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Credit rating- and credit score-based carbon emission quota trading model of city dwellers

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Introduction: The reduction of electricity-related carbon emissions by city dwellers (CDs) is important for China to achieve low-carbon development and sustainable energy transformation. Due to the lack of incentives for reduction, electricity-related carbon emissions from CDs are increasing year by year. To this end, this paper proposes an electricity-related carbon emission quota trading model that integrates a credit rating and credit score system, particularly for motivating CDs to actively participate in carbon emission reduction.

Methods: With the history of electricity bill payment data, the density-based spatial clustering of applications with noise (DBSCAN) algorithm is used to cluster CDs, forming different clusters of CDs with different sensitivity levels to carbon emission quota prices. Thereafter, based on the total carbon emission quota and tiered electricity prices from the power company, incentive rules according to the classification result and credit scores of CDs are formulated. Under certain conditions, a leader–follower Stackelberg game between CDs and the power company is built to determine the base price of the carbon emission quota, and thereby, referring to the credit scores of CDs, floating carbon emission quota prices are offered to them in the final settlement.

Results: The simulation results for an actual community in a city in China show that the proposed method can considerably reduce the carbon emissions.

Discussion: The proposed credit rating and credit score system outperforms the asymmetric Nash negotiation method in terms of promoting carbon emission reduction.

KEYWORDS

carbon emissions, electricity, credit score, city dweller, Stackelberg game

1 Introduction

Inspired by the government's carbon peak and carbon neutrality goal, the demand for carbon emission reduction is increasingly prominent in China (Ji et al., 2021). In 2021, the State Council of China issued a work opinion on the carbon peak and carbon neutrality goal, requiring speeding up the establishment of a national carbon emission credit trading market and standardizing the carbon emission accounting system (Sichuan Daily, 2022). Carbon emission credits, in fact, refer to the allowed carbon emission amounts, i.e., the quotas, allocated to entities within a specific period. Complying with the limit of the total carbon emission amount, entities could participate in the carbon emission credit trading market to purchase extra quotas or sell their surplus (Long and Han, 2020). Carbon emission credit trading is also referred to as carbon emission quota trading in this paper.

Focusing on the carbon peak and carbon neutrality goal, carbon emission quota trading is an important way to strongly promote the low-carbon dispatch of the energy system economy, fully integrate carbon emission resources based on their market-oriented characteristics, and comprehensively improve their comprehensive benefits in the carbon emission quota trading market. The power industry, as the most important part of the energy industry, accounts for a large proportion of carbon emissions. A particular power generation and consumption-related carbon emission quota trading market can help considerably promote the green and sustainable development of the power system.

Many existing references have discussed the low-carbon economic dispatch of the energy system under the background of the carbon emission credit trading market. Yang et al. (2021) integrated the cost of carbon emission credits into the optimal operation model of energy systems and analyzed the influence of carbon emission credit prices on the operation of the system Wang et al. (2020); He et al. (2020) built an energy scheduling model based on carbon emission credits, which are instructive for the cost analysis of carbon emission credit trading in energy systems. Xiang et al. (2021) proposed an optimal operation model for energy systems that integrate multiple resources such as gas turbines, photovoltaic power farms, and energy storage systems. This model integrates the cost of carbon emission credit trading into its objective to better reflect the actual operation cost. Luo et al. (2021) optimized the energy structure through proposing a carbon emission credit trading mechanism and studied the role of energy storage systems on low-carbon economic dispatch with the designed trading mechanism. However, because the carbon emission quota trading market of China is in the early stages of development, the trading mechanism, the accounting system, and the market framework are mainly industrial sector-oriented, while little consideration is made regarding city dwellers (CDs) to incentivize their participation.

It has been shown that the rapidly increasing electricity demand of CDs in China has become the main driving force for the increase in carbon emissions (Peng et al., 2021; Wang et al., 2021). According to statistics, the electricity-related carbon emissions from CDs in China account for around 30% of the country's total electricity-related carbon emissions. Moreover, in terms of carbon emission *per capita*, the contribution of CDs is as high as 65% (Wang et al., 2022). Therefore, extensively exploring the potential of CDs in carbon emission reduction is an important manner to achieve carbon peak and carbon neutrality in China.

In fact, promoting carbon emission reduction on the CD side is complicated and should be systematic. A series of pilot schemes have been issued by many countries. The governments of Sweden and France levied carbon emission and energy efficiency taxes to force CDs to reduce carbon emissions (Petrik and Anita, 2020; Cyril et al., 2021). However, the disadvantages of the regressive effect of carbon emission tax are striking (Feng et al., 2021; Zhang and Zhang, 2022). Finland implements carbon emission quotas to control the total amount of electricity-related carbon emissions (Kuokkanen et al., 2020; Wang and Wang, 2021; Wu and Zhang, 2021), which could shed light on ideas for China's carbon emission quota allocation and trading mechanism design. It is worth mentioning that since still being in the early stages of development, currently, the carbon emission credit spot price in China is only a few tenths of that in Finland (Li P. et al., 2021a; Chen and Zhao, 2021). This results in the problem of insufficient trading incentives. As an example, assuming that the annual electricity consumption of a single CD is 3600 kWh and the electricity price is 0.572¥/kWh, the total electricity bill for this CD is 2059.2¥. Considering that 60% of the annual electricity consumption (3600 kWh) comes from thermal power, the carbon emissions of thermal power is 0.997 kg/kWh, and the carbon emission quota price is 52.8¥/ton, even the proportion of sold carbon emission quota takes a half, i.e., the corresponding annual total income merely accounts for 2.76% of the CD's electricity bill, namely, 56.85¥. For a CD with an annual income of 60,000¥, this only accounts for 0.09% of his/her annual income. Intuitively, due to the tiny proportion, the aforementioned methods can hardly provide sufficient incentives to CDs for letting them participate in carbon emission reduction.

Considering the large number and wide distribution of CDs and their significant diversity in price sensitivity, regulatory intention, carbon emission, and electricity consumption, how to reasonably cluster CDs and based on the mechanisms of the current China electricity market and carbon emission quota trading market to formulate suitable incentive policies guiding CDs to actively participate in electricity-related carbon emission quota trading has become the focus of research. Tiered electricity pricing, which is essentially a quota management manner, has been implemented in cities in China. With tiered electricity prices, after the electricity quota with a low price is consumed, a CD will purchase additional electricity quota at a higher price (Chu and Zhu, 2020; Wu and Gao, 2021; Tang et al., 2022) to meet further electricity demand. This already implemented tiered electricity pricing mechanism and actual operation data can provide good features for clustering CDs and help the refined management and practical implementation of electricity-related carbon emission quota trading of CDs.

