

Transitional Revenue Scheme for High-cost Generator Unit in Guangdong Electricity Market Based on Government Authorized Contracts

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Abstract—High-cost generator units are at a cost disadvantage in electricity spot markets. This study focuses on revenue mechanisms of gas-fired units affected by power market reform in Guangdong province, China. For the first time, we compare impacts on market indicators of five settlement mechanisms: feed-in tariff (FiT), location marginal price (LMP), contract for difference (CFD), direct subsidy (DS), and estimated revenue method (ERM). In particular, we design key parameters, including authorized CFD and ERM of two kinds of government authorized contracts based on traditional dispatching patterns to avoid significant profit fluctuations brought by market reforms. We also analyze impact of factors such as climbing performance, seasonal load, and subsidy amount on the overall market and its players. Results of a case study show to directly subsidize gas-fired units will lead higher-cost units to generate more electricity, with a resulting loss of social welfare. Disruption of market prices and provision of unreasonable incentives are fatal disadvantages of this subsidy method. The government and policymakers should consider financial means to adjust benefits to reduce production costs and increase social welfare. Also, by case analysis, the ERM shows its stable performance in revenue of high-cost units, while we find that authorized CFD is not applicable for gas-fired units whose output is unstable as a marginal unit frequently. Therefore, we suggest government agencies adopt ERM to sign contracts with gas-fired units, to attain a balance between fairness and efficiency.

Index Terms—Guangdong electricity market, high-cost generator unit, settlement mechanism, subsidy.

NOMENCLATURE

A. Indices

i	Index of generator units.
l	Index of transmission lines.
n	Index of buses.
t	Index of time intervals.

B. Parameters

Δp	Price gap of annual reduction.
$\Delta P_i^U, \Delta P_i^D$	Maximum uphill/downhill climb rate of G_i .

C_i^L	Long-term average cost of G_i .
$F_{n,l}$	Power transfer distribution factor of the n -th node net power on the l -th transmission line.
H	Equivalent annual generation hours of G_i .
H^P, H^V	Hourage that peak/valley time covers.
M	Line power flow off-limit penalty factor.
$P_i^{G,B}$	Contract capacity of G_i .
$p_i^{G,B}$	On-grid price of G_i .
$P_i^{\max}$	Rated capacity of G_i .
SL_l^+, SL_l^-	Positive/negative volume of power flow off-limit.
T', T''	Peak/valley time of load.
T_D, T_U	Minimum continuous on/off time.
c_i'	Average cost of G_i approved by the government.

C. Variables

$\alpha_{i,t}$	Binary decision variable indicating the on/off status of G_i .
$\bar{\theta}$	Average contract completion degree of all I units.
$\bar{c}$	Average generation cost of system.
β_i	Proportion between Q_i^C and Q_{Σ}^C .
δ_{θ}	Variance of plan completion degree.
θ_i	Contract completion degree of G_i .
$C_{i,t}$	Clearing cost of G_i in the t th period.
I_t	Binary variable indicating whether a gas-fired unit is regarded as winning bidding.
m	Ratio of peak to total load.
p_i^C	Authorized contract price.
$p_{i,t}$	Clearing price of the spot market.
$P_{i,t}$	Clearing volume of G_i during the t -th period.
$P_{l,t}$	Power flow of the l -th transmission line at the t -th interval.
$P_{n,t}$	Net power of the n -th buses at the t -th interval.
Q_{Σ}^L	Electricity volume of total load.
Q_{Σ}^P	Total peak power of system.
Q_A	Annual generation volume of G_i .
Q_i^{Σ}	Total planned generation volume of G_i during T periods.
Q_i^C	Total volume of G_i determined by the energy-saving power generation schedule mode.
Q_i^P, Q_i^V	Contract volume of G_i in T' and T'' .
$Q_{i,t}^P, Q_{i,t}^V$	Contract volume of G_i at the t th period in T' and T'' .

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R_i	Final settlement for G_i .
R_i''	Extra revenue for gas-fired unit under ERM.
R_i^Y, R_i^D	Annual/daily permitted profit of G_i .
$R_{i,t}', R_{i,t}'$	Revenue per hour/day of G_i .
$T_{i,t}^D, T_{i,t}^U$	Duration time of on/off.

I. INTRODUCTION

MOST provincial power markets in China are in the early stages of construction. How to design the market mechanism for generator units with different cost characteristics to compete in a centralized market is a major problem. Full competition will gradually eliminate high-cost units; hence they need special treatment to ensure stable income. Reasons are summarized from four perspectives, as follows.

Most decisions to build high-cost units were made before power market reform, when a certain number of generating hours were promised and electricity generated was paid according to the feed-in tariff. However, such stranded cost cannot be recovered in the current electricity market [1]. In terms of people's livelihood, to ensure heating, many high-cost units with heating capacity are indispensable and cannot be eliminated from the market. In terms of social factors, after market-oriented reforms, generation volume of high-cost units will be reduced, and market clearing price may be lower. A sharp change in interests will have an impact on social stability, and may lead to bankruptcy, unemployment, and other consequences. From the point of view of China's socialist market system, these consequences are not acceptable. Natural gas prices are high in China, and contracts are mostly "take or pay", so it is necessary to ensure certain natural gas consumption [2]. From the perspective of power system operation, it is necessary to configure a system with a specific capacity and regulation performance to maintain system stability. With advantages of high efficiency, environmental friendliness, excellent flexibility, and short construction periods, gas-fired units are important in the power system [3]. Gas-fired units in the market environment are at a cost disadvantage, but still play an important role in operation of the power system. Installed capacity of gas-fired units in the Guangdong power grid is increasing each year. However, with power marketization, operating income of gas-fired units faces two challenges: fuel cost is high [4] and electricity price based on market competition is low. Although gas-fired units, as peak-load units, can receive a certain peak electricity price, their economic benefits often fail to meet expectations, as they are restricted by the impact of high fuel costs, short peak load times, insufficient operating hours, and market price caps. Absence of a reasonable market pricing mechanism is the core factor restricting China's natural gas power-generation industry.

Gas-fired units can recoup their costs in countries with relatively mature electricity markets. The auxiliary service market has been operating for many years in Northeast China, showing its market-incentive effect [5]. However, Guangdong is still in the initial stage of the spot market, and capacity and ancillary service markets have not been established. Gas-fired units lack market competitiveness because they depend mainly

on imported fuel. With development of the spot market, gas-fired units face the problem of bidding against coal-fired units on the same platform. Some researchers focus on a forward-looking scheduling method that takes multi-range pricing into account [6], [7]. Given real-time offers are required, forward-looking scheduling is not suitable for Guangdong's current market situation.

Since the market environment varies by country, the key factors considered in market reform are different. For example, the North American electricity market stresses market efficiency, while the Chinese electricity market takes more factors into account, such as fairness and interest coordination among market entities [8]. Research has focused on improving market efficiency while ignoring the benefit coordination method of market reform. In this context, design of a market mechanism to ensure profit of gas-fired units has become a research hotspot. Compared to some research on the clearing algorithm, to study the influence of hill-climbing performance on electricity price and optimize it, we study the revenue settlement mechanism based on the reality of Guangdong province. The subsidy, as a financial means of the government, has been widely applied in many countries, especially developing countries [9]. The World Trade Organization defines a subsidy as any form of preferential treatment given by government to consumers or producers [10]. There are four types of subsidies to electricity generation: direct and indirect transfer of funds and liabilities, government revenue foregone, provision of goods or services, and income or price support. Zhejiang province, Jiangsu province, and Shanghai have implemented a two-part pricing system for gas-fired units, which is conducive to relieving survival pressure of gas-generating enterprises [11]–[13]. Guangdong province is implementing a single energy tariff. Favorable tax treatment, such as a production tax credit policy for wind energy industry and investment tax credit policy for the solar energy industry, has been adopted in the United States to support some energy resources [9]. In Canada, the Ontario government signed a clean energy supply (CES) contract with gas-fired units and implemented an estimated revenue method to guarantee their revenue and guide generators to make bidding decisions according to their marginal production costs [14]–[16].

Subsidies have stimulated development of power generation industries to some extent. They have also caused problems, such as financial pressure and market price disorder [17]–[19]. Researchers are more inclined to consider impact of subsidies on users' final consumption costs. Researchers proposed subsidy policies should focus on maximization of social welfare and minimize interference to the market [20]. Impact of energy subsidies was analyzed using a computable general equilibrium model [21]. Results show elimination of anomalous energy subsidies would lead to a significant decline in energy demand and carbon dioxide emissions, but would exert a negative effect on the macroeconomy. The DS mechanism pays a fixed subsidy on each unit of electric power produced by generator units. No allowance is given when a unit does not generate electricity. The direct subsidy mechanism for gas-fired units in the Guangdong market is controversial, for such a mechanism provides unreasonable incentives.

