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Optimization Modeling of Integrated Energy Systems Considering User Response Characteristics

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Abstract: With the continuous interaction and integration of various energy systems and the reform of energy trading marketization, the traditional power demand response can no longer meet the business needs of multi-energy coupling. For the joint response problem of multi-energy, this paper proposes a comprehensive demand response optimization incentive model considering the user response characteristics, with the complete energy service providers and multiple users as the participants of the comprehensive demand response, to solve the response strategy for the optimal goal of all parties. The implementation architecture of integrated demand response and the electrothermal energy hub model is introduced first. Secondly, the integrated demand response collaborative optimization strategy of the integrated energy service providers and users is established, and the existence and uniqueness of the optimal solution are proved. Finally, the example analysis demonstrates that the proposed strategy can reduce the integrated energy service providers' response cost and user dissatisfaction under multiple scenarios.

Keywords: response characteristics; integrated energy system; comprehensive demand response; integrated energy service provider; incentive strategy

0. Introduction

At present, the comprehensive energy system is becoming more and more widely used, and its advantages are gradually emerging. Because in recent years, such distributed energy, in the clean energy generation growth at the same time, the influence of distributed energy volatility on the power grid and the problem of given capacity also gradually emerged, integrated energy system can not only effectively promote the distributed clean energy given, also can reduce its impact on the stability of the system [1,2].

Demand-side management research has also developed rapidly in recent years, enabling users to more flexibly and actively participate in energy allocation and system optimization. Demand response (Demand response, DR) refers to the power demand response [3], reflecting the end load user response to the power supply company price or incentive policy at the user level according to their economic interests "response" or "response", "power supply company level system" peak filling ", to ensure the user demand and enterprise interests and improve the stability of the power system. Literature [4] defines comprehensive demand response as the mechanism. It means guiding integrated energy consumers to change or adjust their extensive energy utilization mode by responding to multi-energy market price or incentive signals. Literature [5] introduces the concept of complete demand response, analyzes its value, summarizes the current situation of research in multi-energy systems, introduces related projects worldwide, and discusses the main problems facing future development and critical research problems.

From the perspective of industrial users, based on the traditional power demand response, literature [6] integrates cold and heat into the scope of demand response and puts forward the electric thermal integrated demand response mechanism based on multi-energy complementarity. Considering that the heat and electric loads have similar dispatching values in the integrated energy management, the literature [7] further proposes the optimization model of the park micro-grid integrated energy system considering the comprehensive demand response of multiple electric heat loads. Based on the established cogeneration park system, document [8,9] puts forward a multi-energy park daily economic scheduling model considering the combined thermoelectric demand response to improve the permeability of renewable energy further.

The response characteristics of users are mainly reflected in the user's response willingness, response-ability, and price elasticity [10]. Literature [11] summarizes the current research status of user response characteristics in the background of intelligent grids and classifies and analyzes the influencing factors. Based on historical data and questionnaires, document [12] extracts the electrical equipment load curve strongly related to demand response, then obtain the user response characteristics to TOU electricity price. Literature [13–15] studies the influence of user behavior uncertainty, equipment failure, and response delay based on the coupling of information physics systems. Literature [16] analyzes and summarizes the research progress in power user behaviour modelling, including three different levels of user behaviour characterization, user behaviour analysis and quantitative user behaviour modelling. Literature [17] analyzed and summarized the characteristics of demand response under a new type of power system, based on which the DR potential assessment index system was constructed from four dimensions, namely, user load, user willingness to participate, level of intelligence, and economy, and the main factors affecting the response potential of users were derived. In addition, there is also literature focusing on the differentiation of electricity consumption behavior and user thermal comfort on the demand side. However, the above study mainly addresses the user response characteristics in the power DR. It considers less about the change [18–20] in the response characteristics when the user continuously participates in the response.

In conclusion, this paper proposes a comprehensive demand response optimization incentive strategy considering user response characteristics, introduces an architecture and model of incentive IDR（Integrated demand response）, and optimizes the response cost of IESP（Integrated energy service provider） and the user's energy benefit, and realizes the compatibility of multiple response scenarios and the coupling optimization of continuous periods by considering user response characteristics with differentiated incentive mechanism. Finally, the adaptability and economy of the proposed strategy in multiple scenarios are verified, and the influence of the changing user response characteristics on the IDR effect in the continuous response scenarios is analyzed. The main contributions are as follows:

1) An incentive comprehensive demand response model is established, which solves the joint response problem of multiple energy sources based on the coordinated optimization of IESP and users, proving a unique Stackelberg equilibrium solution for the proposed model.

