints on decision variables p_i^{G} and p_j^{R}, which denote the clearing outputs of the i^{th} FFGU and the j^{th} REG unit, respectively.

The clearing price in the energy market depends on the quoted price from the marginal generation unit that has won the bid, as shown in Fig. 3.

2.2.2. Lower-Level: FRS market clearing model

In the FRS market, each participant (including FFGUs) submits a bid $\left(r_n^{\mathrm{bid,cap,up}},r_n^{\mathrm{bid,mil,up}},p_n^{\mathrm{bid,cap,up}}\right)$ with $n\in N^{\mathrm{up}}$ for providing up FRS or a bid $\left(r_m^{\mathrm{bid,cap,dw}},r_m^{\mathrm{bid,mil,dw}},p_m^{\mathrm{bid,cap,dw}}\right)$ with $m\in N^{\mathrm{dw}}$ for providing down FRS. $r_n^{\mathrm{bid,cap,up}},r_n^{\mathrm{bid,mil,up}}/r_m^{\mathrm{bid,cap,dw}},r_m^{\mathrm{bid,mil,dw}}$ represent the bidding capacity price and bidding mileage price for up/down FRS, respectively. $p_n^{\mathrm{bid,cap,up}}/p_m^{\mathrm{bid,cap,dw}}$ denote the maximum capacity from the up/down FRS providers.N^{up} and N^{dw} represent the numbers of up and down FRS providers, respectively.

To determine the system's demand for FRSs, each REG unit needs to submit a vector of forecasted power outputs $\mathbf{p}_{\mathbf{j},\mathbf{t}}^{\mathbf{R}}(t\in T)$ for the target dispatch interval T to the electricity market trading system. Given that the FRS market maintains a continuous balance of generation and load at a very fine-grained level, the time granularity of $\mathbf{p}_{\mathbf{j},\mathbf{t}}^{\mathbf{R}}$ should be consistent with or less than that of the FRS signal. Since the process is carried out ex-ante, the power output of the REG unit j , $p_j^{\mathrm{R,bid}}$, is actually uncertain. Therefore, $p_j^{\mathrm{R,bid}}$ and $\mathbf{p}_{\mathbf{j},\mathbf{t}}^{\mathbf{R}}$ contain information about the power outputs of REGs featured by uncertainty.

REG units submit predicted generation outputs in the target dispatch interval, which are employed in determining FRS requirements in the studied power system. The FRS market clearing model is formulated as follows.

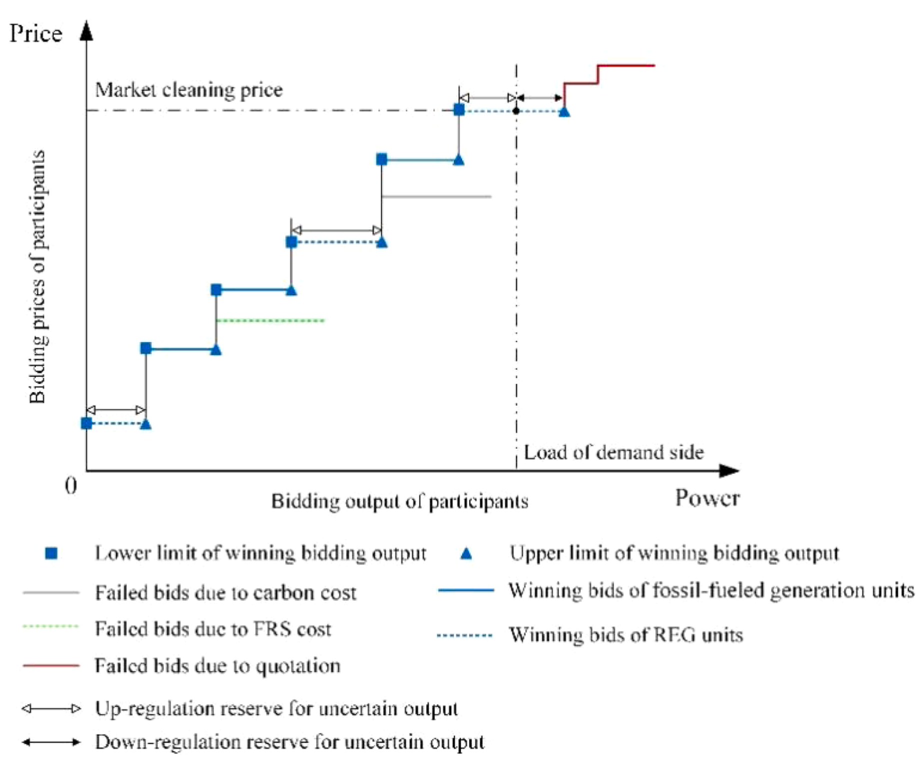

Fig. 3. Schematic diagram of the energy market clearing.

$$\min \sum_{n\in N^{up}} r_n^{cap,up} p_n^{cap,up} + \sum_{m\in N^{dw}} r_m^{cap,dw} p_m^{cap,dw} \tag{8}$$

$$s.t.\quad P^{syn} + \left(\sum_{j\in N^R} p_j^R\right)\cdot\frac{H^{cpl}}{H^{cpl,max}} = \sum_{n\in N^{up}} p_n^{cap,up} \tag{9}$$

$$\left[\sum_{j\in N^R}\left(p_j^{R,bid} - p_j^R\right)\right]\frac{H^{cpl}}{H^{cpl,max}} = \sum_{m\in N^{dw}} p_m^{cap,dw} \tag{10}$$

$$0 \leqslant p_n^{cap,up} \leqslant p_n^{bid,cap,up} \tag{11}$$

$$0 \leqslant p_m^{cap,dw} \leqslant p_m^{bid,cap,dw} \tag{12}$$

where the objective function (8) is to minimize the up and down FRS cost. Equations (9)-(10) represent the market balance including the up and down FRS, where the complementarity effect of intermittent REG outputs is considered. In (9), P^{syn} represents the minimum reserve capacity required even if the predicted changes can offset each other out so as to account for the inherent generation output changes from REGs. Equations (11)-(12) represent constraints on decision variables $p_n^{cap,up}$ and $p_m^{cap,dw}$, which denote the capacity for up FRS of the n^{th} up FRS provider and the capacity for down FRS of the m^{th} down FRS provider, respectively. H^{cpl} and $H^{cpl,max}$ measure the complementarity among REGs, where the change in absolute value of forecasting results submitted by generators is taken into consideration. H^{cpl} and $H^{cpl,max}$ can be attained by Equations (13)-(16).

