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A Carbon Emission Allowance Bargaining Model For Energy Transactions Among Prosumers

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***Abstract*—The carbon pricing is the main issue of the carbon trading market for enabling cost-effective decarbonization in the energy networks. A nodal carbon pricing model is firstly proposed based on the sharing and integration of the intra-regional carbon emission allowance. In this regard, the game theory is introduced to construct a multi-agent carbon emission allowance bargaining model in this letter. The alternating direction multiplier method is adopted to solve the model considering the competitional burden and privacy-preserving. Numerical results demonstrate that it could significantly reduce the carbon emissions of regional energy networks and improve the economic benefits of prosumers.**

Keywords—prosumers; energy transaction; carbon emission allowance bargaining; optimal trading and scheduling

I. Introduction

THE proposal of the Chinese "dual carbon" target has promoted the penetration rate of distributed energy resources (DERs) in the new-type power system to a large extent[1]. More and more DERs are operating as prosumers. As the subject with the duality of load and generation, prosumers are becoming paramount participants in the carbon market[2]. For prosumers, the carbon market not only is a mandatory environmental constraint but also an economic source of profit.

At the present stage, academic circles consider that carbon trading of prosumers usually directly depends on the price of the upper carbon market, ignoring the subjective initiative of consumers themselves, which limits the effect of carbon emission reduction. Researchers have conducted a survey on carbon emissions in the market and concluded that increasing carbon prices is associated with more significant emissions reductions and higher carbon costs[3]. The primary goal of the prosumer is to maximize its economic interests, rather than voluntarily achieving a low-carbon transition by bearing a higher carbon price. A carbon aware network charging system was designed to introduce carbon preferences in the retail electricity market[4]. Although the above literature has explored the impact of low-carbon preference on the operation of energy systems, the model are still limited to trading at a flat price to the upper carbon market.

Given the above insights, a novel carbon trading model is urgently needed for achieving a prosumer economy and low-carbon transition. Therefore, a bi-level carbon emission allowance bargaining model is proposed in this letter. The upper layer introduces the nodal carbon response coefficient to formulate a carbon flow-led nodal carbon price, based on the carbon emission flow (CEF) technique. At the lower level, the carbon emission allowances (CEA) bargaining model is CEA trading among prosumers. It is then converted into two subproblems for cooperative alliance maximization and benefit distribution. The whole operation model is solved by the alternating direction multiplier method (ADMM) considering computational burden. With the proposed CEA bargaining model, the operation of prosumers could be fully coordinated, leading to a more efficient and economical carbon trading.

II. Model Formulation

A. Framework

It is implemented based on the bi-level framework of the multi-market joint clearing of the regional energy system and the optimal operation of the prosumers, as shown in Fig 1. The upper layer is a multi-market regional energy system operation model, and the node carbon response coefficient is introduced to build a carbon flow-led node carbon price, which provides a way for the carbon trading among prosumers at the lower level. The prosumers in the lower level play a negotiation game with CEA/Chinese Certified Emission Reduction(CCER), to obtain the best trading strategy and return the energy demand to the upper level.

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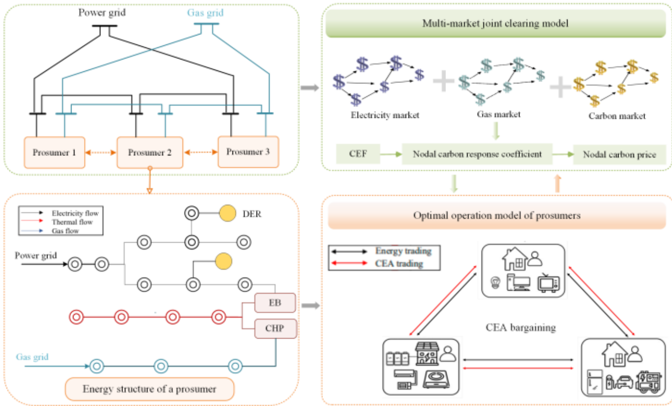

Fig. 1. The proposed bi-level CEA bargaining framework

B. *Mathematical Formulation*

1) The Upper-level Formulation

The upper model provides the price signals for lower-level prosumers to negotiate the CEA prices. The specific implementation process is to consider the joint clearing of regional energy systems in multi-energy markets → network carbon emission flow distribution → nodal carbon response coefficient → nodal carbon price, which is elaborated as follows:

The prosumers' unit set: $S_m = (P, x, L)$, where P is the input matrix of the unit, x is the energy conversion matrix and L is the multi-energy output matrix.

