Dual Interval Optimization Based Trading Strategy for ESCO in Day-ahead Market with Bilateral Contracts

Shengmin Tan, Xu Wang, and Chuanwen Jiang

***Abstract*—Being capable of aggregating multiple energy resources, the energy service company (ESCO) has been regarded as a promising alternative for improving power system flexibility and facilitating the consumption of renewable resources in the electricity market. Considering the uncertain variables in day-ahead (DA) market trading, an ESCO can hardly determine their accurate probability distribution functions. Traditional interval optimization methods are used to process these uncertain variables without specific probability distribution functions. However, the lower and upper bounds of the intervals may change due to extreme weather conditions and other emergent events. Hence, a dual interval optimization based trading strategy (DIOTS) for ESCO in a DA market with bilateral contracts (BCs) is proposed. First, we transfer the dual interval optimization model into a simple model consisting of several interval optimization models. Then, a pessimistic preference ordering method is applied to solve the derived model. Case studies illustrating an actual test system corroborate the validity and the robustness of the proposed model, and also reveal that ECSO is critical in improving power system flexibility and facilitating the ability of absorbing renewable resources.**

***Index Terms*—Dual interval optimization, energy service company (ESCO), day-ahead market, bilateral contract market.**

I. INTRODUCTION

IN the face of the climate change and the ongoing sustainable development, many countries put energy conservation and emission reduction as part of their primary strategic positions. It is effective to improve the efficiency and low-carbon level in energy systems with the integrated technology of renewable energy resources [1]. However, a renewable energy plant cannot directly participate in a deregulated power market due to its intermittent characteristics [2] and it may also introduce distributed energy management problems in a power system [3]. Generally, integration conceptions such as a virtual power plant (VPP) and microgrid are used to manage the distributed energy resources [4]. Reference [5] proposed an economic rescheduling strategy using a medium of imbalanced price to reduce deviation losses and increase total profits in a VPP. Reference [6] indicated that the efficient operation of a microgrid connecting to the main grid was able to improve market involvement. Nevertheless, most existing researches only involve the power energy management in the electrical power system. In this paper, we propose the concept of an energy service company (ESCO) to provide a highly effective management service for coupled heat and power systems.

ESCOs provide energy services to the end-user, aiming to reduce operation and maintenance costs of the system [7]-[9]. To obtain the optimal management strategy with the goals of ensuring system efficiency, optimization control and regular maintenance [10], numerous programming methods have been developed. Reference [11] proposed an agent-based model to examine the possibility of energy service companies to enhance the large-scale promotion of the energy efficiency in households. In order to evaluate the potential energy saving profit and make the optimal investment decisions for an ESCO, a simulation-based model is developed to maximize the owner's profit, and satisfy ECSO's expected rate of return in [12]. Considering the fluctuations of energy market price [13], weather conditions, load forecasting errors and varied human operations [14], the total actual energy revenue of an ESCO is still uncertain due to the interactions among the uncertainties [15], which would also result in unpredictable financial losses.

To further deal with the uncertainties in energy system planning, a series of uncertain models have been proposed [16] - [19]. Variables with detailed distribution information can be expressed as stochastic distributions [20], [21] or fuzzy distributions [22], [23], while those without detailed distribution information are presented as interval numbers [24]. Though capable of dealing with most uncertainty problems in the power systems, the above methods fail to describe some highly uncertain variables which are caused by extreme weather conditions or other emergent events [25]. Thus, because of the ability to process highly uncertain variables, the dual interval approach is regarded as an effective method and has attracted global attention.

To tackle uncertainties presented as dual intervals, [26]

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proposed an interactive algorithm and a vertex analysis approach to identify desired pollution-abatement strategies with minimized costs and maximized environmental efficiencies. Reference [27] developed a dual interval fixed-mix stochastic programming method for planning water resources management under uncertainty. Dual interval programming has been widely applied to pollution-abatement and waste management [28]. However, few studies with the dual interval programming in energy market of ESCOs are reported. Therefore, it would be desirable that a dual interval optimization based trading strategy (DIOTS) for an ESCO in a day-ahead (DA) market with bilateral contracts (BCs) is addressed.

This paper proposes a DIOTS for an ESCO in multi-energy market. The proposed method is capable of processing an optimization problem with highly uncertain variables. The primary contributions are summarized as follows:

1) This paper proposes the concept of ESCO, which provides an effective management service for a system with multiple energies to achieve the goal of energy conservation and emission reduction.

2) A DIOTS-ESCO model in a DA market with BCs is established, which is more applicative and efficient than conventional models in handling uncertainty problems.

3) This paper employs dual-interval decomposition technology and a pessimistic preference ordering method to solve the proposed DIOTS problem. The proposed method deals with uncertainties concisely and effectively. Moreover, the risk pessimistic degree of ESCOs is taken into account.

The remaining sections of this paper are organized as follows. Section II describes the concept of an ESCO and introduces the mathematical model based on dual interval optimization theory. Section III covers the solution method. Section IV presents some cases and discussions to demonstrate the effectiveness of the proposed method, and the conclusions are presented in Section V.

II. Mathematical Formulation of an ESCO

A. ESCO

The schematic diagram of an ESCO is shown in Fig. 1.