$$\Delta p_{j,t}^{R,im} = p_{j,t}^{R,im} - p_{j,t-1}^{R,im}, \forall t \in T \tag{13}$$

$$H^{cpl} = \frac{1}{|T|}\sum_{t\in T}\left|\sum_{j\in N^R} b_j \Delta p_{j,t}^{R,im}\right| \tag{14}$$

$$H^{cpl,max} = \frac{1}{|T|}\sum_{t\in T}\left(\sum_{j\in N^R}\left|b_j \Delta p_{j,t}^{R,im}\right|\right) \tag{15}$$

$$p_j^R - b_j \eta_j = 0 \tag{16}$$

where $p_{j,t}^{R,im}$ is extracted from $\mathbf{p}_{j,t}^{\mathbf{R}}$, and represents the forecasting value of the output from the j^{th} REG unit. The larger H^{cpl} is, the worse the complementarity effect of the total REG output will be. H^{cpl} reaches its maximum $H^{cpl,max}$ when all REG outputs change in the same direction simultaneously. Equations (14)-(15) are used to determine the FRS requirements by the system. Equation (16) guarantees that the FRS cost be considered when p_j^R is scheduled. b_j is a binary variable, and η_j is an auxiliary variable larger than 0.

The proposed market mechanism employs a two-part pricing scheme including a capacity price and a mileage price as payment basis for each FRS provider [29,30]. Equations (17)-(18) demonstrate the method to determine capacity prices for up- and down-FRS, which are represented by $r_n^{cap,up}$ and $r_m^{cap,dw}$, respectively.

$$r_n^{cap,up} = \frac{\chi_n^{cap,up} r_n^{bid,cap,up} + \chi_n^{mil,up} r_n^{bid,mil,up}}{p_n^{bid,cap,up}} \tag{17}$$

$$r_m^{cap,dw} = \frac{\chi_m^{cap,dw} r_m^{bid,cap,dw} + \chi_m^{mil,dw} r_m^{bid,mil,dw}}{p_m^{bid,cap,dw}} \tag{18}$$

where $\chi_n^{cap,up}$, $\chi_n^{mil,up}$, $\chi_m^{cap,dw}$, and $\chi_m^{mil,dw}$ are all weighting factors.

By modeling the uncertain characteristics of the forecasted power outputs from REGs, the required FRS capacity in the system can be determined in the next period of power system operation. The purchased cost of FRS should be undertaken by the market participants who cause this service demand.

2.2.3. Reformulation and solution

The developed bi-level market clearing models could be reformulated for improving the solving efficiency. The well-established Karush-Kuhn-Tucker (KKT) condition could be employed to solve the problem, because the lower-level model is a linear programming problem. Specifically, the FRS market clearing model can be replaced with its KKT conditions which are then integrated into the upper-level model. Finally, the original problem is transformed into a single-level optimization model. Based on (8) and (12), the Lagrangian function Γ of the lower-level model can be reformulated as follows.

$$\begin{aligned}\Gamma = &\sum_{n\in N^{up}} r_n^{cap,up} p_n^{cap,up} + \sum_{m\in N^{dw}} r_m^{cap,dw} p_m^{cap,dw}\\ &+\lambda^{up}\left(\sum_{n\in N^{up}} p_n^{cap,up} - P^{syn} - \left(\sum_{j\in N^R} p_j^R\right)\cdot\frac{H^{cpl}}{H^{cpl,max}}\right)\\ &+\lambda^{dw}\left(\sum_{m\in N^{dw}} p_m^{cap,dw} - \left[\sum_{j\in N^R}\left(p_j^{R,bid} - p_j^R\right)\right]\frac{H^{cpl}}{H^{cpl,max}}\right)\\ &-\sum_{n\in N^{up}}\widehat{\mu}_n^{up}\left(p_n^{bid,cap,up} - p_n^{cap,up}\right) - \sum_{n\in N^{up}}\breve{\mu}_n^{up} p_n^{cap,up}\\ &-\sum_{m\in N^{dw}}\widehat{\nu}_m^{dw}\left(p_m^{bid,cap,dw} - p_m^{cap,dw}\right) - \sum_{m\in N^{dw}}\breve{\nu}_m^{dw} p_m^{cap,dw}\end{aligned} \tag{19}$$

where λ^{up}, λ^{dw}, $\widehat{\mu}_n^{up}$, $\breve{\mu}_n^{up}$, $\widehat{\nu}_m^{dw}$ and $\breve{\nu}_m^{dw}$ are auxiliary variables.

Thus, the KKT conditions of the FRS market clearing model can be expressed by (20)-(29).

