Research on the Synergistic Optimization Operation Mechanism of the Environmental Rights Trading Market in Chongming District

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Abstract: Focusing on Chongming District (a typical ecologically sensitive area), this study decomposes environmental rights transaction costs into four key dimensions (carbon cost intensity [CCI], carbon emission intensity [CEI], production efficiency level [PEL], employment scale effect [ESE]) via the Logarithmic Mean Divisia Index (LMDI) method, using enterprise and resident data. It also constructs environmental rights (green certificates, green electricity) potential models and a "mutual recognition ratio model". Results show CCI and PEL drive cost growth, while CEI and ESE inhibit costs. The multi-market mutual recognition mechanism reduces comprehensive transaction costs and total carbon emissions; the "prioritizing high-value product development" strategy achieves full coverage of photovoltaic grid-connected electricity. The multi-market coordination mechanism cuts enterprises' transaction costs and supports green, high-quality transformation of ecologically constrained regions.

Keywords: Environmental Rights; Multi-Market Coordination; Carbon Market; Decomposition Analysis; Ecologically Sensitive Region

1. Introduction

As a key policy tool for addressing climate change, the environmental rights trading market comprises three complementary systems: the carbon emissions trading system (ETS), renewable energy certificate (REC) trading mechanism, and carbon inclusion system [1]. With China's carbon market advancing—evidenced by Shanghai's 2026-2030 reform plan and national new energy pricing policies—coordination gaps persist between the carbon market, green electricity/certificate markets, and carbon benefit-sharing mechanism [2]. This fragmentation reduces environmental rights allocation efficiency and curbs enterprises' emission reduction enthusiasm, calling for a systematic multi-market coordination mechanism to enhance overall emission reduction effectiveness.

Internationally, typical environmental rights markets exhibit diverse development traits: the US evolved green electricity/certificate policies and adjusted carbon markets with politics [3]; the UK advanced such markets for net-zero goals and shifted carbon systems [4]; Germany promoted them via Renewable Energy Law revisions [5]. Mechanism-wise, the US has compulsory/voluntary dual markets, the UK integrates long-term power purchase and carbon trading, and Germany centers on day-ahead trading for green electricity [6]. Domestically, policies for green electricity, green certificates, carbon markets, and CCER have advanced progressively, with matured mechanisms like unified green electricity trading rules, 2-year valid green certificates, and a complementary national mandatory carbon market and voluntary CCER market.

Environmental rights transaction costs—a key factor for enterprises in carbon neutrality—are shaped by multi-dimensional factors. From a price perspective, Guo Wenjun [7] used the adaptive Lasso method and found China's regional carbon prices are strongly influenced by exchange rates and economic environments but weakly by international carbon prices; Xiang Weimin and Zhong Chao [8] applied regression models and identified the yuan-euro exchange rate as the most significant driver of China's carbon market prices. In terms of emission reduction costs, Shi et al. [9] studied marginal emission reduction cost convergence under carbon markets, noting quota ambiguity and policy shifts may hinder transactions and that high compliance costs/limited expertise lead enterprises to prefer direct emission reduction;

Li et al. [10] surveyed 2015 and 2018 pilot carbon market entities, finding nearly half lack clear emission reduction targets and understand marginal emission reduction costs poorly. For multi-market coordination, Yan et al. [11] proposed integrating carbon pricing into energy markets to promote renewable energy adoption; Paravee et al. [12] suggested combining carbon quotas with green bond investments to buffer market volatility and enhance carbon market resilience; Wang Ting et al. [13] developed an integrated energy system scheduling method under green certificate-carbon market mutual recognition, verifying cost reductions via simulation. However, existing research focuses more on macro indicators than micro attributes, lacks quantitative analysis of direct emission reduction costs, fails to explore carbon benefit-sharing synergies across environmental rights markets or build multi-market cost optimization models, and has scarce empirical studies on high-energy enterprises in ecologically sensitive regions.