Lack of a capacity market, sharp decline in revenue of gas-fired units, and controversy caused by the DS method all make it urgent to study the design of revenue mechanisms based on the current situation of the Guangdong market. The paper [22] designs a settlement mechanism for marginal units, in which the offer price of the first unsuccessful unit is selected as settlement price of marginal units. But the effect of this approach will be greatly mitigated if potential marginal unit offers are closer. The contract for the difference has been proven can effectively restrain market power in China's provincial electricity markets [23]. Also, from the perspective of the decomposition principle of the authorized CFD, some research proposed the decomposition curve of generation contracts should be treated differently, and that contract volume should not exceed generator unit's maximum clear volume [24]. However, due to fluctuation of load, this is hard to achieve. At the same time, subsidized units may change their bidding strategies to become non-marginal units. This study researches the subsidy problem of high-cost units under different scheduling modes, analyzes influence of different revenue mechanisms on social welfare and power generation plans, and proposes solutions based on the ERM. The main contributions of this study are as follows. 1) From the perspective of social equity, a method is designed based on the traditional dispatch model to formulate key parameters in government-authorized contracts, to achieve a smooth transition of benefits. 2) From the perspective of quantitative models, we summarize key factors affecting benefits of high-cost units, including load curve shape, seasonal load, and climbing performance. 3) From the perspective of market efficiency, this study analyzes necessity of replacing the DS mode by government authorized contracts. 4) We apply the ERM to settlement of gas-fired units, and evaluate its applicability to marginal units through stability of revenue.

The remainder of this paper is organized as follows. Section II introduces and models traditional scheduling and spot markets. Section III proposes designs of authorized contracts for the difference and estimated revenue methods. In Section IV, a case study is designed for different settlement mechanism simulations, and key indicators are compared and evaluated. We also analyze factors that cause revenue fluctuations of gas-fired units. Section V draws conclusions as they relate to China's power market construction.

II. GUANGDONG POWER SYSTEM AND SPOT MARKET

A. Energy-saving Power Generation Schedule

In Guangdong province, the energy-saving power generation schedule replaces even distribution of generation volume in accordance with the administrative plan. For thermal units, the volume of power generation is scheduled with consideration of level of fuel consumption and rated capacity. The lower the average fuel consumption, the more total generation is allocated, and vice versa [25], [26]. We assume that the total volume is determined as:

$$\beta_i = \frac{Q_i^C}{Q_\Sigma^C} = \gamma_i \left(1 - \delta \frac{c'_i - \bar{c}}{\bar{c}} \right) \quad (1)$$

where

$$\sum_{i=1}^I \beta_i = 1 \quad (2)$$

$$\gamma_i = P_i^{\max} / \sum_{i=1}^I P_i^{\max} \quad (3)$$

$$\bar{c} = \sum_{i=1}^I c'_i Q_i / \sum_{i=1}^I Q_i \quad (4)$$

where γ_i is the capacity rate of G_i , $\bar{c}$ is the average generation cost of the whole system, and Q_Σ^C is the total contract volume for all units. β_i satisfies (1) and (2). δ is a coefficient set by the government to determine the extent to which fuel consumption affects generation volume.

B. Open, Just, and Fair Power Dispatching Principle

Open, just, and fair power dispatching has been implemented in China's power system for a long time [27]. Power system operators obey this principle to meet requirements of system safety and stability. The aim is to coordinate power system security and economic benefits of all parties. Before a spot market is implemented, the government formulates the annual power generation plan for all kinds of power plants (units). Operators complete the annual power generation plan in equal proportion according to contract volume of the generator unit. When a spot market is implemented, operators make plans to generate electricity according to operating rules of the market [28]. In this study, the scheduling goal is to minimize variance of plan completion degree (δ_θ), that is,

$$\min \delta_\theta = \min \sum_{i=1}^I \frac{(\theta_i - \bar{\theta})^2}{I} \quad (5)$$

$$\bar{\theta} = \frac{\sum_{i=1}^I \theta_i}{I} \quad (6)$$

$$\theta_i = \frac{\sum_{t=1}^T P_{i,t}}{Q_i^\Sigma} \quad (7)$$

The yearly generation plan can be decomposed into monthly, weekly, and daily plans. A government agency determines the feed-in tariff for each power plant or unit in conformity with criteria such as type of generator set, cost, and permitted revenue. The feed-in tariff of the on-grid benchmark price is operative in most generating units at present. Constraints considered in the scheduling model include power supply balance of the system, technical output of the unit, ramping rate, line transmission power, and minimum continuous on/off time, as follows.

1) Power balance constraint

$$\sum_{i=1}^I P_{i,t} = L_t^\Sigma \quad (8)$$

2) Output constraint of generator unit

$$P_i^{\min} \leq P_{i,t} \leq P_i^{\max} \quad (9)$$

3) Line transmission capacity constraint

$$\begin{cases} -P_l^{\max} \leq P_{l,t} \leq P_l^{\max} \\ P_{l,t} = \sum_{n=1}^N P_{n,t} F_{n,l} \end{cases} \quad (10)$$

4) Maximum up/down climb constraint

$$\begin{cases} P_{i,t} - P_{i,t-1} \leq \Delta P_i^U \\ P_{i,t-1} - P_{i,t} \leq \Delta P_i^D \end{cases} \quad (11)$$

5) Minimum continuous on/off time constraint

$$\begin{cases} T_{i,t}^D - (\alpha_{i,t} - \alpha_{i,t-1})T_D \geq 0 \\ T_{i,t}^U - (\alpha_{i,t-1} - \alpha_{i,t})T_U \geq 0 \end{cases} \quad (12)$$

C. Guangdong Power Generation Installation and Spot Market

Table I presents statistics of the installed capacity of various units in Guangdong at the end of June 2019 [29]. Coal- and gas-fired units are the two main types of power source, accounting for 49.1% and 18.3%, respectively. A detailed overview of the Guangdong power system can be found in reference [30]. The Guangdong power market includes a medium- and long-term market, day-ahead and real-time spot markets, and a frequency-regulation market, the last of which is beyond the scope of this paper. Medium- and long-term market members purchase/sell electricity by signing contracts for differences (CFDs). When the spot market opens, generators submit multi-segment offers to the trading center on the basis of a non-monotonic decreasing price with increasing quantity, whose minimum and maximum output are the respective minimum and maximum technical output of generator units. For electricity users in the day-ahead market, only inelastic demand is submitted to the power exchange in the initial stage of the spot market [31]. The day-ahead spot market will carry the clearing program based on the security constrained unit commitment (SCUC) and security constrained economic dispatch (SCED) to arrange the next-day generation plan. For a thorough SCUC/SCED model, please refer to [32] and [33]. The objective function of the clearing model consists of minimizing the total generation cost,

$$\min \left[\sum_{i=1}^I \sum_{t=1}^T \alpha_{i,t} C_{i,t} + \sum_{l=1}^L \sum_{t=1}^T M(SL_l^+ + SL_l^-) \right] \quad (13)$$

where $C_{i,t}$ is clearing cost of G_i in the t -th period. LMP information will be released to each generator unit at the appointed time. Given power transmission and distribution price are determined separately in Guangdong province, the LMP released does not include network loss price component. Several settlements and trial operations were carried out in 2019 and 2020 [34]. Model constraints consist of equality and inequality constraints (8)–(12).

D. Cost-based Offer for Non-monotonic Cost Characteristics

Given Guangdong has not established a capacity market, we propose an offer decision method based on non-monotonic cost characteristics. Cubic polynomials are used to describe the total variable cost (ignoring the start-up cost) of G_i during the t th time period,

$$C_{i,t}^T = a_{i,3}Q_{i,t}^3 + a_{i,2}Q_{i,t}^2 + a_{i,1}Q_{i,t} \quad (14)$$

where $a_{i,1}$, $a_{i,2}$, and $a_{i,3}$ are respective coefficients of the primary, quadratic, and cubic terms of total cost function of G_i . Offer assumption is an important premise of this paper. Strategies of generators in the electricity market are complex

TABLE I
GUANGDONG INSTALLED CAPACITY OF VARIOUS UNITS

Unit type	Capacity (MW)	Ratio (%)
Total	120840	100.0
Coal	59320	49.1
Gas	22090	18.3
Hydro	9260	7.7
Nuclear	13300	11.0
Wind	3750	3.1
Solar	3680	3.0
Other	9450	7.8

and varied. In a competitive market, it is rational to offer/bid as marginal cost (MC). However, due to some imperfect factors in the real market, a quotation is often not based on marginal cost. Given China's current power market construction, we propose an ideal bid strategy based on power generation cost characteristics of thermal power generating units. The offer of China's Guangdong spot-power market has two parts: start-up cost and energy bid. Therefore, we must explain the method of participation in the energy market. Fig. 1 presents the proposed three-segment offer curve. According to cost characteristics of thermal power units, the average variable cost (AVC) curve is usually monotone decreasing when delivered power locates between minimum technical output and economic output, and monotone increasing when it locates between economic output point and maximum technical output. The economic output point differs according to cost characteristics of each unit. Based on the described cost characteristics, we adopt the three-segment offer curve shown in Fig. 1. After formatting the offer of the first segment (C_{1st}) according to minimum output power, P_1 can be determined. Surplus volume ($P_{\max} - P_1$) is divided equally into two parts. Therefore, we can obtain three-segment offers like (C_{1st}, Q_{1st}) , (C_{2nd}, Q_{2nd}) , and (C_{3rd}, Q_{3rd}) ; see Appendix for details.