(1) Equality constraints

$$\frac{\partial\Gamma}{\partial p_n^{cap,up}} = r_n^{cap,up} + \lambda^{up} + \widehat{\mu}_n^{up} - \breve{\mu}_n^{up} = 0 \tag{20}$$

$$\frac{\partial\Gamma}{\partial p_m^{cap,dw}} = r_m^{cap,dw} + \lambda^{dw} + \widehat{\nu}_m^{dw} - \breve{\nu}_m^{dw} = 0 \tag{21}$$

$$\frac{\partial\Gamma}{\partial\lambda^{up}} = \sum_{n\in N^{up}} p_n^{cap,up} - P^{syn} - \left(\sum_{j\in N^R} p_j^R\right)\cdot\frac{H^{cpl}}{H^{cpl,max}} = 0 \tag{22}$$

$$\frac{\partial\Gamma}{\partial\lambda^{dw}} = \sum_{m\in N^{dw}} p_m^{cap,dw} - \left[\sum_{j\in N^R}\left(p_j^{R,bid} - p_j^R\right)\right]\frac{H^{cpl}}{H^{cpl,max}} = 0 \tag{23}$$

(2) Inequality constraints

$$0 \leqslant p_n^{cap,up} \leqslant p_n^{bid,cap,up} \tag{24}$$

$$0 \leqslant p_m^{cap,dw} \leqslant p_m^{bid,cap,dw} \tag{25}$$

(3) Dual complementary constraints

$$0 \leqslant \widehat{\mu}_n^{up} \perp \left(p_n^{bid,cap,up} - p_n^{cap,up}\right) \geqslant 0 \tag{26}$$

$$0 \leqslant \widehat{\nu}_m^{dw} \perp \left(p_m^{bid,cap,dw} - p_m^{cap,dw}\right) \geqslant 0 \tag{27}$$

$$0 \leqslant \breve{\mu}_n^{up} \perp p_n^{cap,up} \geqslant 0 \tag{28}$$

$$0 \leqslant \breve{\nu}_m^{dw} \perp p_m^{cap,dw} \geqslant 0 \tag{29}$$

The big M method can be used to transform the above dual complementary constraints into linear ones. For instance, a binary variable τ_n^{up} is introduced to convert (26) into (30) and (31).

$$0 \leqslant \widehat{\mu}_n^{up} \leqslant M\tau_n^{up} \tag{30}$$

$$0 \leqslant \left(p_n^{\text{bid,cap,up}} - p_n^{\text{cap,up}}\right) \leqslant M\left(1 - \tau_n^{\text{up}}\right) \tag{31}$$

where M denotes a sufficiently large positive number.

Together with Equations (13)-(18), the bi-level model is thus transformed into a Mixed-Integer Linear Programming (MILP) problem, and can be efficiently solved by the GUROBI solver in MATLAB.

2.2.4. Advantages of the proposed market mechanism

Some advantages of the proposed market mechanism are presented below:

(1) The incurred carbon emission cost of FFGUs and the incurred FRS cost of intermittent REG units are both properly considered in the joint energy-regulation market. The joint market clearing can promote the employment of clean and low-carbon electrical energy in the power system, and ensure that sufficient FRS capacity be obtained. This helps to enable an appropriate trade-off between the portfolio of different kinds of energy supply and the amount of required FRS in final market clearing outcomes.

(2) In the proposed market mechanism, a dynamic method is proposed to determine the FRS service price. The participating FFGUs in the FRS market could be profitable. At the same time, because the FRS purchased cost reserved for variable REG is considered, REG units are incentivized to proactively manage their uncertain power outputs so as to avoid being penalized, and the operation efficiency of the power system with a high penetration level of REG could then be improved.

(3) Subsidy policies for pushing the role transformation of FFGUs are remodeled by incorporating weighting factors α and β in the energy market clearing model, where the values of α and β represent the respective weights on the environmental cost and system security, and are variable with practical situations and the transformation progress of FFGUs. More detailed analysis is presented in Section IV.

3. Decision-Making Model of fossil-fueled generation units

According to the proposed electricity market mechanism, the revenue of FFGUs includes three parts, including the spot energy market revenue, the FRS market revenue and the actual regulation mileage revenue, as shown in Equation (32).

$$R_i^{\text{sum}} = R_i^{\text{sp}} + R_i^{\text{cap}} + R_i^{\text{mil}} \tag{32}$$

where R_i^{sum}, R_i^{sp}, R_i^{cap} and R_i^{mil} denote the total revenue, the spot energy market revenue, the FRS market revenue and the actual regulation mileage revenue of the i^{th} FFGU, respectively.

Since the regulation mileage revenue of each FFGU is settled ex-post, this part of revenue is thus not considered in the decision-making model of the FFGU. The decision-making model for determining the offered outputs of FFGUs is formulated by Equations (33)-(37).

$$\max r_T^{\text{energy}} p_{i,T}^{\text{G,bid}} + r_T^{\text{frs,cap,up}} p_{i,T}^{\text{bid,cap,up}} + r_T^{\text{frs,cap,dw}} p_{i,T}^{\text{bid,cap,dw}} - C_i^{\text{carbon}} - C_i^{\text{energy}} \tag{33}$$

$$s.t. \quad C_{i,T}^{\text{carbon}} = p_{i,T}^{\text{G,bid}} \cdot e_i^{\text{G}} \cdot r_T^{\text{carbon}} \cdot \Delta T \tag{34}$$

$$C_i^{\text{energy}} = a_i \cdot \left(p_{i,T}^{\text{G,bid}}\right)^2 + b_i \cdot p_{i,T}^{\text{G,bid}} + c_i \tag{35}$$

$$p_i^{\text{G,min}} \leqslant p_{i,T}^{\text{G,bid}} \leqslant p_i^{\text{G,max}} \tag{36}$$

$$-p_i^{\text{G,rdw}} \leqslant p_{i,T}^{\text{G,bid}} - p_{i,T-1}^{\text{G,acl}} \leqslant p_i^{\text{G,rup}} \tag{37}$$