As a Yangtze River estuary alluvial island with unique ecological sensitivity, Chongming District serves as a core for Shanghai's "world-class ecological island" initiative and a typical case to study environmental rights transaction cost differences in ecologically constrained regions. Its industrial energy consumption traits paired with strict eco-protection requirements create an ideal scenario to analyze transaction cost formation under dual policy and industrial constraints. Using data from local enterprises and residents, this study constructs development and consumption potential models for environmental rights (green certificates, green electricity, carbon benefit-sharing emission reductions), decomposes transaction costs into four key dimensions (CCI, CEI, PEL, ESE) via the LMDI method to analyze factor impacts, and proposes a "mutual recognition ratio model" to verify the minimum comprehensive carbon transaction cost under multi-market coordination. The research extends transaction cost analysis dimensions, innovates multi-market synergy assessment tools, and provides optimal transaction references for entities in ecologically sensitive regions.

2. Materials and Methods

2.1 Enterprise Carbon Emissions and Carbon Quotas

2.1.1 Enterprise carbon emissions

In the environmental rights trading system of the electricity market, electricity consumption is an important component of enterprise carbon emissions and also a key link connecting the carbon quota market with green electricity and green certificate markets. Based on the theoretical framework of environmental rights trading in the electricity market, this research focuses on carbon emissions generated by enterprise electricity consumption. Using Shanghai's power grid emission factor multiplied by the corresponding electricity consumption, the carbon emissions from electricity consumption are obtained. Specifically:

$$E_{CO_2} = P_{\text{load}_{\text{e,k}}} \times \text{EF}_{\text{elec}} \tag{1}$$

Where E_{CO2} is the enterprise's electricity consumption carbon emissions; $P_{loade,k}$ is enterprise k's electricity consumption; EF_{elec} is the Shanghai power grid emission factor.

2.1.2 Enterprise carbon quotas

Based on the Shanghai 2025 Carbon Emissions Quota Allocation Plan, the carbon emissions and carbon quota calculations for covered enterprises in Chongming District follow the quota allocation and management system established by the Shanghai Ecological Environment Bureau. For covered enterprises in Chongming District, considering their industry characteristics and production features, the calculation of annual basic quotas adopts the historical emissions method. The main reasons for choosing the historical emissions method are: covered enterprises in Chongming District are mainly concentrated in heavy industries such as shipbuilding, which have characteristics of high product complexity, large production boundary changes, and complex measurement systems, making it difficult to adopt the industry benchmark method or historical intensity method. The historical emissions method is the most suitable allocation method. Specifically:

$$\begin{aligned} &Enterprise\,annual\,basic\,quota = \\ &Historical\,carbon\,emissions\,baseline \end{aligned} \tag{2}$$

$$\begin{aligned} &Enterprise\,annual\,basic\,quota = \\ &Historical\,carbon\,emissions\,baseline \end{aligned} \tag{3}$$

Where the historical carbon emissions baseline generally takes the average of the enterprise's carbon emissions over the previous three years. When enterprise carbon emissions within three years show continuous increase or decrease, 2023 carbon emissions are ≥1 million tons with cumulative change exceeding 30%, or 2023 carbon emissions are <1 million tons with cumulative change exceeding 40%, the 2023 carbon emissions data is used. If the above conditions are not met but annual carbon emissions change exceeds 20%, the arithmetic average of each year's changed carbon emissions is taken; the direct allocation quota ratio is calculated according to the parameters in the Shanghai 2024 Carbon Emissions Quota Allocation Plan, as shown in Table 1.

Table 1. Direct Allocation Quota Ratios for Different Types of Enterprises

Classification	Carbon energy emissions ratio (a)	Direct allocation quota ratio
Industrial enterprises	a≥75%	93%
	50%≤a<75%	95%
	25%≤a<50%	97%
	a<25%	99%
Power and heat enterprises	a≥50%	96%
	a<50%	99%
Non-industrial enterprises	99%	

2.2 Environmental Rights Transaction Costs

2.2.1 Green electricity and green certificate development and consumption potential

Collect actual power generation output data from renewable energy units in Chongming District, accumulate and calculate by hour to obtain the green certificate development potential, where each megawatt-hour of green electricity corresponds to one green certificate. The specific calculation is as follows:

$$N_{LZ} = \sum_{t=1}^{T} P_{ZS}(t) \tag{4}$$

Where *NLZ* is the total amount of green certificates generated by renewable energy units (1MWh=1 green certificate), i.e., green certificate development potential; $P_{ZS}(t)$ is the actual grid-connected electricity from renewable energy units in period t.