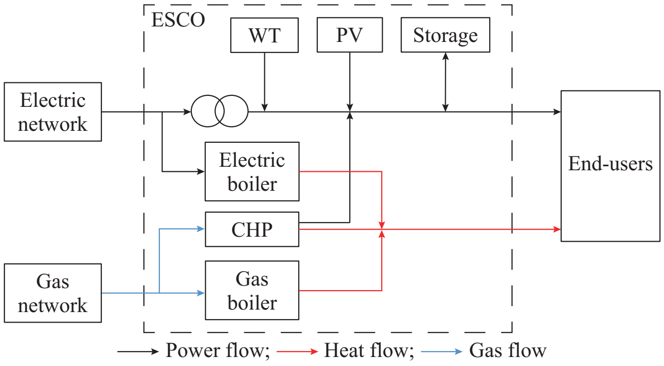

Fig. 1. Schematic diagram of ESCO.

The ESCO shown in Fig. 1 is composed of two parts, which serve the electric network and the gas network separately. The electrical network contains a wind turbine (WT), a photovoltaic (PV) module system, an electric boiler, a combined heat and power (CHP) unit and a storage serving as a buffer. The gas network consists of a CHP unit and a gas boiler.

Figure 2 depicts a price-taker ESCO participating in a DA market with BCs. The energy resources are assumed to first satisfy the local demand, and then to trade the redundant energy in the DA market or the BC market.

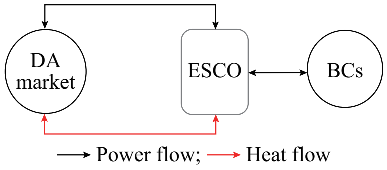

Fig. 2. Brief framework of ESCO in an energy market.

B. Mathematical Model

1) Brief Introduction of Dual Interval Number

A interval number is a real number set composed of a closed interval which defines the range of a random variable with its upper limit and lower limit. For arbitrary x^L, x^R subject to $x^L \le x^R$, $X^\pm = [x^L, x^R]$ is named as an interval number in which x^R is the upper bound and x^L is the lower bound. $X^\pm$ is alternatively represented by its mid-point and half-width, as shown in (1)-(3). Mid-point $m(X)$ indicates the middle location of the interval number. Half-width $w(X)$ shows the range of the interval number. As to the basic mathematical operations of the interval number, which include the operations of addition, subtraction, multiplication and division, [29]-[31] have discussed them in detail.

$$X^\pm = \langle m(X), w(X) \rangle \tag{1}$$

$$m(X) = \frac{1}{2}\left(x^L + x^R\right) \tag{2}$$

$$w(X) = \frac{1}{2}\left(x^R - x^L\right) \tag{3}$$

A dual interval number is derived from the interval number due to the high uncertainties in the lower and upper bounds of the intervals, which can be represented as $[X^\pm]^\pm = [[a,c],[d,b]]$. The interval bounds $x^{L\pm} = [a,c]$ and $x^{R\pm} = [d,b]$ separately represent the uncertainties in the lower and upper bounds of the dual interval number.

2) Objective Function

The objective function of ESCO is to maximize the profits of selling or purchasing the energy in DA and BC markets including a measure of cost. As expressed in (4), the profit interval of ESCO is divided into two types of incomes respectively obtained from DA market and BC market. The former contains the revenue from trading power and heat with the network by (5)-(7), and the latter can be computed by (8). The cost of ESCO contains fuel and maintenance costs expressed by (9). The expected profit of ESCO can be defined as follows:

$$\max\left[P_{r,ESCO}{}^{\pm}\right]^{\pm} = \sum_{t=1}^{N_T}\left(\left[P^t_{r,DA}{}^{\pm}\right]^{\pm} + \left[P^t_{r,BC}{}^{\pm}\right]^{\pm} - \left[C^t_{total}{}^{\pm}\right]^{\pm}\right) \tag{4}$$

$$\left[P_{r,DA}^{t\ \pm}\right]^{\pm}=\left[P_{r,DA,grid}^{t\ \pm}\right]^{\pm}+\left[P_{r,DA,heat}^{t\ \pm}\right]^{\pm} \tag{5}$$

$$\left[P_{r,DA,grid}^{t\ \pm}\right]^{\pm}=\left[P_{DA,sell}^{t\ \pm}\right]^{\pm}\lambda_{DA,g,sell}^{t}-\left[P_{DA,buy}^{t\ \pm}\right]^{\pm}\lambda_{DA,g,buy}^{t} \tag{6}$$

$$\left[P_{r,DA,heat}^{t\ \pm}\right]^{\pm}=\left[H_{DA,sell}^{t\ \pm}\right]^{\pm}\lambda_{DA,h,sell}^{t}-\left[H_{DA,buy}^{t\ \pm}\right]^{\pm}\lambda_{DA,h,buy}^{t} \tag{7}$$

$$\left[P_{r,BC}^{t\ \pm}\right]^{\pm}=\left[P_{BC}^{t\ \pm}\right]^{\pm}\lambda_{BC}^{t} \tag{8}$$

$$\left[C_{total}^{t\ \pm}\right]^{\pm}=\left[C_{fuel}^{t\ \pm}\right]^{\pm}+\left[C_{OM}^{t\ \pm}\right]^{\pm} \tag{9}$$

where t is the index of the time period; N_T is the total number of hours; $P_{r,DA}^{t}$ and $P_{r,BC}^{t}$ are the profits from participating in the DA and BC markets, respectively; $P_{r,DA,grid}^{t}$ and $P_{r,DA,heat}^{t}$ are the revenues from trading power and heat in the DA market, respectively; $\lambda_{DA,g,sell}^{t}$, $\lambda_{DA,g,buy}^{t}$, $\lambda_{DA,h,sell}^{t}$, $\lambda_{DA,h,buy}^{t}$, and λ_{BC}^{t} are the prices of selling or purchasing energy in the DA and BC markets; $P_{DA,sell}^{t}$, $P_{DA,buy}^{t}$, $H_{DA,sell}^{t}$, $H_{DA,buy}^{t}$, and P_{BC}^{t} are the amounts of selling and purchasing energy in the DA and BC markets; and C_{total}^{t}, C_{fuel}^{t}, and C_{OM}^{t} are the total, fuel, and maintenance costs, respectively.