2) The traditional incentive IDR model has been improved, so it has good economic advantages in the scenarios such as reduced absorption and mixed response.

3) The proposed IDR model can further reduce the overall cost through multi-period coupling in the continuous response scenario and improve the accuracy of the IDR model by considering the changes in the user response characteristics.

1. Incentive-type integrated demand response architecture

1.1. Implementation Architecture

Power DR standard IEC62746-3 TS defines the traditional power DR three-layer theme interaction architecture: the power trading market operator, service provider/aggregator, and user/response resources[21–23]. Based on this architecture, the implementation architecture of the incentive-type IDR for multi-energy collaboration can be designed, as shown in Figure 1.

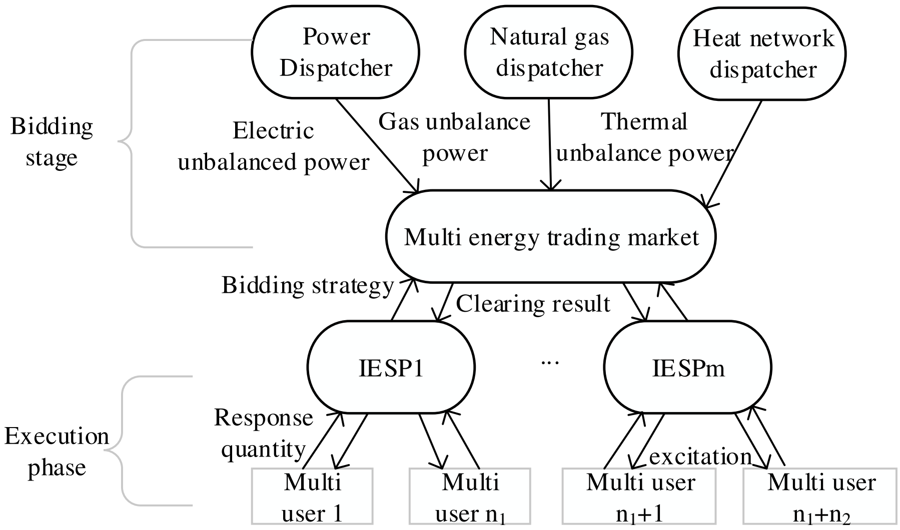

Figure 1. Incentive-type integrated demand response architecture.

As shown in Figure 1, the incentive comprehensive demand response is divided into two stages (bidding stage and execution stage), covering three subjects (multi-energy trading market, IESP, and end-user). Compared with traditional electricity trading, the multi-energy trading market can realize the trading and clearing of energy, heat, gas, and other energy sources. Unlike traditional DR aggregators/service providers, IESP in IDR can provide users with various energy sources, such as electricity and heat gas, and realize the mutual transformation and coordinated utilization of different energy sources through energy coupling equipment. In addition, end-users in IDR scenarios can also flexibly adjust their needs for multiple energy sources, not just responding to electricity.

1.2. Two-stage execution process

The comprehensive incentive demand response includes two stages: bidding and execution. The bidding stage is the interaction between the multi-energy market and IESP, and the execution stage is the interaction between IESP and users[24]. The specific execution process is shown in Figure 2.

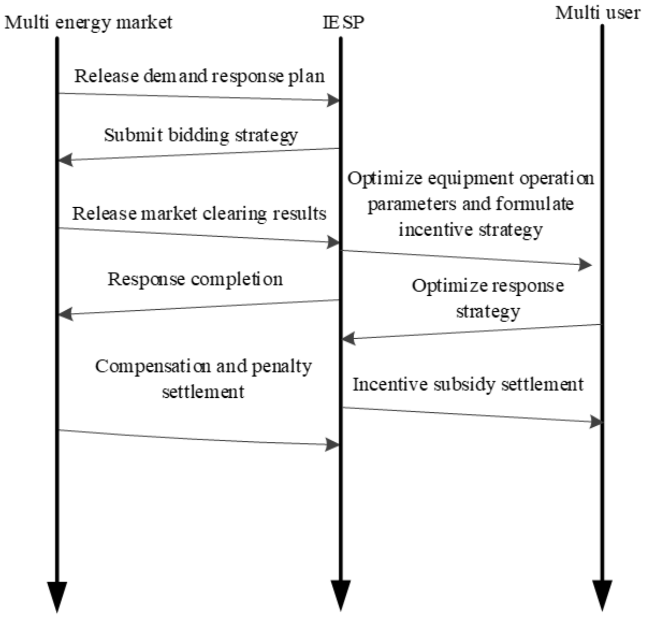

Figure 2. Execution process of incentive-type comprehensive demand response.