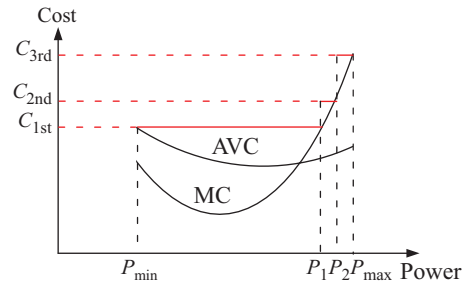


Fig. 1. Cost curve of a generator unit. (AVC and MC denote average variable cost and marginal cost, respectively. The red solid line represents the unit's offer).

III. DESIGNS OF TWO KINDS OF GOVERNMENT AUTHORIZED CONTRACTS

A. Authorized contract for difference

The authorized contract for difference, called a *vesting contract* in Singapore and Australia, has been widely adopted and is often used as a financial hedge tool during transition of an electricity market from partial to full competition [35]. This can ensure financial viability of participants. We design a contract making process according to the Guangdong power

market reform process [36]. When implementing the authorized CFD, a contract stating time-varying volume and price is signed with each generator unit through a government agency. Beyond the volume covered by the authorized CFD, deviations are settled in accordance with clearing price of the spot market ($p_{i,t}$). The total volume of authorized CFDs for all units (Q_{Σ}^C) is usually determined as:

$$Q_{\Sigma}^C = \alpha Q_{\Sigma}^L \quad (15)$$

where α is proportion of all units between total authorized volume of CFDs and total electricity load volume, and Q_{Σ}^C is total volume of authorized CFDs. To reflect load characteristics in the contract, we can simply define ratio of peak load to total load,

$$m = Q_{\Sigma}^P / Q_{\Sigma}^L \quad (16)$$

We can set contract quantity for each period according to the principle of equal proportion,

$$\begin{cases} Q_{\Sigma}^P = \sum_{t \in T'} Q_t \\ Q_i^P = m Q_i^C \\ Q_{i,t}^P = \frac{Q_i^P}{H^P} \\ Q_{i,t}^V = (1 - m) Q_i^C \\ Q_{i,t}^V = \frac{Q_i^V}{H^V} \\ T = T' + T'' \end{cases} \quad (17)$$

The authorized contract price for G_i can be set to p_i^C by a government agency, where $p_i^C = p_i^B - \Delta p$, and p_i^B and Δp are, respectively, the benchmark price of G_i and price gap of annual reduction. It is easy to perceive the revenue formula for G_i as:

$$R_i = \sum_{t \in T} R_{i,t} = \sum_{t \in T'} (p_i^C - p_{i,t}) Q_{i,t}^P$$

$$+ \sum_{t \in T''} (p_i^C - p_{i,t}) Q_{i,t}^V + \sum_{t \in T} p_{i,t} Q_{i,t} \quad (18)$$

A revenue scheme based on authorized CFDs is shown in Fig. 2.

B. Estimated Revenue Mechanism

The estimated revenue method (ERM) is a kind of general CFD that calculates net revenue based on energy market income estimated by spot-market price. Estimated net revenue is used to offset fixed income. To implement this method can constrain market power of the generator, which can obtain a stable income. Implementation of a CES contract is described in an internet document which was published by the Ontario Power Authority [15]. Learning from the CES contract, we propose a method to estimate revenue for the Guangdong market when dealing with a high-cost unit's cost-recovery problem. Estimated revenue settlement is a contingent settlement method, by which a power exchange center can recover a certain proportion of income when estimated profit of a unit in the spot market exceeds permitted profit (PP), and can be compensated when the estimated profit is lower than permitted profit. Revenue components of a unit under the estimated revenue method are shown in Fig. 3. Annual permitted profit (R_i^Y) of G_i is calculated as

$$R_i^Y = (p_i^{G,B} - C_i^L) H P_i^{\max} = (p_i^{G,B} - C_i^L) Q_A \quad (19)$$

where $p_i^{G,B}$ is on-grid price, C_i^L and $P_i^{\max}$ are respectively long-term average cost and rated capacity of G_i , and H and Q_A are equivalent annual generation hours and annual generation volume, respectively, which can be obtained from historical data under the traditional scheduling mode. Daily permitted fixed profit is

$$R_i^D = R_i^Y / 365 \quad (20)$$

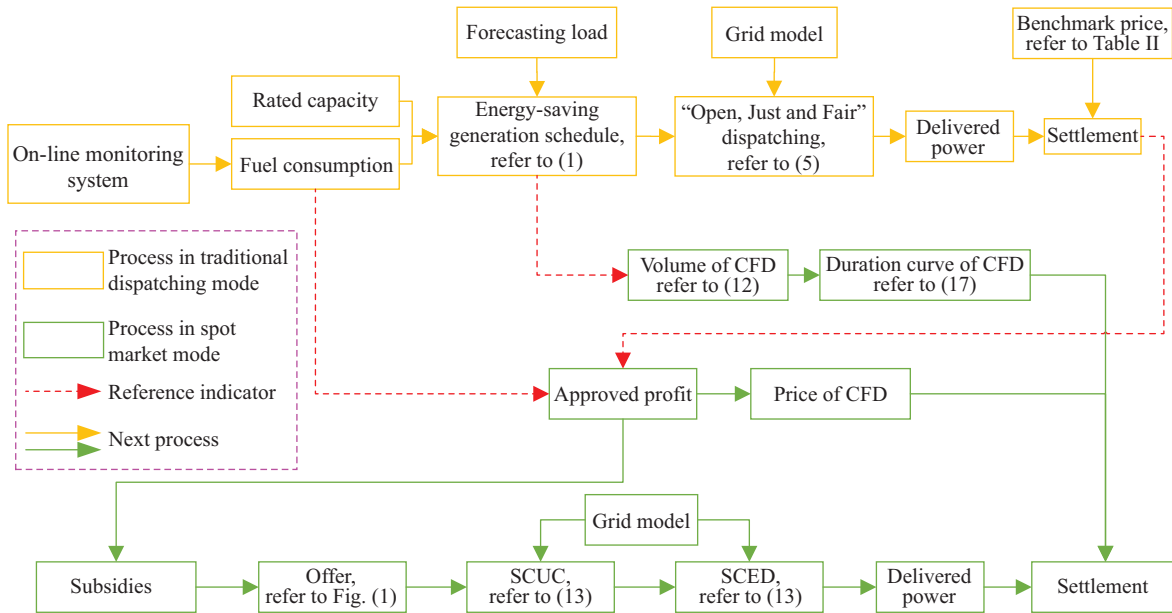


Fig. 2. Electricity market reform transition scheme considering both efficiency and fairness factors through government authorized contracts. Government institutions or their agencies can adjust the distribution of benefits among market entities through financial settlement, but the efficiency of the electricity spot market should not be reduced. It is a wise manner to deal with the relationship and interaction between the government and the market.

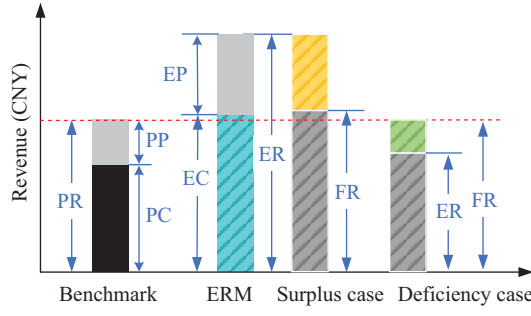


Fig. 3. Final revenue (FR) is determined by estimated revenue (ER) from the spot market and permitted revenue (PR). The surplus case occurs when ER is in excess of PR; similarly, a deficiency occurs when PR is in excess of ER. (PP: permitted profit; EC: estimated cost; EP: estimated profit; FR: final revenue.)

We set up a binary variable,

$$\begin{cases} p_{i,t} \geq c'_i, & I_t = 1 \\ p_{i,t} < c'_i, & I_t = 0 \end{cases} \quad (21)$$

$I_t = 1$ for estimated production intervals in which the gas-fired unit is deemed to have operated. By calculating generator unit's revenue per hour ($R'_{i,t}$), we can obtain total market profit for a daily cycle as:

$$R'_{i,t} = (p_{i,t} - c'_i)P_i I_t \quad (22)$$

where contract capacity of G_i is

$$P_i = k_i P_i^{\max} \quad (23)$$

and k_i is a capacity conversion coefficient. Finally, we make final settlement (R_i) for G_i by comparing R'_i with R_i^D . If R'_i exceeds R_i^D (surplus case in Fig. 3), then 95% of the difference between R'_i and R_i^D is taken back. Otherwise (deficiency case in Fig. 3), extra revenue (R''_i) for the gas-fired unit is subsidized as:

$$R_i = \sum_{t \in T} p_{i,t} q_{i,t} + R'' \quad (24)$$

$$R'' = \begin{cases} -0.95(R'_i - R_i^D) & R'_i \geq R_i^D \\ R_i^D & R'_i < R_i^D \end{cases} \quad (25)$$

IV. CASE STUDIES

A. Scenario Description and Assumptions

In the designed simulation scenario, ten generator units, eight coal-fired and two gas-fired, are located at different buses, as shown in Fig. 4. The simulation cycle covers 24 consecutive hours in a day. Power network model is a modified IEEE 10-mechanism 39-bus system, in which G_5 and G_7 are gas-fired units and others are coal-fired. The system load curve is shown in Fig. 5 [37]. Generator unit parameters are listed in Table II.