where r_T^{energy}, $r_T^{\text{frs,cap,up}}$ and $r_T^{\text{frs,cap,dw}}$ denote the predicted values of the spot energy market price, up-FRS capacity price and down-FRS capacity price in the target dispatch interval T, respectively. C_i^{carbon} and C_i^{energy} represent the incurred cost of carbon emissions and the fuel, respectively, and can be attained by Equations (34)-(35). A quadratic function is introduced to describe the energy cost of each FFGU, where a_i, b_i and c_i are all the coefficients of this expression. Equations (36)-(37) represent the constraints on the decision variable $p_{i,T}^{\text{G,bid}}$. $p_i^{\text{G,max}}$ and $p_i^{\text{G,min}}$ denote upper and lower limits of the $p_{i,T}^{\text{G,bid}}$, respectively. $p_i^{\text{G,rup}}$ and $p_i^{\text{G,rdw}}$ are ramp-up and ramp-down limits of the i^{th} FFGU, respectively. $p_{i,T-1}^{\text{G,acl}}$ is the actual power output of the i^{th} FFGU during interval T-1.

Besides, the bidding capacity of FFGUs in the FRS market can be expressed as

$$p_{i,T}^{\text{bid,cap,up}} = \min\left(p_i^{\text{G,rup}}, p_i^{\text{G,max}} - p_{i,T}^{\text{G,bid}}\right) \tag{38}$$

$$p_{i,T}^{\text{bid,cap,dw}} = \min\left(p_i^{\text{G,rdw}}, p_{i,T}^{\text{G,bid}} - p_i^{\text{G,min}}\right) \tag{39}$$

where $\min(x, y)$ denotes the smaller one between x and y.

With the implementation of carbon emission reduction policies and the guidance from market regulators, FFGUs may be more inclined to make decisions regarding reducing generation outputs and providing more FRS capacity services, their role transformation in the electricity market environment can then be gradually completed.

4. Case study

4.1. Simulation data

Numerical experiments are carried out with real-world electricity market data in a province in eastern China. It is supposed that the transformation of FFGUs begined in 2021. Parameter settings of market participants including photovoltaics units, wind turbines, fossil-fueled generators and other FRS providers in 2021 are shown in Table 2. The annual growth rate of REG installed capacity is set based on governmental policies [31]. The REG power output is predicted according to historical data. The parameters of the carbon emission market are set according to the China's national carbon market [32]. It is assumed that FFGUs are required to pay for carbon emission allowances.

4.2. Analysis of short-term simulation results

Based on the set data in 2021, short-term simulation results are examined. In order to demonstrate the effectiveness of the model proposed, two cases are investigated:

(1) The traditional market clearing model is adopted to clear the combined energy and FRS market without considering carbon emissions.

(2) The market clearing model proposed in this paper is adopted with carbon emissions considered.

In case 2, the changes in market regulation measures according to government policy for RES, environmental benefits, and power supply reliability are simulated by changing the weighting factors in the electricity spot market model, as shown in Table 3. The higher the ratio of β/α is, the higher the tolerance for carbon emissions of FFGUs will be.

Figs. 4 and 5 show the spot market clearing outcomes and the revenue or cost of FFGUs in two cases.

Table 2
Parameter settings of market participants in 2021.

Generator type	Number	Total installed capacity (MW)
Wind turbines	21	3802
Photovoltaics	10	940
Fossil-fueled generators	20	10,120
Other FRS providers	10	630

Table 3
Parameter settings of β/α Ratio in each month.

Month	1	2	3	4	5	6	7	8	9	10	11	12
β/α	0.9338	0.8874	0.9463	0.9876	1.0925	0.9566	0.8469	0.8576	0.9199	0.9789	1.0684	1.0144

In Fig. 4, it is shown that the cleared generation output curve of FFGUs in case 2 is below that in case 1, which means that REG units gain more energy market share in the proposed mechanism. More importantly, by adjusting the ratio of β/α, the market regulator can guide the transformation of the FFGUs. For example, a lowest ratio of β/α in the summer means that the market regulator is much more stringent on the cost of carbon emissions in the concerned time period than in the other periods, but is less restrictive on FRS costs. This is because of the significant increase in the REG output in this time period, and the FFGUs should be guided to participate in the FRS market so that electricity consumers can enjoy cheap and clean electricity energy from REG units. Fig. 5 shows the effect of the proposed mechanism on the revenue of FFGUs. In case 2, the revenue of FFGUs from the energy market decreases slightly, but that from the FRS market increases substantially. This is because the supply-demand relationship of FRS is properly reflected, and FFGUs recover the opportunity cost by providing capacity service to the FRS market. Specifically, in February, when carbon emissions are usually high for heating, the revenue of FFGUs from the FRS market even exceeds that from the energy market, resulting in the lowest carbon emission cost of the year.

4.3. Analysis of medium and long-term results

According to the “14th Five-Year Plan” in China, the “carbon peaking” goal in 2030, and the outline of the long-term goal in 2035 [31,33], results of the transformation of FFGUs in the next 15 years starting from 2021 are attained, as shown in Fig. 6.

As can be seen from Fig. 6, during the transformation of FFGUs, due to the growing demand for FRS brought by the continuous development of REG, the clearing capacity of FFGUs in the FRS market increases gradually. In the meantime, the cleared total generation output from FFGUs in the energy market reduces gradually. By 2030, the tenth year after the start of the simulation, the market shares of FFGUs in the energy market and the FRS market will level off, and the transformation of FFGUs will be basically complete. On the other hand, it is obvious that the cost from carbon emission and the revenue from the energy market of FFGUs will decrease year by year, while the revenue from the FRS market continuously will increase. Although the net revenue of FFGUs would decrease slightly in the first three years of the transformation, probably due to relatively low market demand for FRS in these three years, the overall revenue of FFGUs during the transformation period would remain stable and even increase slightly.