The markets set: $M_n = (P, c, Y)$, including electric/gas/carbon market, where c is the price matrix of the markets, Y is the cost matrix of prosumers participating in the markets.

The detailed process of multi-market joint clearance and power system flow calculation could be referred in [5].

Carbon flow-led nodal carbon pricing model: The average carbon emission intensity is used to describe the network carbon flow, in which the node carbon emission intensity (NCI) $\varepsilon_{i,t}^{\mathrm{NCI,e}}$ and other indices [6] would be utilized. Specifically, $\varepsilon_{i,t}^{\mathrm{NCI,e}}$ is formulated as shown in (1),

$$\varepsilon_{i,t}^{\mathrm{NCI,e}} = \frac{\sum_{n\in\Omega_i^{\mathrm{CU}}} \varepsilon_n^{\mathrm{CU}} P_{n,t}^{\mathrm{CU}} + \sum_{n\in\Omega_i^{\mathrm{GU}}} \varepsilon_n^{\mathrm{GU}} P_{n,t}^{\mathrm{GU}} + \sum_{k:k\to i} \rho_{ki,t}^{\mathrm{BCI,e}} P_{ki,t}}{\sum_{n\in\Omega_i^{\mathrm{CU}}} P_{n,t}^{\mathrm{CU}} + \sum_{n\in\Omega_i^{\mathrm{GU}}} P_{n,t}^{\mathrm{GU}} + \sum_{n\in\Omega_i^{\mathrm{WT}}} P_{n,t}^{\mathrm{WT}} + \sum_{k:k\to i} P_{ki,t}} \tag{1}$$

where $P_{n,t}^{\mathrm{CU}}$, $P_{n,t}^{\mathrm{GU}}$ and $P_{n,t}^{\mathrm{WT}}$ are respectively the power supply power of the n_{th} coal-fired unit, gas unit and wind turbine at time t, $P_{ki,t}$ is the power exchange between node k and node i at time t, $\varepsilon_n^{\mathrm{CU}}$ and $\varepsilon_n^{\mathrm{GU}}$ are the carbon emission intensity of the n_{th} coal-fired unit and gas unit respectively.

Then, the node carbon response coefficient $\varphi_{i,t}$ would be established to reflect the carbon emission contribution of each node, as shown in (2).

$$\varphi_{i,t} = \frac{\varepsilon_{i,t}^{\mathrm{NCI}}}{\sum_{i\in\Omega^{\mathrm{B}}} \varepsilon_{i,t}^{\mathrm{NCI}}}, \forall i \in \Omega^{\mathrm{B}} \tag{2}$$

where Ω^{B} represents a set of nodes in the power system.

Finally, the carbon price of each node $\lambda_{\mathrm{c,e}}^{i,t}$ is established according to the price of the superior carbon market λ_{CEA}, as shown in (3).

$$\lambda_{\mathrm{c,e}}^{i,t} = \varphi_{i,t}^{\mathrm{e}} \lambda_{\mathrm{CEA}}, \quad \forall i \in \Omega^{\mathrm{B}} \tag{3}$$

2) The Lower-level Formulation

After the upper-level operation scheme, the carbon price λ_{CEA}^n can be obtained, the prosumers should then determine operational strategies, driven by the ambition to maximize their interests. The crux of the model centers on the minimization of the prosumers' overall costs, including operation costs and carbon trading costs. In the carbon trading process, prosumers can either participate in the trading of CEA in the superior carbon market according to λ_{CEA}^n or trade CEA with other prosumers through game theory λ_{CEA}^{nm}. Therefore, the total carbon transaction cost C_{carbon}^n is composed of CCER cost C_{CCER}^n, the cost of CEA transaction with the market C_{CEA}^n, and the cost of CEA transaction among prosumers $C_{CEA,ex}^n$. The use of CCER needs to consider its offset ratio with CEA ω_{CCER}.