To facilitate analysis of simulation results, it is assumed a transmission line's capacity is sufficient and there is no blocking of power flow. To simulate market behavior that may exist when a line is blocked, we add several blocking scenarios under which to perform simulation analysis. Revenues of all generator units are calculated under different settlement

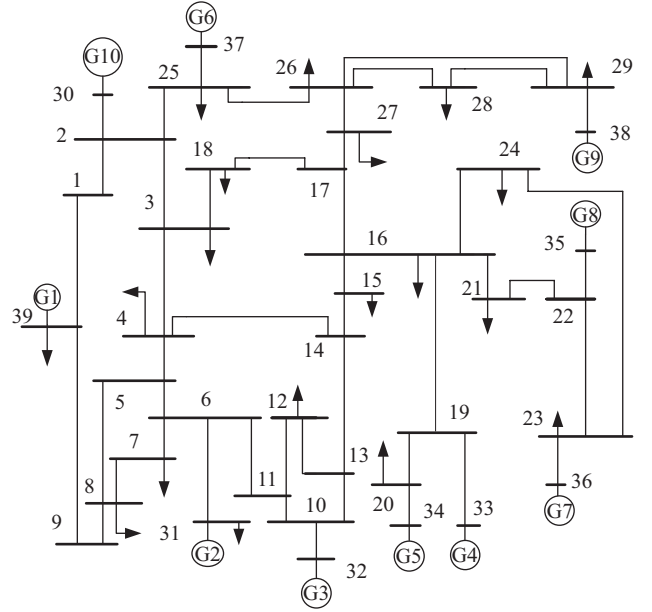


Fig. 4. IEEE 10-machine 39-bus test system network diagram.

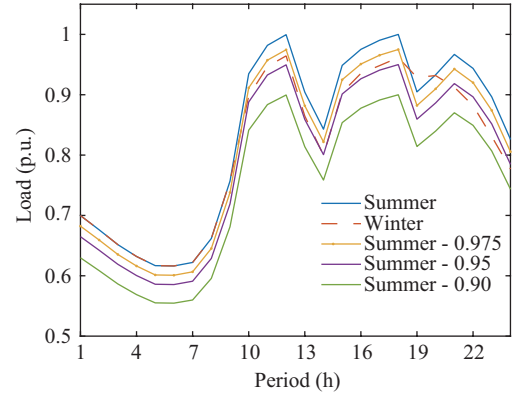


Fig. 5. Different load curves are used in this paper. The spring, summer, and autumn load curves are very close; we choose the summer load curve as representative. Summer - 0.975 means multiple of summer load, and vice versa. The maximum load is regarded as 1.0 p.u.

mechanisms. Under ERM, only gas-fired units are paid with ERM, while coal-fired units are paid with authorized CFDs. This enables use of original market design of authorized CFDs.

B. Case and Parameter Settings

As a reference, the traditional scheduling model is used to simulate generation scheduling before the spot market is implemented. It provides important historical data for the spot market, such as revenue and utilization hours of generator units. Feed-in tariffs are fixed prices paid for each unit of energy produced by generator units, seeking a settlement method based on approved prices under *open*, *just*, and *fair* power dispatching. Feed-in tariff for most coal-fired units is benchmark price [38]. Permitted cost and feed-in tariff of each unit are shown in Table II. Another four settlement mechanisms, LMP, DS, CFD, and ERM, are implemented under market competition mode. With rich economic information, LMP is widely applied in the spot market. Under LMP

TABLE II
GENERATOR UNIT BASIC INFORMATION

ID	Bus	Max power (MW)	Min power (MW)	Ramp (%/h)	Unit type	$a_{i,3}$	$a_{i,2}$	$a_{i,1}$	Min. on time (h)	Min. off time (h)	Permitted cost (CNY/MWh)	FiT (CNY/MWh)
1	30	400	200	11	Coal-fired	0.00060	-0.408	260.2	24	24	190.88	463
2	31	300	150	11	Coal-fired	0.00185	-0.954	305.8	24	24	182.77	463
3	32	300	150	11	Coal-fired	0.00235	-0.962	329.6	24	24	231.15	463
4	33	250	125	11	Coal-fired	0.00140	-0.575	364.0	24	24	304.96	463
5	34	200	60	40	Gas-fired	0.00330	-1.051	505.6	4	4	421.96	533
6	35	300	150	11	Coal-fired	0.00190	-0.975	318.6	24	24	193.52	463
7	36	240	72	40	Gas-fired	0.00350	-1.187	597.0	4	4	496.36	665
8	37	250	125	11	Coal-fired	0.00135	-0.586	301.0	24	24	237.41	463
9	38	300	150	11	Coal-fired	0.00166	-0.650	271.0	24	24	207.37	463
10	39	300	150	11	Coal-fired	0.00300	-1.212	330.0	24	24	207.59	463

Cost parameters are taken from the environmental protection costs of different unit types. For example, for coal-fired units, the approved cost of 463 CNY/MWh includes desulfurization, denitrification, and ultra-low emission cost.

mode, settlement revenue depends on spot-market clearing price and clearing volume. Generator units make their offer decisions based on cost assumption. In particular, under a direct subsidy mechanism, high-cost units lower the offer according to the price gap between coal- and gas-fired on-grid benchmark prices, as shown in Table II. At present, p_B^C is 463 CNY/MWh, and subsidy price gap is $p_i^B - p_B^C$. According to the power market report of the first half of 2019 released by the Guangdong Power Exchange Center, average price gap of annual bilateral negotiated transactions in Guangdong is -45.1 CNY/MWh [29]. This study assumes the contract price can be made for each unit based on feed-in tariff and historical price gap. Therefore, the authorized contract price for G_i is $p_i^C = p_i^B - \Delta p$, where Δp is set to 45.1 CNY/MWh. In addition, peak time intervals T' are defined as the 11th to 19th periods, and others are valley periods. α is set to 90%, and it represents the proportion of contract volume to total forecast power generation volume in the traditional model. Under the estimated revenue settlement mechanism, we determine permitted profit of gas-fired units in the market according to historical power generation volume and cost.

C. Analysis of Results

Development environment of the case model is MATLAB (version 2018). The clearing algorithm is solved by Gurobi solver (version 9.0.0), which supports mixed integer and quadratic programming [39].

1) Overview of Power Generation under Different Schedule Modes

Figure 6 presents delivery power curves of generator units under three scenarios. Fig. 6(a) is output of generator units under traditional scheduling mode, whose output curves have no distinguishing features except they look somewhat messy. This is attributed to pursuit of consistency of contract completion degree under this mode. Different scheduling schemes may exist in optimization intervals during a day. Considering output of high-cost units is guaranteed, output plans of G_5 and G_7 are maintained at a relatively high level. Utilization hours of the two generator units reach 16.03 hours and 15.53 hours, respectively.

Clearing result based on marginal cost is shown in Fig. 6(b), where G_1 , with a low-cost advantage, produces more electricity. This means low-cost units are more competitive under

TABLE III
UTILIZATION HOURS UNDER DIFFERENT SCHEDULING MODES AND LOAD CURVES (UNIT: HOURS)

Unit ID	S_1	S_2	S_3	0.975 Load	0.95 Load
1	17.5871	23.1190	23.2084	23.0364	22.9543
2	17.6419	22.7679	22.9984	22.3829	22.0628
3	17.3154	17.3152	16.8782	16.9567	16.3279
4	16.8173	17.7356	14.8509	16.6509	15.2443
5	16.0278	2.9534	1.2683	1.3000	1.2799
6	17.5693	20.7474	20.9773	20.3607	20.1235
7	15.5258	1.2736	7.2322	1.2284	1.2000
8	17.2732	19.4671	19.6811	19.4600	19.1600
9	17.4759	19.6710	18.1480	18.9112	18.1946
10	17.4744	17.1241	17.0867	17.1115	16.5210

market-based economic scheduling. For gas-fired units G_5 and G_7 , clearing amount is small, and mainly undertakes peak regulation of the system from the 9th to 19th intervals. Compared with utilization hours under the traditional dispatching mode, coal-fired units occupy power generation space of the gas-fired units, and the gas-fired units only occupy 4.23 hours, with a decrease of 86.60%.

When subsidies are available, gas-fired units can offer relatively low prices to increase their output, as shown in Fig. 6(c). This brings an increase in total generation volume of gas-fired units. In comparison, power generation volume of coal-fired units is reduced.