3) *Energy Balance Constraints*

Equations (10) and (11) present the power balance and thermal balance of ECSO. As can be seen in (10) and (11), the left side represents the energy output from ECSO, while the right side contains the energy demands and the traded energy.

$$\left[P_{chp}^{t\ \pm}\right]^{\pm}+P_{w}^{t\ \pm}+P_{pv}^{t\ \pm}+\left[P_{s}^{t\ \pm}\right]^{\pm}=\left[P_{L}^{t\ \pm}\right]^{\pm}+\left[P_{BC}^{t\ \pm}\right]^{\pm}+\left[P_{DA,sell}^{t\ \pm}\right]^{\pm}-\left[P_{DA,buy}^{t\ \pm}\right]^{\pm} \tag{10}$$

$$\left[H_{chp}^{t\ \pm}\right]^{\pm}+\left[H_{boiler}^{t\ \pm}\right]^{\pm}=\left[H_{L}^{t\ \pm}\right]^{\pm}+\left[H_{DA,sell}^{t\ \pm}\right]^{\pm}-\left[H_{DA,buy}^{t\ \pm}\right]^{\pm} \tag{11}$$

where P_{chp}^{t}, P_{w}^{t}, P_{pv}^{t}, and P_{s}^{t} are the power outputs of CHP units, WTs, PV and storage at time t, respectively; P_{L}^{t} is the load demand; and H_{chp}^{t}, H_{boiler}^{t}, and H_{L}^{t} are the thermal outputs of CHP units, boiler, and the thermal demand, respectively.

4) *Constraints of CHP Units*

The fuel cost and thermal output of CHP as a function of output power can be represented by (12) and (13).

$$\left[F_{chp}^{t\ \pm}\right]^{\pm}=a_f\left[P_{chp}^{t\ \pm}\right]^{\pm}+b_f I_{chp}^{t} \tag{12}$$

$$\left[H_{chp}^{t\ \pm}\right]^{\pm}=a_h\left[P_{chp}^{t\ \pm}\right]^{\pm}+b_h I_{chp}^{t} \tag{13}$$

where F_{chp}^{t} and H_{chp}^{t} are the fuel consumption and thermal output of CHP, respectively; and a_f, a_h, b_f, and b_h are the characteristic parameters of CHP unit.

The operation state of CHP should be in its limited range, which is constrained by (14)-(16). Constraints (17) and (18) show the ramp-up and ramp-down rate limits of CHP unit.

$$P_{chp,\min}I_{chp}^{t}\le\left[P_{chp}^{t\ \pm}\right]^{\pm}\le P_{chp,\max}I_{chp}^{t} \tag{14}$$

$$y^t+z^t\le 1 \tag{15}$$

$$y^t-z^t=I_{chp}^{t}-I_{chp}^{t-1} \tag{16}$$

$$\left[P_{chp}^{t\ \pm}\right]^{\pm}-\left[P_{chp}^{t-1\ \pm}\right]^{\pm}\le(1-y^t)R_U+y^tS_U \tag{17}$$

$$\left[P_{chp}^{t\ \pm}\right]^{\pm}-\left[P_{chp}^{t-1\ \pm}\right]^{\pm}\le(z^t-1)R_D+z^tS_D \tag{18}$$

where $P_{chp,\min}$ and $P_{chp,\max}$ are the minimum and maximum power outputs, respectively; I_{chp}^{t} is the state of CHP with $I_{chp}^{t}=1$ and $I_{chp}^{t}=0$, indicating that CHP is in an operational state and a stopped state, respectively; y^t and z^t are auxiliary binary variables to indicate the start-up and shut-down states of CHP, respectively; and R_U, R_D, S_U, and S_D are the speed limits of the ramp-up, ramp-down, start-up, and shut-down status, respectively.

5) *Boiler Constraints*

The thermal output of the boiler should be limited in its regular range as follows:

$$H_{boiler,\min}\le\left[H_{boiler}^{t\ \pm}\right]^{\pm}\le H_{boiler,\max} \tag{19}$$

where H_{boiler}^{t} is the thermal output of the boiler; and $H_{boiler,\min}$ and $H_{boiler,\max}$ are the minimum and maximum thermal outputs of the boiler, respectively. The fuel cost of the boiler as a function of the output thermal can be computed in (20).

$$\left[F_{boiler}^{t\ \pm}\right]^{\pm}=\frac{\left[H_{boiler}^{t\ \pm}\right]^{\pm}}{e_{boiler}} \tag{20}$$

where F_{boiler}^{t} is the fuel consumption of the boiler; and e_{boiler} is the efficiency of the boiler.

