Research Article

Evaluation Model of Generation Dispatching Optimization considering Participation of Electricity Retailers

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Received 30 August 2018; Revised 5 January 2019; Accepted 7 February 2019; Published 26 February 2019

Academic Editor: Gaetano Zizzo

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The sales aspect of electricity reform is one of the focuses of current reform in China. Independent retailers are involved in the purchase of electricity, which is a sign of a mature electricity market. With the increasing degree of market opening, it is expected to become an important link between the generation side and demand side, and its degree of participation will directly affect the benefits of the demand response. From the analysis of the operation pattern of future electricity retailers that are involved in optimal generation dispatching, the load-calculation model of the customer response and the dispatching model of electricity retailers involved in generation are established. Then, based on the principle of dynamics, a comprehensive assessment model is established. The results show that customers' response to electricity retailers involved in the generation dispatch can improve the load rate by about 4%. The overall efficiency of various stakeholders is positive, and the investment cost of the government environmental management is gradually decreased.

1. Introduction

Since the release of the “No. 9 Document” in 2015 in China, some supporting documents have also been introduced, which indicates that electricity reform in China has reached an important stage [1]. For the electricity reform on the demand side, the main content is to open the electricity sale market and to set up independent electricity retailers to facilitate the direct trade between the demand side and generation side. Therefore, electricity retailers have become an important link between producers and customers, which provides a good market environment for electricity retailers involved in optimal generation dispatching [2, 3].

The influence of the opening degree of the demand side on the electricity retailers is clear. As the opening degree increases, the market share is greater in that electricity retailers could participate, and there is an influence on the generation dispatching. According to the most recent reports, it is expected that there will be full liberalization of industrial land by the end of 2018, and by the end of 2020, there will be full liberalization of commercial land. This clearly speeds up the pace at which the demand increases, increasing

chips for the influence of electricity retailers participating in generation dispatching [4, 5].

At present, although some scholars have researched aspects of the problems related to the electricity market after the establishment of electricity retailers in China, there are few studies about the influence on the generation side after the establishment of electricity retailers [6, 7]. With respect to the modelling of DR (Demand Response), Mahmoudi N [8] modeled different types of demand response resources in the Australian electricity market, including long-term resources, real-time resources, spot-market resources, peak price resources, long-term contract market resources, and price returns resources. It also models how retailers purchase different types of demand response resources from load aggregators, as well as establishes an electricity-purchasing strategy model that considers the contract price and user participation. Li Z [9] considers the users' participation in terms of the demand response during peak periods and uses the load-price curve to establish the utility model of customers, thereby maximizing the utility of customers and achieving the goal of optimizing the network operating cost during the peak period. Zhang C [10] further classifies the

FIGURE 1: Operation pattern of electricity retailers in price-based demand response.

user loads that can participate in the demand response and divides them into nonelastic loads and elastic loads. Elastic loads are further divided into load reduction and transferable loads, and, on this basis, a mathematics-based approach is established. The model proposes a purchase and sale electricity model that combines customer load aggregators.

However, based on the present situation with respect to the deepening of electricity reform as well as current problems that exist in power-grid operation, there is an urgent need to research electricity retailers involved in generation dispatching [11, 12]. This paper proposes a model of generation dispatching considering the participation of electricity retailers and the response of customers. Moreover, based on the analysis investigating the market behavior of customers, electricity retailers, and producers, the paper studies the comprehensive benefits of various stakeholders and provides theoretical support for electricity retailers involved in the dispatch of optimal generation dispatching.

2. Materials and Methods

2.1. Analysis on Operation Pattern of Electricity Retailers. According to the electricity reform framework in the No.9 Document, it is necessary to release the demand side and generation side and to control the power grid. Combined with the practice of electricity market construction in different countries, as well as the positions and features of electricity retailers in the operation pattern, this paper proposes the operation pattern of electricity retailers using a price-based demand response, as shown in Figure 1.

From Figure 1, the DR of a buyer refers to general electricity customers [13]. During peak periods, the buyer can reduce the peak load by reducing the electricity demand and realize a demand response according to the reduced load. In addition, the DR of a seller refers to the electricity customers

with supply capacity, including distributed power and electric vehicles [14]. During peak periods, the seller can increase the peak response capacity of the power grid by increasing their power supply and can realize the demand response according to the supplied power.

Electricity retailers are the critical connect between customers and generation companies. The function of electricity retailers in an operation pattern is equivalent to those of aggregation service providers. Generation companies propose a load-reduction plan or electricity supply plan during the peak period, and electricity retailers integrate these plans and issue a demand response plan to customers, after which they conduct settlement evaluation in accordance with the final response degree of customers.

2.2. Customer Response Load-Calculation Model. Four types of load-calculation model were analyzed for cases where customers participated in demand response, including industrial, commercial, and residential customers and electric vehicles [15, 16]. According to the classification, industrial and commercial customers belong to the DR of buyer resources, and residential customers and electric vehicles both belong to the DR of seller and buyer resources.

According to the analysis on the operation pattern of electricity retailers, generation companies publish a load-reduction plan, and electricity retailers change customers' electricity modes by employing price or incentive measures [17, 18]. As the load-reduction plan is completed, the reserve capacity on the generation side as well as the costs of start-up and shutdown are reduced, and then the generating efficiency is increased. First, according to the customer demand response used to calculate the load, the assumptions of the specific model are as follows.

(1) The typical daily load curve has two peak periods and a valley period; there are two peak prices and one valley price.

(2) There are upper limits on the adjustable power for different customers, and among them, the residential adjustable power factor is the minimum, and the electric vehicle is the maximum.

(3) Compensation should be given to customers who reduce their loads during the peak period, and it is based on the principle of contribution, regardless of the customer category.