2) Several Key Factors Affecting Revenue

Figure 8 shows the spot-market clearing price for the case where units bid as marginal cost. Market prices vary with loads over time. It is worth noting electricity prices in the 9th and 19th period are relatively low. When bidding as marginal cost, gas-fired units submit a relatively high offer. Furthermore, when system load changes rapidly and output of the generator unit is adjusted synchronously, low electricity price caused by constraints may cause the clearing price to be smaller than offer price. When a gas-fired unit is not subsidized, the relatively high offer price decreases its clearing power. During off-peak period, two price curves come close because gas-fired units fail to win the bid. According to analysis above, when the gas-fired unit offer is lowered, the degree of price mutation will become weaker under the same climbing constraint. When we adjust climbing performance parameter of coal-fired units to 15%, system ramp ability is enhanced, and the sharp price curve becomes smoother, as shown in Fig. 9. Also, we observe

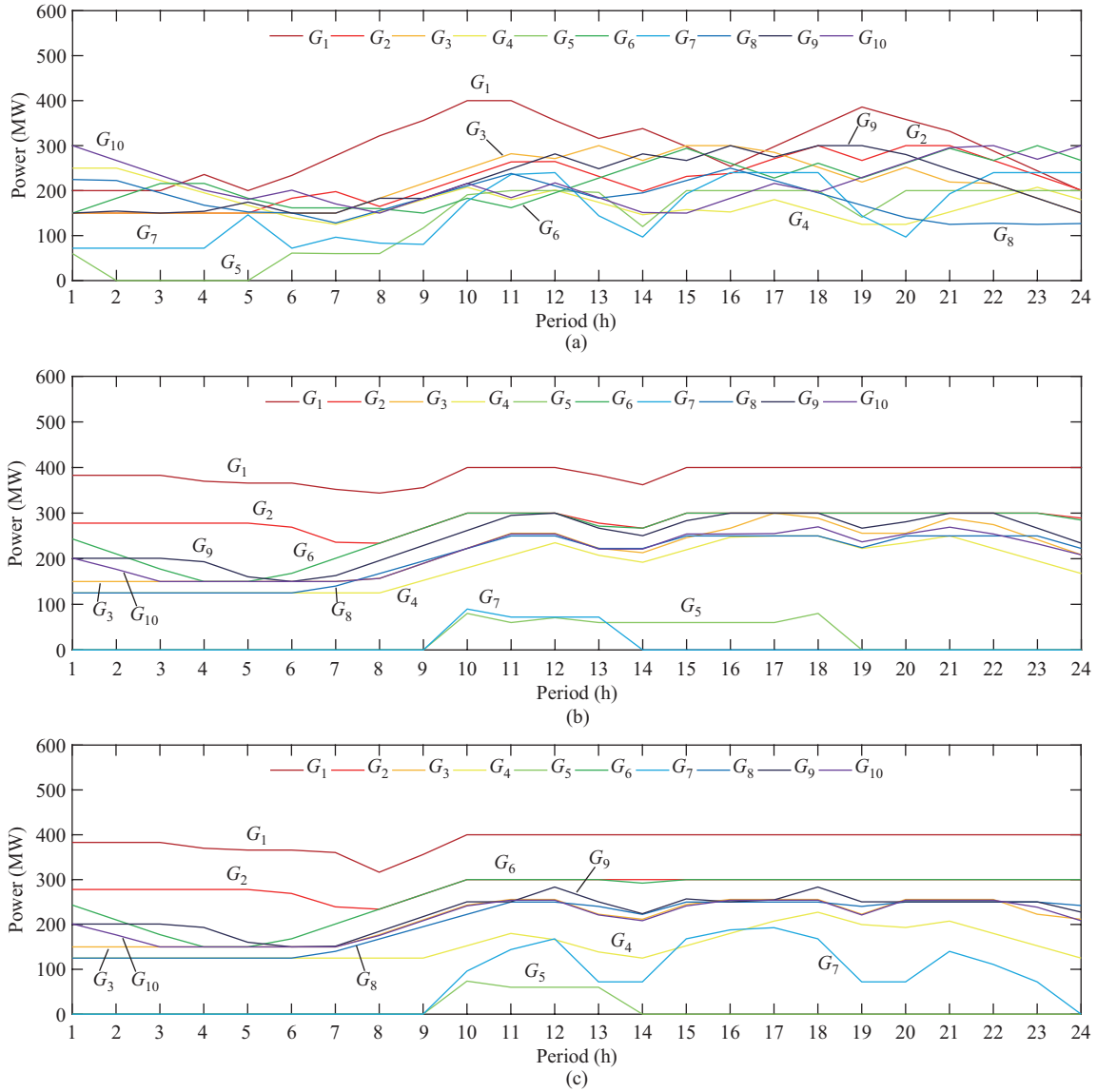


Fig. 6. Output of generator units under different dispatch modes. (a) Output power of generator units under traditional schedule mode. (b) Output of generator units under market competition mode. (c) Output of generator units under direct subsidy mode.

a smaller gap between the two curves; see Fig. 8. This is due to influence of climbing performance constraints on the Lagrange multiplier. The larger price gap comes from coal- and gas-fired units, and the higher the climbing demand the lower the clearing price in periods of steep climbing. These abnormal prices have been illustrated in literature [40]. Although the Guangdong market has restrictions on the scope of clearing prices, low prices still weigh heavily on revenues.

As we can see from Fig. 10, under traditional scheduling mode with FiT, total generating volume of the units and FiT are fixed, which makes all units' generation revenue high. However, in LMP settlement mode, gas-fired units G_5 and G_7 become marginal units. A low clearing price and delivered power yield low returns. When implementing direct subsidies, revenue of coal-fired units decreases, but revenue of gas-fired unit G_7 increases. Considering G_5 loses some clearing volume when G_7 has a more competitive offer under direct subsidy, its revenue decreases. G_4 , a coal-fired unit with high fuel costs,

clearly loses in direct subsidy mode. The revenue of units under both CFD and ERM are also stable, so high-cost units can get a more powerful market incentive.

Figure 11 shows the profit of all units, where G_5 and G_7 are used as peaking units, but low electricity price appears in up- and down-climb periods, which leads to difficulty in cost recovery under direct subsidy and LMP modes. It should be noted gas-fired units still cannot benefit, for the clearing amount is small. To obtain more profits, we must provide a lower offer than set in this study. It can be expected coal-fired units will be further squeezed out. For gas-fired units, estimated revenue is usually less than permitted revenue, which is mainly because their operating hours are much less than those of coal-fired units. In direct subsidy mode, G_4 , which was not originally a marginal unit, becomes one, and revenue is significantly affected. Obviously, under the FiT settlement mechanism, profit of each unit is relatively stable. For gas-fired units G_5 and G_7 , profit is very low under LMP

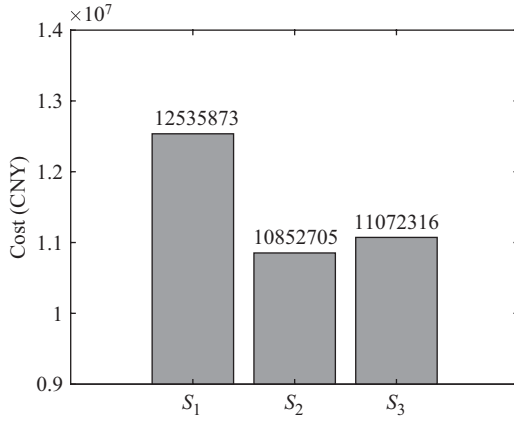


Fig. 7. Total cost under different schedule modes and offers. (S₁ represents the traditional scheduling model, S₂ the bid as marginal cost under the spot-market model, and S₃ a reduced offer in a spot-market model).

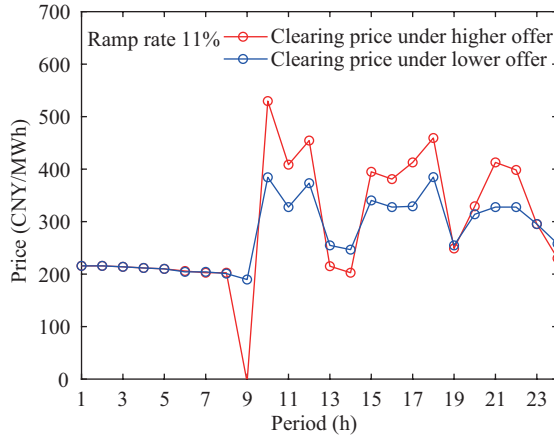


Fig. 8. Locational marginal price of 24 intervals when climbing constraints work. Blue and red lines respectively represent clearing price with/without direct subsidy.

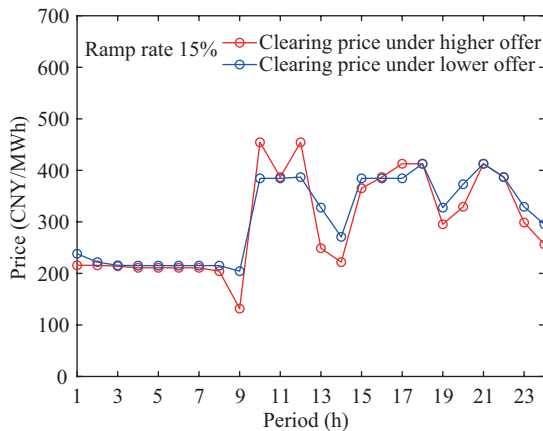


Fig. 9. Locational marginal price of 24 intervals when the climbing performance of coal-fired units is improved. Blue and red lines respectively represent clearing price with/without direct subsidy.

and direct subsidy settlement mechanisms, and unit G_5 , which runs at minimum output level, makes zero profit. This is common for marginal units, considering multi-segment offers described above are adopted in this paper. To some extent, a

unit's profit is guaranteed when bidding as a marginal cost under the CFD and ERM settlement mechanisms.

Climbing performance of coal- and gas-fired units is different. Climbing performance of gas-fired units is comparatively better. As need for flexibility grows in a power system, flexibility of coal-fired power plants increases. Table IV shows power generation volume of gas-fired units under different seasons and different climbing rates of coal-fired units. In summary, gas-fired units gain market share in two situations. Load changes rapidly while the regulating capacity of coal-fired units is insufficient, requiring gas-fired units to quickly adjust power (up or down). When system load is near its peak, supply cost of coal-fired units is too high.