Bidding stage: After the upper power system dispatcher (the power system dispatcher, the natural gas system dispatcher, and the power system dispatcher of the regional thermal system) predicts the future period, the power imbalance information is sent to the multi-energy trading market. Subsequently, the multi-energy market sends this information to each IESP. After the IESP receives data from the multi-energy market, it provides a bidding strategy to the multi-energy market according to its users' response potential and response willingness, including unit minimum compensation price, response price elasticity, and maximum response amount. After receiving the bidding strategy of each IESP, the energy market has cleared the market according to the principle of minimum compensation cost of comprehensive demand response. The clearing information mainly includes the target response quantity and unit compensation price of each IESP. If the IESP fails to meet the target response volume of the multi-energy market clearing, it will be fined somewhat.

Execution phase: After bidding, each IESP determines the target response amount of electric heat in a specific period. To achieve the response target at a minimum cost, the IESP both regulates the scheduling parameters of various energy conversion devices and storage devices and provides different incentive prices to different users on the other hand. When the user receives the unit incentive price from IESP, it will adjust according to his energy level and habits, and the user's energy adjustment is the response to participate in the comprehensive demand response. After the users participate in the complete demand response, IESP will give users incentive subsidies according to the agreement.

Among them, the interests of the three major subjects are, respectively:

Multi-energy market operator: The optimization goal of the multi-energy market is to complete the clearing of the market's unbalanced power with the minimum compensation cost based on the bidding strategy of each IESP.

IESP: IESP's optimization goal is to maximize its participation in IDR, including the compensation from the multi-energy market minus the total cost of performing IDR. The total price of IESP includes the incentive cost of guiding users to participate in IDR and the penalty for failing to complete the specified response target amount.

User: The optimization goal of the user is to maximize the benefit of IDR participation, which is the incentive subsidy obtained from the IESP minus the comfort loss of it due to the pluripotent load change.

2. The IDR-optimized incentive strategy model

2.1. Traditional response model

After the IESP releases the current period incentive price, the user optimizes the current period's response to maximize the current period's benefits.

$$\begin{aligned} &\max U_{i,k}(x_{i,k}) = \pi_{i,k}^T x_{i,k} - \varphi_{i,k}(x_{i,k}) \\ &s.t. \quad x_{i,k}^{\min} \le x_{i,k} \le x_{i,k}^{\max} \end{aligned} \tag{1}$$

Formula: indicates the benefit function of the user in the period;$x_{i,k} = \left[x_{ei,k}, x_{h,i,k}, x_{gi,k}\right]^T$represents the response amount of the user in the period, among which three of them are electric load response, heat load response, and gas load response; $\pi_{i,k} = \left[\pi_{ei,k}, \pi_{h,i,k}, \pi_{gi,k}\right]^T$ represents the unit incentive price provided by IESP to the user, three of which are the unit electric power incentive price, unit thermal power incentive price, and unit gas power incentive price grid;$x_{i,k}^{min}$and$x_{i,k}^{max}$ respectively are the upper and lower limits of user i response in k. The user's response cost function is reflected as the comfort loss after the user changes the load demand. Generally, a quadratic function can represent the user's response cost function.

$$\varphi_{i,k}(x_{i,k}) = \frac{1}{2} x_{i,k}^T diag(\theta_{i,k}) x_{i,k} + \lambda_{i,k}^T x_{i,k} \tag{2}$$

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Formula: $\theta_{i,k} = \left[\theta_{ei,k}, \theta_{hi,k}, \theta_{gi,k}\right]^T$ indicates the response elasticity of users during the time, including electric load response elasticity, heat load response elasticity, and air load response elasticity;$\lambda_{i,k} = \left[\lambda_{ei,k}, \lambda_{hi,k}, \lambda_{gi,k}\right]^T$ indicates the time minimum incentive price acceptable for users, including the minimum incentive price for the electric load, minimum incentive price for heat load, and minimum incentive price for the gas load.

