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Optimal Strategy Analysis of a Large-Scale Consumer considering Day-ahead and Real-time Power Market Coupling

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ABSTRACT

This paper aims to establish the strategy of the large-scale consumer for maximizing the total benefits under the circumstance of the day-ahead (DA) and real-time (RT) coupling market. Among the various possible bidding behaviors in demand side, three typical bidding modes are concluded and four typical trade scenes are further formulated. Moreover, a unified general function for trades has been constructed and the corresponding solutions have been discussed. Furthermore, an optimal bidding model is proposed for the large-scale consumer and the corresponding assessment indices have been utilized to quantify the effectiveness of the proposed method. A case study based on the data from a provincial power market is carried out, which demonstrates that the reasonable power portfolios between the DA and RT market can decrease the purchase costs of the large-scale consumer.

Keywords: Large-scale Consumers, Day-ahead and Real-time coupling market, Optimal Strategy.

1. INTRODUCTION

The deregulated electricity markets enable various kinds of participants including generation units, retailers, consumers, demand response resources or others to take part in the trades [1]. The competitive framework of electric industry is designed to promote quality of power supply, encourage the effective investment, and enhance the options of consumers [2]. In power market, the retailers can bid on behalf of small consumers, while other consumers especially the large-scale ones are willing to participant in the trades directly. Meanwhile, the development of smart grid technology, the Advanced Metering Infrastructure (AMI) and progressive Information/Communication Technologies (ICT) facilitate the strategic behaviors of load serving entities such as large consumers or retailers in the spot market [3].

Generally, the spot power market consists of part or all of the day-ahead (DA) market, intra-day (ID) market, and real-time (RT) market. Moreover, most of the current power markets (e.g. the PJM, etc.) have chosen the two-settlement modes, which can be also called as “energy deviation settlement (EDS)” mode, for the trades in spot markets. In such centralized power markets, the consumers or retailers can submit their prices and quantities to purchase the generation power in both DA and RT market. The clearance results of DA market are not physical, which will be carried out in the financial level [4]. Meanwhile, when the load cannot match the amount in DA market, the RT market will provide the chances for additional trades in both supply and demand sides. The prices of RT market are often not equal to the DA market due to the load prediction deviation or other reasons [5]. Under the ideal circumstances, the cleared prices of DA and RT market will tend to be the same.

There are many previous studies on the strategies of retailers or consumers. As for the optimal strategies, ref. [6] presented an optimal bidding method of a demand side agent operating in the DA and ID market subject to the imbalance penalty mechanism. Ref. [7] also proposed a stochastic linear programming model for constructing piecewise-linear bidding curves to be submitted by retailers. Besides, ref. [8] established a model to characterize the strategic behavior of large consumers to derive their bidding strategies to alter pool prices to their benefits. Many researchers have taken the risks into account in modeling the strategies. For instance, ref. [9] put forward a decision-making framework for retailers based on time-of-use rates, where the risks are measured using conditional value at risk (CVaR) methodology. Ref. [10] compared three different stochastic-based procurement strategy for retailers in controlling financial risks and maximizing profit. Moreover, many scholars considered more potential features or behaviors of retailers or consumers. For example, ref. [11] proposed an alliance income strategy for retailers to reduce the deviation through contract transfer. Ref. [12] investigated the customers' switching behaviors and retailers' contract trading and designed a Bertrand-based game model for the retail market. Ref. [13-14] tried to determine the day-ahead market purchase bidding strategy for retailers with flexible power demand. Ref. [15] presented a stochastic multi-layer agent-based model, which includes both the power producers and responsive customers such as a plug-in electric vehicle (PEV) or demand response (DR). However, to the best of our knowledge, as for the optimal strategies of consumers, few types of research in the literature calculated the analytical solutions and the corresponding effectiveness considering the DA and RT market coupling circumstances.