To this end, focusing on CDs, this paper proposes a credit score-based electricity-related carbon emission quota trading model. In this model, the power company is responsible for initializing the credit ratings of CDs according to the CD clustering results and formulating trading and credit score updating rules. The credit score system, credit ratings, and floating price mechanism are formulated referring to standards issued by the Sichuan Association of Circular Economy (SACE). On the basis of the tiered electricity price, a floating price-based carbon emission fee will be levied on CDs, while market-oriented surplus quota trading among CDs is realized. The proposed market framework is conducive to improving the actual benefits and enthusiasm of CDs participating in electricity-related carbon emission reduction and promoting China's low-carbon transformation. For the

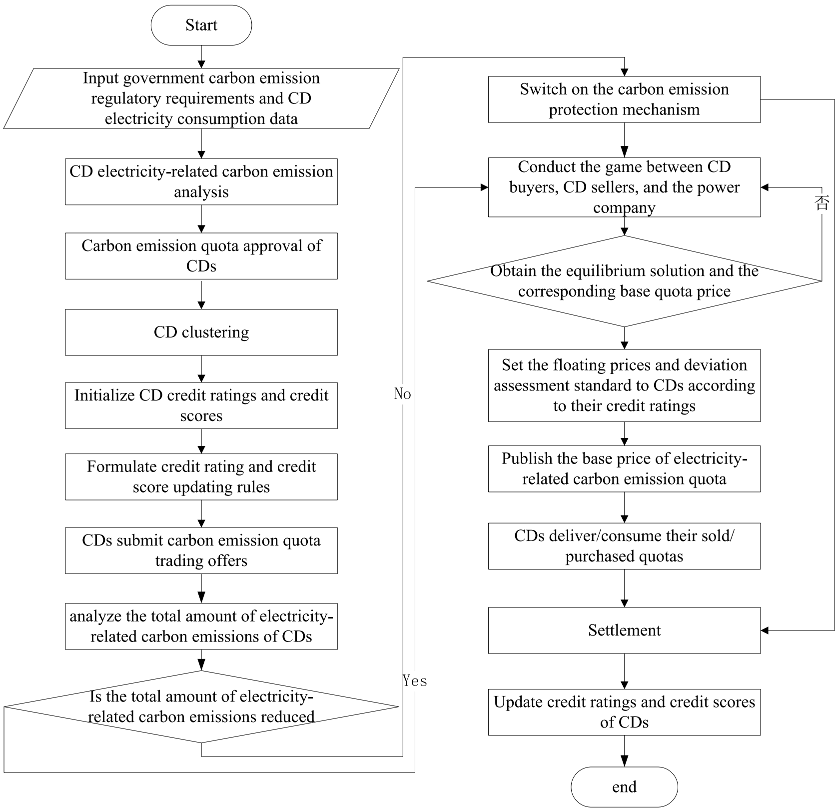

FIGURE 1
Flowchart of the electricity-related carbon emission quota trading process.

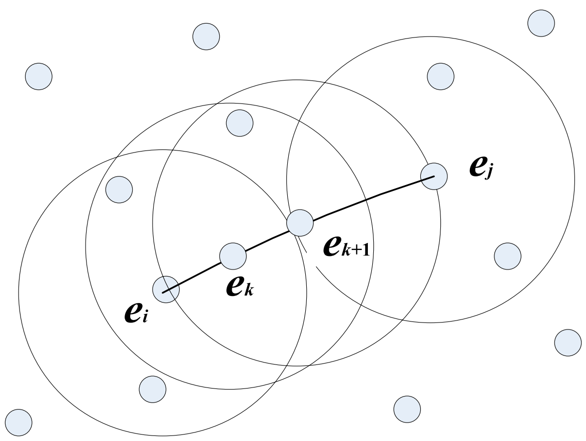

FIGURE 2
An illustrative example of density-reachable samples.

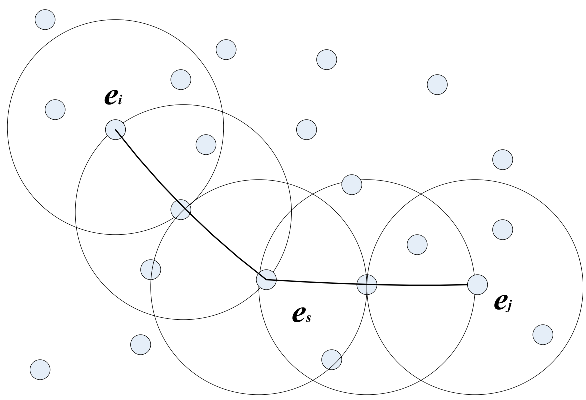

FIGURE 3
An illustrative example of density connection.

power industry, by governing the sources of carbon emissions, namely, power consumption, the proposed method can help the energy consumption pattern and energy consumption structure transformation of CDs, thereby promoting the reduction of their electricity-related carbon emissions. For the society, it helps promote the comprehensive green transformation of economic and social development and relieve climate change.

2 The carbon emission quota trading process

The underlying idea of credit incentive trading is to realize the total electricity-related carbon emission reduction through motivating CDs to actively participate in carbon emission reduction. Power companies in China generally charge CDs at government-regulated prices. Therefore, the municipal

TABLE 1 Credit ratings of CDs and corresponding floating prices.

Category	Score	Credit ratings	Floating prices
Quota seller CD (the first and second tiers of the tiered electricity prices)	90–100	S7	$(1+\Delta l7)$ ×base price
	80–89	S6	$(1+\Delta l6)$ ×base price
	61–79	S5	$(1+\Delta l5)$ ×base price
	60	S4	Base price Δs
	50–59	S3	$(1-\Delta l3)$ ×base price
	31–49	S2	$(1-\Delta l2)$ ×base price
	0–30	S1	$(1-\Delta l1)$ ×base price
Quota buyer CD (the second tier of the tiered electricity prices)	90–100	B7	$(1-\Delta b7)$ ×base price
	80–89	B6	$(1-\Delta b6)$ ×base price
	61–79	B5	$(1-\Delta b7)$ ×base price
	60	B4	Base price
	50–59	B3	$(1+\Delta b3)$ ×base price
	31–49	B2	$(1+\Delta b2)$ ×base price
	0–30	B1	$(1+\Delta b1)$ ×base price
Quota buyer CD (the third tier of the tiered electricity prices)	90–100	C7	$(1-\Delta c7)$ ×base price
	80–89	C6	$(1-\Delta c6)$ ×base price
	61–79	C5	$(1-\Delta c5)$ ×base price
	60	C4	Base price
	50–59	C3	$(1-\Delta c3)$ ×base price
	31–49	C2	$(1-\Delta c2)$ ×base price
	0–30	C1	$(1-\Delta c1)$ ×base price

TABLE 2 Credit score updating rules.

Category	Rule	Credit score adjustment
Quota seller CD	The negative carbon emission deviation in a trading cycle exceeds $\triangle k_1$	$-\triangle f_1$
	Traded quota amount (per $\triangle k$)	$+\triangle f_2$
	Seller adjustable factor $\triangle k_3$	$\triangle f_3$
Quota buyer CD	The positive carbon emission deviation in a trading cycle exceeds $\triangle h_1$	$-\triangle j_1$
	Traded quota amount (per $\triangle h2$)	$+\triangle j_2$
	Buyer adjustable factor $\triangle h_3$	$\triangle j_3$

government entrusts the power company to collect electricity-related carbon emission fees. First, according to the government's carbon emission regulatory requirements, the power company calculates the CDs' carbon emission quotas within a statistical period based on their tiered electricity consumptions. The power company also formulates the carbon emission quota trading rules.

Thereafter, CDs can participate in electricity-related carbon emission quota trading. In the trading process, floating prices will be finally offered referring to the credit ratings of the CDs, which helps in increasing the benefits of the CDs, thereby motivating them to actively participate in carbon emission reduction.