2.2. Analysis of the demand-side coupling characteristics of the integrated energy system with electricity-gas-heat

In IDR, the user to different energy response strategies also has the characteristics of mutual coupling, the coupling characteristics for the user to restrict the relationship of different energy responses, such as the user in the process of heating through electric heating, can also through the gas heating, when the user in a period of a power cut more, the reduction of gas energy may be smaller. On the contrary, when the user increases the electrical energy at a certain point, the reduction of gas energy during that period may increase. To consider such coupling characteristics, the following user response quantity coupling inequality is established:

$$x_{i,k}^{\min} \le \begin{bmatrix} q_{eei,k} & q_{ehi,k} & q_{egi,k} \\ q_{hei,k} & q_{hhi,k} & q_{hgi,k} \\ q_{gei,k} & q_{ghi,k} & q_{ggi,k} \end{bmatrix} \begin{bmatrix} x_{ei,k} \\ x_{hi,k} \\ x_{gi,k} \end{bmatrix} \le x_{i,k}^{\max} \tag{3}$$

Formula: represents the coupling response characteristic matrix of the user in the period, where the element is the coupling coefficient characteristic matrix, where the element is the coupling coefficient. In the coupled response matrix, the value of the diagonal element is one. All elements off-diagonal are positive, indicating that the simultaneous transformation of different energy sources (increasing/reducing energy and energy) will reduce each other's responsiveness. In contrast, reverse changes (one energy increases energy, another reduces energy) will increase each other's responsiveness.

2.3. Dynamic response characteristics of Users

It can be seen from equation (2) that the traditional user response model only considers the optimal response policy of each user in the current period and does not consider the impact of the response policy of the current period on the response policy of the future period, that is, the dynamic response characteristics of users are ignored. The concept of active and actual IDR response is proposed to solve the problem of the dynamic response characteristics of IDR. The active response amount represents the dynamic adjustment of the user participation in the IDR, which affects the user's comfort loss; the actual response amount indicates the user's baseline load after considering the dynamic response characteristics of the demand side, which is affected by the previous response behavior in each time period. Based on the traditional model shown in (1) ~ (2), the user model considering the dynamic response characteristics of the demand side can be expressed as:

$$\begin{aligned} &\max U_{i,k}(x'_{i,k}) = \pi_{i,k}^T x'_{i,k} - \varphi_{i,k}(\tilde{x}_{i,k}) \\ &s.t \quad x_{i,k}^{\min} + \sum_{t=1}^{k-1} \phi_{i,t,k}(x'_{i,j}) \le x'_{i,j} \le x_{i,k}^{\max} + \sum_{t=1}^{k-1} \phi_{i,t,k}(x'_{i,j}) \\ &\qquad \varphi_{i,k}(\tilde{x}_{i,k}) = \frac{1}{2}\tilde{x}_{i,k}^T diag(\theta_{i,k})\tilde{x}_{i,k} + \lambda_{i,k}^T \tilde{x}_{i,k} \\ &\qquad x'_{i,k} = \tilde{x}_{i,k} + \sum_{t=1}^{k-1} \phi_{i,t,k}(x'_{i,j}) \end{aligned} \tag{4}$$

Formula:$x'_{i,k} = \left[x'_{ei,k}, x'_{hi,k}, x'_{gi,k}\right]^T$ represents the actual response amount of the user during the time period when considering the dynamic response characteristics of the demand side. It can be seen from the above formula that the impact of the user's dynamic characteristics on the user's participation in IDR mainly includes two aspects:

1) The response policy of the previous period affects the actual response potential of the user during the current period, as shown in the first constraint;

2) The actual response amount of the current time period is affected by the previous time period response policy, that is, the user's active response amount is not equal to the actual response amount, as shown in the third constraint.

The function in the above equation is shown in the following equation.

$$\begin{aligned} &\phi_{i,t,k}(x'_{i,t}) = -diag(\omega_{i,t,k})x'_{i,t} \\ &s.t.\quad 0_{3\times 1} \le \sum_{k=t+1}^{N} \omega_{i,t,k} \le 1_{3\times 1} \end{aligned} \tag{5}$$

Formula:$\omega_{i,t,k} = [\omega_{e,i,t,k}, \omega_{h,i,t,k}, \omega_{g,i,t,k}]^T$indicates the influence of the response policy in period t on the response policy in the k time period.

2.4. User-motivated IDR model considering dynamic characteristics and coupling effects

The above user model only applies to a single scenario in the demand response, that is, reduced or absorbed demand response. This is well adapted in traditional incentive DR because incentive DR in a specific time period is either reduced DR or absorbed DR, and there is no scenario of both reduced DR and absorbed DR. However, in IDR, users may face the scenario of reducing IDR and absorption IDR at a certain period of time. If the heat consumption may be in the peak period, the power load is the reduced demand response, and the heat load is the absorption demand response. The following user response model was developed to address the adaptation of IDR in complex scenarios.