6) *Storage Constraints*

The power output of storage depends on the discharging and charging power as shown in (21), and limited by the maximum capacity in (22). The state of charge (SoC) at time t is calculated by (23), and is also limited to the regular range. Constraint (25) ensures that the capacity status in the last moment is no less than the initial state in the whole cycle.

$$\left[P_{s}^{t\ \pm}\right]^{\pm}=\left[P_{s,d}^{t\ \pm}\right]^{\pm}-\left[P_{s,c}^{t\ \pm}\right]^{\pm} \tag{21}$$

$$-P_{s,\max}\le\left[P_{s}^{t\ \pm}\right]^{\pm}\le P_{s,\max} \tag{22}$$

$$SoC^t=SoC^{t-1}+P_{s,c}^{t}e_c-P_{s,d}^{t}/e_d \tag{23}$$

$$SoC_{\min}\le SoC^t\le SoC_{\max} \tag{24}$$

$$SoC^{N_T}\ge SoC_{init} \tag{25}$$

where $P_{s,d}^{t}$, $P_{s,c}^{t}$, and $P_{s,\max}$ are the discharging, charging and maximum power, respectively; SoC^t, SoC^{N_T}, and SoC_{init} are the SoC at time t, N_T, and the beginning, respectively; $SoC_{\min}$ and $SoC_{\max}$ are the minimum and maximum SoCs, respectively; and e_c and e_d are the efficiencies of charging and discharging, respectively.

7) *Cost Constraints*

The total cost of ECSO consists of the fuel cost and maintenance cost. The first part contains the fuel consumptions of CHP and boiler, as shown in (26). The second part contains the maintenance costs of CHP, WTs, PV, boiler and storage computed by (27).

$$\left[C_{fuel}^{t\ \pm}\right]^{\pm}=\left(\left[F_{chp}^{t\ \pm}\right]^{\pm}+\left[F_{boiler}^{t\ \pm}\right]^{\pm}\right)\lambda_{gas} \tag{26}$$

$$\left[C_{OM}^{t\ \pm}\right]^{\pm}=c_{chp}^{OM}\left[P_{chp}^{t\ \pm}\right]^{\pm}+c_{w}^{OM}P_{w}^{t\ \pm}+c_{pv}^{OM}P_{pv}^{t\ \pm}+c_{boiler}^{OM}\left[H_{boiler}^{t\ \pm}\right]^{\pm}+c_{boiler}^{OM}\left(\left[P_{s,d}^{t\ \pm}\right]^{\pm}+\left[P_{s,c}^{t\ \pm}\right]^{\pm}\right) \tag{27}$$

where λ_{gas} is the price of gas; and c_{boiler}^{OM}, c_{chp}^{OM}, c_{w}^{OM} and c_{pv}^{OM} are the maintenance costs of the boiler, CHP units, WTs and PV, respectively. To summarize, a DIOTS for an ESCO in a DA market with BCs is proposed. The objective function of the model is (4), and its constraints are (5)-(27).

III. SOLUTION METHODOLOGY

To solve the DIOTS-ESCO model, the dual interval optimization model should be transformed into a simple model consisting of several interval optimization models. Then, a pessimistic preference ordering method is applied to solve the derived interval optimization model.

A. Dual Interval Model Decomposition Method

During the first process, the dual interval parameters will be decomposed into an equivalence class of random interval parameters [32]. Assume $[X^{\pm}]^{\pm} = [[a, c], [d, b]]$, the subintervals are shown in Fig. 3. The equivalence class of viable intervals which cover $[a, b]$ can be expressed as:

$$\begin{aligned} Q = \{&\{C\},\{B,C\},\{B,E\},\{C,D\},\{C,E\},\\ &\{B,C,D\},\{B,C,E\},\{B,D,E\},\{C,D,E\},\\ &\{B,C,D,E\}\} = \{v_i\colon 1 \le i \le 10\} \end{aligned} \tag{28}$$

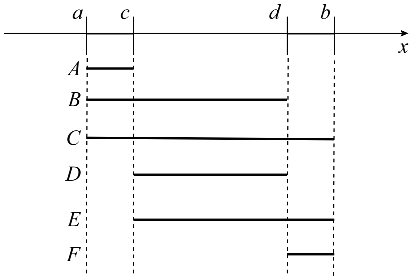

Fig. 3. Subintervals of dual interval parameters.

Reference [32] has proved that each collection v_i has the same probabilities of $1/|v_i|$. Hence, the dual interval parameters can be presented as the combination of C and D expressed as v_4 in (28), and the dual interval optimization model can be converted into a combination of two interval optimization models. The decomposition algorithm can be described in a pseudo-code format as follows.

Step 1: initialize input parameters.

Step 2: formulate the DIOTS-ESCO model corresponding to dual intervals $[[a, c], [d, b]]$.

Step 3: decompose dual intervals into an equivalence class of intervals $\{A, B, C, D, E, F\}$.

Step 4: choose the combination of C and D to present dual intervals $[[a, c], [d, b]]$.

Step 5: convert the DIOTS model into two sub-IOTS models with single intervals C and D.