This paper aims to quantify the optimal strategy of a large-scale consumer in the DA and RT coupling power market situation. The behaviors of large-scale consumers are divided into three categories in this paper, which could further constitute four typical scenes. Given the algorithm function of bidding curves (e.g. linear, quadratic, or more general ones, etc.) in both supply and demand, the corresponding optimal solutions can be calculated to minimize the purchase costs. Moreover, a simulation case is provided to illustrate the effectiveness of the proposed method.

The rest of this paper is organized as follows. Section 2 analyses and summarizes the typical behaviors and trade scenarios. In Section 3 an optimal strategy model of large-scale consumers is formulated. The case studies are made in Section 4. Finally, Section 5 provides the conclusion.

2. TYPICAL BEHAVIORS, TRADE SCENARIOS, AND UNIFIED GENERAL FUNCTION

2.1 Typical Behaviors of Large-scale Consumers

From the perspective of price and power, the behaviors of profit-driven large-scale consumers can be divided into the following three categories.

Fig 1 can represent the normal bidding behaviors, withholding bidding behaviors, and upraising bidding

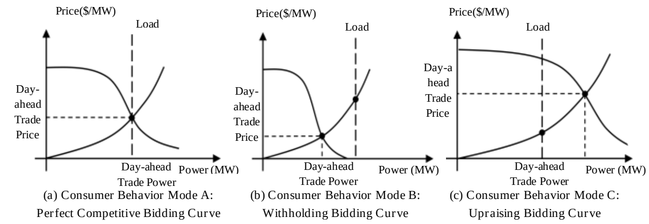


Fig 1 Three typical behaviors of large-scale consumers

behaviors. Specifically, Fig 1(a) shows that large-scale consumers may bid based on their objective needs. In this case, the clearing price in DA market may be nearly the same as that in RT market when the operation of the market is mature and the competition is sufficient. As for the Fig 1(b), the large-scale consumers may submit the withholding bidding curves, that is, the declared price or power may be relatively low. Correspondingly, in Fig 1(c) the large-scale consumers can choose to upraise the bidding curve, in which the price or power will be comparatively higher. In summary, Fig 1(a) to Fig 1(c) respectively show the objective, withholding, and upraising bidding behaviors in spot market trade.

2.2 Typical Trade Scenarios

According to DA and RT market trade mechanism and the deviation settlement mode, the total cost of large-scale consumers may consist of the purchase fees in both DA and RT market, which can be defined as power clearing fee (PCF). Based on the three bidding behaviors mentioned in subsection II-A, four typical trade scenarios can be further constituted, as shown in Fig 2.

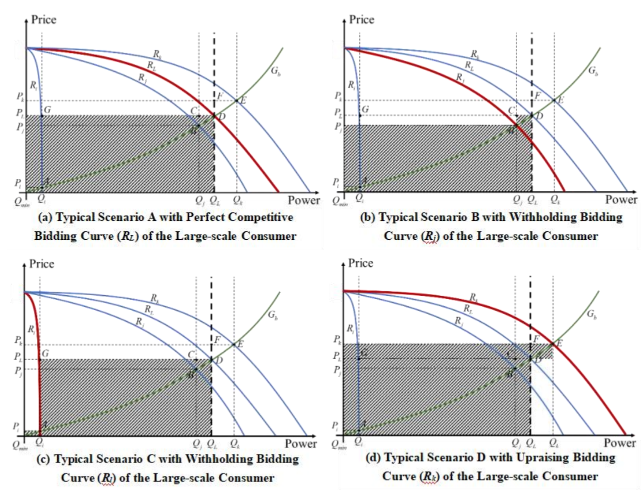


Fig 2 Four typical scenarios in DA and RT market according to the corresponding behaviors of large-scale consumers

The various trade scenarios based on the different bidding behaviors of consumers are shown in Fig 2, where R_i and G_b represent the curve from the demand and supply side, respectively. The value of PCF can be indicated as the shaded area. As for the buyers in the wholesale market, the less purchase cost, also the smaller value of PCF of the consumers is equal to the higher revenue.