In this case, to 2035, the revenue composition of FFGUs will be relatively fixed, and the curve will only fluctuate with changes in load demand or unexpected situations. When FFGUs complete the transformation, the new electricity market mechanism will be implemented to meet the future development need of REG and policy requirements.

It should be noted that the actual situation in China is taken as the basis for the research work in this paper, which does not mean that the proposed mechanism is only applicable to China. In fact, the proposed mechanism could be implemented or adapted in different electricity markets in the transformation period for FFGUs.

4.4. Sensitivity analysis

The sensitivity analysis of the market clearing outcomes of fossil fuel generating units in the energy market and the FRS market against boundary conditions such as the REG penetration level and load demand in the power system is carried out. Specifically, 5% as a step is set to gradually change the system load demand from −15% to +15%, while

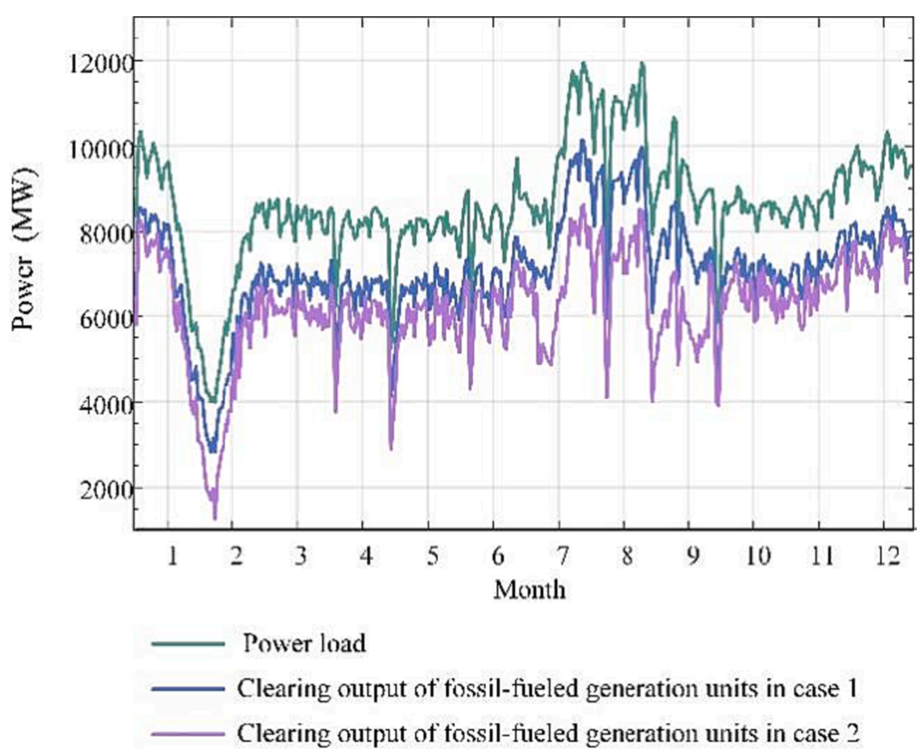

Fig. 4. Spot market clearing outcomes of FFGUs in two cases.

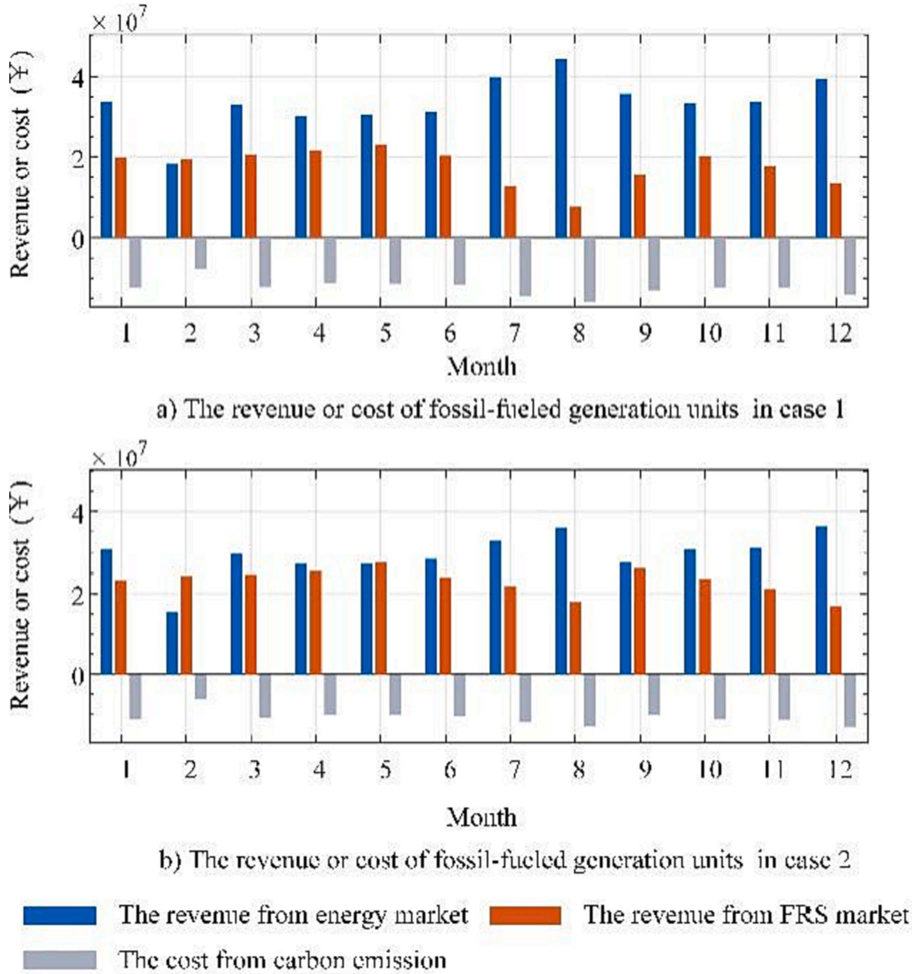

Fig. 5. Revenue or cost of FFGUs in two cases.

with 10% as a step of the REG penetration level in the power system is adjusted gradually from −20% to +20%. Taking the simulation data in 2021 as an example, the clearing results of FFGUs from the energy market and FRS market are respectively shown in Fig. 7 and Fig. 8.