B. Pessimistic Preference Ordering Method of Interval Numbers

In the interval optimization model, the objective value such as profit can be expressed in the form of intervals. In order to determine the optimal value, any two interval numbers should be compared. As to the derived interval optimization model in Section III-A, [33] applied a pessimistic preference ordering method to the order interval numbers. Assume that A and B are two interval profits and the mid-point of A is less than or equal to B. First, define a function $\phi(A < B) = [m(B) - m(A)]/[w(B) + w(A)]$, which is interpreted as the grade of acceptability of the first interval inferior to the second interval. It can be classified and interpreted further based on the comparative position of the mid-point and width of the interval B with respect to those of interval A as follows:

$$\begin{cases} \phi(A < B) = 0 & m(A) = m(B) \\ 0 < \phi(A < B) < 1 & m(A) < m(B) \text{ and } a^R > b^L \\ \phi(A < B) \ge 1 & m(A) < m(B) \text{ and } a^R \le b^L \end{cases} \tag{29}$$

According to the width, any pair of two interval numbers can be classified into two sets ξ_1 and ξ_2 as follows:

1) Set 1: $(A, B) \in \xi_1$, if $\phi(A < B) \ge 0$ and $w(A) \ge w(B)$.

2) Set 2: $(A, B) \in \xi_2$, if $\phi(A < B) \ge 0$ and $w(A) < w(B)$.

In set 1, for a maximization problem for $(A, B) \in \xi_1$, unless A and B are identical, profit interval B always has a larger mid-point and less uncertainty, so B is always the better choice. Thus, B is strictly preferred to A.

In set 2, if $\phi(A < B) \ge 1$, B is strictly preferred to A. If $\phi(A < B) = 0$, A is strictly preferred to B. If $\phi(A < B) \in (0,1)$, there exists a fuzzy preference between A and B, and decision maker (DM) has to make a tradeoff between profit and uncertainty. Reference [34] defined a fuzzy preference between the pair (A, B) in this situation. Reference [35] defined a fuzzy set B' in ξ_2, $B' = \{\, (X, B) \mid \phi(A < B) \ge 0, w(A) < w(B) \,\}$ as the rejection of B', with membership function $\mu_{B'}(X)$ mapping ξ_2 to the interval $[0, 1]$.

$$\mu_{B'}(X) = \begin{cases} 1 & m(X) = m(B) \\ \max\left\{0, \dfrac{m(X) - \left(b^L + w(X)\right)}{m(B) - \left(b^L + w(X)\right)}\right\} & m(B) > m(X) \ge b^L + w(X) \\ 0 & \text{otherwise} \end{cases} \tag{30}$$

Based on the risk tolerance of the DM described by a degree of pessimistic β, [34] proved that (31) is the necessary and sufficient condition of $A < B$.

$$m(A) + (\beta - 1)\, w(A) < m(B) + (\beta - 1)\, w(B) \tag{31}$$

Therefore, the dual interval optimization model is transformed into a combination of two derived interval optimization models through the dual interval model decomposition method in Section III-A. Then, the derived interval optimization model is solved by a pessimistic preference ordering method of interval numbers in Section III-B. Finally, combine the solutions of the derived models into the final solution of the DIOTS-ESCO. Figure 4 shows the flowchart of the proposed method.

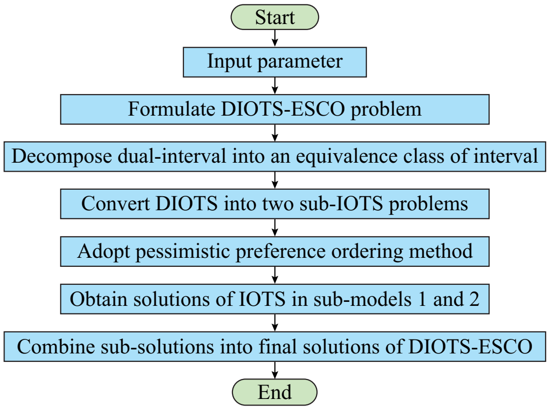

Fig. 4. Flowchart of DIOTS-ESCO.

IV. SIMULATION AND RESULTS

A. Parameter and Setting

The developed DIOTS-ESCO model is applied to a real demonstration project in China, which is conceptualized with representative costs and technical data from numerous previous studies. The components of ECSO are one CHP (600 kW), one boiler (500 kW), one WT (300 kW), one PV (305 kW), and four storages (4×200 kWh) [36]. The parameters of CHP unit are: $P_{chp,\max}$ = 600 kW, $P_{chp,\min}$ = 15 kW, R_U = 420 kW/h, R_D = 480 kW, S_U = 480 kW/h, S_D = 600 kW/h, c_{chp}^{OM} = 0.04 CNY/kWh, a_f = 2.64, a_h = 1.36, b_f = 66.2, b_h = 30.2. The parameters of each storage are: $P_{s,\max}$ = 100 kW, $SoC_{\max}$ = 160 kWh, $SoC_{\min}$ = 40 kWh, SoC_{init} = 100 kWh, SoC^{N_T} = 100 kWh, e_c = 0.9, e_d = 0.9, c_s^{OM} = 0.1 CNY/kWh. The maintenance costs of boiler, WT and PV are 0.03, 0.11 and 0.08 CNY/kWh, respectively. The efficiency of the boiler is assumed as 0.8, and the risk tolerance β is 0.3.

The dual interval model primarily focuses on the outputs, not the prices, so we assume that the prices for electricity and gas are known to simplify the calculation of the model. The purchasing and selling prices between ECSO and the energy network company are shown in Table I.