The electricity-related carbon emission quota trading process designed in this paper has no cash flow between CDs. All related funds from either buyers or sellers are deposited in the public account of the power company. The power company finally settles the trading together with the settlement of CDs' electricity bills. The electricity-related carbon emission quota trading process is illustrated in Figure 1.

TABLE 3 Floating price settings.

Parameter	$\Delta l7$	$\Delta l6$	$\Delta l5$	Δs	$\Delta l3$	$\Delta l2$	$\Delta l1$
Value	30%	20%	10%	0	5%	10%	20%
Parameter	$\Delta b7$	$\Delta b6$	$\Delta b5$	Δs	$\Delta b3$	$\Delta b2$	$\Delta b1$
Value	5%	3%	1%	0	5%	10%	20%
Parameter	$\Delta c7$	$\Delta c6$	$\Delta c5$	Δs	$\Delta c3$	$\Delta c2$	$\Delta c1$
Value	3%	2%	1%	0	10%	20%	40%

TABLE 4 Updating rule settings.

Parameter	$-\Delta f_1$	$+\Delta f_1$	Δf_1	$-\Delta j_1$	$+\Delta j_1$	Δj_1
Value	−0.3	+0.2	1%	−0.4	+0.1%	1%

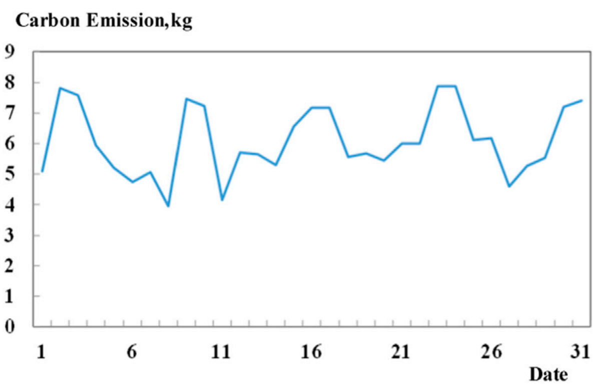

FIGURE 4
Carbon emissions of the studied community in January 2021.

As shown in Figure 1, first, based on the carbon emission forecast of the city, the power company purchases the city's total electricity-related carbon emission quota from the carbon emission credit spot market and approves the electricity carbon emission quotas of individual CDs.

Then, based on the historical electricity bill data of CDs, the power company carries out a clustering analysis, after which credit scores and credit ratings of individual CDs can be initialized. The updating rules of CDs' credit scores are proposed by the power company, realizing the rolling update of credit scores of CDs.

Thereafter, the power company analyzes the total urban electricity carbon emissions based on the carbon emission quota trading information released by CDs:

1) If the total amount of the electricity-related electricity carbon emissions of the city remains unchanged, the settlement of the carbon emission quota trading will be in accordance with the government-approved ceiling price.
2) If the total amount of electricity-related carbon emissions of the city is reduced, a leader–follower Stackelberg game between CDs and the power company will be built to determine the base price of the carbon emission quota.

Lastly, according to the credit ratings of CDs, the price floating levels and deviation assessment standards of individual CDs are determined. The credit scores and credit ratings of CDs are also updated.

3 The carbon emission quota trading model

3.1 Approval of carbon emission quotas for DCs

Urban *per capita* carbon emission is a core indicator of the carbon emission level of a city, and CD electricity-related carbon emission contributes 65% of it (Zhang and Lu, 2021). Obviously, reductions in electricity-related carbon emissions of CDs are the key for the Chinese government to pave the path to the carbon peak and carbon neutrality goal. In 2021, the National Development and Reform Commission of China issued a notice on "Further Deepening the Market-oriented Reform of Feed-in Tariff for Coal-fired Power Generation," requiring the power company to undertake CD power supply and maintenance tasks and charge electricity bills based on tiered electricity prices (Li Z. et al., 2021b). Obviously, the power company has become the best candidate for administrating the electricity-related carbon emission quota trading of CDs. Therefore, in this paper, the proposed electricity-related carbon emission quota trading market is administrated by a power company that is entrusted by the municipal government. In summary, the government devises the carbon emission policy. The power company is the executor of the electricity carbon emission policy entrusted by the government. City dwellers are regulated by the power company and are responsible for their carbon emissions. At the same time, CDs become participants in electricity-related carbon emission reduction.

The electricity-related carbon emission quota trading model is designed via drawing on the experiences of how household-based garbage removal fees are collected and the manner of tiered electricity pricing that increases prices after a given quota has been exceeded. In the trading model, first, the power company analyzes the carbon emission levels of individual CDs and formulates a total quota on the carbon emission over all CDs. Then, the power company purchases the calculated amount of carbon emission quota in the provincial carbon emission credit spot market and approves the basic carbon emission quotas of individual CDs according to the total urban resident population. For CDs with family size exceeding corresponding to the basic quota, their quotas will be adjusted according to their actual family sizes. The 2019 edition of the National Greenhouse Gas Inventory Guidelines issued by the Intergovernmental Panel on Climate Change (IPCC) is the basis for approving CDs' electricity-related carbon emission quotas (Viola, 2020; McLean and Gibbs, 2022).

In fact, carbon emissions are not generated by the electricity consumption of CDs but from the thermal units that burn coal for generating the consumed electricity. In addition to thermal units,

 10.3389/fenrg.2023.1250717

TABLE 5 Clustering results of CDs.

	Category	Name	Tiered electricity price	Sensitivity	Number of CDs
CD buyer	High-income CD	LB3	Third tier	Very low	78
		LB2	Third tier	Relatively low	367
		LB1	Third tier	Low	575
	Medium-income CD	MB3	Third tier	Very low	654
		MB2	Third tier	Relatively low	585
		MB1	Third tier	Low	794
	Low-income CD	SB3	Second tier	Very low	894
		SB2	Second tier	Relatively low	671
		SB1	Second tier	Low	387
CD seller	High-income CD	LX3	First tier	Very high	247
		LX2	First tier	Relatively high	574
		LX1	First tier	High	627
	Medium-income CD	MX3	First tier	Very high	662
		MX2	First tier	Relatively high	745
		MX1	First tier	High	439
	Low-income CD	SX3	First tier	Very high	942
		SX2	First tier	Relatively high	528
		SX1	First tier	High	784
Idle CDs	Vacant CD	XZ1	First tier	-	124
	Unfurnished CD	KZ1	First tier	-	85

TABLE 6 Comparison of the improved DBSCAN and the K-means algorithms.

Number of CDs	Clustering accuracy rate (%)	
	K-means clustering algorithm	Improved DBSCAN clustering algorithm
1000	89.7	99.2
2000	90.7	99.5
3000	89.9	99.6
4000	89.7	99.5
5000	90.2	99.2
6000	89.9	99.6
8000	89.5	99.0
10000	90.2	99.3

supply resources of CDs typically include green energy resources and energy storage systems. Among them, the carbon emission intensities of thermal units are determined according to unit types; the carbon emission intensities of green energy resources, such as hydropower, solar energy, and wind energy, are set as 0. Energy storage systems do not directly generate carbon emissions, but their stored electricity could partly come from thermal units, therefore implicitly introducing carbon emissions.