It can be found that with load increase, the cleared total generation output from FFGUs from the energy market basically presents a linearly increasing trend. This is because the REG output is limited, and the task of balancing the fluctuating load can only be completed by the FFGUs in the studied power system, which highlights the role of the FFGUs as the FRS providers for the real-time balance in the power system. However, when the system load changes beyond the adjustment range of the FFGUs, the system will suffer security risk. Changes in the REG penetration level can alter the market share of FFGUs in the energy market. The higher the penetration level of REG is, the stronger the regulation capability of the FFGUs will be.

The cleared capacity of FFGUs in the FRS market decreases non-smoothly with load increasing. This is because the load variation affects the offering strategy of FFGUs in the FRS market, and hence affecting the supply-demand relationship of the FRS capacity. At the same time, a higher REG penetration level will inevitably increase the demand for FRS capacity. However, due to uncertain power output from REG, the cleared capacity from FFGUs in the FRS market substantially changes in different clearing periods.

5. Conclusion

In the context of energy transition, it is necessary to guide the transition of FFGUs from energy suppliers to regulation service providers. A joint energy-regulation electricity market mechanism is proposed in this paper for this purpose. Different from the existing electricity market mechanisms, the proposed one incorporates the incurred environmental cost of FFGUs and the incurred FRS cost of REG units into the objective function of the energy market clearing model. In addition, a method of dynamically determining the FRS demand in a power system is presented for the FRS market, which not only provides incentives for REGs to manage their power outputs, but also helps to discover the supply-demand relationship for reserve capacity in the system, thus determining a reasonable FRS price to ensure the profitability of FFGUs. The weighting factor in the proposed market mechanism is used as the policy control measure to ensure the smooth transition of FFGUs. An optimal decision-making model for fossil-fueled generators is presented so as to maximize their benefits. A large number of numerical experiments have been conducted to demonstrate the feasibility and efficiency of the proposed model. Simulation results show that the role transformation of FFGUs could basically be completed in China by 2035.

In our future research efforts, the impacts of the proposed electricity spot market mechanism on other FRS providers and the incentives for flexible consumers will be systematically investigated.

CRediT authorship contribution statement

Kun Wang: Methodology, Software, Investigation, Writing – original draft. **Jiajia Yang:** Conceptualization, Formal analysis, Writing – review

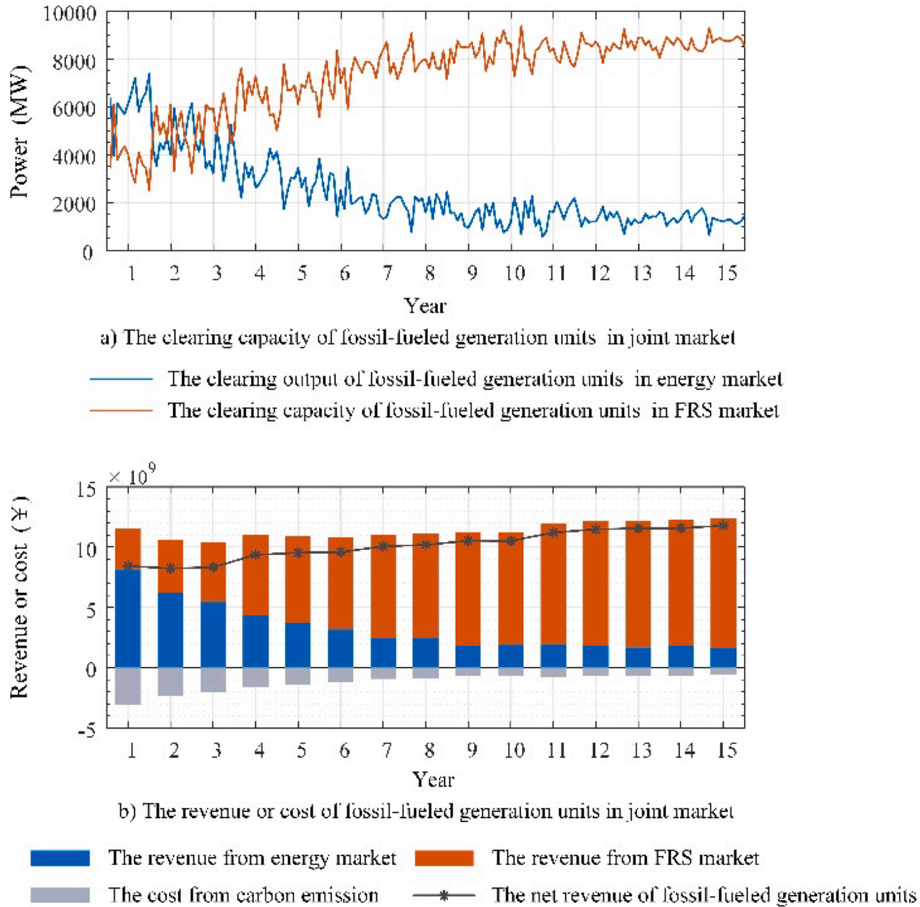

Fig. 6. Changes in clearing capacity and the revenue share of FFGUs in the next 15 years starting from 2021.