The three bidding behaviors and four typical trade scenarios have been summarized in Table. I. The obvious conclusion is that the withholding bidding strategies are more likely to be carried out by retail oligarchs rather than upraising bidding declaration. In the process of the intersection of two trading curves changing from point A, B to the point D, the total PCF will first decrease and then increase (PCF_L→PCF_i (PCF_j)→PCF_L), where the minimum PCF value will appear in such process.

TABLE I. SUMMARY OF THE THREE BEHAVIOR MODES AND FOUR TYPICAL TRADE SCENARIOS

Behavior Mode	Mode A: Perfect Competitive Bidding Curve	Mode B: Withholding Bidding Curve		Mode C: Upraising Bidding Curve
Trade Scenarios	Scenario A (R_L)	Scenario B (R_j)	Scenario C (R_i)	Scenario D (R_k)
Intersection	Point D	Point B	Point A	Point E
PCF	$PCF_L=S(Q_{min}Q_L DP_L)$	$PCF_j \le PCF_L$	$PCF_i \le PCF_L$	$PCF_k \ge PCF_L$

2.3 Unified General Function for Trades

Prior content in subsection II-A and II-B provides a preliminary conclusion of the strategic behaviors of large-scale consumers. Here, we initiate a discussion on the optimal strategy that represents a step toward a unifying function.

Theorem: Define the bidding curve in the supply side as $y = F(x) = f(x) + g$

Remark: Defined x and $F(x)$ as the power and the corresponding marginal bidding price, respectively. And the forecasting load is x_0.

a) The value of the optimal bidding power of consumers must be less than x_0;

b) The optimal result with respect to bidding power x can be calculated by:

$$x = \frac{y_0 - y}{y'} = \frac{F(x_0) - F(x)}{F'(x)} = \frac{f(x_0) - f(x)}{f'(x)}\bigg|_{f'(x)\neq 0} \tag{1}$$

Proof: Define the PCF and bidding power as W_1 and x_1, respectively. It is straightforward to show that the expected purchase cost is given by:

$$W_1 = y_1 x_1 + y_0(x_0 - x_1) = f(x_1)x_1 + (g - y_0)x_1 + y_0 x_0 \tag{2}$$

$$\frac{\partial W_1}{\partial x_1} = f(x_1) + x_1 f'(x_1) + (g - y_0) = f(x_1) + x_1 f'(x_1) - f(x_0) \tag{3}$$

$$\frac{\partial W_1}{\partial x_1} = 0 \Rightarrow f(x_1) + x_1 f'(x_1) - f(x_0) = 0 \tag{4}$$

$$f(x) + xf'(x) - f(x_0) = 0$$
$$\Rightarrow \begin{cases} x = 0, \because x_0 > 0,\ f(0) < f(x_0) \\ x = x_0,\ f(x_0) + x_0 f'(x_0) > f(x_0) \end{cases} \tag{5}$$

therefore, $\exists\, x \in [0, x_0]$, W_1 can reach its minimum value. Besides, $\because W_1|_{x_1=0} = W_1|_{x_1=x_0} = W_0$, the value of PCF will present an earlier increase and later decrease trend. And the valley point appears among it.

The proof for part b) follows a similar process of the proof for Theorem II. a):

$$f(x) + xf'(x) = f(x_0)(x_0 > 0) \Rightarrow x = \frac{f(x_0) - f(x)}{f'(x)}\bigg|_{f'(x)\neq 0} \tag{6}$$

The optimal solution results of several typical functions are shown in the following Table. II.

TABLE II. RESULTS FOR VARIOUS FUNCTIONS IN SUPPLY

***f*(*x*)**	***x***	***f*(*x*)**	***x***
b	/ (*PCF not change*)	$ax+b$	$x_0 / 2$
ax^2+b	$x_0 / \sqrt{3}$	ax^n+b	$x_0 / \sqrt[n]{n+1}$

3. OPTIMAL STRATEGY OF LARGE-SCALE CONSUMERS

For a trading, an optimal strategy decision model is constructed for a large-scale consumer to determine its bidding curve. The risk-based Pareto frontier and the corresponding constraints are combined in this model.