The demand response analysis only considers the peak load reduction of various customers according to their adjustable usage of electricity, after electricity retailers break down their load-reduction plan. Before responding to the reduction plan of the load, the electricity cost-calculation model is given as follows.

$$c_i = \int_0^{t_1} L_{it} \cdot p_{ig} d_t + \int_{t_1}^{t_2} L_{it} \cdot p_{if} d_t + \int_{t_2}^{t_3} L_{it} \cdot p_{ip} d_t + \int_{t_3}^{t_4} L_{it} \cdot p_{if} d_t + \int_{t_4}^{24} L_{it} \cdot p_{ig} d_t \quad (1)$$

where c_i is the electricity cost for the category i of customers, when $i = 1$ represents electric vehicles, $i = 2$ represents industrial customers, $i = 3$ represents commercial customers, and $i = 4$ represents residential customers. t_i shows the nodes during different periods, where $0 - t_1$ and $t_4 - 24$ are the valley period, $t_1 - t_2$ and $t_3 - t_4$ are the peak period, and others are the flat period. L_{it} is the load of category i of customers in time t ; p_{if} is peak price of category i of customers, p_{ip} is the flat price of category i of customers, and p_{ig} is the valley price of category i of customers.

Assuming that the total load-reduction plan is Q_p , shared by the reduced load of all kinds of customers, define Q_p^- , and shared by the supply load of electric vehicles, define Q_p^+ . The cost-calculation model of various customers responding to the incentive mechanism is as follows.

$$c_i^a = \int_0^{t_1} L_{it}^a \cdot p_{ig} d_t + \int_{t_1}^{t_2} L_{it}^a \cdot p_{if} d_t + \int_{t_2}^{t_3} L_{it} \cdot p_{ip} d_t + \int_{t_3}^{t_4} L_{it}^a \cdot p_{if} d_t + \int_{t_4}^{24} L_{it}^a \cdot p_{ig} d_t \quad (2)$$

where c_i^a is the electricity cost of the category i of customers after the response and L_{it}^a is the load function of the category i of customers at time t after the response.

Thus, the load-change status of various customers during the peak period can be calculated, and the calculation model is as follows.

$$\Delta Q_{if} = \int_{t_1}^{t_2} (L_{it} - L_{it}^a) d_i + \int_{t_3}^{t_4} (L_{it} - L_{it}^a) d_i \quad (3)$$

where ΔQ_{if} is the load reduction of the category i of customers during the peak period. For electric vehicles, which can charge and discharge, the discharge of electricity corresponds to the reduced charge of electricity, so it is all considered as a load reduction.

$$\Delta Q_{ig} = \int_0^{t_1} (L_{it}^a - L_{it}) d_i + \int_{t_4}^{24} (L_{it}^a - L_{it}) d_i \quad (4)$$

where ΔQ_{ig} is the load increase of the category i of customers in the valley period. Considering the reduced electricity consumption of some customers, it will be supplemented during the valley period.

$$\Delta Q_{if} + \Delta Q_{ig} \leq Q_i^u \quad (5)$$

where Q_i^u is the upper limit of the variable electricity of customers. The upper limit is related to customer characteristics, and θ_i is a variable. The calculation model of the variable electricity upper limit of various customers is as follows.

$$Q_i^u = \int_0^{24} L_{it} d_t \cdot \theta_i \quad (6)$$

For the incentive mechanism, subsidies are given to customers who reduce power consumption during the peak period. Assume that there is a fixed maximum subsidy that can be provided by electricity retailers, defined as A_T . The subsidy of various customers is given as follows.

$$A_i = A_T \cdot \frac{\Delta Q_{if} + \Delta Q_{ig}}{\sum_{i=1}^4 (\Delta Q_{if} + \Delta Q_{ig})} \quad (7)$$

where A_i represents subsidies of the category i of customers.

Thus, it should consider the subsidies when calculating the electricity cost after the response, which is given as follows.

$$c_{is}^a = c_i^a - \alpha \cdot \Delta Q_{if} + p_{ig} \cdot \Delta Q_{ig} \quad (8)$$

where c_{is}^a is the electricity cost of category i of customers after considering the subsidies; α is the unit cost of subsidies of the peak load.

$$\alpha \cdot \sum_{i=1}^4 \Delta Q_{if} \leq A_T \quad (9)$$

2.3. Generation Dispatch Model. The generation side will be affected by the implementation of the response policy on the demand side, including the load reduction during the peak period and the load increase during the valley period. Assume that there are n peak adjusting reserve units in total. Before the implementation of the demand response policy, these units operate during peak time, and the coal consumption rate of the start-up and shutdown is higher than that in normal time. The calculation model to determine the coal consumption cost of peak adjusting units before the demand response is given as follows.

$$c_{at} = \xi \cdot \sum_{i=1}^4 \left(\int_{t_1}^{t_2} L_{it} d_t + \int_{t_3}^{t_4} L_{it} d_t \right) \cdot c_c + \gamma \cdot n \cdot c_c \quad (10)$$

where c_{at} is the generation coal consumption cost of reserve units, ξ is the unit power coal consumption rate during normal operation time, c_c is the unit coal cost, and γ is the coal consumption rate during the start-up and shutdown times.

After the implementation of the load-reduction plan, the peak load is reduced, and the number of reserve units that needs to be started decreases. Then, the calculation formula to determine the coal consumption cost of reserve units is given as follows.

$$c_{at}^a = \xi \cdot \sum_{i=1}^4 \left(\int_{t_1}^{t_2} L_{it}^a d_t + \int_{t_3}^{t_4} L_{it}^a d_t \right) \cdot c_c + \gamma \cdot n_j \cdot c_c \quad (11)$$

where c_{at}^a is the coal consumption cost of reserve units after the response, and n_j is the number of units for peak adjusting after the response.

$$\Delta c_{at} = \left[\xi \cdot \sum_{i=1}^4 \Delta Q_{if} + \gamma \cdot (n - n_j) \right] \cdot c_c \quad (12)$$

where Δc_{at} is the cost fluctuation of reserve units during the peak period.