We use n to denote the number of resources. All resources are considered current resources. After the network power flow snapshot is selected, all the ground branches at the CD connection node b can be considered equivalent impedances

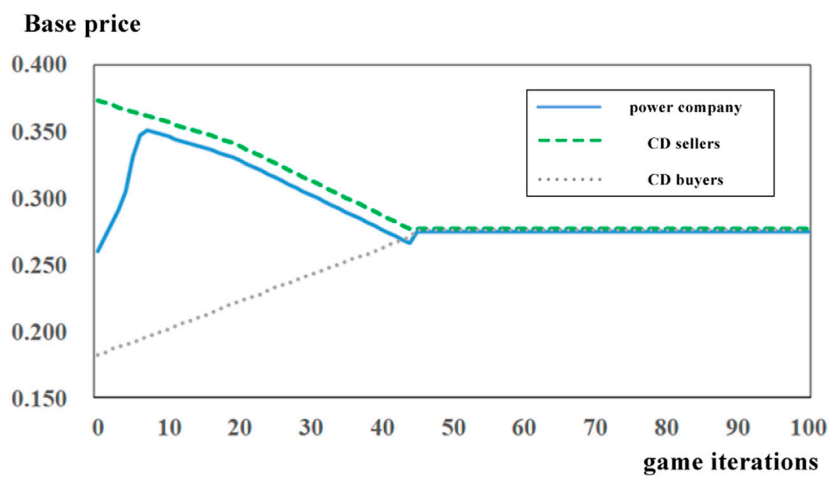

FIGURE 5
Process of the game between the power company and CDs.

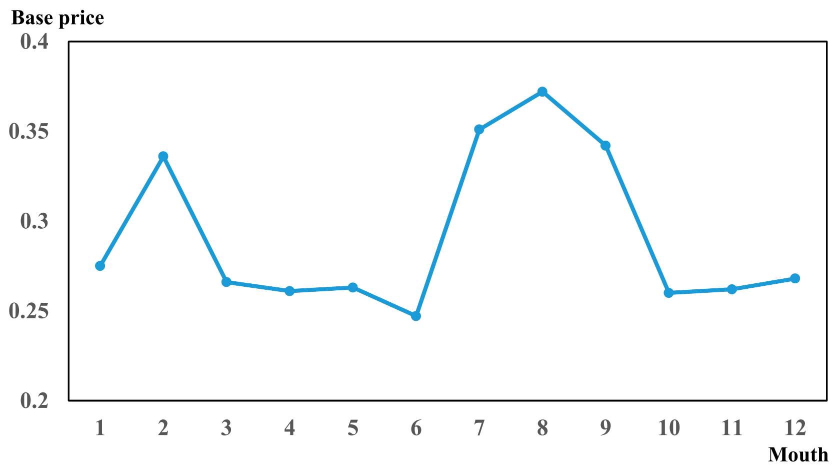

FIGURE 6
Prices of carbon emission quota in a year.

connected to node b, denoted as r. The current injected to node b can be represented as the sum of the currents from all resources in the network, and the power injected to node b can be calculated as in (1), where I_j^{All} is the current from resource j. In fact, P_b^{All} consists of three parts: thermal power, green power, and power from energy storage systems that are correspondingly denoted as P_b^T, P_b^G, and P_b^S. As an example, P_b^D represents the power drawn by node b from resource c.

$$P_b^{All} = \sum_{j=1}^{n} \left(r \left(I_j^{All} \right)^2 \right), \tag{1}$$

$$P_c^T = \left(\frac{P_c^D}{\left(P_b^T + P_b^G + P_b^S \right)} \right) P_b^D. \tag{2}$$

In Eq. 1, the line losses of the distribution area caused by supplying CDs are not considered. However, the municipal government may require including the line losses in the calculation of carbon emissions in order to accurately capture the actual amounts. We use t to denote the total number of time intervals in a statistical period and τ_j to denote the electricity-related carbon emission of different resources. The carbon emission of green energy resources is 0, and the carbon emission of the energy storage is determined by its stored energy from thermal units. P_i^{At} represents the total power injection to node b; P_i^{Loss} is the line loss at time interval j. The total carbon emissions of node b in a statistical period can be calculated as in Eq. 3.

$$C_c^T = \sum_{j=1, i=1}^{t,n} \left(P_i^{AT} \tau_j \times \left(1 + P_i^{Loss} \right) \right). \tag{3}$$

Using Eq. 3, the total carbon emissions of all CDs in the city can be obtained. In order to avoid the increase of alternative energy usage that leads to extra carbon emissions due to enforced reduction

TABLE 7 Market settlement results.

Category	Credit rating	Number of CDs		Market settlement in January		Market settlement in February	
		Credit score before updating	Credit score after updating	Traded amount (kg)	Income/ expenditure (¥)	Traded amount	Income/ expenditure (¥)
Quota seller CD (the first and second tiers of the tiered electricity prices)	S7	321	297	14766	5279	12771	4566
	S6	894	914	59898	19766	59410	19605
	S5	1245	1352	89640	27116	95992	29038
	S4	6	2	378	104	146	40
	S3	967	976	65756	17179	66108	17271
	S2	1323	1256	42336	10478	40192	9948
	S1	792	751	35640	7841	33795	7435
	Subtotal	5548	5548	308414	87763	308414	87902
Quota buyer CD (the second tier of the tiered electricity prices)	B7	127	118	5842	1526	5428	1418
	B6	472	467	33984	9065	33624	8969
	B5	527	627	30566	8322	36366	9901
	B4	3	2	141	39	112	31
	B3	452	624	34804	10050	48048	13874
	B2	576	629	26496	8015	28934	8753
	B1	294	361	14046	4635	14046	4635
	Subtotal	2451	2828	145879	41652	166558	47580
Quota buyer CD (the third tier of the tiered electricity prices)	B7	141	102	6909	1843	4998	1333
	B6	269	253	15602	4205	14927	4023
	B5	552	495	58512	15930	52965	14420
	B4	5	4	260	72	214	59
	B3	775	674	44175	13363	39092	11825
	B2	537	455	24702	8152	20930	6907
	B1	275	194	12375	4764	8730	3361
	Subtotal	2554	2177	162535	48328	141856	41928
Total		5005	5005	308414	89980	308414	89508
The power company profit					11104		10477

in the proportion of CDs' electricity-related carbon emissions, a proportion factor is adopted to approve the basic quota of CDs' electricity-related carbon emissions. The proportion factor is usually issued by carbon emission regulatory agencies based on their statistics and monitoring data. In our case, the proportion factor was issued by the SACE.

According to the forecasted total electricity-related carbon emissions of CDs, the power company purchases an equivalent amount of carbon emissions quota C_c^{All} from the carbon emission credit spot market. We denote the number of CDs in the city as m. When the proportion of all CDs' electricity-related carbon emission amount fluctuates beyond the threshold by $\Delta\varphi$, the quota will be deducted by $\Delta\sigma$. The fluctuation threshold is set referring to the typical value issued by the SACE.