$$\begin{aligned} &\max U_{i,k}(x'_{i,k}) = \pi_{i,k}^T diag(S_{MEA.k})x'_{i,k} - \varphi_{i,k}(\tilde{x}_{i,k}) \\ &s.t.\quad x_{i,k}^{\min} + \sum_{t=1}^{k-1}\phi_{i,t,k}(x'_{i,j}) \le x'_{i,j} \le x_{i,k}^{\max} + \sum_{t=1}^{k-1}\phi_{i,t,k}(x'_{i,j}) \\ &\qquad \varphi_{i,k}(\tilde{x}_{i,k}) = \frac{1}{2}\tilde{x}_{i,k}^T diag(\rho_{i,k}\cdot\theta_{i,k})\tilde{x}_{i,k} + (\rho_{i,k}\cdot\lambda_{i,k})diag(s_{i,k})\tilde{x}_{i,k} \\ &\qquad x'_{i,k} = \tilde{x}_{i,k} + \sum_{t=1}^{k-1}\phi_{i,t,k}(x'_{i,j}) \\ &\qquad i = 1,\ldots,N \\ &\qquad k = 1,\ldots,K \end{aligned} \tag{6}$$

In the formula, Reducreduction response when the value of $x'_{i.k}$'corresponding element is greater than 0, Less than 0 is less than 0; N represents the number of users in a 1, *IESP;*$s_{MEA,k} = \left[s_{MEA,e,k}, s_{MEA,h,k}, s_{MEA,gk}\right]^T$indicates the type indicator parameter of the IDR, For a reduced IDR, The value is 1, If it is an absorbed IDR, The corresponding element value is -1, $s_{i,k} = \left[s_{e,i,k}, s_{h,i,k}, s_{i,k}\right]^T$provides user type of response power, If the user makes a load reduction, The value of the corresponding element is 1, If the user increases the load, The value of its corresponding element is-1.

2.5. The IESP cost model

IESP obtains the response balance power from the energy trading market bidding and achieves the response target by dispatching the EH scheduling factors and the incentive price issued to users to minimize the total response cost. The target function is:

$$\min C_{IESP}=\sum_{t=1}^{T}(C_t^U+C_t^{ES}+C_t^{EH}) \tag{7}$$

Formula: IESP is the total response cost of IESP, C_t^U is the total incentive cost issued to users by t period IESP; C_t^{ES} is the operating cost of t period energy storage equipment, and C_t^{ES} is the operating cost of t period coupling equipment.

1) Total incentive cost

The total incentive cost is the product of the actual response amount of each user and the incentive price.

$$C_t^U=\sum_{i=1}^{N}\sum_{j=1}^{3}\pi_{i,j,t}S_{j,t}^{IESP}\xi_{i,j,t} \tag{8}$$

Formula: $\pi_{i,j,t}$ is the incentive price of the j energy issued to user i under the IESP in t; the actual response power of the j energy in t; and $\xi_{i,j,t}$ is the j energy source in t.

IDR type, when minus IDR,$S_{j,t}^{IESP}$is 1 and-1; N is the number of users. Regulation *j* when 1,2 and 3 represent electric energy, heat energy, and gas energy respectively.

2) Operating cost of energy storage equipment

The maintenance cost of energy storage equipment includes depreciation cost and maintenance cost, which can be equivalent to a quadratic function of charge and discharge power, namely:

$$C_t^{ES}=\sum_{j=1}^{3}\frac{1}{2}\alpha_j\cdot\Delta S_{j,t}^{ES^2} \tag{9}$$

Formula: α_j is the cost coefficient of the *j* th energy storage equipment; $\Delta S_{j,t}^{ES}$ is the response power provided for the *j* th energy storage equipment in the t period.

3) Operating cost of the coupling equipment

The operating cost of coupling equipment includes the cost of the electric boiler, gas turbine, and cogeneration unit.

$$C_t^{EH}=(L_{1,t}^O-\Delta P_{1,t}^{req})r_1\mu_{EB}+(L_{3,t}^O-\Delta P_{3,t}^{req})r_2\mu_{GT}+(L_{3,t}^O-\Delta P_{3,t}^{req})r_3\mu_{CHP} \tag{10}$$

Formula:$L_{j,t}^O$ is the baseline load of energy j at time t,$\Delta P_{j,t}^{req}$ is the response demand of energy j in time t, namely the response target obtained by IESP declaration, and μ_{EB}、μ_{GT}、μ_{CHP} represent the unit operating price of coupling equipment EB, GT, and CHP respectively.