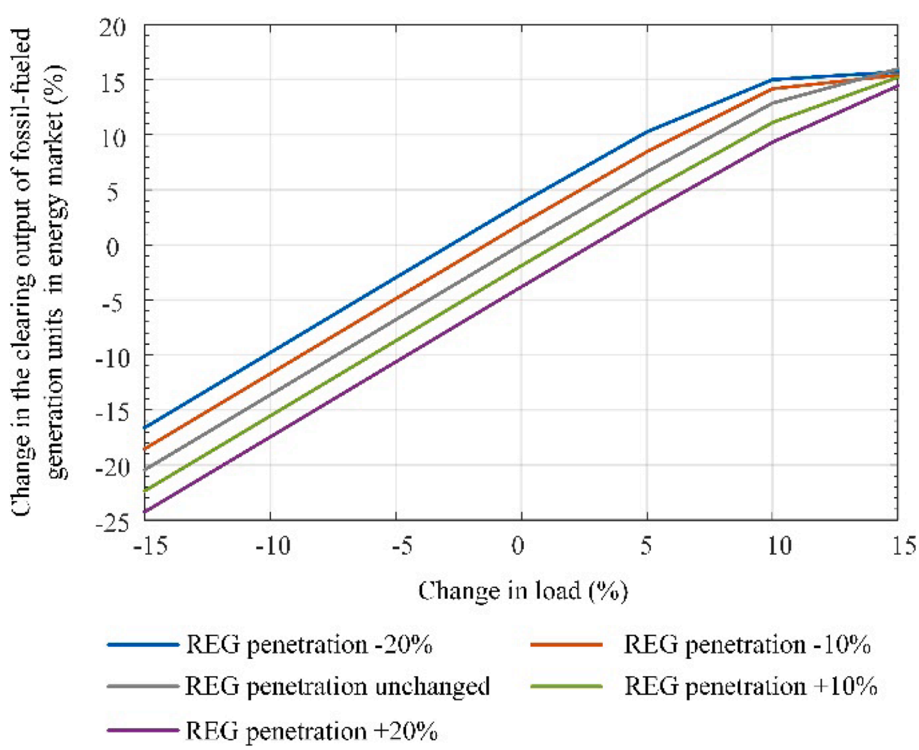

Fig. 7. Changes in the cleared total generation output from FFGUs in the energy market under different boundary conditions.

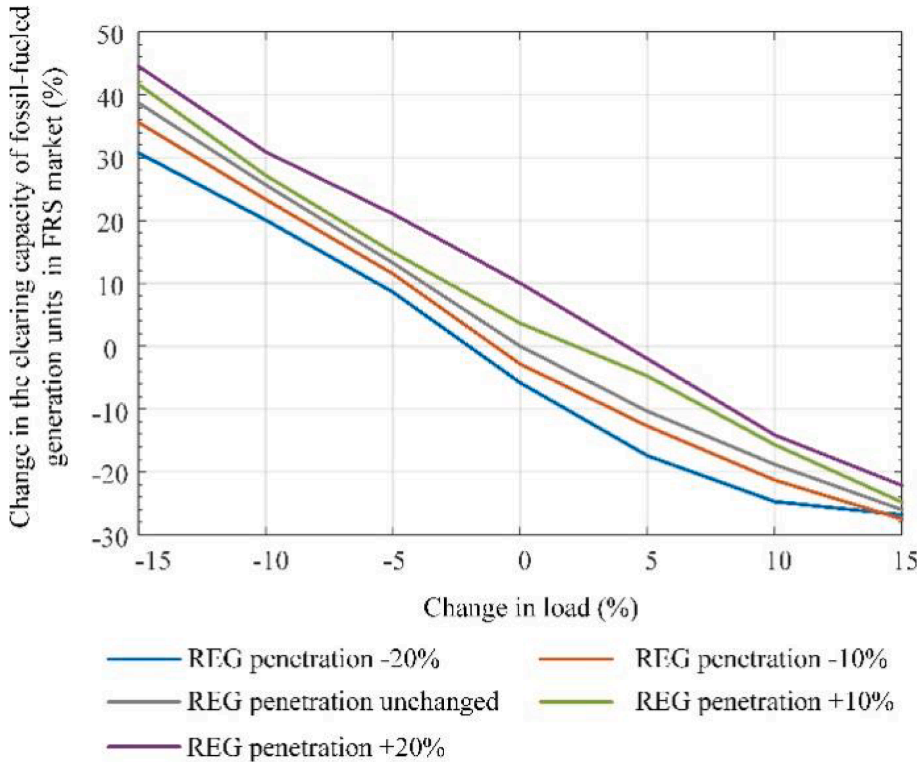

Fig. 8. Changes in the cleared total capacity from FFGUs in the FRS market under different boundary conditions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