TABLE IV
TOTAL GENERATION VOLUME OF GAS-FIRED UNITS UNDER DIFFERENT CLIMBING PERFORMANCE OF COAL-FIRED UNITS AND SEASONS (UNIT: MWH)

Coal-fired units ramp rate	Winter		Summer	
	G_5	G_7	G_5	G_7
10%	376.6225	288	infeasible	infeasible
11%	269.1532	0	590.6747	305.6571
13%	250.8361	0	547.3523	288
15%	0	0	577.1472	0
20%	0	0	420	0

3) Subsidies Leading to Undesirable Effects

Based on analysis of Fig. 6, it is not difficult to understand cost differences in Fig. 7. Social welfare usually refers to the difference between production benefit and production costs. However, in most scenarios, the benefits generated by certain energy consumption on the user side are fixed, so we can think that production costs determine the value of social welfare. The more the production costs (fuel costs in this article) the lower the social welfare. And the financial subsidy brings financial pressure but does not increase the production cost.

According to requirement of the National Development and Reform Commission of China, subsidy of gas-fired units should not exceed coal-fired unit's on-grid benchmark price of 350 CNY/MWh. We calculate total power generation cost of support from 70 CNY/MWh to 350 CNY/MWh. The total power generation cost of the system under different subsidies is shown in Fig. 12. Different incremental costs are caused according to subsidy amounts. System costs increase as subsidies increase. In particular, when subsidy amount increases from 0.21 CNY/kWh to 0.28 CNY/kWh, total production cost of the system increases by 8.40%. This is a warning to market designers that excessive subsidies can lead to substantial cuts in social welfare. When the gas-fired unit runs at maximum power, system cost will not continue to increase significantly. In most extreme case, when the subsidy is 0.35 CNY/kWh, total power generation cost in the spot-market mode exceeds the total power generation cost in traditional scheduling mode (see Fig. 7).

4) The ERM is an Ideal Mechanism to Solve the Problem of High-cost Units

To analyze impact of load profile on profit variation of high-cost units, this study adopts different real-time load profiles for the case study. Table V shows profit and its coefficient

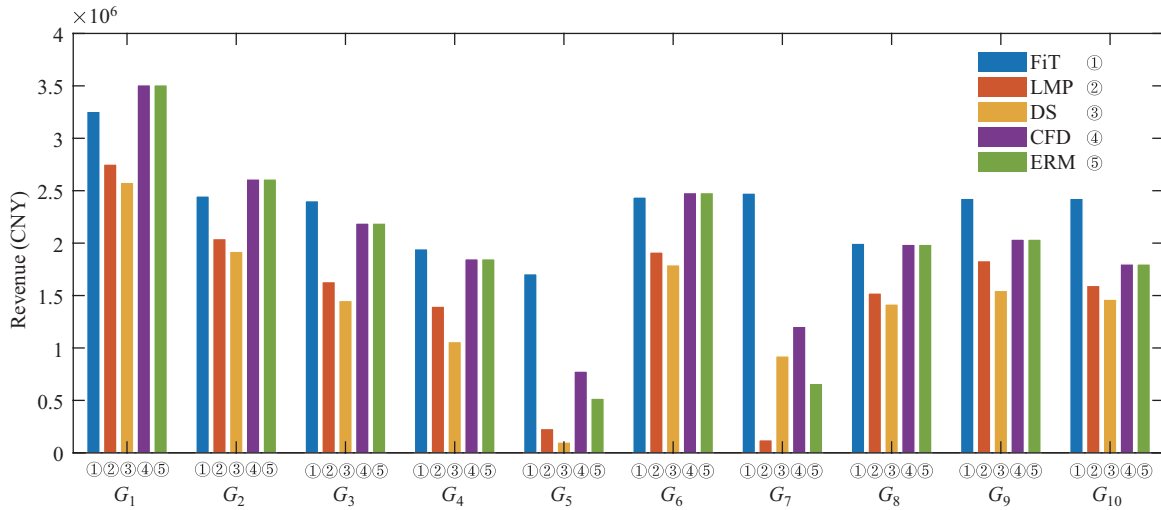


Fig. 10. Revenue of units under different settlement mechanisms.

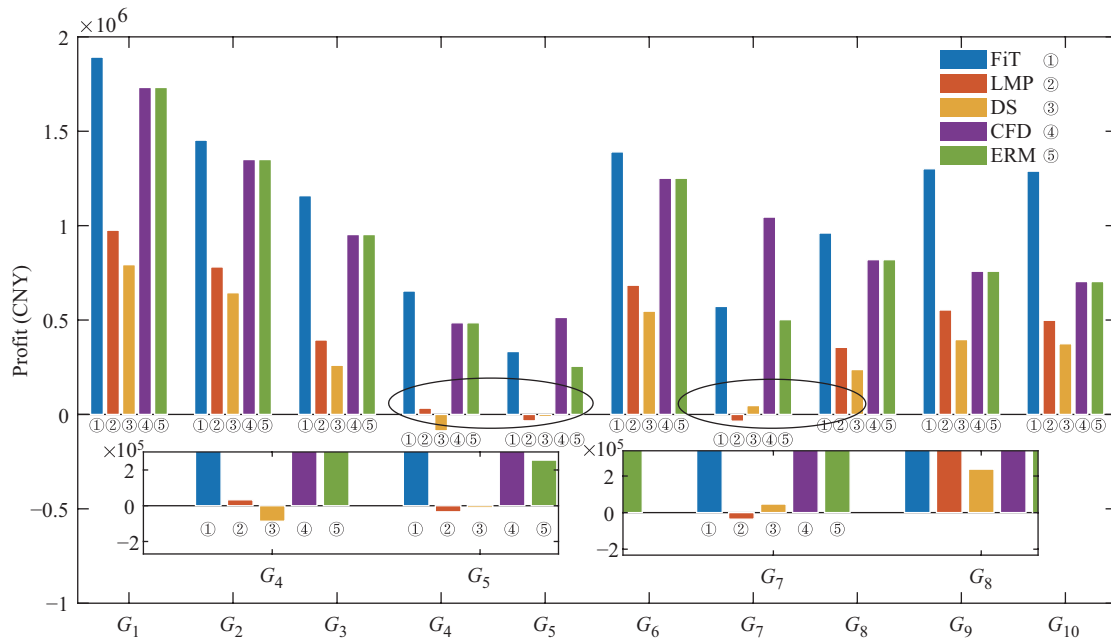


Fig. 11. Profit of units under different settlement mechanisms.

TABLE V
GAS-FIRED UNIT G_5 AND G_7 PROFIT AND VARIATION COEFFICIENT UNDER DIFFERENT LOAD PROFILES (UNIT: CNY)

Load profile	G_5					G_7				
	FiT	LMP	DS	CFD	ERM	FiT	LMP	DS	CFD	ERM
Summer - 0.90	291771.6	-39177.09	-18492	520956.94	249932.92	527123.6	-42654.36	2616.46	1052973.55	495035.62
Summer - 0.95	321178.6	-26787.804	-6600.14	592148.33	262322.2	544502.2	-54685.863	110506.4	1109334.16	483004.12
Summer	333205	-33950.84	-11248.44	513692.32	255159.17	572118.2	-35807.2	46818.13	1045292.66	501882.78
C·V	6.76%	-18.68%	-49.47%	7.99%	2.43%	4.14%	-21.53%	101.73%	3.27%	1.94%

of variation (C·V) of gas-fired unit under the settlement mechanisms mentioned above when different real-time load curves are adopted. When LMP is adopted for settlement, profit fluctuation of units is the greatest, which is a direct reflection of price volatility of the spot market. Under FiT and DS settlement, profit volatility is reduced. Generating volume of the unit is settled according to a fixed tariff under the FiT

mechanism, and its profit is relatively stable. The main reason for instability is the uncertainty of delivered volume. Under direct subsidy settlement mechanism, profit is also directly related to a unit's power generation, which brings obvious volatility. Under the CFD and ERM models, unit's revenue volatility is much less. CFD is a financial contract, which can avoid risk of unit profit fluctuation to a certain extent. The

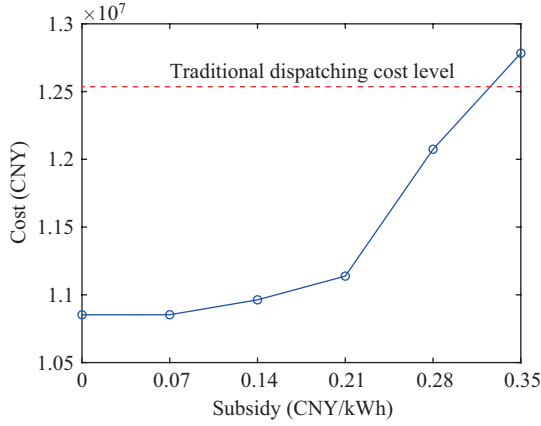


Fig. 12. Effect of subsidy amount on incremental cost.

main factor that affects profits is fluctuation of the spot-market price caused by load change.