For the increased electricity demand during the valley period, the corresponding number of units that need to be shut down is reduced, leading to a reduced unit cost. The calculation formula of the coal consumption cost fluctuation during the valley time is shown as follows.

$$\Delta c_{tg} = \left[\xi \cdot \sum_{i=1}^4 \Delta Q_{ig} - \gamma \cdot n_k \right] \cdot c_c \quad (13)$$

where Δc_{tg} is the variable cost of the coal consumption during the valley period and n_k is the reduced number of units that needs to be shut down.

Thus, we can calculate the change in the total revenue on the generation side, which is calculated as follows.

$$\Delta \pi_p = p_o \cdot \sum_{i=1}^4 (\Delta Q_{ig} - \Delta Q_{if}) - \Delta c_{at} - \Delta c_{tg} \quad (14)$$

For electricity retailers, before the response to the load-reduction plan, the formula to determine their income of them is as follows.

$$\pi_s = \sum_{i=1}^4 c_i - (p_o + p_l) \cdot \sum_{i=1}^4 \int_0^{24} L_{it} d_t \quad (15)$$

where π_s is the income of electricity retailers before the demand response and p_l is the transmission and distribution price. After the implementation of the load-reduction plan, the income of the electricity retailers is determined as follows.

$$\pi_s^a = \sum_{i=1}^4 c_i^a - (p_o + p_l) \cdot \sum_{i=1}^4 \int_0^{24} L_{it}^a d_t - A_T + \varepsilon \quad (16)$$

where π_s^a is the income function after the demand response of electricity retailers and ε is the government subsidy.

From this, the income change formula of electricity retailers before and after the response to the load-reduction plan is as follows.

$$\Delta \pi_s = \sum_{i=1}^4 (c_i^a - c_i) - (p_o + p_l) \cdot \sum_{i=1}^4 \int_0^{24} (L_{it}^a - L_{it}) d_t - A_T + \varepsilon \quad (17)$$

2.4. Comprehensive Benefit Assessment Model

2.4.1. Simulation Ideas. The implementation of the demand response can be classified as a price demand response and an incentive demand response. At the beginning of the implementation, owing to the investment of government subsidies, some categories of customers will actively participate. A reduction or transfer of the load will result in a significant decrease in the systemic peak load, and the load rate will increase. Meanwhile, it also enables access to distributed power and the use of electric vehicles. As the government subsidizes customers and electricity retailers, the costs are correspondingly reduced. Various stakeholders benefit from the demand response project, thereby leading to an increased input into demand response projects. Customers may choose to enter or exit the project at will, and electricity retailers may choose to continue or reduce their investment based on the benefits of the demand response. If the government increases the subsidy, the electricity retailers will increase the input of the demand response, but because of the limitations of the customers' adjustable power, once it exceeds a certain range, it will have negative effects. When the efficiency of the increased investment is poor, government will reduce the subsidy, and this cyclic process constitutes the basis for the establishment of a dynamic model [19, 20]. The specific simulation schematic is shown in Figure 2.

2.4.2. Causal Circuit Diagram. According to the simulation schematic diagram, the causal relationship between the various elements in the system is analyzed, as shown in Figure 3. From the figure, the causal circuit involving the subject has three main parts.

(1) For customers, the greater the number of demand response project inputs, the greater is the number of subsidies. Therefore, the direct revenues of customers who participate in demand response will increase. However, the transfer of load increases that lead to the decline of customers' satisfaction, which will affect customer participation level and constitute a negative cycle.

(2) For electricity retailers, as the dispatcher of demand response, the greater the number of demand response project inputs is, the greater the subsidy that can be earned by the electricity retailers will be. When the load rate increases, the power generation cost of the unit and the electricity purchase cost of retailers both decrease; thus, the efficiency of the electricity retailers increases, constituting a positive cycle.

(3) Electricity producers are also among the beneficiaries of the demand response. When the load rate is increased, the cost of the generator decreases and there are increased benefits to electricity producers. However, the loss of electricity generation owing to the load reduction will affect the advantages of electricity producers and constitute a negative cycle.

2.4.3. Development of Simulation Model. According to the analysis of the causal circuit diagram [21], the simulation model can be divided into six modules, i.e., the customer module, subsidy module, electricity retailer module,

FIGURE 2: Simulation schematic.

FIGURE 3: Causal circuit diagrams.

electricity price module, electricity producer module, and load module, as shown in Figure 4.

(1) *Customer Module*. For this module, this paper mainly considers customer benefits for two demand response policies, namely, the price-based and incentive-based policies. The relationship between the parameters in the model is as follows.

$$C_c.R = C_{DR}.R + C_i.R - A_{G-C}.R \quad (18)$$

$$\Delta R_u.R = \Delta R_{TOU-M}.R / C_c.R \times 100\% \quad (19)$$

$$\Delta D_c.R = DELAY((D_{goal} - D_c.R) * (\Delta R_u * \alpha + R_s * \beta), t_1, 0) \quad (20)$$

$$D_c.R = INTEG(\Delta D_c.R, 0.01) \quad (21)$$

$$R_u.R = INTEG(\Delta R_{TOU-M}.R, 0) \quad (22)$$

$$S_{ed}.R = C_E.R - C_E^a.R \quad (23)$$

$$C_E.R = Q_E.R * P_p \quad (24)$$

$$C_E^a.R = Q_f.R * P_f + Q_p.R * P_p + Q_g.R * P_g \quad (25)$$

$$R_s.R = INTEG(\Delta R_s, 0) \quad (26)$$

$$\Delta R_s.R = DELAY((R_{TOU-S}.R - R_s.R), t_2) \quad (27)$$

$$R_{TOU-S}.R = 1 - \Delta Q_{ABS}^a / Q_d.R \quad (28)$$

FIGURE 4: Simulation model of comprehensive benefit assessment.