We use C_c^P and C_c^C to, respectively, denote the electricity-related carbon emission of CD b in the previous and current statistical periods and C_c^{AP} and C_c^{AC} to, respectively, denote the total electricity electricity-related carbon emission of the city in the previous and current statistical periods. On this basis, a CD's basic electricity-related carbon emission quota can be calculated as in Eq. 4, where $\frac{C_c^P}{C_c^{AP}}$ and $\frac{C_c^C}{C_c^{AC}}$ satisfy Eq. 5. (5) represents the simple fact that the share of the electricity-related carbon emission of a CD over the total electricity-related carbon emission of the city must be less than 1 in both the previous and current statistical periods. Based on Eq. 4, the

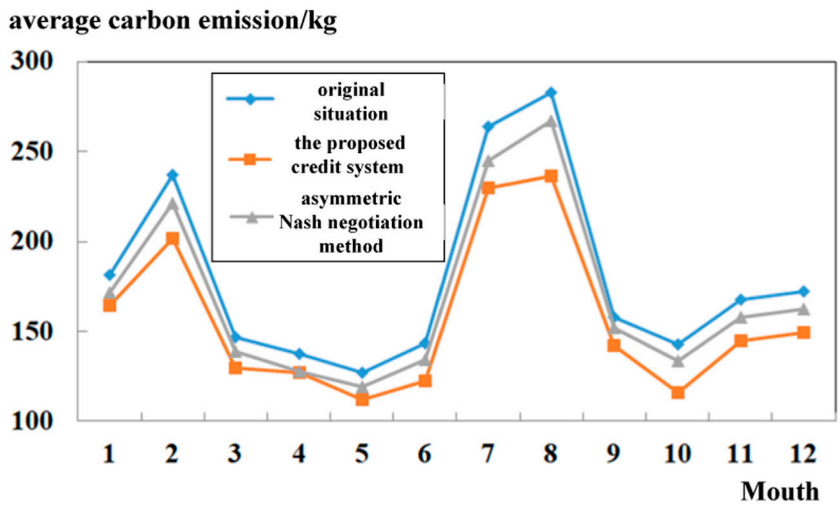

FIGURE 7
Monthly average carbon emission of CDs.

power company charges CDs the basic carbon emission fees from their deposits.

$$C_c^F = \frac{C_c^{All}}{m} \times \left(1 - \left(\left|\frac{C_c^P}{C_c^{AP}} - \frac{C_c^C}{C_c^{AC}}\right| \times \Delta\sigma\right)\right), \tag{4}$$

$$\begin{cases} 0 \le \dfrac{C_c^P}{C_c^{AP}} \le 1 \\ 0 \le \dfrac{C_c^C}{C_c^{AC}} \le 1 \end{cases}. \tag{5}$$

3.2 Clustering of CDs

The purpose of establishing the electricity-related carbon emission quota trading market is to help CDs recognize the limitations on carbon emissions and thereby motivate them to actively reduce their carbon emissions. In the electricity-related carbon emission quota trading market, CDs with different incomes would show different degrees of sensitivity to the carbon emission fee. Intuitively, high-income CDs would be less sensitive to it and might be willing to pay extra beyond the bill of the basic quota; by contrast, low-income CDs would be highly sensitive to the carbon emission fee and might be willing to sell their remaining quotas for offsetting part of their electricity bills. To this end, in this paper, a clustering analysis based on CDs' electricity usage is conducted to obtain their sensitivity level classification.

Density-based spatial clustering of applications with noise (DBSCAN) is a clustering method based on density detection and with noise canceling ability. This method has the ability to form clusters from high-density regions with limited features (Juan et al., 2021; He et al., 2022) and does not require pre-specifying the number of clusters. However, in the case of large CD samples, its convergence efficiency would be of concern. In other words, when facing a large number of CD samples, the convergence time of the DBSCAN algorithm may become unacceptable and divergence may happen. To this end, in this paper, the DBSCAN algorithm is improved through limiting the size of searching neighbors, achieving the processing capability of a large number of CD samples.

Considering the Mahalanobis distance involves covariance of distances and can comprehensively consider the characteristic relationship between CD samples (Chen et al., 2019; Cui and Xia, 2022), in the DBSCAN algorithm, it is used to measure the distances between CD samples.

Using e_i and e_k to represent the feature vectors of CD samples i and k, respectively, the Mahalanobis distance of the two CD samples can be calculated as in Eq. 6, where n_c is the number of features and O_a is the covariance matrix of the Mahalanobis distances.

$$d_{ik} = \sqrt{(e_i - e_k)^{n_c} O^{-1} (e_i - e_k)}. \tag{6}$$

A neighborhood parameter, ϖ, is used by the DBSCAN algorithm to depict the tightness of the CD cluster distribution. For e_i, taking it as the center, the circle with radius of ϖ forms its neighborhood V_ϖ, as represented in Eq. 7, where G_a is the total number of samples.

$$V_\varpi = \{e_i \in G_a \mid d_{ik} \le \varpi\}. \tag{7}$$

In the DBSCAN algorithm, if the neighborhood of e_i contains multiple CD samples, it becomes the core object, and these CD samples in its neighborhood are directly density-reachable to e_i. For any e_i and e_j, if they are not directly density-reachable, but if there exists a path of samples that starts from e_i and ends at e_j, while any two consecutive DC samples are directly density-reachable, e_i and e_j are density-reachable and form a directly density-reachable closure. As an example, considering e_i, e_k, e_{k+1}, and e_j, if the pairs of e_i and e_k, e_k and e_{k+1}, and e_{k+1} and e_j are all directly density-reachable, e_i and e_j are density-reachable. This is further illustrated as in Figure 2. For e_i and e_k, if there exists e_s, that

TABLE 8 Market settlement results with different methods.

	Credit rating	Number of CDs		Market settlement in January		
				Traded amount	Asymmetric Nash negotiation income/expenditure (¥)	The proposed credit system income/expenditure (¥)
Quota seller CD (the first and second tiers of the tiered electricity prices)	S7	321	297	14766	3972	5279
	S6	894	914	59898	16113	19766
	S5	1245	1352	89640	24113	27116
	S4	6	2	378	102	104
	S3	967	976	65756	17688	17179
	S2	1323	1256	42336	11388	10478
	S1	792	751	35640	9587	7841
	Subtotal	5548	5548	308414	82963	87763
Quota buyer CD (the second tier of the tiered electricity prices)	B7	127	118	5842	1571	1526
	B6	472	467	33984	9142	9065
	B5	527	627	30566	8222	8322
	B4	3	2	141	38	39
	B3	452	624	34804	9362	10050
	B2	576	629	26496	7127	8015
	B1	294	361	14046	3778	4635
	Subtotal	2451	2828	145879	39241	41652
Quota buyer CD (the third tier of the tiered electricity prices)	B7	141	102	6909	1859	1843
	B6	269	253	15602	4197	4205
	B5	552	495	58512	15740	15930
	B4	5	4	260	70	72
	B3	775	674	44175	11883	13363
	B2	537	455	24702	6645	8152
	B1	275	194	12375	3329	4764
	Subtotal	2554	2177	162535	43722	48328
Total		5005	5005	308414	82963	89980
The power company profit					8481	11104

is, density-reachable to e_i and e_k, e_i and e_k are density-connected, as illustrated in Figure 3. Thereafter, based on the regional scale of the urban power supply grid, the searching threshold is set as $\Delta\lambda$.

From Figures 2, 3, it can be seen that the DBSCAN algorithm explores density-connected CDs from density-reachable CDs and clusters those CDs into one cluster, finally forming clusters of CDs. This process is repeated until all samples are traversed.