$$C_{CCER}^n = \lambda_{CCER}(E_{CCER,used} - \delta_{\mathrm{CCER}}^{\mathrm{WT}} \sum_{k\in\Omega_n^{WT}} P_{k,t}^{\mathrm{WT}} - \delta_{\mathrm{CCER}}^{\mathrm{PV}} \sum_{k\in\Omega_n^{PV}} P_{k,t}^{\mathrm{PV}}) \tag{4}$$

$$s.t. \quad E_{CCER,used} \le \omega_{\mathrm{CCER}} \left(\sum_{n=1}^{N}\sum_{t=1}^{T} (\delta_{e,n}^{\mathrm{WT}} P_{n,t}^{\mathrm{WT}} + \delta_{e,n}^{\mathrm{PV}} P_{n,t}^{\mathrm{PV}})\right) \tag{5}$$

where $\delta_{\mathrm{CCER}}^{\mathrm{WT}}$ and $\delta_{\mathrm{CCER}}^{\mathrm{PV}}$ represent the CCER value of wind power and photovoltaic, $E_{CCER,used}$ represents the amount of CCER offset used by the n_{th} prosumer.

For the CEA transactions between prosumers, a CEA bargaining model is built. In this process, each prosumer is treated as an independent and rational stakeholder. That is, each prosumer will minimize the total costs through cooperative alliances and shared quotas and then distribute the cooperative benefits through negotiation. The standard form of the proposed model is shown in (6) :

$$\begin{cases} \max \prod_{n=1}^{N} C_n^0 - C_n \\ s.t. \quad C_n^0 - C_n \ge 0 \end{cases} \tag{6}$$

where N represents the number of prosumers participating in the bargaining. C_n^0 is the breakdown point of the negotiation, that is, the cost before the prosumers participating, and C_n is the cost after its participation. When $C_n^0 - C_n \ge 0$, it means that the prosumers will save costs from the process of Nash bargaining, that is, the benefits gained through the cooperative alliance. The above model can be equivalently converted into the cooperative alliance maximization subproblem Q1 and the benefit distribution subproblem Q2:

Cooperative alliance maximization subproblem Q1:

$$\begin{cases} \min C_{run}^{n} + C_{carbon}^{n} + C_{CCER}^{n} \\ s.t. \ \sum_{n \in \Omega_1} P(n, i_e, j_e, t) = 0; \sum_{n \in \Omega_1} V(n, i_g, j_g, t) = 0, \forall t \\ \sum_{n=1}^{n_\omega} \sum_{t=1}^{T} E_{gap}(n,t) = 0 \end{cases} \tag{7}$$

Benefit distribution subproblem Q2:

$$\begin{cases} \min \sum_{n=1}^{N} -\ln(C_0^n - C_{total}^{n\ *} - \sum_{m \in \Omega, m \neq n} \lambda_{CEA}^{nm} E_{CEA}^{nm\ *}) \\ s.t. \ \ C_0^n - C_{total}^{n\ *} - \sum_{m \in \Omega, m \neq n} \lambda_{CEA}^{nm} E_{CEA}^{nm\ *} \geq 0 \\ \min(\lambda_{CEA}^{n}, \lambda_{CEA}^{m}) \leq \lambda_{\mathrm{CEA}}^{nm} \leq \max(\lambda_{CEA}^{n}, \lambda_{CEA}^{m}) \end{cases} \tag{8}$$

where $E_{\mathrm{CEA}}^{nm\ *}$ and $C_{total}^{n\ *}$ are the optimal solution of Q1. It is necessary to meet the nodal balance constraint of the regional energy network and the CEA and CCER balance constraint of carbon trading. $C_{total}^{n\ *}$ are the total cost of optimization when the prosumer is not considered the cost of CEA transaction among prosumers $C_{CEA,ex}^{n}$, and C_0^n is the total cost when the prosumer does not participate in the negotiation.

By solving subproblems Q1 and Q2 with ADMM, the optimal CEA trading volume $E_{\mathrm{CEA}}^{nm\ *}$ and the optimal transaction price $\lambda_{\mathrm{CEA}}^{nm\ *}$ among prosumers can be derived. See [7] for the specific solving process.

III. Case Study

A. Test system description and parameters settings

The E30G20-3P system which is coupled by an IEEE 30-node power grid and an improved Belgian 20-node natural gas grid, as well as three prosumers, is employed to verify the effectiveness and superiority of the proposed method. The calculation period is hours. The price of CEA is 20\$/tCO_2, the price of CCER is 18\$/tCO_2 and $\omega_{\mathrm{CEER}} = 0.05$. The parameters of the regional energy system and prosumers are given in [7].