The renewable energy portfolio standard (RPS) as a key policy for promoting clean energy consumption requires electricity consumption entities to ensure a certain proportion of renewable energy electricity use, with this proportion specified through the new energy quota ratio. Based on the Notice from the National Development and Reform Commission and National Energy Administration on Establishing and Improving the Renewable Energy Power Consumption Guarantee Mechanism, this research calculates the enterprise's green certificate demand potential. The specific calculation is as follows:

$$N_{CM} = \sum_{t=1}^{T} \omega Pload_e(t) \tag{5}$$

Where *NCM* is the enterprise's green certificate demand potential based on RPS requirements, $P_{loade}(t)$ is the electricity consumption in period t, ω is the corresponding new energy quota ratio, calculated according to Shanghai's historical renewable energy power consumption responsibility weights.

Further quantifying the green certificate supply-demand relationship under RPS and calculating the green electricity and green certificate consumption potential. The specific calculation is as follows:

$$POT_{LZ} = N_{CM} - N_{LZ} \tag{6}$$

Where POT_{LZ} is the green electricity and green certificate consumption potential. If $POT_{LZ} > 0$, it indicates the need to purchase green certificates externally to meet quotas; if $POT_{LZ} < 0$, surplus green certificates can participate in market trading.

2.2.2 Carbon benefit-sharing development and consumption potential

This research focuses on emission reduction potential under the carbon benefit-sharing mechanism. By quantifying distributed photovoltaic power generation projects with a single project capacity of 1MW or less, combined with corresponding emission factors, we construct a carbon benefit-sharing development potential model. Specifically:

$$EB = \sum_{i=1}^{n} (BE_i - PE_i) \tag{7}$$

$$BE_i = \sum_{i=1}^{n} (BA_i - BEF_i) \tag{8}$$

$$PE_i = \sum_{i=1}^{n} (PA_i \times PEF_i) \tag{9}$$

Where *EB* is the carbon benefit-sharing emission reduction development potential, *BEi* is the baseline emissions for type *i* carbon benefit-sharing emission reduction projects, *PEi* is the actual emissions for type *i* carbon benefit-sharing emission reduction projects; *BAi* is the baseline activity quantity for type *i* projects, BEF_i is the baseline behavior emission factor for type *i* projects; *PAi* is the actual activity quantity for type *i* projects, PEF_i is the low-carbon behavior emission factor for type *i* projects. This research considers distributed photovoltaic projects under Shanghai's carbon benefit-sharing emission reduction scenario methodology.

Further quantifying enterprise carbon benefit-sharing behavior consumption potential under Shanghai Ecological Environment Bureau's carbon emissions trading compliance requirements, that is, enterprises can use Shanghai carbon benefit-sharing emission reduction (SHCERCIR) for quota settlement. Each ton of SHCERCIR is equivalent to 1 ton of carbon emissions quota, but the total proportion shall not exceed 5% of the enterprise's actual total carbon quotas obtained. Specifically:

$$POT_{PH} = \sum_{i=1}^{K} 5\% EQ - EB \tag{10}$$

Where POT_{PH} is the carbon benefit-sharing project consumption potential, EQ is the carbon quota amount, EB is the development potential of carbon benefit-sharing projects. If $EB < 5\% EQ$, it indicates that carbon benefit-sharing can be purchased to meet quotas; if $EB \geq 5\% EQ$, it indicates that quotas allocated for carbon benefit-sharing settlement have reached the limit, and surplus carbon benefit-sharing can participate in market trading.

2.2.3 Environmental rights transaction costs under multi-market mechanisms

All environmental rights transaction costs for enterprises in Chongming District include carbon quota trading costs, green electricity and green certificate trading costs, and carbon benefit-sharing trading costs. Specifically:

$$ET = \lambda_{LZ} \times POT_{LZ} + \lambda_{ph} \times POT_{ph} + \lambda_{pe} \times EQ \tag{11}$$

Where ET is the total environmental rights transaction cost under multi-market mechanisms, λ_{lz} is the green certificate trading price, λ_{ph} is the carbon benefit-sharing trading price, λ_{pe} is the carbon quota trading price, EQ is the carbon quota amount.