where C_c is the cost of customers who participate in DR, C_{DR} is the response cost of the price-based DR, C_i is the equipment cost of price-based DR, A_{G-C} represents the government subsidies to customers, ΔR_u is the added rate of return, ΔR_{TOU-M} is the added monthly revenue of TOU (time-of-use), ΔD_c is the added participation level of price-based DR, and D_{goal} is the target participation level of price-based DR. D_c represents the participation level, R_s is the satisfaction of the electricity-using mode, α is the impact factor of the added rate of return, β is the impact factor of the satisfaction of the electricity-using mode, and t_1 is the delay time. R_u is the direct revenue of customers who participate in DR, S_{ed} is the daily electricity tariff savings of TOU customers, C_E is the original daily electricity tariff before DR, C_E^a is the daily electricity tariff after TOU, Q_E is the original daily electricity consumption before DR, P_p is the electricity price during the flat period, and Q_f is the electricity consumption during the peak period. P_f represents the electricity price during the peak period, and Q_p is the electricity consumption during the flat period. Q_g is the electricity consumption during the valley period, P_g is the electricity price during the valley period, and ΔR_s is the transition rate of the satisfaction electricity-using mode.

R_{TOU-S} is the customers' satisfaction of the electricity-using mode who participates in the TOU. t_2 is the sensory delay, ΔQ_{ABS}^a is the sum of the absolute value of the transferred electricity who participate in TOU, and Q_d is the original daily electricity consumption in the area.

(2) *Load Module.* In this module, the design function mainly considers load changes during the peak period, which is given as follows.

$$\xi_b = \frac{(Q_f + Q_p + Q_g)}{(24 * L_p)} \quad (29)$$

$$L_p \cdot R = L_p^b \cdot R * (1 + \delta_l) \quad (30)$$

$$\zeta_l = L_{ap} \cdot R / L_p \cdot R * 100\% \quad (31)$$

$$L_p^a \cdot R = L_p \cdot R - L_{ap} \cdot R \quad (32)$$

$$\xi_b^a = \frac{(Q_f^a + Q_p^a + Q_g^a)}{(24 * L_p^a)} \quad (33)$$

$$\Delta \xi_b = \xi_b^a - \xi_b \quad (34)$$

wherein ξ_b is load rate before DR. L_p is load of the region in peak period. L_p^b is the initial value of load in peak period. δ_l is the natural growth rate of load. ζ_l is the ratio of avoidable load in peak period. L_{ap} is the avoidable load in peak period. ξ_b^a is load rate after DR. Q_f^a is regional electricity consumption in peak period after TOU. Q_p^a is regional electricity consumption in flat period after TOU. Q_g^a is regional electricity consumption in valley period after TOU. $\Delta\xi_b$ is increase ratio of load rate.

(3) *Electricity Producer Module.* Here, the electricity producer module mainly considers two factors, including the efficiency and cost of power generation. Consider the cost reduction of the start-up and shutdown and of the power generation as the junction point in the model, which is shown as follows.

$$B_p.R = B_{ai}.R + B_{ar}.R + B_{au}.R \quad (35)$$

$$B_{ai}.R = \text{INTEG}(\Delta B_{ai}, 0) \quad (36)$$

$$\Delta B_{ai} = u_{ai} * L_{ap} * \gamma_{c,c-p} \quad (37)$$

$$B_{ar}.R = \text{INTEG}(\Delta B_{ar}, 0) \quad (38)$$

$$\Delta B_{ar} = u_{ar} * Q_{re} * \gamma_{q,c-p} \quad (39)$$

$$B_{au}.R = \text{INTEG}(\Delta B_{au}, 0) \quad (40)$$

$$\Delta B_{au} = \eta * \gamma_{q,c-p} * Q_d^a * P_c * \Delta\xi_b * \lambda_{\xi-c} \quad (41)$$

$$U_s = U_{so} * (1 - \Delta\xi_b * \lambda_{\xi-c}) \quad (42)$$

$$U_{pc} = U_s * \theta_s + U_c * \theta_c + U_\varepsilon \quad (43)$$

$$p_{go} = \text{INTEG}(\Delta p_{go}, 0.03) \quad (44)$$

$$\Delta p_{go} = \frac{(p_{ae} - p_{go})}{t_3} \quad (45)$$

$$\Delta L_p = p_{go} * Q_{re} \quad (46)$$

$$L_p = \text{INTEG}(\Delta L_p, 0) \quad (47)$$

where B_p is the power generation efficiency. B_{ai} is excusable investment cost. B_{ar} is excusable operating cost. B_{au} is excusable cost of start-up and shutdown. ΔB_{ai} is monthly excusable investment cost of power generation. u_{ai} is unit excusable investment cost of power generation. $\gamma_{c,c-p}$ is capacity-reduction factor of customer-electricity producer. ΔB_{ar} is monthly excusable operating cost of power generation. u_{ar} is unit excusable operating cost of power generation. $\gamma_{q,c-p}$ is electricity reduction factor of customer-electricity producer. Q_{re} is load reduction of TOU. ΔB_{au} is unit coal consumption of thermal power. Q_d^a is daily regional electricity consumption after DR. P_c is price of electric coal. $\lambda_{\xi-c}$ is the correlation factor of load rate and coal consumption. U_s is unit cost of start-up and shutdown. U_{so} is the initial value of cost of start-up and shutdown. U_{pc} is the cost of unit power generation. θ_s is impact factor of cost of start-up and shutdown. θ_c is impact factor of capacity cost. U_ε is unit

capacity cost. U_ε is other generation costs. p_{go} is the price of on-grid electricity. Δp_g is the regulation rate of price of on-grid electricity. p_{ae} is expected generation price. ΔL_p is monthly sale loss of power generation. L_p is the loss of power generation.