The response balance power of the *j* energy obtained by IESP in period t is $\Delta P_{j,t}^{req}$, whose value is positive time represents the reduced demand, and when its value is negative, it represents the absorbed demand. The IESP will send the response target to all users and energy storage equipment to complete the response tasks. If the baseline load of the j energy in period t is $L_{j,t}^O$, the difference between the IESP expected actual response and the response balance power and energy storage response power through the energy conversion of EH shall meet:

$$\Delta P_{j,t}^{act}=L_{j,t}^O-\sum_{k=1}^{3}d_{jk}(L_{k,t}^O-\Delta P_{k,t}^{req})+\Delta S_{j,t}^{ES} \tag{11}$$

Formula: $\Delta P_{j,t}^{act}$ is the actual total response target of the t period IESP to the j energy sources, $d_{j,k}$ is the element in the EH energy coupling matrix already given in equation (3), and $\Delta S_{j,t}^{ES}$ is the power provided for the j-type energy storage device in the t time period.

IESP energy conversion through EH can optimize the energy structure and reshape the response demand. The scheduling factor of each coupling equipment should be positive and not higher than 1, that is:

$$\begin{cases} 0 \le r_1, r_2, r_3 \le 1 \\ r_2 + r_3 \le 1 \end{cases} \tag{12}$$

In addition, to extend the service life of energy storage equipment, the charging and discharging power of energy storage will be limited by the maximum capacity and residual capacity of energy storage equipment, and the following constraints should be met:

$$\begin{cases} S_{j,t}^{ES} = S_{j,0}^{ES} + \sum_{\tau=1}^{t} \eta^{ES} \Delta S_{j,\tau}^{ES} \\ v_{\min} S_j^{\max} \le S_{j,t}^{ES} \le v_{\max} S_j^{\max} \\ \sum_{t=1}^{T} \Delta S_{j,t}^{ES} = 0 \end{cases} \tag{13}$$

Formula: $\Delta S_{j,t}^{ES}$ represents the residual capacity of the j energy storage device in t; $\Delta S_{j,0}^{ES}$ represents the initial capacity of the j energy storage device,η^{ES} is the charging and discharging efficiency coefficient of energy storage, 0.9 and 1.1;S_j^{MAX} represents the maximum capacity of the j energy storage device; v_{min} and v_{max} represent the minimum and maximum load energy states of the energy storage device, at 0.1 and 0.9, respectively. The above formula indicates that the energy storage device status remains unchanged after the entire response cycle.

The incentive price issued to users under the IESP shall be greater than the minimum incentive price for user participation in demand response and less than the subsidy price obtained when reporting the response target from the energy market, namely:

$$\rho_{i,j,t} \le \pi_{i,j,t} \le \pi_j^{req} \tag{14}$$

Formula: π_j^{req} is the subsidy price that IESP receives from the energy market.

3. Solving method

According to the establishment of the above model, this is a two-layer optimization problem. The upper IESP is the leader and issues the incentive price to the user; the lower user follows and determines their response according to the received incentive price. The interaction process between the two can be seen as a Stackelberg game model with one master and multiple followers. The upper goal is the minimum response cost, and the lower goal is the most significant benefit for each user. There is a unique optimal equilibrium solution in this model. According to the proof conditions given in the literature [25], the proof process is given as follows:

1) According to the established comprehensive demand response model, the policy of the upper IESP needs to meet the constraints (8) - (13), the user's policy needs to meet the constraints (14), and the policy set of each IDR participant is non-empty tight convex set;

2) Prove that when the strategy of the top leader is given, all the bottom layers follow and only one optimal solution.

For the first partial derivative of the user benefit objective function of about, you can obtain the following:

$$\frac{\partial U_{i,t}(\xi_{i,j,t})}{\partial \xi_{i,j,t}} = \pi_{i,j,t} S_{i,j,t}^{IESP} - \frac{\xi_{i,j,t}}{\theta_{i,j,t}} - \rho_{i,j,t} \lambda_{i,j} \tag{15}$$

Make the first partial derivative equal to 0, which can be obtained:

$$\tilde{\xi}_{i,j,t} = \theta_{i,j,t} (\pi_{i,j,t} S_{i,j,t}^{IESP} - \rho_{i,j,t} \lambda_{i,j}) \tag{16}$$

Further, obtain the second-order partial guide:

$$\frac{\partial^2 U_{i,t}(\xi_{i,j,t})}{\partial \xi_{i,j,t}{}^{2}} = -\frac{1}{\theta_{i,j,t}} \tag{17}$$

Due to the user response willingness, which is positive, here the second-order deflection value is always less than 0, indicating that the user objective function is strictly concave, so there must be maximum power. Therefore, when the incentive price issued by IESP is issued, each user has a unique optimal solution.