2.3 Decomposition of Environmental Rights Transaction Cost Factors

Environmental rights transaction cost changes are influenced by multiple factors. To quantify the contribution degree of each driving factor, this research constructs a decomposition framework for environmental rights transaction costs based on the Kaya identity. The Kaya identity connects costs with carbon emissions, economic output, enterprise scale, and employee numbers through mathematical forms, possessing clear policy implications and explanatory power. The Logarithmic Mean Divisia Index (LMDI) method, due to its advantages of complete decomposition, no residuals, and zero value handling, has been widely applied to energy and emissions driving factor analysis. Combining Chongming District enterprise characteristics, this research decomposes environmental rights transaction costs into the following four categories of driving factors:

(1) Carbon Cost Intensity (CCI), representing the environmental rights transaction cost borne per ton of carbon emissions, reflecting the strength of carbon market price signals and enterprise emission reduction cost efficiency. Rising CCI may originate from carbon quota tightening or price increases, while declining CCI indicates enterprises have found more economical emission reduction methods.

(2) Carbon Emission Intensity (CEI), measuring the carbon emissions level per unit economic output, reflecting the low-carbon degree of enterprise production processes. Declining CEI indicates enterprises have achieved green transformation through energy structure adjustment, energy efficiency improvement, or process improvement.

(3) Production Efficiency Level (PEL), representing economic output efficiency per unit human resource input, comprehensively reflecting the promoting effects of technological progress, management optimization, and capital deepening on production efficiency improvement. PEL improvement is often accompanied by intensive use of production factors and declining carbon emission intensity.

(4) Employment Scale Effect (ESE), representing the labor input scale of enterprise production and operation.

In the Kaya expression, environmental rights transaction costs can be expressed as:

$$ET = \frac{ET}{CE} \times \frac{CE}{EV} \times \frac{EV}{NE} \times NE \tag{12}$$

Where ET represents environmental rights transaction costs; CErepresents enterprise carbon emissions; EV is enterprise production value; NE represents enterprise employee numbers.

In LMDI decomposition, additive decomposition compared to traditional multiplicative decomposition can completely decompose driving factors and better handle data residuals and zero values, with multiple decomposition forms. Therefore, the decomposition of environmental rights transaction cost influencing factors is as follows:

$$\Delta ET = ET_T - ET_0 = \Delta CCI + \Delta CEI + \Delta PEL + \Delta ESE \quad (13)$$

Where *ΔET* represents environmental rights transaction cost changes. *ETT* and *ET0* are target and base period environmental rights transaction costs respectively; *ΔCCI* = ΔET/ΔCE represents changes in carbon cost intensity-related factors; *ΔCEI* = ΔCE/ΔEV represents changes in carbon emission intensity-related factors; *ΔPEL* = ΔEV/ΔNE represents changes in production efficiency level-related factors; *ΔESE* represents changes in employee number-related factors. The specific formulas for these expressions are as follows:

$$\Delta CCI = \frac{ET_T - ET_0}{\ln ET_T - \ln ET_0} \times \ln \frac{CCI_T}{CCI_0} \quad (14)$$

$$\Delta CEI = \frac{ET_T - ET_0}{\ln ET_T - \ln ET_0} \times \ln \frac{CEI_T}{CEI_0} \quad (15)$$

$$\Delta PEL = \frac{ET_T - ET_0}{\ln ET_T - \ln ET_0} \times \ln \frac{PEL_T}{PEL_0} \quad (16)$$

$$\Delta ESE = \frac{ET_T - ET_0}{\ln ET_T - \ln ET_0} \times \ln \frac{ESE_T}{ESE_0} \quad (17)$$

ETT and *ET0* in equations (14) through (17) have the same meaning as in equation (13). When the coefficients of *ΔCCI*, *ΔCEI*, *ΔPEL*, *ΔESE* are positive (negative), it indicates that this factor has a promoting (restraining) effect on the increase (decrease) of environmental rights transaction costs. Specifically:

(1) ΔCCI (Carbon Cost Intensity): Positive values indicate rising environmental rights transaction costs per unit carbon emissions, mainly from carbon quota supply tightening or price increases; negative values reflect carbon market loosening or improved enterprise emission reduction efficiency bringing declining unit carbon costs.

(2) ΔCEI (Carbon Emission Intensity): Positive values indicate increased per-unit-value carbon emissions, usually caused by declining energy efficiency or increased high-carbon energy proportion; negative values correspond to production process improvement or clean energy substitution bringing reduced carbon emission intensity.