(4) *Electricity Price Module.* For this module, the main consideration is the design function of the electricity price during the peak period, in the flat period, and in the valley period, which are given as follows.

$$\Delta P_p = \frac{(p_{be} - P_p)}{t_4} \quad (48)$$

$$P_f = P_p * \phi_f \quad (49)$$

$$P_g = P_p * \phi_g \quad (50)$$

$$\tilde{p} = \frac{\sum_{i=f,p,g} (Q_i^a * P_i)}{\sum_{i=f,p,g} Q_i^a} \quad (51)$$

$$p_{be} = u_e + p_{go} \quad (52)$$

$$\Delta u_e = u_{pro} - u_{pr} \quad (53)$$

$$u_{pr} = \tilde{p} - p_{go} \quad (54)$$

where ΔP_p is the regulation rate of benchmark price. p_{be} is the expected benchmark price. t_4 is the adjustment time. ϕ_f is the peak-to-flat electricity price ratio. ϕ_g is the valley-to-flat electricity price ratio. $\tilde{p}$ is the average electricity price. u_e is expected profit of electricity supply. Δu_e is the regulation rate of profit of electricity supply. u_{pro} is initial profit of power supply. u_{pr} is unit profit of power supply.

(5) *Electricity Retailer Module.* This module mainly considers the relationship between the efficiency and the cost of electricity retailers, which is shown as follows.

$$B_s = B_{ss} + B_{si} + B_{sc} \quad (55)$$

$$\Delta B_{ss-M} = (S_{ed} + S_{ued}) * 30 \quad (56)$$

$$B_{si} = A_{G-S} + A_{P-S} \quad (57)$$

$$A_{P-S} = B_p * \varphi \quad (58)$$

$$C_s = C_{DR} + C_\varepsilon - A_{G-S} - A_{P-S} \quad (59)$$

$$B_{sc} = L_p + Q_{re} * p_v \quad (60)$$

where B_s is the income of electricity retailers. B_{ss} represents the revenues from the sale of electricity. B_{si} is the revenue from incentives. B_{sc} is the cost reduction of electricity purchase of electricity retailers. ΔB_{ss-M} is monthly income owing to electricity sales. A_{G-S} represents the government subsidies to electricity retailers. A_{P-S} represents the subsidies by electricity producers to electricity retailers. φ is benefit-sharing proportion of electricity producers. C_s is the cost of electricity retailers. C_{DR} is the management cost of DR. C_ε represents other costs to electricity retailers participating

FIGURE 5: Typical customer load curve.

in DR. p_v is average price of electricity transmission and distribution.

(6) *Subsidy Module*. This module mainly considers the subsidy between the government, the electricity retailers, the electricity producers, and the customers, which is given as follows.

$$A_G = A_{G-C} + A_{G-S} \quad (61)$$

where A_G represents the total amount of government subsidies.

3. Results and Discussion

This paper considers as an example a region in China that collects generated data of a typical daily load, considers the different types of customers based on the flexibility of price changes, and calculates the load fluctuation of the different customers and changes in revenue of the electricity producers under the demand response. Typical daily load curves for various customers are shown in Figure 5.

Figure 5 shows that daily load curves of industrial and commercial customers correspond to the primary axis (left side), and those of residential and electric vehicle customers correspond to the secondary axis (right side). The study obtains electricity prices of this area in the peak, flat, and valley periods, as shown in Table 1.

3.1. Customer Response Load Calculation. The utilization of reserve units is low because of the peak load, and the start-up and shutdown costs are too high during the peak period. Therefore, the electricity producers issue the load-reduction plans to electricity retailers and plan to reduce electricity consumption by 6,000 MWh during the peak period, and the maximum load reduction is 1,000 MW. The electricity retailers are required to reduce the customer loads during the peak period by implementing the demand response strategy. The electricity retailers motivate customers to change electricity-using modes by adjusting the time-of-use electricity price, as

TABLE 1: Distribution of time-of-use electricity price.

User Category	Average electricity price before response (\$/MWh)		
	Peak	Flat	Valley
Industry	157.19	98.48	43.13
Residents	79.71	72.46	47.83
Commerce	172.94	109.06	48.83
Electric vehicles	213.04	172.46	128.99
User Category	Average electricity price after response (\$/MWh)		
	Peak	Flat	Valley
Industry	165.05	98.48	38.82
Residents	83.70	72.46	43.04
Commerce	181.59	109.06	43.94
Electric vehicles	223.70	172.46	116.09

well as providing related subsidies to customers, which are provided by electricity producers and government.

The electricity retailers choose to increase by 5% based on the electricity price during the peak period and decrease by 10% based on the electricity price during the valley period. The reduced electricity consumption of customers during peak periods is subsidized based on a price of \$1.45/MWh, and the discharge subsidy of electric vehicles during the peak period is subsidized in accordance with the price charged. Combined with the price elasticity of various customers, the results of the load, cost, and revenue of various customers after the response are shown in Figure 6.

In Figure 6, the daily load curves of industrial and commercial customers correspond to the primary axis (left side), and those of the residential and electric vehicle customers correspond to the secondary axis (right side). Combined with Figure 1, the load curve of electric vehicles has the most obvious changes, and these are related to the characteristics of electric vehicles. Electric vehicles can not only reduce the charge, but also discharge, which can ease the pressure on the grid during the peak period.

From Figure 7, we see that electricity retailers change the electricity habits of customers by implementing an electricity price strategy and an incentive strategy. Therefore, the daily load curve significantly improves; i.e., the peak load decreases and the valley load rises, which is shown as Table 2.