Finally, to analyze possible market manipulation where blocked lines exist, different transmission capacity values are set artificially for the concerned blocked line (line between buses 19 and 20), and profits of high-cost units are calculated at different multiples of offers when ERM is adopted. Table VI shows higher offers bring lower profits when the key line is blocked. This can be attributed to two factors. One is excess profits will be recovered, and the other is more output of the units will generate higher costs. This brief analysis suggests ERM can play a role in restraining market power.

TABLE VI
PROFIT OF G_5 WITH MARKET POWER WHEN A LINE IS BLOCKED
(UNIT: CNY)

Offer multiplier	Transmission capacity (between bus 19 and bus 20)		
	100 MW	150 MW	200 MW
1.1	96985.80	211272.88	201278.77
1.2	31614.50	-79403.33	204478.64
1.3	-30936.00	-145288.60	208469.36

V. CONCLUSION

The goals of electricity market reform include not only improved efficiency of electricity production, transmission, and consumption, but reasonable distribution of social welfare. To achieve these goals, the government must implement some regulations in the market. Subsidizing high-cost units is a conventional means to exercise control measures.

We designed an example to analyze impact of different settlement mechanisms, including FiT, LMP, CFD, DS, and ERM, on high-cost generator units. Feed-in tariff is a kind of implicit subsidy to generator units. Such a settlement mechanism guarantees revenue of the generator units. When settlement is conducted according to LMP, high-cost units obtain relatively low profits and may miss money in some situations. At the same time, it faces significant fluctuation in market price. CFD is a tool to influence social welfare distribution without affecting market efficiency. The government can design different types of CFDs for various market entities

to achieve different goals. Under the DS mechanism, gas-fired units can lower their prices to obtain more generation and gain more profits. When this settlement mechanism is adopted, clearing price is relatively low. Results of analysis also show high-cost generator units will increase total power generation cost of the system and reduce social welfare under DS settlement mode. Based on analysis of the case study, we can draw several conclusions.

1) As we can see from Fig. 11, carrying settlement operations based on LMP has significant influence on profit of a marginal unit. In particular, when impact of ramp rate constraints on LMP is considered, non-positive electricity prices may occur (in Fig. 8, electricity price is close to zero at the 9th time interval), hence production cost cannot be covered. It seems urgent to avoid this unfavorable situation for the gas-fired unit, which is likely to be a marginal unit.

2) Seasonal load and hill-climbing performance affect clearing volume of high-cost units, and revenue is obviously uncertain, which warrants special attention. As we can see from Table IV, when coal-fired units improve their climbing performance, gas-fired units gradually lose their market competitiveness and will gain less clearing volume. Reduction of peak-regulating demand of the system also brings less clearing volume of gas-fired units. These features often come into play for G_7 , whose cost is relatively high.

3) The DS model will bring about several undesired effects, such as loss of social welfare, distortion of market prices, and decreased profit of low-cost units. It can be found from Fig. 12 with an extra subsidy, total generation cost reaches 12,783 thousand CNY, which is higher than traditional dispatching cost level of 12,535 thousand CNY.

4) CFD is applicable to coal-fired units with relatively stable power output, and ERM to gas-fired units with unstable output. This can be seen from Table V under ERM settlement, where the coefficients of variation of two high-cost units' profit are 2.43% and 1.94%.

5) ERM has many advantages. It is incentive-compatible to stabilize profit of gas-fired units and motivate marginal bidding behavior. This is due to its incentive mechanism, as described above, which also has been demonstrated in a few studies [16].

The first goal of market-oriented reform is to increase total welfare of society, and then we can achieve Pareto improvement through better welfare measures. Revenue of high-cost units based on ERM is more stable. However, it is important to note this method relies on estimated long-term costs, which is not realistic for a large number of coal-fired units. Considering delivered power of coal-fired units is more stable than of gas-fired units, we apply the scheme of combining contracts for differences with ERM. Hence, we make the following suggestions.

1) Considering its effect on efficiency of the power market, DS is an unjustifiable manner to deal with the revenue problem of high-cost generator units, and it should be replaced.

2) Reconstructing Guangdong market can attempt to adopt authorized CFD and ERM, respectively, for coal- and gas-fired units' market settlements. This provides a good balance in the power market between fairness and efficiency.

Although this study is specific to the market environment of Guangdong, similar conditions occur in many provinces in China, with a wide range of practical applications. The government can gradually reduce its influence by changing some parameters. This study has adopted some assumptions regarding market data to obtain more reliable conclusions. The case of real system data and decision algorithms is worth considering.

APPENDIX

A. A brief description of income in several settlement modes

Feed-in tariffs are fixed prices paid to generator units for energy production. They are usually approved by governments under the principle of open, just, and fair power dispatching. The feed-in tariff (p^{FiT}) for most coal-fired units is the benchmark price of such units. Q^{FiT} denotes delivered volume. Settlement revenue (R^{FiT}) using the feed-in tariff is

$$R^{\text{FiT}} = p^{\text{FiT}} Q^{\text{FiT}} \quad (\text{A1})$$

In the location marginal price (LMP) mode, settlement revenue ($R_{i,t}$) depends on spot market clearing price ($p_{i,t}$) and clearing volume ($Q_{i,t}$). It is easy to see

$$R_{i,t} = p_{i,t} Q_{i,t} \quad (\text{A2})$$

The direct subsidy mechanism gives a fixed subsidy for each unit of electric energy produced by gas-fired units, and no allowance is given when the unit does not generate electricity. Revenue of unit i at time t is calculated as

$$R_{i,t} = (p_{i,t} + p_i^S) Q_{i,t} \quad (\text{A3})$$

where p_i^S is subsidy price of each unit of delivered power.

B. Non-monotonic Cost Characteristics and Bidding Strategy for Thermal Units

The following analysis applies to a single time interval for a thermal generator unit. The offer provided by a thermal generator unit should be higher than the larger of AVC and MC. As seen in Fig. A1, when declared supply volume is P , declared price based on AVC is C . Unit clearance volume is at P_3 . At this point, unit clearance is lower than declaration amount (partially winning the bid), but cost is higher than clearing price, and unit income is lower than unit cost (the

area of R_2). Geometrically, the area of R_1 is economic loss. To keep production loss-free, prices should be no lower than C_{1st} . For the non-monotonic characteristics of unit cost while the market requires an incremental offer curve, no-load cost quotation can effectively solve this problem in a mature power market. When the no-load cost is paid to the unit, the offer curve can start from a relatively low position.

According to total variable cost function $C_{i,t}^T$, average cost $C_{i,t}$ and marginal cost $C_{i,t}^M$ can be obtained as

$$C_{i,t} = \frac{C_{i,t}^T}{Q_{i,t}} = a_{i,3} Q_{i,t}^2 + a_{i,2} Q_{i,t} + a_{i,1} \quad (\text{A4})$$

$$C_{i,t}^M = 3a_{i,3} Q_{i,t}^2 + 2a_{i,2} Q_{i,t} + a_{i,1} \quad (\text{A5})$$

The price of the first segment offer (C_{1st}) should be the higher of $C_{i,t}$ and $C_{i,t}^M$, which usually can be formulated as

$$C_{1st} = a_{i,3} q_i^{\min^2} + a_{i,2} q_i^{\min} + a_{i,1} \quad (\text{A6})$$

Let

$$a_{i,3} P_i^{\min^2} + a_{i,2} P_i^{\min} + a_{i,1} = 3a_{i,3} P_1^2 + 2a_{i,2} P_1^2 + a_{i,1} \quad (\text{A7})$$

from which we can get an expression of P_1 .

$$Q_{1st} = P_1 - P_{\min} = \frac{-a_{i,2} + \sqrt{a_{i,2}^2 + 3a_{i,3}(a_{i,3} P_{\min}^2 + a_{i,2} P_{\min})}}{3a_{i,3}} - P_{\min} \quad (\text{A8})$$

The last two segments divide the remaining generation capacity equally. Price and volume of the second segment offer (C_{2nd} and Q_{2nd}) are given as follows:

$$P_2 = (P_{\max} - P_1)/2 + P_1 \quad (\text{A9})$$

$$C_{2nd} = 3a_{i,3} P_2^2 + 2a_{i,2} P_2 + a_{i,1} \quad (\text{A10})$$

$$Q_{2nd} = P_2 - P_1 = \frac{1}{2}(P_{\max} - P_1) \\ = \frac{1}{2} P_{\max} - \frac{-a_{i,2} + \sqrt{a_{i,2}^2 + 3a_{i,3}(a_{i,3} P_{\min}^2 + a_{i,2} P_{\min})}}{6a_{i,3}} \quad (\text{A11})$$

Similarly, price and volume of the third segment offer (C_{3rd} and Q_{3rd}) are given as:

$$C_{3rd} = 3a_{i,3} P_i^{\max^2} + 2a_{i,2} P_i^{\max} + a_{i,1} \quad (\text{A12})$$

$$Q_{3rd} = P_{\max} - P_2 = P_2 - P_1 \quad (\text{A13})$$

REFERENCES

- [1] H. Y. Guo, M. R. Davidson, Q. X. Chen, D. Zhang, N. Jiang, Q. Xia, C. Q. Kang, and X. L. Zhang, "Power market reform in China: Motivations, progress, and recommendations," *Energy Policy*, vol. 145, pp. 111717, Oct. 2020.
- [2] 2B1st Consulting. (2012, May). Take-or-pay contract. Available: <https://2b1stconsulting.com/take-or-pay-contract/>
- [3] H. Fan, Z. F. Duan, and W. G. Shan, "Development status and prospect of natural gas power generation in China," *Energy of China*, vol. 37, no. 2, pp. 37–42, Feb. 2015.
- [4] P. Breeze, "The cost of electricity generation from natural gas-fired power plants," in *Gas-Turbine Power Generation*, P. Breeze, Ed. Academic Press, 2016.