3.1 Risk-earning Frontier Based Bidding Behaviors

Considering the characteristics of consumers' profit-driven intrinsically attributes, the total benefits of consumers are affected by their risk preferences. Therefore, the large-scale consumers will try to achieve the best bidding strategy by balancing the earning and risk in the process in power market trade, which can be reflected in the risk-earning Pareto frontier $\Psi(\mathrm{E}, \sigma^2)$. The bidding power can be treated as a random variable in the front curve. Meanwhile, the earning is measured by its mean and the risk is measured by its variance. As shown in Fig 3, there are different effective frontiers for the consumer, where the upper bounds of the available $E_{p,t}$ and $\sigma_{p,t}$ combinations are referred to as the effective boundary or the efficient frontier. The combinations of the values of $E_{p,t}$ and $\sigma_{p,t}$ on the effective frontier constitute an efficient set of solutions.

The frontier with estimated expectation $E_{p,t}$ and deviation $\sigma_{p,t}$ can be utilized to model the bidding scenario of large-scale consumers. The set of bidding scenario is assumed as $\mathcal{I}$, and the studied consumer $\mathcal{K}$ can be also assumed as a set of consumers. Therefore, the price and power submitted in DA market can be described as $\{[\eta_{i,k}^{D}, \rho_{i,k}^{D}]: \forall i \in \mathcal{I}, k \in \mathcal{K}\}$. At the scenario *i*, the risk-based curve of the large-scale consumers and other retailers or consumers make up the bidding curves in demand side together.

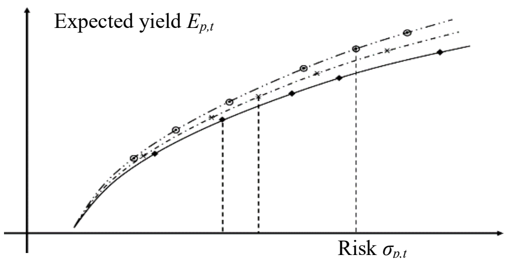


Fig 3 The effective frontier of the $E_{p,t}$ and $\sigma_{p,t}$ combination

3.2 Objective Function

The purpose of the studied large-scale consumer based on the coupling DA and RT market is to maximize the benefit, which can be equal to minimizing total PCF.

$$\text{Minimum } \vartheta_{i,\mathcal{K}} = PCF_{i,\mathcal{K}}^{D} + PCF_{i,\mathcal{K}}^{R} \tag{7}$$

$$PCF_{i,\mathcal{K}}^{D} = \sum\nolimits_{k\in\mathcal{K}} \rho_i^{D} \cdot \eta\ (\eta_{i,k}^{D}) \quad \forall i \in \mathcal{I}, k \in \mathcal{K} \tag{8}$$

$$PCF_{i,\mathcal{K}}^{R} = \sum\nolimits_{k\in\mathcal{K}} \rho_i^{R} \cdot \eta\ (\eta_{i,k}^{R}) \quad \forall i \in \mathcal{I}, k \in \mathcal{K} \tag{9}$$

where $PCF_{i,\mathcal{K}}^{D}$ and $PCF_{i,\mathcal{K}}^{R}$ stand for the purchase fees in DA and RT market, respectively. $\eta\ (\eta_{i,k}^{D})$ and $\eta\ (\eta_{i,k}^{R})$ represent the winning power of the k^{th} consumer belong to the studied consumer $\mathcal{K}$. ρ_i^{D} and ρ_i^{R} are the corresponding market clearing price for the DA and RT market.