(3) ΔPEL (Production Efficiency Level): Positive values show declining economic output efficiency per unit human resources, possibly from production management deterioration or technology iteration lag; negative values reflect organization optimization or technology innovation bringing efficiency improvement.

(4) ΔESE (Employment Scale Effect): Represents changes in employee number-related factors.

2.4 Carbon – Certificate – Benefit - Sharing Mutual Recognition Mechanism

2.4.1 Green certificate-carbon quota mutual recognition mechanism

Based on the price ratio relationship between green electricity/certificates and carbon quota trading, we establish a dynamically adjustable mutual recognition ratio model, comprehensively considering the impact of marginal electricity emission factors and marginal capacity emission factors. Specifically:

$$E_{LZ} = \sum_{t=1}^{T} (EF_{OM} \times \omega_{OM} + EF_{BM} \times \omega_{BM}) \times \frac{\lambda}{a} \times POT_{LZ} \quad (18)$$

$$E_{LZ} = \sum_{t=1}^{T} (EF_{OM} \times \omega_{OM} + EF_{BM} \times \omega_{BM}) \times \frac{\lambda_{lz}}{a} \times POT_{LZ} \quad (19)$$

Where E_{LZ} is the equivalent carbon quota amount that green certificates can offset; EF_{OM} is the electricity marginal emission factor, *EFBM* is the capacity marginal emission factor, ω_{OM} is the electricity marginal emission factor weight, ω_{BM} is the capacity marginal emission factor weight; λ_{lz} is the green certificate trading price, α is the carbon quota trading price.

2.4.2 Carbon benefit-sharing-carbon quota mutual recognition mechanism

Shanghai stipulates that covered enterprises can use Shanghai carbon benefit-sharing emission reductions for quota settlement. Each ton of carbon benefit-sharing emission reduction is equivalent to 1 ton of carbon emissions quota. Specifically:

$$E_{PH} = POT_{PH} \quad (20)$$

Where *EPH* is the equivalent carbon quota amount that carbon benefit-sharing can offset.

3. Empirical Analysis

3.1 Basic Data

This study selects the electricity consumption and electricity-related carbon emission data of a carbon-emitting regulated enterprise in Chongming District from 2020 to 2025, as well as the power generation and grid-connected electricity data of renewable energy units owned by non-carbon-emitting regulated enterprises and residents in Chongming District in 2025 for result calculation and analysis. The electricity consumption data of the carbon-emitting regulated enterprise is shown in Table 2, the prices of the carbon market, carbon public welfare, and green certificates are shown in Table 3, the grid-connected electricity data of renewable energy units of non-carbon-emitting regulated enterprises and residents are shown in Table 4, and other relevant parameters are shown in Table 5.

Table 2. Electricity Consumption Data of a Carbon-Emitting Regulated Enterprise in Chongming District

Year	Electricity Consumption (10,000 kWh)
2020-2021	15,414
2021-2022	6,597
2022-2023	6,422
2023-2024	9,561
2024-2025	7,909

Table 3. Carbon Market, Carbon Public Welfare, and Green Certificate Price Data

Year	Carbon Market Price (yuan/ton)	Carbon Public Welfare Price (yuan/ton)	Green Certificate Price (yuan/piece)
2020-2021	50	65	0.33
2021-2022	56	65	0.33
2022-2023	69	65	0.33
2023-2024	88	65	0.33
2024-2025	76	65	2.76

Table 4. Grid-Connected Electricity of Renewable Energy Units for Non-Carbon-Emitting Regulated Enterprises and Residents

User Type	Distributed PV Grid-Connected Electricity (kWh)	
	Installed Capacity ≤ 1MW	Installed Capacity > 1MW
Enterprise Users	5,536,832	2,663,832
Residential Users	1,322,053	-