Because of the influence of socio-economic development and population growth, the demands can be described as interval parameters. Hence, we assume the fluctuating intervals of renewable resources and demands as ±20% and ±10%, respectively [27], and the forecasted graph is shown in Fig. 5. However, emergent events and abnormal weather conditions may cause additional demand uncertainties. In this situation, the fluctuating intervals may change as [−8%, 12%]. Based on the above method of interval decomposition, fluctuating intervals of demand D_M, $[-0.1D_M, 0.1D_M]$, $[-0.08D_M, 0.12D_M]$ are an equivalence class of the dual interval $[[-0.1D_M, -0.08D_M], [0.1D_M, 0.12D_M]]$. The two intervals are considered for scenarios 1 and 2, and each scenario occurs with a probability of 0.5.

TABLE I
PURCHASING AND SELLING ENERGY PRICES

Operation state	Power price (CNY/kWh)			Heat price (CNY/kWh)	Gas price (CNY/kWh)
	Peak	Flat	Valley		
Purchase	1.56	0.70	0.43	0.86	0.3
Sell	1.28	0.54	0.32	0.85	-

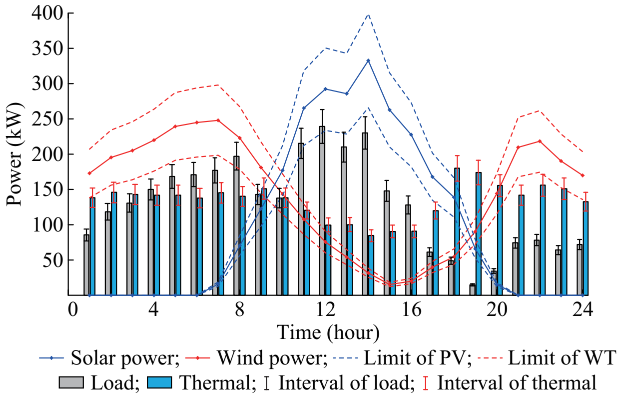

Fig. 5. Forecasted interval of renewable resources and demands.

All case studies are performed on a PC with an 8 GB RAM and a 2.6 GHz Intel Core i5-3320M processor by the commercial solver CPLEX 12.4.

B. Results of Proposed DIOTS-ESCO Model

Table II shows the solutions of the DIOTS-ESCO model in different scenarios. The increase of the DA market profit is greater than the BC market profit, which indicates that the DA market provides the major profits to ECSO compared with a less important role of the BC market.

TABLE II
SOLUTION OF DIOTS-ESCO

Case	DA market profit (CNY)	BC market profit (CNY)	Total cost (CNY)	ESCO profit (CNY)	Output of DA market (kW)	Output of BC market (kW)
Scenario 1	[12050, 13608]	[168.00, 411.17]	[9890.3, 10523.0]	[1695.2, 4128.7]	[6447.8, 8708.8]	[480.0, 1174.8]
Scenario 2	[12144, 13216]	[168.00, 402.79]	[9575.3, 10835.0]	[1476.8, 4043.3]	[6294.5, 8670.9]	[480.0, 1150.8]
Dual interval	[[12050, 12144], [13216, 13608]]	[168.00, [402.79, 411.17]]	[[9575.3, 9890.3], [10523.0, 10835.0]]	[[1476.8, 1695.2], [4043.3, 4128.7]]	[[6294.5, 6447.8], [8670.9, 8708.8]]	[480.0, [1150.8, 1174.8]]

The outputs of power and thermal are illustrated in Figs. 6 and 7. The red vertical lines and red points represent the interval of each variate. Since the electricity price changes at different hours, the power output of ECSO is at a lower level only to satisfy the local load demands at valley hours. ESCO even purchases power from the network company for storage, such as hour 5. Meanwhile, the storage is also charging to store energy so as to make preparations for selling at peak hours. Because of the expensive fuel costs of CHP units, CHP units are shut down at valley hours, and ECSO purchases thermal from the network company to supply local thermal demands. Correspondingly, the power output of ECSO is at high levels in order to sell power as much as possible at peak hours, and the storage is at a discharging state in order to bring in profits.

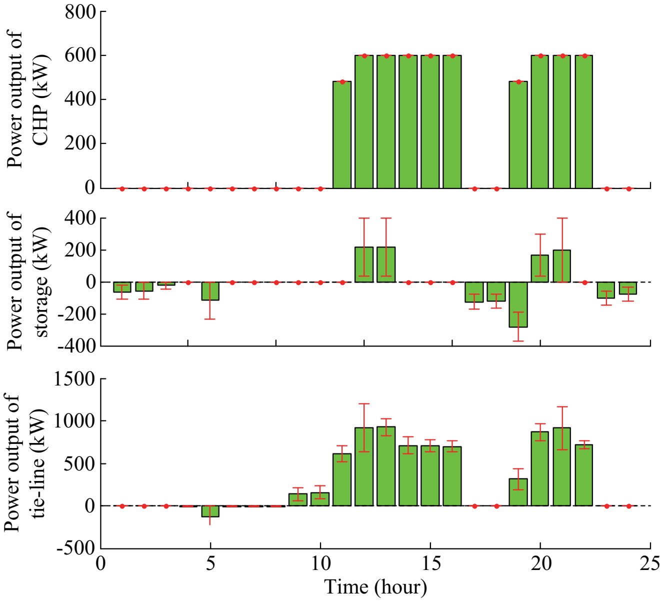

Fig. 6. Power output in scenario 1.