3.3 Power Trade Constraints

There exist various constraints in the process of such power trade. Firstly, the supply and demand balance constraints are shown as follows:

$$\forall i \in \mathcal{I}, k \in \mathcal{K}, z \in \mathcal{Z}$$

$$H_L = \sum\nolimits_{z\in\mathcal{Z}} \eta\ (\eta_{i,z}^{D}) + \sum\nolimits_{k\in\mathcal{K}} \eta\ (\eta_{i,k}^{D}) + \sum\nolimits_{j\in\mathcal{K},\mathcal{Z}} \eta\ (\eta_{i,j}^{R}) \tag{10}$$

where H_L is the load, which is equal to the sum of winning power of the studied consumer $\mathcal{K}$ in DA market $\sum\nolimits_{k\in\mathcal{K}} \eta\ (\eta_{i,k}^{D})$, the remaining retailer (or consumer) set $\mathcal{Z}$ in DA market $\sum\nolimits_{z\in\mathcal{Z}} \eta\ (\eta_{i,z}^{D})$, and the trade power in RT market $\sum\nolimits_{j\in\mathcal{K},\mathcal{Z}} \eta\ (\eta_{i,j}^{R})$.

Besides, the bidding parameters constraints, including the power and price, should be also considered:

$$\eta_{\min}^{D} \le \eta_{i,k}^{D} \le \eta_{\max}^{D}, \forall i \in \mathcal{I}, k \in \mathcal{K} \tag{11}$$

$$\eta_{\min}^{D} \le \eta_{i,z}^{D} \le \eta_{\max}^{D}, \forall i \in \mathcal{I}, z \in \mathcal{Z} \tag{12}$$

$$\rho_{\min}^{D} \le \rho_{i,k}^{D} \le \rho_{\max}^{D}, \forall i \in \mathcal{I}, k \in \mathcal{K} \tag{13}$$

$$\rho_{\min}^{D} \le \rho_{i,z}^{D} \le \rho_{\max}^{D}, \forall i \in \mathcal{I}, z \in \mathcal{Z} \tag{14}$$

where $\eta_{\min}^{D}$ and $\eta_{\max}^{D}$ represent the floor and ceiling value of the declared power. Correspondingly, $\rho_{\min}^{D}$ and $\rho_{\max}^{D}$ are the lower and upper limits of price submitted by the studied consumer or other buyers.

Furthermore, the curves in the supply and demand side, $P_{i,G}^{D}(\eta)$ and $P_{i,R}^{D}(\eta)$, are formulated according to the bidding behaviors of market participants. The clearing results can be represented as follows:

$$\forall i \in \mathcal{I},\ j \in \{\mathcal{K} \cup \mathcal{Z}\}$$

$$\eta\ (\eta_{i,j}^{D}) = \begin{cases} \eta_{i,j}^{D,n} & (\eta_{i,j}^{D,n+1} \le H_L^{D}) \\ H_L^{D} - \eta_{i,j}^{D,n} & (\eta_{i,j}^{D,n} \le H_L^{D} \le \eta_{i,j}^{D,n+1}) \\ 0 & (H_L^{D} \le \eta_{i,j}^{D,n}) \end{cases} \tag{15}$$

$$\rho_i^{D} = P_{i,R}^{D}(\eta)|_{\eta=H_L^{D}} = P_{i,G}^{D}(\eta)|_{\eta=H_L^{D}} \tag{16}$$

$$\rho_i^{R} = P_{i,G}^{D}(\eta)|_{\eta=H_L} \tag{17}$$

$$\eta\ (\eta_{i,j}^{R}) = (H_L - H_L^{D}) \times \gamma_{i,j} \tag{18}$$

where H_L^{D} is the trading power in the DA market, $\eta\ (\eta_{i,j}^{D})$ stands for the winning power of the j^{th} market participant in demand side at the scenario *i*. And the clearing DA and RT prices, ρ_i^{D} and ρ_i^{R}, can be obtained from the curves $P_{i,G}^{D}(\eta)$ an $P_{i,R}^{D}(\eta)$. Besides, $\gamma_{i,j}$ represents the proportion of the power in RT market for different retailers or consumers, which is determined by the corresponding market share.