In conclusion, two points can prove a unique Stackelberg equilibrium solution for the IDR optimization excitation strategy proposed in this chapter.

4. Example analysis

The solution is solved using the IPOPT toolbox based on the MATLAB platform. Because reporting response power to the energy market is not the focus of this chapter, the response target is given directly in the example. The simulation scenario includes 50 users. The baseline load of IESP is 3000kw, thermal energy 2500KW, gas energy 2500KW, and the subsidized price offered to IESP in the multi-energy market is 2 yuan/KW. The value of other parameters is shown in Table 1.

Table 1. Example parameters.

parameter	Value	parameter	Value
$\theta_{i,e,0}$	[7.5,9]	η_{CHP}^{e}	0.35
$\theta_{i,\hbar,0}$	[4.5,6]	$\eta_{CHP}^{\hbar}$	0.45
$\theta_{i,g,0}$	[6,7.5]	α_1	0.003
$\lambda_{i,e}$	[0.15,0.3]	α_2	0.002
$\lambda_{i,\hbar}$	[0.25,0.4]	α_3	0.001
$\lambda_{i,g}$	[0.2,0.35]	μ_{EB}	0.015
η_{GT}	[0.80]	μ_{GT}	0.025
η_{EB}	[0.85]	μ_{CHP}	0.020

Multi-Scenario IDR effect analysis

In order to verify the effectiveness and economy of the proposed IDR strategy in subtraction scenarios, absorption scenarios, and hybrid scenarios, four comprehensive demand response experiment scenarios under a single period are set up without considering the participation of energy storage. The specific scenario parameters are shown in Table 2. The electricity incentive prices and response power obtained by each user are shown in Figure 3.

Scenario 1: The three energy sources of electricity and heat gas are all absorbed IDR;

Scenario 2: The three energy sources of electric and hot gas are all reduced IDR;

Scenario 3: Electric energy and heat energy are IDR, and gas energy is IDR;

Scenario 4: Electric and gas energy are reduced IDR, and heat energy is absorbed IDR.

The contrast experiment is set as the traditional demand response DR, regardless of the coupled interaction between the different energy sources, and is limited to the exchange use between the same energy sources. The total cost comparison under different scenarios is shown in Table 3.

Table 2. Response targets for 4 scenarios.

Response target/KW	electric energy	heat energy	Natural gas energy
scenario 1	400	600	400
scenario 2	-400	-200	-400
scenario 3	400	400	-300
scenario 4	-300	400	-200

Table 3. Comparison of total costs in different scenarios.

Total response cost/yuan	DR	IDR
scenario 1	1645.6	1517.3
scenario 2	1444.3	1365.9
scenario 3	1115.6	192.5
scenario 4	985.1	124.5

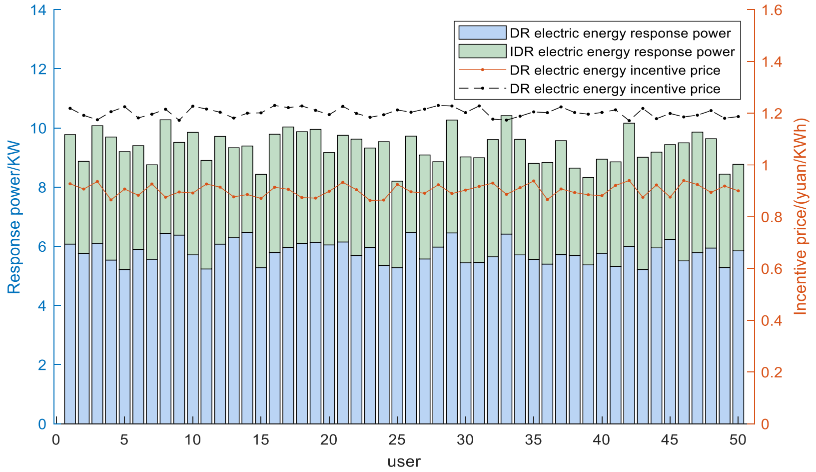

Figure 3. Response power and price of user electric energy.

Figure 4 shows the cost of user dissatisfaction in four scenarios. Under the incentive-based comprehensive demand response strategy proposed in this chapter, the cost of user dissatisfaction decreases in all four scenarios, and the decrease is evident in scenario 3 and scenario 4 but not in scenario 1 and scenario 2. The reason is whether the response direction of the three energy sources is the same when the response direction of the three energy sources is the same, i.e., they are all abatement type, or they are all consumption type, only a tiny amount of energy is converted. When the response direction of the three energy sources is not the same, the complementary coupling characteristic between different energy sources will come into play. The abatement-type energy can be converted into consumption-type energy so that the energy response of the user becomes less. The user's dissatisfaction cost decreases. Satisfaction is reduced, and thus the cost of the user is reduced.