Table 5. Other Relevant Parameters

Parameter	Coefficient
EFOM	0.9014
EFBM	0.3597
ωOM	0.75
ωBM	0.25

3.2 Analysis of Carbon Emissions and Environmental Rights Transaction Costs

3.2.1 Analysis of electricity consumption and carbon emissions

The electricity consumption and carbon emission data of the carbon-emitting regulated enterprise from 2020 to 2025 indicate that the electricity consumption reached the highest level during the observation period in 2020-2021, at 154 million kWh. It dropped significantly by 57% to 66 million kWh in 2021-2022. Correspondingly, the carbon emissions peaked at 64,739 tons in 2020-2021 and then fell to 27,708 tons in 2021-2022, a decrease of over 50%. In 2022-2023, the electricity consumption remained at a relatively stable low level of 64 million kWh, with no significant difference from the previous year, and the corresponding carbon emissions were 26,972 tons, basically maintaining a low level. Starting from 2023-2024, the electricity consumption showed a recovery trend, reaching 96 million kWh, a month-on-month increase of about 49%, indicating that the power demand was in a recovery stage. Correspondingly, the carbon emissions also rose to 40,155 tons that year. In 2024-2025, the electricity consumption decreased slightly to 79 million kWh, and the carbon emissions dropped to 33,218 tons accordingly (Figure 1).

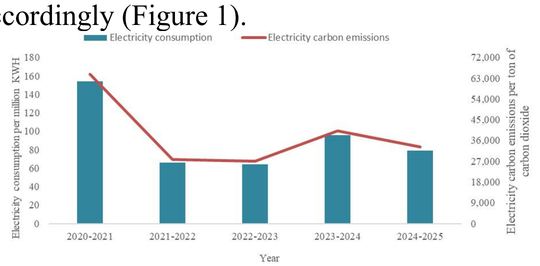

Figure 1. Electricity Consumption and Carbon Emissions of a Carbon-Emitting Regulated Enterprise in Chongming District

3.2.2 Analysis of environmental rights trading absorption of carbon-emitting regulated enterprises

Table 6 shows the composition of the multi-environmental rights trading market for the carbon-emitting regulated enterprise from 2020 to 2025. From the perspective of carbon quota transaction costs, the fluctuation range is very large. In 2020-2021, the enterprise needed to spend 226,586 yuan on carbon quota transactions, while in 2021-2022 and 2022-2023, the enterprise had a surplus of carbon quotas and obtained income by selling them, with amounts of 1,819,937 yuan and 1,105,108 yuan respectively. In 2023-2024 and 2024-2025, the enterprise faced a carbon quota gap again, spending 99,232 yuan and 164,022 yuan respectively to purchase carbon quotas to meet compliance requirements. This fluctuation reflects the impact of various factors such as the enterprise's production activities, energy conservation and emission reduction measures, and carbon market policies on the supply and demand of carbon quotas. Combined with the historical electricity consumption data, the carbon quotas of this carbon-emitting regulated enterprise are calculated using the historical emission method based on the past three years. From 2020-2021 to 2021-2022, the electricity consumption dropped sharply from 15,414 10,000 kWh to 6,597 10,000 kWh, and the corresponding reduction in electricity-related carbon emissions may have led to a large surplus of carbon quotas for the enterprise in 2021-2023. Since the carbon market allows enterprises to trade carbon quotas, the enterprise sold the surplus carbon quotas to obtain income. In 2022-2023, the electricity consumption of 6,422 10,000 kWh was similar to the previous year, continuing the situation of surplus carbon quotas for sale. However, in 2023-2024, the electricity consumption rose to 9,561 10,000 kWh, leading to an increase in electricity-related carbon emissions. In addition, the carbon quotas calculated based on the emissions of the past three years may no longer meet the current emission needs, resulting in a carbon quota gap for the enterprise, which needed to purchase quotas from the market. In 2024-2025, although the electricity consumption decreased to 7,909 10,000 kWh, there was still a carbon quota gap due to factors such as previous emission accumulation and policies, requiring continued purchase of carbon quotas.

The change in green certificate transaction costs is comprehensively affected by fluctuations in green certificate prices, adjustments to absorption weights under the renewable portfolio standard (RPS) mechanism, and changes in historical electricity consumption. From 2020 to 2023, the green certificate price remained stable at 0.33 yuan/piece, and the transaction cost was mainly affected by the green certificate absorption weight under the RPS mechanism due to the stable price. However, starting from 2023-2024, the price surged to 2.76 yuan/piece, reaching 6.48 yuan/piece in 2024-2025, and the transaction cost rose sharply accordingly. In addition, the absorption weight under the RPS mechanism increased from 8% in 2023-2024 to 10.7%, resulting in a green certificate transaction cost of 21,110 yuan in 2023-2024 and as high as 54,838 yuan in 2024-2025. It can be seen that price increases are the key factor driving cost growth, and changes in absorption weights also have an impact on green certificate transaction costs. Since the carbon public welfare price was higher than the carbon quota price in 2020-2021, the compliance settlement cost that year came entirely from the purchase of additional carbon quotas, so there was no carbon public welfare transaction cost that year. In 2021-2022 and 2022-2023, the enterprise's carbon quota volume was sufficient to meet its own needs, so no market transactions were required. When the carbon public welfare price exceeded the carbon quota price in 2023-2024 and 2024-2025, 5% of the annual carbon emissions were used for quota settlement, and the remaining gap was covered by purchasing additional carbon quotas.