[1] The REN21 community. Renewables 2022 Global Status Report; 2022, Available: https://www.ren21.net/gsr-2022/ (accessed on: 13 October 2022).
[2] A Sense of Place Magazine (2022, 27 November). Australia's Energy Crisis. Available: https://asenseofplacemagazine.com/australias-energy-crisis/.
[3] Nyasapoh MA, Debrah SK, Anku NE, Yamoah S. Estimation of CO2 emissions of fossil-fueled power plants in Ghana: message analytical model. J Energy 2022;2022.
[4] Eberle A, Heath GA. Projected Growth in Small-Scale, Fossil-Fueled Distributed Generation: Potential Implications for the US Greenhouse Gas Inventory. National Renewable Energy Lab.(NREL), Golden, CO (United States); 2018.
[5] Aydın L. Towards a Low Carbon Economy in Turkish Energy Policy: Nuclear and Renewable vs. Fossil Fueled Plants in Power Generation. Kırıkkale Üniversitesi Sosyal Bilimler Dergisi 2011;1(2):49–73.
[6] Cormos C-C. Techno-economic assessment of calcium and magnesium-based sorbents for post-combustion CO2 capture applied in fossil-fueled power plants. Fuel 2021;298:120794.
[7] Algarni AS, Suryanarayanan S, Siegel HJ, Maciejewski AA. Combined Impact of Demand Response Aggregators and Carbon Taxation on Emissions Reduction in Electric Power Systems. IEEE Trans Smart Grid 2020;12(2):1825–7.
[8] Chen Q, Kang C, Xia Q, Zhong J. Power Generation Expansion Planning Model Towards Low-Carbon Economy and Its Application in China. IEEE Trans Power Syst 2010;25(2):1117–25.
[9] Piperagkas GS, Anastasiadis AG, Hatziargyriou ND. Stochastic PSO-based heat and power dispatch under environmental constraints incorporating CHP and wind power units. Electr Pow Syst Res 2011;81(1):209–18.
[10] Cheng Y, Zhang N, Kirschen DS, Huang W, Kang C. Planning multiple energy systems for low-carbon districts with high penetration of renewable energy: An empirical study in China. Appl Energy 2020;261:114390.
[11] Cheng Y, Zhang N, Lu Z, Kang C. Planning Multiple Energy Systems Toward Low-Carbon Society: A Decentralized Approach. IEEE Trans Smart Grid 2019;10(5):4859–69.
[12] Mohandes B, Moursi MSE, Hatziargyriou N, Khatib SE. A Review of Power System Flexibility With High Penetration of Renewables. IEEE Trans Power Syst 2019;34(4):3140–55.
[13] Xu C, Wen F, Palu I. Electricity market regulation: Global status, development trend, and prospect in China. Energy Convers Econom 2020;1:151–70.
[14] Lahon R, Gupta CP. Energy management of cooperative microgrids with high-penetration renewables. IET Renew Power Gener 2018;12(6):680–90.
[15] Impram S, Nese SV, Oral B. Challenges of renewable energy penetration on power system flexibility: A survey. Energ Strat Rev 2020;31:1–12.
[16] Yang J, Dong ZY, Wen F, Chen Q, Liang B. Spot electricity market design for a power system characterized by high penetration of renewable energy generation. Energy Convers Econom 2021;2(2):67–78.
[17] Singh R, Paniyil P, Zhang Z. Transformative Role of Power Electronics: In solving climate emergency. IEEE Power Electron Mag 2022;9(2):39–47.
[18] O'Malley M, et al. Enabling power system transformation globally: a system operator research agenda for bulk power system issues. IEEE Power Energy Magazine 2021;19(6):45–55.
[19] Salzinger M, Remppis S, Gutekunst F, Scheffknecht G. Influence of selected flexibility options on the operation of fossil-fuelled power plants. In: International ETG Congress 2015; Die Energiewende-Blueprints for the new energy age, 2015, pp. 1-7: VDE.
[20] Löffler K, Burandt T, Hainsch K, Oei P-Y. Modeling the low-carbon transition of the European energy system-a quantitative assessment of the stranded assets problem. Energ Strat Rev 2019;26:100422.
[21] Perez-Sindin XS. Are energy megaprojects socially disruptive? Assessing the impacts of the As Pontes fossil fueled power plant in Spain. Energy Res Soc Sci 2021;80:102229.
[22] Sheble GB. Real-time economic dispatch and reserve allocation using merit order loading and linear programming rules. IEEE Trans Power Syst 1989;4(4):1414–20.
[23] Lee FN, Chen Q, Breipohl A. Unit commitment risk with sequential rescheduling. IEEE Trans Power Syst 1991;6(3):1017–23.
[24] Ding T, Wu Z, Lv J, Bie Z, Zhang X. Robust Co-Optimization to Energy and Ancillary Service Joint Dispatch Considering Wind Power Uncertainties in Real-Time Electricity Markets. IEEE Trans Sustainable Energy 2016;7(4):1547–57.

[25] Chen Y, Gribik P, Gardner J. Incorporating Post Zonal Reserve Deployment Transmission Constraints Into Energy and Ancillary Service Co-Optimization. IEEE Trans Power Syst 2014;29(2):537–49.
[26] Chen Y, Leonard R, Keyser M, Gardner J. Development of Performance-Based Two-Part Regulating Reserve Compensation on MISO Energy and Ancillary Service Market. IEEE Trans Power Syst 2015;30(1):142–55.
[27] Guo Z, Pinson P, Chen S, Yang Q, Yang Z. Chance-Constrained Peer-to-Peer Joint Energy and Reserve Market Considering Renewable Generation Uncertainty. IEEE Trans Smart Grid 2021;12(1):798–809.
[28] Zhang Z-S, Sun Y-Z, Gao DW, Lin J, Cheng L. A Versatile Probability Distribution Model for Wind Power Forecast Errors and Its Application in Economic Dispatch. IEEE Trans Power Syst 2013;28(3):3114–25.
[29] Papalexopoulos AD, Andrianesis PE. Performance-based pricing of frequency regulation in electricity markets. IEEE Trans Power Syst 2014;29(1):441–9.
[30] Zhang G, Ela E, Wang Q. Market Scheduling and Pricing for Primary and Secondary Frequency Reserve. IEEE Trans Power Syst 2019;34(4):2914–24.
[31] The State Council Information Office of the People's Republic of China. Energy in China's New Era; 2020.
[32] Shanghai Environment and Energy Exchange. 2021 Carbon Market Work Report; 2022, Available: https://www.cneeex.com/tpfjy/xx/yjybg/tscbg/.
[33] National Development and Reform Commission of China. The 14th Five-Year Plan for National Economic and Social Development of the People's Republic of China and Outline of the Vision for 2035; 2021. Available: http://www.gov.cn/xinwen/2021-03/13/content_5592681.htm.