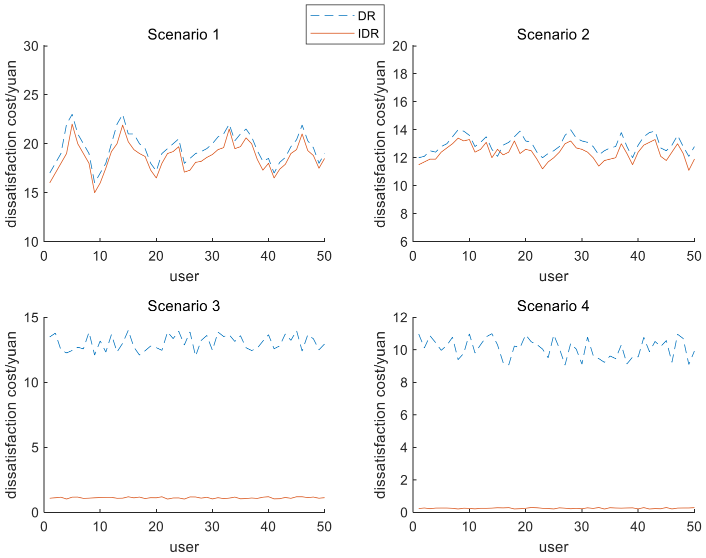

Figure 4. Cost comparison of user dissatisfaction.

As can be seen from Table 4 in the scenario 1 pure reduction response target, the proposed IDR strategy of electric energy and actual gas power is higher than DR, and thermal energy actual power is lower than DR. This shows that part of the energy and gas through the electric boiler, gas boiler, cogeneration unit, and other energy coupling equipment into heat energy, so that the total incentive cost of IDR strategy reduced by 11.39% than DR. This is because the initial thermal energy response target is higher than that of electric energy and gas energy. In contrast, the users' response willingness to thermal energy is low. The minimum incentive price is high, resulting in IESP reducing thermal energy reduction demand through energy conversion, thus reducing the total incentive cost. This can also be seen from the incentive price in the table. In DR, the heat energy incentive price is much greater than the electric and gas energy incentives. Energy coupling greatly reduces the incentive price difference of energy in 3. In addition, it can be seen from Table 4 that the total response power of IDR is slightly greater than DR because of the conversion efficiency of energy coupling equipment. Some energy will be lost during conversion, resulting in the reduction of users slightly higher than the response target.

Table 4. Comparison of integrated energy service providers under two response modes.

parameter	DR	IDR	Change ratio
Electric response power /KW	320	458.352	43.24%
Thermal response power /KW	540	382.658	-29.14%
Gas response power /KW	330	372.514	12.88%
Total response power /KW	1190	1213.524	1.98%
Average electric incentive price /(yuan/KW·h)	0.910	1.119	22.97%
Average thermal incentive price /(yuan/KW·h)	1.932	1.412	-26.91%
Average gas incentive price /(yuan/KW·h)	1.056	1.176	12.00%
Total response cost /yuan	1683.0	1491.3	-11.39%

5. Conclusions

This paper proposes a comprehensive demand response optimization model that considers the multi-energy joint response problem. Based on the coordinated interaction model between the IESP and the user, the optimal incentive strategy is solved, which realizes the economy of the IESP and the user participating in the multi-energy joint response scenario. Finally, the validity of the proposed model is verified by an example analysis. This paper mainly draws the following conclusions:

1) Through analysis and derivation, we prove that the proposed IDR model has a unique equilibrium solution, which can reduce the response cost of IESP but also reduce user dissatisfaction.

2) The proposed IDR model can be applied to various comprehensive demand response scenarios such as reduction, consumption, and mixed type by formulating a differentiated incentive mechanism by considering the user response characteristics. In addition, multi-period coupling optimization can be realized in continuous response scenarios to further tap the optimization potential of IDR.

3) By comparing the response cost and user dissatisfaction in the continuous response scenario and the change in user response characteristics, the optimized incentive strategy proposed in this paper can improve the accuracy of IDR and reduce the response cost. In conclusion, the comprehensive demand response optimization incentive strategy, which considers the user response characteristics, is helping to solve the problem of coordinated optimization between IESP and user under multi-energy joint response and has good adaptability and economy.

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