Table 6. Transaction Costs of Carbon-Emitting Regulated Enterprises under Multi-Environmental Rights Market Transactions (Yuan)

Transaction Costs	2020-2021	2021-2022	2022-2023	2023-2024	2024-2025
Carbon Quota Transaction Cost	226,586	-1,819,937	-1,105,108	99,232	164,022
Green Certificate Transaction Cost	2,238	1,241	1,272	21,110	54,838
Carbon Public Welfare Transaction Cost	-	-	-	130,504	107,959

3.3 Factor Decomposition Analysis of Environmental Rights Transaction Costs

The analysis and decomposition results shown in Figure 2 clearly present the driving mechanism of the environmental rights transaction costs of regulated enterprises in Chongming District from 2020 to 2025. The quantitative data of each decomposition dimension are highly correlated with the enterprise's production and operation data, policy adjustments, and market environment changes during the research period.

In terms of carbon cost intensity (CCI), its positive contribution of +281,438 yuan makes it the core driving factor for the growth of environmental rights transaction costs. The key reason for this change lies in the tightening of carbon market policies and the phased strengthening of price signals. On the one hand, in accordance with the "Shanghai Carbon Market Comprehensive Deepening Reform Action Plan (2026-2030)", the Shanghai carbon market implemented a stricter quota allocation mechanism during the research period, significantly increasing the difficulty for regulated enterprises in Chongming District to obtain carbon quotas. From 2020 to 2025, the enterprise's carbon quota volume continued to decrease due to the reduction in electricity-related carbon emissions, and the tightening of quota supply directly pushed up the transaction cost per unit of carbon emissions. On the other hand, combined with the carbon market price data in Table 3, the carbon price rose from 50 yuan/ton to 88 yuan/ton from 2020 to 2024, an increase of 76%. Although it fell slightly to 76 yuan/ton in 2024-2025, it remained at a high level overall, ultimately leading to a significant positive contribution of carbon cost intensity.

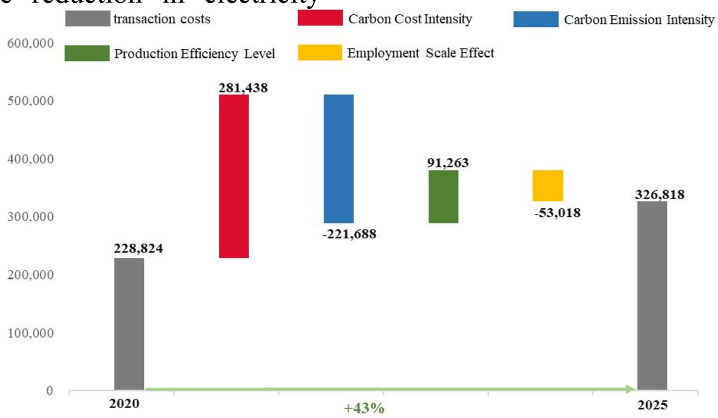

Figure 2. Factor Decomposition Analysis of Cost Changes under the Multi-Environmental Rights Trading Market

Carbon emission intensity (CEI) became a key force in inhibiting cost growth with a significant negative contribution of -221,688 yuan, which is closely related to the optimization of the enterprise's electricity structure and the implementation of energy conservation and emission reduction measures. From the electricity consumption data, the enterprise's electricity consumption reached 154 million kWh in 2020-2021, corresponding to 64,739 tons of electricity-related carbon emissions. However, the electricity consumption plummeted to 66 million kWh in 2021-2022, a decrease of 57%, and carbon emissions dropped to 27,708 tons simultaneously. Although the electricity consumption recovered to 96 million kWh in 2023-2024, the enterprise continuously reduced carbon emissions per unit of output value by introducing efficient production equipment and optimizing the energy consumption structure. In addition, as a "world-class ecological island", Chongming District imposes stricter environmental constraints on enterprises, and the green power substitution effect further reduces the enterprise's carbon emission intensity, ultimately forming a strong inhibitory effect on environmental rights transaction costs.