3.3 Credit ratings of CDs

The proposed credit system is essentially a user incentive model. By setting different preferential quota prices for CDs with different credit ratings, CDs could be motivated to participate in carbon emission reduction. The power company establishes and operates the credit system for CDs, including updating their credit scores and credit ratings and adjusting the floating carbon emission quota prices.

The designed credit system adopts a hundred-mark system. The range of 60–100 points indicates qualified credit. The 60th point corresponds to the base price of electricity-related carbon emission quota. With credit scores between 61 and 100 points for CDs who purchase and sell quotas, the prices will be respectively lowered and increased to different degrees on the basis of the base price. The range of 0–59 points indicates unqualified credit. For CDs in this area, on the contrary, on the basis of the base price, their purchase and sell prices will be respectively lowered and increased to different degrees. Table 1 shows the carbon emission credit ratings and the corresponding floating prices.

3.4 Credit score and credit rating initialization and updating

A CD's initial credit score is set by the power company based on the standards issued by the electricity–carbon industry association. For simplicity, in this paper, the credit score initialization is based on the punctuality of the CDs' electricity bill payment. Considering the due time of an electricity bill is T_{ei} and the actual payment time is T_{hi}, if T_{hi} is earlier than T_{ei}, a normal payment will be recorded; otherwise, it will be recorded as a default.

In a statistical period Z_a, the number of normal payments is denoted as f_a and the total number of bill cycles is denoted as F_a. Then, the normal payment ratio is equal to $\frac{f_a}{F_a}$. If there is no default, namely, delayed payments, this ratio is equal to 1. The initial credit score of a CD is determined by the normal payment ratio and the delayed time in the presence of defaults. Assuming the basic credit score is G_b, the initial credit score of a CD, namely, G_c, can be calculated as in Eq. 8, where $G_c \in [0, 100]$.

$$G_c = G_b + \left(\frac{f_a}{F_a} - \sum_{i=1}^{n^T}\left(\frac{T_i^R - T_i^E}{T_i^E}\right)\right). \tag{8}$$

A CD's electricity-related carbon emission quota trading records, as well as violations on delivering traded quotas, will be stored, and at the same time, its credit scores will be dynamically updated based on these records. The power company supervises the carbon emission trading between CDs and rewards or penalizes CDs based on the rules in Table 1. Before the final delivery of traded quotas, all deals are first checked by the power company and then reviewed by the municipal government to verify the fairness and protect the interests of all involved parties.

On the basis of the initial credit score, the power company enforces the rules of credit score updating, as designed in Table 2. The rules are designed referring the standards of the electricity–carbon industry association.

3.5 Carbon emission quota trading mechanism

The purpose of analyzing the total selling and purchasing offers is to judge whether the total carbon emission quota of CDs has been reduced based on the trading information. If the total amount of purchasing offers of CDs is greater than that of the selling offers, which means the total amount of carbon emissions will increase, the government will apply the carbon emission protection mechanism. Carbon emission quota trading will be settled with the government-approved ceiling price. For the part that exceeds the supply, the power company will purchase more green electricity on behalf of CDs so that CDs can offset their excess. The corresponding price will increase on the basis of the government-approved ceiling price. If the total amount of purchasing offers of CDs is less than that of the selling offers, a Stackelberg game between CD buyers, CD sellers, and the power company will be carried out to determine the price.

The total amount of CDs' electricity-related carbon emissions, C_c^{CA}, can be calculated as in Eq. 9, where C_c^F represents the basic quota of a CD; C_c^{SA} represents the total sold quota; and C_c^{BA} represents the total purchased quota.

$$C_c^{CA} = C_c^F \times m + \left(C_c^{SA} - C_c^{BA}\right). \tag{9}$$

If C_c^{CA} increases, the protection price of the carbon emission quota price will be implemented. For a CD who purchases carbon emission quota, its electricity carbon emission expenditure can be calculated as in Eq. 1, where V^F represents the base price; $C_c^{Reality}$ represents the actual carbon emission quota; V^{Max} represents the maximum price; C_c^{Buy} represents quota purchased from other CDs; and Z^E is the power company's green power purchase price.

$$Z^E = C_c^F \times V^F + C_c^{Buy} \times V^{Max} + \left(C_c^{Reality} - C_c^F - C_c^{Buy}\right) \times \left(V^F + V^{Max}\right). \tag{10}$$

For a CD who sells carbon emission quota, the income of the CD, Z^S, can be calculated as in Eq. 11, where C_l represents quota sold to other CDs. It is worthwhile to mention that a fee taking s of the income will be charged by the power company.

$$Z^S = C_c^{Buy} \times V^{Max} \times (1 - s). \tag{11}$$

The carbon emission pricing analysis is used to determine the base price. On the premise that the price in carbon emission quota trading is higher than that in the carbon emission credit spot market, CD sellers, CD buyers, and the power company will play a Stackelberg game, seeking an equilibrium price for the three parties. This equilibrium price will be set as the settlement price.

The Stackelberg game is a leader–follower game model. In this model, the leader with advantages first gives its competitive strategy, and then the followers give their own strategies responding to the strategy of the leader (Mukaidani et al., 2021; Bouchaib et al., 2023). In the proposed carbon emission quota trading market, the competitive positions of the power company and CDs are obviously not equal. Intuitively, the power company will be the leader in the game and CDs, either as buyers or sellers, are the followers in the game.

In the game, we use q to denote the power company, u_c to denote CD sellers, and u_d to denote CD buyers. They are collected by O as in Eq. 12.

$$O = \{u_c, u_d, q\}. \tag{12}$$

In the game, considering the power company as the leader bids θ prices, denoted by l, the leader's bidding price vector can be written as Eq. 13.

$$L = \{l_1, l_2, \ldots l_\theta\}. \tag{13}$$

Considering the CD buyers, as the follower, bid ε quantities, denoted by y, the buying quantity vector can be written as Eq. 14.

$$Y = \{y_1, y_2, \ldots y_\varepsilon\}. \tag{14}$$

Considering the CD sellers, as the follower, bid ψ quantities, denoted by x, the selling quantity vector can be written as Eq. 15.

$$X = \{x_1, x_2, \ldots x_\psi\}. \tag{15}$$

In the Stackelberg game, the expenditure of CD buyers is denoted as Z_i^{Buy}; the income of CD sellers is denoted as Z_i^S; and the profit of the power company is denoted as Z_i^{ST}. The Stackelberg game model can be expressed as in Eq. 16.

$$W = \{O; L; \{Y, X\}; \{Z_i^{Buy}, Z_i^S, Z_i^{ST}\}\}. \quad (16)$$

In the gaming process represented by Eq. 16, the CD sellers pursue higher incomes and credit scores; and the CD buyers pursue lower expenditures and higher credit scores. The power company pursues the highest trading agency fee under the condition that the overall electricity-related carbon emissions can be reduced. All the three parties use benefit-maximizing strategies in the game until they reach an equilibrium.