From Table 2, the maximum industrial, commercial, and residential loads all declined after the response, and the load rate increased, with the industrial load rate reaching 0.87. However, the maximum load of electric vehicles increased and the load rate declined, which is related to the particularity of electric vehicles. Combined with the load curve of electric vehicles after the response, its maximum load appears in the valley period, which improves the overall load rate. The total electricity reduction in the peak period reaches 5806.6 MWh, and the maximum load decreases by 1118 MW. Compared with the expected plan, the maximum load reduction meets the requirements, and the compliance rate of electricity reduction is 96.78%, so it completes the requirements of the electricity producers.

TABLE 2: Load change data before and after the demand response.

Parameters		Industry	Commerce	Residents	Electric vehicles	Total load
Maximum load (MW)	Before the response	17,400	3,744	277	103	2,0897
	After the response	16,300	3,600	260	130	1,9743
Average load (MW)	Before the response	14,226	2,274	196	73	16,769
	After the response	14,193	2,254	176	74	16,697
Load rate (MW)	Before the response	0.82	0.61	0.71	0.71	0.80
	After the response	0.87	0.63	0.68	0.57	0.85
Consumption during peak period (MWh)	Before the response	127,970	23,184	2964	546	154,664
	After the response	123,520	22,000	2484	495	148,499
Decrease in consumption during peak time (MWh)		4,450	1,184	480	51	6,165

FIGURE 6: Customer load curve after the response.

FIGURE 7: Comparison of daily load curves before and after the response.

Combined with the changes of the time-of-use electricity price, the paper calculates the electricity costs of various customers before and after the response as well as the subsidies of the reduced electricity during the peak period, as shown in Table 3.

From Table 3, the purchase cost of all customers after the response is reduced. In addition, considering the additional subsidies, the customers' revenues are increased. The response degree and the additional revenue of industrial customers are both the highest.

3.2. Calculation of Dispatch Cost for Electricity Producers. Assume that the power generation above the minimum load line is derived from the thermal power units. In this example, the minimum load before the response is 11,705 MW, and the minimum load after the response is 12,870 MW. Therefore, it stipulates that the power generation, which is higher than 11,705.2 MW, be derived from thermal power units. Nine 600-MW and ten 300-MW thermal power units were used as generating units, and four 400-MW thermal power units were used for peak adjusting. The operating coal consumption rate of the 600-MW thermal power units is 360 g/kWh, that of the 300-MW thermal power units is 370 g/kWh, and that of the 200-MW thermal power units is 378 g/kWh. The coal consumption rate of the start-up and shutdown is 5 g/kWh, and the unit coal price is \$57.97/ton. According to the load fluctuation before and after the response, the start-up and shutdown cases of units in different periods are obtained. According to the results, based on the minimum generation load, the maximum increased

TABLE 3: Cost fluctuations of customers (thousands of dollars).

	Industry	Commerce	Residents	Electric vehicles
Purchase cost before the response	35,773.36	6,982.01	319.14	301.32
Purchase cost after the response	35,588.51	6,968.07	283.23	296.12
Cost reduction	184.86	13.94	35.91	5.20
Reduction in consumption during peak period	6,449.28	1,715.94	695.07	73.91
Subsidies	644.93	171.59	69.51	7.39
Revenue increase value	829.78	185.54	105.42	12.59

TABLE 4: Comparison of coal consumption cost before and after the response.

	Before the response	After the response	Descent value	Descent rate
Operating coal consumption (ton)	44,272.36	33,255.66	11,016.7	0.249
Operating cost/ (thousands of dollars)	2,566.51	1,927.86	638.65	0.249
Start-stop capacity/ MW	6,570.80	4,530.00	2,040.80	0.311
Start-stop cost/ (thousands of dollars)	3.81	2.63	1.18	0.311
Total cost/ (thousands of dollars)	2,570.32	1,930.49	639.83	0.249

load capacity before the response is 9191.8 MW, and it is only 6873 MW after the response. Therefore, the peak adjusting capacity decreases by 2318.8 MW. During the peak adjusting period before the response, there were 24 start-stop times of units, and, after the response, there were only nine times. Thus, the coal consumption cost before and after the response can be calculated. The coal consumption cost includes only the required thermal power coal consumption cost, which is outside the basic load (minimum load), as shown in Table 4.

From Table 4, the electricity producers can realize savings in the coal consumption cost of \$639,830.00 thousand dollars after the response. In addition, owing to the reduction of the reserve capacity for peak adjusting, the input cost of power generation equipment incurred by electricity producers will be reduced, and the equipment-related maintenance cost will be reduced. Therefore, after customers respond to the load reduction, it is beneficial for electricity producers to reduce cost. However, because of the reduction in the total electricity consumption, the interest by electricity producers to generate electricity sales will be reduced. Assume that the price of on-grid electricity is fixed at \$43.48/MWh. Combined with the generating capacity before and after the response, the specific electricity sale revenues can be calculated. Among them, the power generation revenue before the response is \$6,715,810.00, and it is \$6,456,780.00 thousand dollar after the response, so it decreases to \$268,030.00 thousand dollar. Compared to these varying incomes and cost, the total revenue of electricity producers is still increased.

Although the government provides subsidies to customers, it would increase the financial burden from the perspective of the environmental emission reduction, and motivating customers to respond to load reduction is beneficial for reducing carbon emissions, thereby reducing the environmental governance cost. Assume that the CO₂ emission of standard coal is 2.46 tCO₂/tee, and the NO_x emission of standard coal is 0.0156 NO_x t/tee. The reduction in the environmental emission before and after the response is shown in Table 5.

TABLE 5: Comparison of environmental emission reduction.

	CO ₂ emission (ton)	NO _x emission (ton)
Before the response	10.88	0.07
After the response	8.17	0.05
Emission reduction	2.71	0.02

From Table 5, by realizing the generation scheduling under a demand response, the cost of government subsidies for environmental carbon-emission reduction is \$0.636/kg, and the cost of NO_x emission reduction is \$4.06/t.