3.4 Corresponding Indicators

Based on the above content, the effectiveness assessment indices can be designed according to the deviations among different market trade consequences. Specifically, the DA Price Deviation Rate ρ_r and DA Power Trade Deviation Rate Q_r are utilized to quantify the influence of the strategy, which are as follows:

$$\rho_r = \frac{\rho_1(S_1) - \rho_1(S_0)}{P_1(S_0)} \tag{19}$$

$$Q_r = \frac{Q_c(S_1) - Q_c(S_0)}{Q_c(S_0)} \tag{20}$$

where S_0 and S_1 stand for the perfect competition circumstance and strategy utilization circumstance, respectively. $\rho_1(S_0)$ and $Q_c(S_0)$ represent the DA market price and power at the market scenario S_0. Correspondingly, $\rho_1(S_1)$ and $Q_c(S_1)$ are the DA market price and power at the market scenario S_1.

Furthermore, another visible manifestation of the proposed strategy for a large-scale consumer is the additional benefits obtained. Besides, such strategies can also reduce the average cost of power purchase. Therefore, the indices Power Market Revenue Deviation PCF_r and Average Purchase Power Cost Deviation W_r are proposed, which are as follows:

$$PCF_r = PCF(S_0) - PCF(S_1) \tag{21}$$

$$W_r = W(S_0) - W(S_1) \tag{22}$$

where $PCF(S_0)$ and $PCF(S_1)$ are the total purchase cost value of the large-scale consumer at market scenario S_0 and S_1, respectively. Besides, $W(S_0)$ and $W(S_1)$ are the average purchase power cost of electricity consumers at market scenario S_0 and S_1. The deviation of the average purchase power cost W_r can reveal the purchase fee decrease of end-users.

4. CASE STUDIES

4.1 Data Description

A simulation is performed using the proposed strategies for a large-scale consumer under the circumstance of the DA and RT market coupling. The bidding curve in supply side is assumed to be in accordance with the generation operation cost in general. Actually, the cost supervision may be carried out on power units, which is also widely utilized in various world-wide power markets [16].

The scale of market trade is formulated and assumed based on a provincial power market. The generation power in supply side can reach 5.8*10^5 MW. The bidding power of market participants ranges between 9,000MW and 15,000MW, and the power price submitted is restricted between $100/MW and $400/MW. Besides, the real load level is assumed at approximately 4.6*10^5 MW. Based on the above assumptions, the environment of DA and RT coupling market for the studied large-scale consumer is constructed.

4.2 Numerical Results with Single Large-scale Consumer

The value of the proposed method is to provide a practical approach for a large-scale consumer to bid strategically on the basis of their risks for maximizing their benefits at the same time. In order to represent the most effectiveness of the proposed method, the numerical results with all market share in demand side concentrated in one single large-scale consumer have been carried out in this subsection.

The general process for the calculation can be described as follows. Firstly, the market participants make the determinations on the bidding parameters according to the risk preferences. Secondly, the corresponding price and power submitted by retailers or consumers are sorted, which will be formed as the power purchase curve as part of the input information in model. Then, through utilizing the bidding curve in supply side as the unchanged parameters in the process of DA and RT trades, an optimal clearing result can be calculated and the intersection point of the two curves will be obtained. Meanwhile, the corresponding assessment indices will be quantified.

At the above circumstance, the results of trades are calculated with the given assumptions, which are represented in Fig 4.

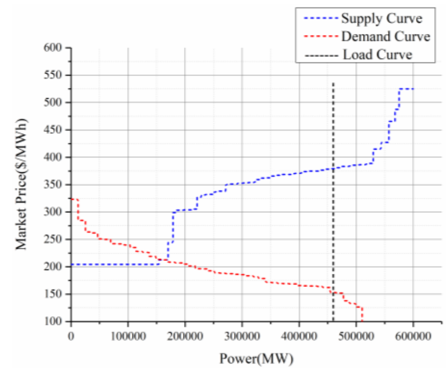


Fig 4 Simulation trade results of all demand market share concentrated in single large-scale consumer

As shown in Fig 4, it can be a workable strategy for a large-scale consumer to guarantee the benefits by adjusting the bidding power. Under the ideal circumstance, according to the advice of the proposed strategy, the large-scale consumer can control the curve in demand, select the optimal DA and RT power combination scheme, and make the intersection lower than 50% of the real load level in DA market.