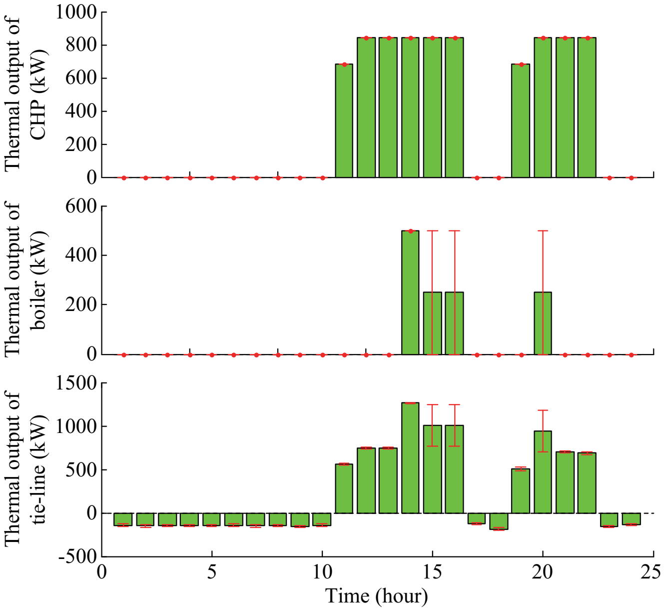

Fig. 7. Thermal output in scenario 1.

Figure 8 shows the possibility of ECSO profit. The possibility of the middle interval [1695.2, 4043.3] is 1, while the marginal intervals [1476.8, 1695.2] and [4043.3, 4128.7] have the possibility of 0.5. According to their possibility distributions, the dual interval value is highly desired in the range of [1695.2, 4043.3]. This interval has a higher possibility level (2 times) than the ranges [1476.8, 1695.2] and [4043.3, 4128.7]. Therefore, the interval range [1695.2, 4043.3] would be given more consideration when ECSO is planning a trading strategy. Depending on the pessimistic degree of the risk of ECSO, it is still possible to plan to obtain the profits at the range of [1476.8, 1695.2] or at the range of [4043.3, 4128.7]. The increases of ECSO profit indicate that these dual intervals are sensitive to the modeling inputs under extreme conditions.

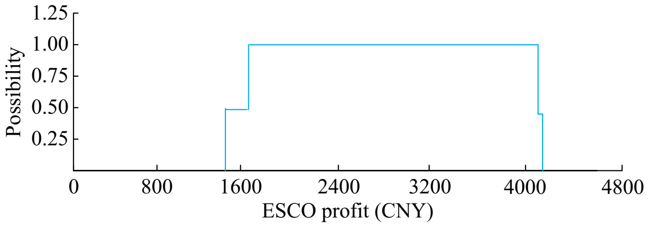

Fig. 8. Possibility distribution of ESCO profit.

C. Sensitivity Analysis

Based on the setting of the above scenarios, we gradually increase BC price to observe the reaction of the various profits of ECSO. With the increase of the BC price, the profit in the DA market and total cost is reduced, while the profit in the BC market and retained profit of ECSO increases. When the BC price is 0.3 CNY/kW, all the overall output is dealt with in the DA market except the minimum guarantee in the BC market. With the BC price increasing, the proportion in the BC market rises while the DA market share drops. When the BC price is 0.45 CNY/kW, all of the overall output is dealt with in the BC market. The processes and detailed data are shown in Tables III and IV.

The degree of pessimism β reflects the risk aversion of ECSO towards profit intervals. With the higher β, ECSO will be more optimistic and risk-preferred. From Table V, the profit of ECSO and the width of the profit interval increase at the same time, which indicates that the profit and the risk increases with the growth of the pessimistic degree. The variation in the BC and DA markets with the change of β presents two phenomena. When β changes from 0.1 to 0.3, there is not any change. However, with further increase of β, the profit in the DA market increases gradually, while the profit in the BC market share drops because ECSO prefers to participate in the high-risk market.

Table VI shows the influence of uncertainties about renewable energy on the results of the model. The uncertainties are represented as the width of the renewable energy interval. With the width broadening of the interval, the interval profit of ECSO greatly increases. When the interval width broadens to 30%, the width of ECSO's profit interval is twice as much as that in a width of 10%. Because of the corresponding high risk, to some extent, the increasing profit does not make sense to ECSO. Thus, optimization results are very sensitive to the intervals of the random input variables and the combination of reasonable profit and risk is very important for ECSO.

TABLE III
PROFIT OF ESCO UNDER DIFFERENT PRICES OF BCS

Price (CNY/kW)	DA market profit (CNY)	BC market profit (CNY)	Total cost (CNY)	ESCO profit (CNY)
0.30	[[12365.0, 13089.0], [13430.0, 13515.0]]	144.00	[9575.3, [10838.0, 11780.0]]	[[1452.8, 1671.2], [3999.2, 4083.9]]
0.35	[[10702.0, 12050.0], [13216.0, 13608.0]]	[168.00, [402.79, 411.17]]	[[9575.3, 9890.3], [10523.0, 10835.0]]	[[1476.8, 1695.2], [4043.3, 4128.7]]
0.40	[[10790.0, 12144.0], [13216.0, 13293.0]]	[192.00, [460.34, 469.91]]	[[9263.0, 9575.0], [9575.3, 10835.0]]	[[1500.8, 1719.2], [4100.8, 4187.4]]
0.45	[[7861.9, 8017.7], [9487.3, 9548.1]]	[[3048.50, 3117.50], [4419.80, 4447.60]]	[[9259.7, 9263.0], 9575.3]	[[1650.7, 1872.2], [4331.8, 4420.4]]