3.3. Comprehensive Benefit Assessment. The results of the example are used as the basic data of the simulation model, and other relevant parameters are set, which is shown in Table 6.

These parameters are inputted into the simulation and operate combined with the functional relationship between other parameters, and the result is shown in Figure 8.

3.3.1. Degree of Customer Participation. From Figure 8, all kinds of customers will cause a large proportion of customers to participate in the initial stage, so it will reduce the load during the peak period and increase the load during the valley period. However, with the natural growth trend of the load, the load rate will subsequently reduce, leading to a decrease in the degree of customer participation, thus requiring more incentives and price intervention to encourage customers to participate. In addition, combined with the delay settings, it causes fluctuations in the degree of customer participation. However, because the customer's variable load is limited by its own characteristics, after a long time, the degree of customer participation will become constant. In this case, the degree of participation of industrial customers remains fixed at around 30%, around 27% for commercial customer, around 10% for residential customers, and around 42% for electric vehicle customers. The electrical elasticity of electric vehicles

TABLE 6: Parameter design.

Customer category		Industry	Commerce	Residential	Electric vehicles
Delay settings	Delay time	2	2	2	2
	Sensory delay	1	1	3	1
	Adjustment time of power supply profit	3	3	3	3
	Adjustment time of benchmark price	6	6	6	6
	Adjustment time of on-grid tariff	6	6	6	6
Electricity price settings	Peak-to-flat electricity price ratio	1.67	1.67	1.5	1.5
	Valley-to-flat electricity price ratio	0.33	0.33	0.5	0.5

FIGURE 8: Comparison of degree of customer participation.

FIGURE 10: Analysis of emission reduction efficiency and cost.

FIGURE 9: Trends of load rate change and avoidable peak load change.

is the highest, but the actual electricity consumption is small. Therefore, in contrast, the effect of industrial customers in the demand response is optimal.

3.3.2. Load Conditions. From Figure 9, the trend is consistent with the changes in the degree of customer participation. When the incentive measures and price measures work together, the degree of participation of the customer increases, and the avoidable peak load ratio will also increase.

When the peak load reduces, it will promote the increase of the load rate, thus resulting in the trends of the two becoming similar. However, as the natural load increases, the trend of the degree of customer participation becomes stable, and the adjustable peak load ratio reaches the upper limit, so the avoidable peak load ratio declines. Therefore, the promotion proportion of the load rate is restricted and finally tends to smoothen the fluctuations. Finally, in this case, the avoidable peak load ratio stabilizes at around 6% and at around 4% as the promotion proportion of load rate stabilizes. Overall, it can increase the load rate and increase the peak load ratio through the customer response; therefore, the overall effect is excellent.

3.3.3. Analysis of Emission Reduction Efficiency. From Figure 10, the total amount of government subsidies is increasing. However, the degree of customer participation tends to be stable in the latter period, which is ineffective with respect to further increasing investments, and thus the total amount of investment subsidies tends to be flat. To realize a reduction in carbon emissions, the increased carbon-emission reduction first increases and then decreases, which is consistent with the change of load rate. The impact of the load rate fluctuation on the generating capacity of thermal power has a certain delay and appears as the curve of Figure 10. For the unit cost of emission reduction subsidies, the overall trend declines and finally becomes stable, indicating

FIGURE 11: Comparison of the efficiency results of various stakeholders.

that the government can achieve the desired effects and reduce carbon emissions by investing in the demand response project. At the same time, with the increase of the scale, the unit cost of the emission reduction subsidies will also be reduced.

3.3.4. Comprehensive Benefit Analysis. From Figure 11, after the implementation of the demand response, all of the stakeholders have good efficiencies. Among them, the electricity producers obtain the highest efficiency in the process of demand response dispatching. Because of the increased load rate and the decreased peak load ratio, the generation side encounters a reduction in the related costs, such as the reserve capacity cost and the start-stop cost, thus reducing the overall costs. Secondly, with respect to the customers, although the change in electricity habits will lead to a decrease in the customer-electricity-using satisfaction, the peak load subsidies will reduce the electricity cost of customers. In addition, when the load rate increases, the price of the on-grid electricity will reduce, and then the sale price of electricity retailers will decrease by a certain percentage, which further reduces the electricity cost of customers. Finally, for the electricity retailers, there is a need to increase the corresponding equipment costs and management costs in response to the load-reduction plan. However, owing to the decrease in the electricity purchase cost, the overall efficiencies of electricity retailers are still increased. According to the simulation results, the growth in the efficiency of electricity retailers is the slowest.

4. Conclusions

The paper puts forward that the customer group responds to the retailers' participation in the power generation dispatching model, analyzes the market behavior of the customer group, the electricity seller, and the power producer, studies the comprehensive benefits of various stakeholders, and provides theoretical support for the sales operators to participate in power generation scheduling optimization. The

overall efficiencies of customers responding to electricity retailers involved in generation dispatching exhibit good performance, and the increase in efficiency is greater than the cost fluctuation for all of the stakeholders. The electricity producers proposed the load-reduction plan, the electricity retailers implement the dispatching, and government determines the subsidy policy. The electricity retailers stimulate customers to respond by implementing price measures and incentives to change electricity usage habits of customers and obtain benefits from the process. This results in a win-win scenario.

(1) Customers who respond to electricity retailers involved in generation dispatching can make the load curve smooth and increase the load rate. For different types of customers, the degree of participation of electric vehicles is the highest, but industrial and commercial customers have the greatest impact on the total load rate. Therefore, there is a need to increase the demand response measures to industrial and commercial customers, and they should be stimulated to participate in dispatching in order to maximize the increase in the load rate.

(2) From the analysis of the electricity cost fluctuation of various customers, as well as the profit fluctuation of electricity retailers and that of electricity producers, customers who respond to electricity retailers involved in generation dispatching would be able to achieve a win-win situation. In addition, when the environmental costs are considered, a low unit input cost is incurred by government to realize environmental governance.