In order to quantify the consequence of the proposed strategy, the indices mentioned above, such as the deviation of price or power, are calculated at the same time. The results of the corresponding indices are shown in Table. III. It can be seen that the deviation value of the average purchase power cost is $61.29/MW. The deviation ratio of the price and power in DA market is 43.83% and 63.03%, respectively. The total purchase cost of the power market can be decreased $2.82*10^8 by utilizing the proposed method.

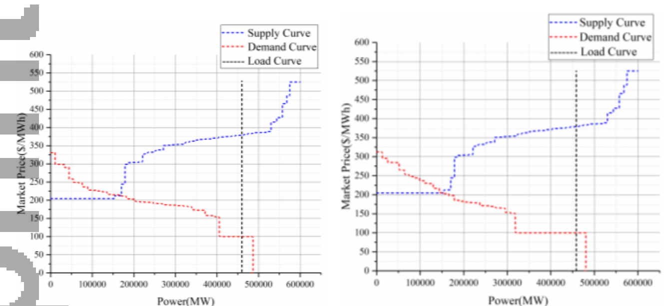
TABLE III. ASSESSMENT INDICES WITH THE SIMULATION RESULTS

Assessment Indices	$PCF(S_0)$($)	$PCF(S_1)$($)	ρ_r (%)
	1.74*10^8	1.46*10^8	43.83
Assessment Indices	Q_r (%)	PCF_r ($)	W_r ($ / MW)
	63.03	2.82*10^8	61.29

4.3 Numerical Results with the Studied Large-scale Consumer at Various Market Shares

At various market concentrations in demand side, the bidding potential for the large-scale consumer is changing, which may result in the effects of the strategy. The case studies in this subsection simulate the various results under the circumstances of different market shares of the studies large-scale consumer. And it demonstrates that the utilization of the proposed strategy is also effective to improve the total benefits to some extent.

Based on the above circumstance that the market share in demand side is concentrated in single large-scale consumer, the additional trade simulations are carried out for the market share of 80% and 60%, respectively. Considering the changing of market share, the trade results of the power market are shown in Fig 5 (a)-(b), respectively.



(a) 80% market share (b) 60% market share

Fig 5 Simulation trade results of the studied large-scale consumer with different market shares

Similarly, the corresponding assessment indices including the total power clearing fee (PCF) and the deviation value considering the scenario S_0 and S_1 are also calculated. The indices are shown in Table. IV.

TABLE IV. CORRESPONDING ASSESSMENT INDICES UNDER DIFFERENT MARKET CONCENTRATION IN DEMAND SIDE

Market Share	ρ_r (%)	Q_r (%)	PCF_r ($)	W_r ($ / MW)
80%	43.83	63.03	$15.33*10^6$	41.35
60%	45.96	66.49	$34.79*10^5$	12.61

The above analysis indicates that the load forecasting deviation between DA and RT market can provide the chance for large-scale consumer to execute the proposed strategy. The large-scale consumer can adjust the bidding power portfolios to increase the benefits.

5. CONCLUSIONS

This paper proposes an optimal strategy for a large-scale consumer in the situation of DA and RT coupling power market, which provides practical references for the power portfolio determination for the market participants in the demand side. Both the unified general function and the optimal model are established to describe the proposed method. The indices such as the purchase power cost deviation, price and power deviation ratio are proposed to quantify the effectiveness of the proposed method. The simulation numerical results illustrate that the optimal curve intersection point reaches within 50% of the real load level, which can increase around 40% of the benefits of the large-scale consumer at most.

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