TABLE IV
OUTPUT OF ESCO UNDER DIFFERENT PRICES OF BCS

Price (CNY/kW)	Output of DA market (kW)	Output of BC market (kW)
0.30	[[7434.0, 7495.8], [10422.0, 10484.0]]	480.00
0.35	[[6294.5, 6447.8], [8670.9, 8708.8]]	[480.00, [1150.80, 1174.80]]
0.40	[[5434, 5495.8], [7590.9, 7628.8]]	[480.00, [1830.84, 1854.76]]
0.45	0	[[7434.00, 7495.80], [14967.00, 15016.00]]

TABLE V
PROFIT OF ESCO UNDER DIFFERENT DEGREES OF PESSIMISM

β	DA market profit (CNY)	BC market profit (CNY)	Total cost (CNY)	ESCO profit (CNY)
0.1	[[10702, 12050], [13216, 13608]]	[168.00, [402.79, 411.17]]	[[9575.3, 9890.3], [10523.0, 10835.0]]	[[1476.8, 1695.2], [4043.3, 4128.7]]
0.3	[[10702, 12050], [13216, 13608]]	[168.00, [402.79, 411.17]]	[[9575.3, 9890.3], [10523.0, 10835.0]]	[[1476.8, 1695.2], [4043.3, 4128.7]]
0.5	[[11052, 11079], [13493, 13529]]	[168.00, [288.79, 296.04]]	[[9655.2, 9920.1], [10713.0, 10826.0]]	[[1572.8, 1783.4], [4231.7, 4274.2]]
0.7	[[11418, 11468], [13582, 13618]]	[168.00, [264.60, 290.70]]	[[9736.1, 9986.3], [10832.0, 11254.0]]	[[1612.5, 1885.2], [4426.4, 4495.6]]
0.9	[[11487, 11526], [13602, 13687]]	[168.00, [252.17, 285.43]]	[[9895.7, 10083.0], [11050.0, 11687.0]]	[[1721.9, 1981.1], [4409.6, 4418.5]]

TABLE VI
PROFIT OF ESCO UNDER DIFFERENT INTERVALS OF RENEWABLE ENERGY

Interval width (%)	DA market profit (CNY)	BC market profit (CNY)	Total cost (CNY)	ESCO profit (CNY)
±10	[[9614, 9625], [12164, 12202]]	[168.00, [326.68, 335.06]]	[[9081.70, 9197.47], [10231, 10583]]	[[1758.0, 1893.2], [3893.5, 3939.3]]
±15	[[10103, 11051], [13043, 13080]]	[168.00, [358.74, 367.11]]	[[9255.80, 9429.37], [10358, 10789]]	[[1647.5, 1795.1], [3972.0, 4017.7]]
±20	[[10702, 12050], [13216, 13608]]	[168.00, [402.79, 411.17]]	[[9575.30, 9890.30], [10523, 10835]]	[[1476.8, 1695.2], [4043.3, 4128.7]]
±25	[[11209, 12157], [13592, 13630]]	[168.00, [422.85, 431.22]]	[[9865.22, 9954.70], [10769, 10996]]	[[1391.8, 1444.1], [4160.7, 4206.4]]
±30	[[11579, 13626], [13783, 13821]]	[168.00, [454.90, 463.28]]	[[9936.30, 10183.47], [10937, 11265]]	[[1242.5, 1290.1], [4355.0, 4400.7]]

It is important to compare the proposed method with the traditional single interval method as to the above model. This paper illustrates and compares the following two cases to investigate the advantages of the proposed method. Case 1 is the traditional single interval method, and case 2 is the proposed method in this paper. The results of two different methods are shown in Table VII.

The results with the dual interval method are more comprehensive to users who participate in the DA market with BCs compared with the single interval method. Due to the complexity of the dual interval method, the numbers of constraints and variables are much more than those of the single interval method, and the calculation time of the CPU is also longer than the single interval method. However, compared to more comprehensive information given to users, these slight disadvantages can be neglected. It is worthwhile to take a little longer time to obtain much more comprehensive information.

TABLE VII
COMPARISON OF COMPUTATIONAL COMPLEXITY

Method	ESCO profit (CNY)	CPU time (s)	Number of constraints	Number of variables
Single interval	[1476.8, 4128.7]	3.54	387	273
Dual interval	[[1476.8, 1695.2], [4043.3, 4128.7]]	5.56	716	475

V. CONCLUSION

A DIOTS for an ESCO in a DA market with BCs is proposed in this paper. The DIOTS-ESCO model is solved by dual interval decomposition technology and the pessimistic preference ordering method. Accordingly, the following conclusions are provided:

1) ESCO characterized by coupling multiple energy and providing effective management service can effectively promote energy conservation and emission reduction.

2) The combination of dual interval decomposition technology and the pessimistic preference ordering method offers a feasible method to handle highly uncertain parameters caused by extreme weather conditions and other emergent events.

3) The DIOTS-ESCO model provides more comprehensive information to users to participate in the day-ahead market with BCs.

4) The proposed approach can be further applied to deal with dual interval uncertainties and dynamics in other types of energy-environmental systems.

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