In the game, in a trading cycle k, the quota selling price is V_i^{SC}; the sold quota is C_i^{SC}; the cost for the basic quota is V_i^Q; and the credit score loss cost is denoted as C_i^C. The income of a CD seller can be calculated as in Eq. 17.

$$C_i^{SR} = \sum_{i=1}^{k} (V_i^{SC} \times C_i^{SC} - V_i^Q) - C_i^C. \quad (17)$$

The CD seller needs to satisfy Eq. 18, where C_i^{SMax} is the basic quota.

$$C_i^{SMin} \le C_i^{SR} \le C_i^{SMax}. \quad (18)$$

In a trading cycle, the quota buying price is V_j^{Buy}; the purchased quota is C_j^{Buy}; the cost for the basic quota is C_j^{Base}; and the credit score loss cost is denoted as C_j^C. The expenditure of a CD buyer can be calculated as in Eq. 19.

$$C_j^E = \sum_{j=1}^{k} \left(V_j^{Buy} \times C_j^{Buy}\right) + C_j^{Base} - C_j^C. \quad (19)$$

CDs are connected to distribution transformers through 0.4 kV distribution lines. The upper bound of their carbon emissions is indeed limited by the rated capacities of the distribution transformers that they are connected to. Thus, the power input to CD buyers needs to satisfy constraint Eq. 20. The upper bound is determined by the rated capacity of the distribution transformer, C_j^{Rated}, and the total load of CDs that connect to the transformer, C_j^{Sum}. Distribution transformer load capacity (kW) = the rated capacity (kVA) × the power factor. The power factor is set as 0.8 according to the industry standard of China. The corresponding description has been revised in the paper.

$$\begin{cases} C_i^{SMin} = C_j^{BMin} \\ C_i^{SMax} \le C_j^{BMax} \\ C_j^{BMax} = C_j^{Rated} - C_j^{Sum} \end{cases}. \quad (20)$$

The power supply company only administrates the trading market and charges agency fees according to the traded amount of carbon emission quotas. The benefit of the power company is, in fact, the collected agency fees as in Eq. 11. The benefit of the power company can be calculated as in Eq. 21, where n_j is the number of CD sellers and n_k is the number of CD buyers. S_{ci} and S_{qj} are the income of CD seller i and the expenditure of CD buyer j, respectively.

$$C_j^R = s\sum_{j=1}^{e} C_i^E. \quad (21)$$

We use β_i, β_j, and β_k strategy spaces of CD sellers, CD buyers, and the power company, respectively, and then the game between them can be represented as Eq. 22.

$$\begin{cases} \max S_c \\ s.t.[c_{m1}, c_{m2}, \ldots, c_{mt_b}] \in \beta_i \\ \max S_q \\ s.t.[c_{n1}, c_{n2}, \ldots, c_{nt_b}] \in \beta_j \\ \max S_d \\ s.t.[v_{h1}, v_{h1}, \ldots v_{h\theta}] \in \beta_k \end{cases}. \quad (22)$$

With a Nash equilibrium solution, neither the power supply company nor any CD buyers and sellers can unilaterally change the strategy to achieve more profit. To achieve Nash equilibrium in the game, the optimal conditions of all participants should be satisfied. Under this premise, CD sellers and the power company look for the best quota buying price from high to low for profit maximization, while CD buyers look for the best quota selling price from low to high for cost minimization. In the process of solving the Nash equilibrium of the Stackelberg game, CD sellers, the power company, and CD buyers offer the initial prices. Then, in each iteration, the price change gradients of the three participants are calculated and their offered prices are updated. The iterative process continues until their current price offers are equal to the maximum values of their strict convex functions so as to obtain the Nash equilibrium. The detailed solving process is available in Jin et al. (2021) and Veeramsetty (2021) and thus is not described redundantly in this paper.

3.6 Carbon emission quota trading settlement

In the settlement, the credit scores can be used to exchange for preferential treatment. When the exchange amount is greater than Δu, the credit score is deducted by Δg. Thereafter, the credit score will be updated following the observation in Table 2. The credit score is updated in every trading cycle. In fact, in the settlement, the credit value deduction mechanism for CDs that have enjoyed preferential treatment is to avoid CDs becoming inert after reaching high credit scores and credit ratings, thereby repeatedly incentivizing CDs to participate in carbon emission quota trading.

For a CD seller, if his/her actual delivered quota changes due to the increase or decrease in his/her own power consumption, there will be a deviation from its offered amount. The ratio of deviation can be calculated as in Eq. 23, where F^S is the ratio of deviation; C_j^{RS} is the offered quota amount; and C_j^R is the actual sold quota amount. When F^S is negtive, i.e., the actual sold is less than offered, default happens.

$$F^S = \frac{C_j^R - C_j^{RS}}{C_j^{RS}}, \quad (23)$$

$$F^B = \frac{C_j^B - C_j^{RB}}{C_j^{RB}}. \quad (24)$$

For a CD buyer, if his/her actual bought quota decreases due to the increase or decrease in his/her own power consumption, there will be a deviation from its asked amount. The ratio of deviation can be calculated as in Eq. 24, where F^B is the ratio of deviation; C_j^{RB} is the actual bought quota amount; and C_j^B is the asked quota amount.

When F^B is positive, i.e., the actual bought amount is less than asked, default happens.

Using Q_a and Q_b to denote the initial credit scores of CD buyers and CD sellers, and v_{c1} and v_{c2} to denote carbon emission quota pruchasing and selling prices, respectively, credit scores, Q_x and Q_y, after updating can be calculated as Eqs 25, 26.

$$Q_x = Q_a + \left(-\frac{F^S}{\Delta k_1}\Delta f_1 + \frac{C_j^R}{\Delta k_2}\Delta f_2 - \frac{C_j^R \times V_j^{RE1}}{\Delta \mu}\Delta g \Delta f_3\right), \quad (25)$$

$$Q_y = Q_b + \left(-\frac{F^B}{\Delta h_1}\Delta j_1 + \frac{C_j^B}{\Delta h_2}\Delta j_2 - \frac{C_j^B \times V_j^{RE2}}{\Delta \mu}\Delta g \Delta j_3\right). \quad (26)$$

4 Case study

4.1 Case setting

An actual community in a city in China is selected to validate the proposed electricity-related carbon emission quota trading market model. This community is equipped with 24 distribution transformers and has 10,762 CDs. The resident population of this community is 22,736. A single CD has only one house. The carbon emission quota trading is carried out monthly from January to December 2021. We consider that each CD corresponds to one unit (apartment) in this community. The typical values from the SACE are shown in Tables 1, 2. Other detailed parameters are shown in Tables 3, 4.

The Hungarian algorithm in Du et al. (2020) is compared with the proposed trading mechanism. The Hungarian algorithm has the characteristics of accurate results and high analysis efficiency and is widely used in carbon emission credit trading markets.

All numerical simulations are conducted on a server with Intel Xeon E5-2650 CPU (8 cores), 32 GB RAM, and 10 TB SSD. The operating system is Windows Server 2019.

The electricity-related carbon emission quota trading market proposed in this paper is cleared once a month. Considering China's carbon emission credit price will gradually be in line with that of Europe and the United States, the initial carbon emission quota price is set at 0.26¥/kg, referring to the price in Europe (Frank, 2021).