(3) The comprehensive benefit assessment results show that the participation level of various customers is generally stable, and the degree of participation of electric vehicles is the highest. The load increase ratio can reach around 4%, and the avoidable peak load ratio can reach around 6%. The investment cost of the unit emission reduction of government is also decreased year on year. Moreover, the investment cost required to realize carbon-emission reduction is about \$0.636/kg.

Data Availability

The initial data of the dissertation mainly comes from the Project Research. Some data have confidentiality agreements. Except for the data mentioned in the dissertation can be disclosed, other data cannot be disclosed due to confidentiality issues. Some of the data is from the official website at <http://www.stats.gov.cn/>.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The paper is supported by the National Science Foundation of China (Grant no. 71573084) and the Shanghai Municipal Social Science Foundation (no. 2018EGL005).

References

- [1] M. Wang, "Commentary on chinese electric regulatory regime reform in light of australian electric regulatory system," *Journal of North China Electric Power University (Social Sciences)*, vol. 06, pp. 34–38, 2015.
- [2] M. Song and M. Amelin, "Price-maker bidding in day-ahead electricity market for a retailer with flexible demands," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1948–1958, 2018.
- [3] X. Peng and X. Tao, "Cooperative game of electricity retailers in China's spot electricity market," *Energy*, vol. 145, pp. 152–170, 2018.
- [4] Y. Bai, L. Xie, Q. Xia, Q. Chen, and H. Zhong, "Institutional design of Chinese retail electricity market reform and related suggestions," *Power System Technology*, vol. 39, no. 14, pp. 1–7, 2015.
- [5] M. Khojasteh and S. Jadid, "Stochastic risk-constraint pricing strategy of electricity retailers based on Dempster-Shafer evidence theory," *Energy Strategy Reviews*, vol. 18, pp. 260–274, 2017.
- [6] A. S. Dagoumas and M. L. Polemis, "An integrated model for assessing electricity retailer's profitability with demand response," *Applied Energy*, vol. 198, pp. 49–64, 2017.
- [7] L. Ma, M. Fan, L. Guo, S. Xue, and K. Li, "Latest development trends of international electricity markets and their enlightenment," *Automation of Electric Power Systems*, vol. 38, no. 13, pp. 1–9, 2014.
- [8] N. Mahmoudi, T. K. Saha, and M. Eghbal, "A new demand response scheme for electricity retailers," *Electric Power Systems Research*, vol. 108, pp. 144–152, 2014.
- [9] Z. Li, S. Wang, X. Zheng, F. De Leon, and T. Hong, "Dynamic demand response using customer coupons considering multiple load aggregators to simultaneously achieve efficiency and fairness," *IEEE Transactions on Smart Grid*, vol. 9, no. 4, pp. 3112–3121, 2016.
- [10] C. Zhang, Q. Wang, and J. Wang, "Real-time procurement strategies of a proactive distribution company with aggregator-based demand response," *IEEE Transactions on Smart Grid*, vol. 9, pp. 99, 2016.
- [11] H. Algarvio, F. Lopes, J. Sousa, and J. Lagarto, "Multi-agent electricity markets: Retailer portfolio optimization using Markowitz theory," *Electric Power Systems Research*, vol. 148, pp. 282–294, 2017.
- [12] M. Song and M. Amelin, "Purchase Bidding Strategy for a Retailer With Flexible Demands in Day-Ahead Electricity Market," *IEEE Transactions on Power Systems*, vol. 32, no. 3, pp. 1839–1850, 2017.
- [13] Z. Wang, Y. Li, Y. Shen, L. Zhou, and C. Wang, "Virtual electricity retailer for residents under single electricity pricing environment," *Journal of Modern Power Systems and Clean Energy*, vol. 5, no. 2, pp. 248–261, 2017.
- [14] S. Tian, B. Wang, and J. Zhang, "Key technologies for demand response in smart grid," *Proceedings of the CSEE*, vol. 34, no. 22, pp. 3576–3589, 2014.
- [15] A. S. M. Khan, R. A. Verzijlbergh, O. C. Sakinci, and L. J. De Vries, "How do demand response and electrical energy storage affect (the need for) a capacity market?" *Applied Energy*, vol. 214, pp. 39–62, 2018.
- [16] L. Romero Rodríguez, J. Sánchez Ramos, S. Álvarez Domínguez, and U. Eicker, "Contributions of heat pumps to demand response: A case study of a plus-energy dwelling," *Applied Energy*, vol. 214, pp. 191–204, 2018.
- [17] Y. Yang, W. Chen, L. Wei, and X. Chen, "Robust optimization for integrated scrap steel charge considering uncertain metal elements concentrations and production scheduling under time-of-use electricity tariff," *Journal of Cleaner Production*, vol. 176, pp. 800–812, 2018.
- [18] J. Liu, X. Han, W. Han, and L. Zhang, "Model and algorithm of customers' responsive behavior under time-of-use price," *Power System Technology*, vol. 37, no. 10, pp. 2973–2978, 2013.
- [19] H. Yang, J. Li, H. Zhang, and S. Liu, "Research on the governance of urban traffic jam based on system dynamics," *Systems Engineering-Theory & Practice*, vol. 8, pp. 2135–2143, 2014.
- [20] F. Fang and J. Zhang, "Modeling and simulation of thermal system in power station based on system dynamics," *Proceedings of the CSEE*, vol. 2, pp. 96–103, 2011.
- [21] X. Yu, Z. Tan, Y. Zhang, D. Peng, and H. Xia, "The feedback mechanism of carbon emission reduction in power industry of delayed systems," *Mathematical Problems in Engineering*, vol. 2017, Article ID 4163729, 14 pages, 2017.

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