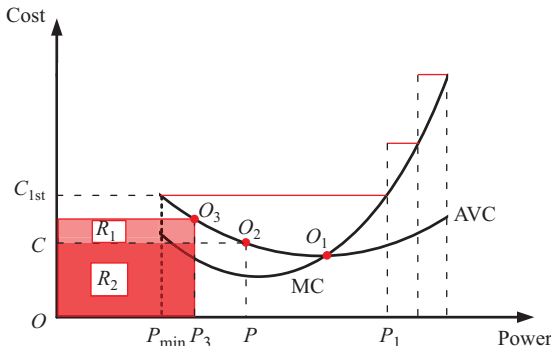


Fig. A1. Bidding strategy based on non-monotonic cost characteristics.

- [5] H. Y. Ma, Z. Yan, M. J. Li, D. Han, X. Han, Y. Q. Song, P. Wei, G. Li, and Y. J. Liu, "Benefit evaluation of the deep peak-regulation market in the northeast China grid," *CSEE Journal of Power and Energy Systems*, vol. 5, no. 4, pp. 533–544, Dec. 2019.
- [6] J. Y. Zhao, T. X. Zheng, and E. Litvinov, "A multi-period market design for markets with intertemporal constraints," *IEEE Transactions on Power Systems*, vol. 35, no. 4, pp. 3015–3025, Jul. 2020.
- [7] Y. Guo, C. Chen, and L. Tong, "Pricing multi-interval dispatch under uncertainty part I: Dispatch-following incentives," *IEEE Transactions on Power Systems*, vol. 36, no. 5, pp. 3865–3877, Sep. 2019.
- [8] G. P. Chen, Z. F. Liang, and Y. Dong, "Analysis and reflection on the marketization construction of electric power with Chinese characteristics based on energy transformation," *Proceedings of the CSEE*, vol. 40, no. 2, pp. 369–378, Jan. 2020.
- [9] J. Badcock and M. Lenzen, "Subsidies for electricity-generating technologies: A review," *Energy Policy*, vol. 38, no. 9, pp. 5038–5047, Sep. 2010.
- [10] L. Kitson, P. Wooders, and T. Moerenhout, "Subsidies and external costs in electric power generation: A comparative review of estimates," The International Institute for Sustainable Development, Manitoba, CAN., Tech. Rep., Sep. 2011.
- [11] Public notice about feed-in tariff adjustment of gas generator unit. [Online]. Available: http://www.zj.gov.cn/art/2018/5/7/art_13929_29754_2.html
- [12] Notice about gas power feed-in tariff management. [Online]. Available: <http://www.jsea.org.cn/end.asp?Id=1858>
- [13] Notice about the optimization of the gas power feed-in tariff adjustment mechanism. [Online]. Available: http://fgw.sh.gov.cn/xxgk/cxxxgk/3639_1.htm
- [14] Independent Electricity System Operator (IESO). Contracted electricity supply. [Online]. Available: <http://www.ieso.ca/Document-Library>
- [15] Ontario Power Authority. CHP standard offer program contract. [Online]. Available: <http://www.ieso.ca/Sector-Participants/Energy-Procurement-Programs-and-Contracts/Combined-Heat-and-Power>
- [16] Z. Luo, Z. Jing, and A. He, "Subsidy for high cost unit based on revenue estimation method," in *Proceedings of 2019 Annual Meeting of the Electricity Market Committee of the CSEE*, Chengdu, China, Sep. 2019.
- [17] T. Wang and B. Q. Lin, "China's natural gas consumption and subsidies—from a sector perspective," *Energy Policy*, vol. 65, pp. 541–551, Feb. 2014.
- [18] B. W. Xiao, D. X. Niu, and X. D. Guo, "Can natural gas-fired power generation break through the dilemma in China? a system dynamics analysis," *Journal of Cleaner Production*, vol. 137, pp. 1191–1204, Nov. 2016.
- [19] B. Q. Lin and Y. M. Kuang, "Natural gas subsidies in the industrial sector in China: National and regional perspectives," *Applied Energy*, vol. 260, pp. 114329, Feb. 2020.
- [20] J. Cavicchi, "Rethinking government subsidies for renewable electricity generation resources," *The Electricity Journal*, vol. 30, no. 6, pp. 1–7, Jul. 2017.
- [21] Z. J. Jiang and B. Q. Lin, "The perverse fossil fuel subsidies in China—the scale and effects," *Energy*, vol. 70, pp. 411–419, Jun. 2014.
- [22] J. X. Wang, H. W. Zhong, Q. Xia, Y. Wang, X. W. Lai, and X. Z. Guo, "Competitive mechanism design in electricity market based on fair benefit allocation," *Automation of Electric Power Systems*, vol. 43, no. 2, pp. 7–17, May 2019.
- [23] L. Qi and W. Huang, "The impact of contract for difference on the market power in the restructured Zhejiang electricity market," in *IEEE PES Power Systems Conference and Exposition, 2004*, New York, NY, USA, Oct. 2004.
- [24] L. Z. Zhang, J. Wang, C. B. Chen, S. H. Yang, and Y. Y. Wang. (2020). Study on the settlement mechanism of CFDS authorized by government under the environment of spot electricity market, *Power System Technology*. vol. 45, no. 4, pp. 1337–1346, 2021.
- [25] National Energy Administration. (2011). Energy-saving power generation dispatching pilot plan and the detailed rules for the implementation. [Online]. Available: http://www.nea.gov.cn/2011-11/22/c_131262571.htm3
- [26] L. Chen, C. Wang, W. Wei, F. Liu, S. W. Mei, Y. Wang, and Y. G. Chen, "Scheduling model and application of Guangdong power grid," *Electric Power*, vol. 46, pp. 38–43, Jun. 2013.
- [27] The General Office of State Council. Open, just and fair power dispatching. [Online]. Available: <http://www.gov.cn/ztl/2006-07/01/contentC324604.htm>
- [28] Y. Lin, "Research on the change of Guangdong power grid scheduling model," M.S. thesis, School of electric power engineering, South China University of Technology, 2008.
- [29] "Guangdong power market semi-annual report of 2019," Guangdong power exchange center, Guangzhou, Tech. Rep., CHN., Aug. 2019.
- [30] J. Lin, F. Kahrl, J. H. Yuan, Q. X. Chen, and X. Liu, "Economic and carbon emission impacts of electricity market transition in China: A case study of Guangdong province," *Applied Energy*, vol. 238, pp. 1093–1107, Mar. 2019.
- [31] Guangdong Economic and Information Technology Commission. (2018). South China (starting with Guangdong) spot power market implementation plan. Available: http://www.gdei.gov.cn/gzhd/wsdw/myzj/201811/t20181102_130784.htm
- [32] X. D. Zheng, H. Y. Chen, Y. Xu, Z. M. Li, Z. J. Lin, and Z. P. Liang, "A mixed-integer SDP solution to distributionally robust unit commitment with second order moment constraints," *CSEE Journal of Power and Energy Systems*, vol. 6, no. 2, pp. 374–383, Jun. 2020.
- [33] X. D. Zheng, H. Y. Chen, Y. Xu, Z. P. Liang, and Y. P. Chen, "A hierarchical method for robust SCUC of multi-area power systems with novel uncertainty sets," *IEEE Transactions on Power Systems*, vol. 35, no. 2, pp. 1364–1375, Mar. 2020.
- [34] Guangdong Power Exchange Center. (2019). South China (starting with Guangdong) spot power market operation. <https://pm.gd.csg.cn>
- [35] E. D. Kee, "Vesting contracts: A tool for electricity market transition," *The Electricity Journal*, vol. 14, no. 6, pp. 11–22, Jul. 2001.
- [36] N. Shang, X. Zhang, T. Tu, and Y. Ding, "Decomposition strategies of long-term contracts for differences and the applications in Guangdong and Zhejiang markets under the background of new-round power system reform," in *Proceedings of 2019 Annual Meeting of the Electricity Market Committee of the CSEE*, Chengdu, China, Sep. 2019.
- [37] J. J. Huan and Z. M. Zuo, "Research on typical day selection method of Guangdong power grid load characteristics," *Journal of Electric Power Science and Technology*, vol. 32, no. 1, pp. 164–170, Mar. 2017.
- [38] J. Lin, F. Kahrl, J. H. Yuan, X. Liu, and W. R. Zhang, "Challenges and strategies for electricity market transition in China," *Energy Policy*, vol. 133, pp. 110899, Oct. 2019.
- [39] (2019). Gurobi optimization documentation. <https://www.gurobi.com/>
- [40] E. Ela and M. O'Malley, "Scheduling and pricing for expected ramp capability in real-time power markets," *IEEE Transactions on Power Systems*, vol. 31, no. 3, pp. 1681–1691, May 2016.



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