In this paper, the tiered electricity prices of CDs have three tiers based on the electricity consumption: 1) within 100 kWh, charged at benchmark electricity price, 2) 101–200 kWh, charged at 120% of the benchmark electricity price, and 3) above 200 kWh, charged at 150% of the benchmark electricity price. Only CDs with electricity consumption in the first tier sell their remaining carbon emission quotas, while CDs in the other two tiers need to purchase quotas. For credit score and rating initialization, the electricity bill payment records of 60 months, from 2015 to 2020, are used. The power and capacity of equipped energy storage systems are 200 and 500 KWh, respectively. The capacity of distribution transformers supplying this community is 2000 KVA. The maximum purchase of carbon emission quota will be restricted by the capacity of the distribution transformers.

The electricity consumption of this community in January 2021 was 1872.6 MWh, and the line loss rate of its distribution area was 4.28%. The daily carbon emissions of this community in January 2021 are shown in Figure 4. In the basic carbon emission quota approval, the proportion of its electricity-related carbon emission in its total carbon emission amount increase does not exceed the threshold of $\Delta\varphi$. As shown in Figure 4, the carbon emission quota for this community is 164.27 kg.

4.2 Result analysis

4.2.1 Clustering result

Clustering on CDs is to obtain their sensitivity levels to carbon emission quota prices. The improved DBSCAN method is used to cluster CDs, and the results are shown in Table 5.

As shown in Table 5, CDs in the studied community can be clustered into three main classes: quota buyers, quota sellers, and idle CDs. Idle CDs are vacant units without or with less power consumption. Among them, CDs in the second and third tiers of the tiered electricity prices are less sensitive to carbon emission prices and are willing to purchase additional quotas. By contrast, CDs in the first tier are willing to sell their remaining quotas and are more sensitive to prices.

This section validates the effectiveness of the improved DBSCAN algorithm with a clustering accuracy rate that ranges from 0% to 100%. Intuitively, a greater value indicates a better performance. The manual clustering results are taken as the benchmark, and thereby the accuracy rate is defined as the proportion of identical clustering results of CDs to the results of manual clustering over all CDs. To avoid the long clustering convergence time of the DBSCAN method, the neighbor search scale in the DBSCAN algorithm is set as 200.

The clustering results of the improved DBSCAN and the K-means clustering algorithm with the number of CDs increasing from 1,000 to 8,000 at a step of 1,000 and being 10,000 are compared in Table 6. It can be seen that with different numbers of CDs, the improved DBSCAN outperforms the K-means clustering algorithm in terms of the clustering accuracy rate.

4.2.2 Trading result

In this section, we study the game between CD buyers, CD sellers, and the power company. In the game, the power company charges agency fees based on a specific proportion of the electricity carbon emission quota price. Taking January 2021 as an example, in the game, the power company first sets the carbon emission quota price to 0.26¥/kg and then the CD buyers and sellers play a game based on their costs, benefits, and credit scores. The carbon emission quota price is adjusted until the Nash equilibrium is reached. The result is shown in Figure 5.

As shown in Figure 6, at the beginning of the game, CD sellers and the power company offer a high price, while CD buyers offer a low price to pursue profit maximization. The Nash equilibrium is reached after about 45 times of gaming, and the final price consensus is 0.275 ¥/kg.

The carbon emission quota price analysis is to verify the price changes with market demand in the trading. When the supply of carbon emission quota exceeds the demand, the price decreases; on the contrary, when carbon emission quotas are in short supply, the price increases. The carbon emission quota prices for the 12 monthly market clearings in 2021 are shown in Figure 6.

As shown in Figure 6, the spring festival in February and the summer period of July, August, and September experience the peak of CD electricity consumption, which are also the peak of carbon emissions. The electricity-related carbon emission quotas are in short supply during these periods, so the trading prices are relatively high. The rest of the months are representative of the valley of electricity consumption, and the supply of carbon emission quotas usually exceeds the demand leading to low prices.

4.2.3 Credit scores and ratings

In this section, the proposed credit system is validated. The better the credit score and rating updating rules work, the higher the profit of the power company, especially when the total carbon emissions of CDs are reduced. Taking January 2021 as an example, the carbon emission quota price in January was 0.275 ¥/kg, as shown in Figure 4. Δg is set as 0.2 points. All CDs except 209 idle CDs, i.e., remaining 10,553 CDs, are considered in the credit system. All CD carbon emission data in January and the adjusted CD credit scores and ratings are used in the simulation of the next month. The results are shown in Table 7.

As shown in Table 7, after the market clearing in January, the credit scores of some CDs are deducted, leading to changes in their credit rating. Using the carbon emissions of January, the adjusted CD credit rating, and January CD electricity carbon emission trading to compare, the fluctuation of the overall income of the three parties is within 500 ¥, maintaining stable operation of the reputation system.

4.2.4 Carbon emission reduction analysis

To verify the reduction effect of carbon emissions after the operation of the proposed method, the average electricity carbon emission capacity of CDs in this community is analyzed. The numerical simulation spans from January to December 2021, with the proposed method being applied. The result is compared with the original operation data (i.e., without carbon emission quota trading) from January to December 2021 and the result with the asymmetric Nash negotiation method. The results are compared in Figures 6, 7. As shown in Figure 7, the average carbon emission of CDs over a year with the proposed credit system decreases from 168.83 to 152.58 kg compared with the asymmetric Nash negotiation method. This shows that the proposed credit system outperforms the asymmetric Nash negotiation method in terms of promoting carbon emission reduction.

The purpose of the income analysis of CDs is to evaluate the incentives to CD buyers and sellers. Intuitively, the incomes of the CD sellers and the power company come from the expenditure of CD buyers. Higher incomes are beneficial to suppress the carbon emission of CDs. The incomes and expenditures of all parties in January 2021 are shown in Table 8.

As shown in Table 8, it can be seen that with the asymmetric Nash negotiation, the carbon emission quota prices to different CD buyers and sellers are identical and not incentives. With the proposed credit system, the incomes of CD sellers with high credit ratings increase, while those of CD sellers with low credit ratings decrease. Similarly, the expenditures of CD buyers with high credit ratings decrease, while those of CD buyers with low credit ratings increase. Through the proposed credit system, the electricity consumption of CDs that arouses carbon emissions is restrained from the economic point of view.

5 Conclusion

To solve the problem that the current policies have limited incentives to motivate CDs, reducing their carbon emissions leads to CD's electricity-related carbon emissions increasing year by year. A credit rating- and credit score-based carbon emission quota trading model is proposed for regulating CDs' carbon emission reduction behaviors. This model is based on the control of the total carbon emissions of all CDs and a reward–punishment mechanism based on the credit rating. From the simulation, the following conclusions can be drawn:

1) On the basis of the control of the total carbon emission and the tiered electricity price, the DBSCAN is used to cluster CDs and obtain the typical classification of CDs. For different numbers of CD samples, the improved DBSCAN is superior to the K-means clustering algorithm in terms of clustering accuracy.
2) A Stackelberg game is built to guide CDs to achieve market-oriented trading. The final quota price after the game between CD sellers, CD buyers, and the power companies can reasonably reflect the balance of supply and demand.
3) The power company charges CDs floating carbon emission fees based on their credit ratings. The proposed trading model is superior to the original situation and the asymmetric Nash negotiation method.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to tangdonglai@sohu.com.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

Authors DT, JZ, and WS were employed by Aostar Information Technology Co., Ltd. Author QL was employed by State Grid Information and Communication Industry Group Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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