B. Results

The result of prosumers participating in the CEA bargaining is shown in Fig. 2. It can be seen that the CEA transaction price of prosumers participating in the negotiation changes from the nodal carbon price to the negotiation price, and both parties obtain a more stable and credible transaction price.

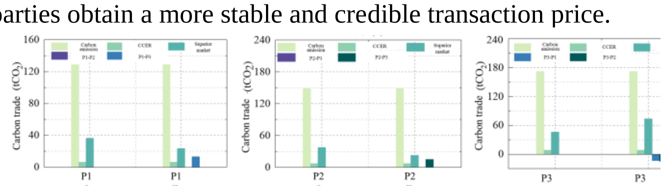

Fig. 2. CEA and CCER transactions with or without CEA bargaining

Fig. 2 shows the prosumers' CEA and CCER trading strategies, compared with the ordinary trading strategies when CEA bargaining behavior is not considered. Case I takes CEA bargaining into account, whereas Case II does not. The presence or absence of CEA bargaining has a minor impact on the initial allowance and the amount of CCER used by prosumers, while it has a major impact on the CEA trading strategy of prosumers. Specifically, when the CEA bargaining behavior is not considered, prosumers participate in the trading of the superior carbon market through their respective nodal carbon prices. At this time, the nodal carbon prices of P1, P2, and P3 are 20.53\$/tCO_2, 31.15\$/tCO_2 and 19.37\$/tCO_2, respectively. The CEA trading volumes are 36.11t, 37.46t, and 46.17t, respectively. After considering the CEA bargaining behavior, each prosumer adjusts the carbon trading strategy according to the real situation, in which P3 sells 12.88t and 14.83t of CEA to P1 and P2 at the price of \$20.21 /tCO_2 and \$26.04 /tCO_2 respectively, and meanwhile increases its CEA trading volume with the superior carbon market to 73.88t. There is no CEA transaction between P1 and P2, and the CEA transaction volume between P1 and P2 and the superior carbon market decrease to 23.23t and 22.63t respectively. Table 1 further shows the changes in the total cost of each prosumer before and after CEA bargaining. When the CEA bargaining behavior is taken into account, the integrated operation cost of P1, P2, and P3 decrease by \$15.15, \$87.42, and \$87.42 respectively, and the carbon trading cost of prosumers is saved by \$189.99 in the form of the cooperative coalition-negotiation.

TABLE I. CARBON TRADING COST

Case	P1 cost(\$)	P2 cost(\$)	P3 cost(\$)	Total cost(\$)
I	48495.88	43000.51	29377.46	120873.86
II	48511.04	43087.94	29464.89	121063.87

Furtherly, multiple prosumers are set and test in the cases. Table II shows the average calculation time and number of iterations for solving the main and sub-problems. The sub-problem is the CEA bargaining among prosumers, which presents a high number of iterations but less calculation time. Therefore, when the number of prosumers increases, the calculation time of the sub-problems does not increase significantly, and the average calculation time is less than 1.5s. However, the average computation time of the main problem increases significantly, from 0.22s to 12.63s, for the sake of the network security constraints and constraints returned by the subproblem. The number of those constraints increases with the growth of the prosumers, exacerbating the computation burden of the main problem. Thus, the growth of prosumers will increase the calculation time and the number of iterations exponentially, but it is still within the acceptable range of the transaction time scale, with feasibility and scalability.

TABLE II. CALCULATION TIME AND ITERATION

Number of prosumers	Calculation time(s)		Iteration
	Main problem	subproblem	
3	0.22	0.13	174
5	0.53	0.21	268
10	1.56	0.46	715
15	5.32	0.79	2182
20	12.63	1.13	4864

IV. CONCLUSION

This letter presents a CEA bargaining model for prosumers in the regional energy network. It is transformed into a cooperative alliance maximization subproblem and benefit distribution subproblem, which is solved by the ADMM algorithm efficiently. Case studies indicate that the proposed model can effectively reduce regional carbon emissions, assist prosumers to choose the optimal carbon trading decision, and improve the profits of prosumers. It is noted that, a prerequisite for the model to work is the existence of a difference in the carbon price at the power system nodes with prosumers.

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