The production efficiency level (PEL) showed a cost-pushing effect with a positive contribution of +91,263 yuan, and this change reflects the phased fluctuations in the efficiency of the enterprise's production factor allocation. During the research period, while the enterprise's electricity consumption dropped sharply in 2021-2022, the employment scale did not achieve synchronous optimization, leading to a temporary decline in the economic output efficiency per unit of human resources. In 2023-2024, the electricity consumption recovered by 49%, but the iteration of production technology lagged behind the speed of capacity recovery, and the equipment utilization rate and production management efficiency failed to match the growth in power demand in a timely manner, resulting in an increase in carbon emission increments corresponding to per unit of human output. In addition, the production cyclical characteristics of the shipbuilding industry led to idle capacity in some years, further reducing the production efficiency level and indirectly pushing up environmental rights transaction costs, which ultimately manifested as a positive contribution of the production efficiency level.

The employment scale effect (ESE) exerted a moderate inhibitory effect on costs with a negative contribution of -53,018 yuan, mainly derived from the optimization and adjustment of the enterprise's employment structure. During the research period, the enterprise reduced its dependence on traditional labor by promoting the transformation of production automation, and the employment scale showed a phased contraction trend. At the same time, after the decrease in electricity consumption in 2021-2022, the enterprise achieved dynamic matching between human resources and production capacity needs by optimizing post allocation and streamlining redundant personnel, avoiding carbon emission redundancy caused by excess employment scale. Combined with the reduction effect of carbon emission intensity, the reasonable regulation of employment scale further reduced the carbon emission increment per unit of output, providing marginal support for the control of environmental rights transaction costs, and ultimately forming a moderate negative contribution.

From the perspective of total cost, the environmental rights transaction cost in 2025 increased significantly compared with that in 2020. This change essentially reflects the combined effect of multiple forces such as the evolution of carbon market policies, the enterprise's technological transformation, the optimization of management efficiency, and the production characteristics of the industry, and also provides empirical evidence for the subsequent construction of a multi-market coordination mechanism to optimize the cost structure.

3.4 Analysis of Environmental Rights Transaction Costs under the Carbon-Certificate-Public Welfare Mutual Recognition Mechanism

To verify the transaction costs under different environmental rights markets, this study constructs 4 scenarios for comparative analysis, including using only carbon quotas, participating in both carbon quotas and green certificates, participating in both carbon quotas and carbon public welfare, and the multi-market mutual recognition mechanism considered in this study. The information of each scenario is shown in Table 7, where "√" indicates consideration and "×" indicates non-consideration.

The participation results of each scenario are shown in Table 8.

Table 7. Scenario Information

Scenario	Carbon Quota	Green Certificate	Carbon Public Welfare
1	√	×	×
2	√	√	×
3	√	×	√
4	√	√	√

As shown in Table 8, compared with Scenario 1, the total cost of Scenario 2 decreased by 220,000 yuan, and carbon emissions decreased by 11%. After introducing the green certificate trading mechanism, the system can not only reduce electricity-related carbon emissions by absorbing wind power but also obtain green certificates by absorbing wind power. Compared with Scenario 1, the total cost of Scenario 3 decreased by 20,000 yuan, and carbon emissions decreased by 5%. After introducing the carbon public welfare mechanism, part of the carbon quota transaction cost can be offset by purchasing carbon public welfare quantities under the distributed photovoltaic power generation methodology of Shanghai's carbon public welfare emission reduction projects. Compared with Scenario 2, the total cost of Scenario 4 decreased by 60,000 yuan, and carbon emissions decreased by 7%. Compared with Scenario 3, the total cost of Scenario 4 decreased by 260,000 yuan, and carbon emissions decreased by 13%. On the basis of meeting the specified emissions, it can also obtain income by selling surplus carbon quotas, reflecting the superiority of the method proposed in this paper in promoting the absorption of clean energy and reducing environmental impacts.

Table 8 Absorption Potential Results of Each Scenario

Scenario	Carbon Emissions (tons of CO_2)	Total Cost (10,000 yuan)	Carbon Quota Transaction Cost (10,000 yuan)	Green Certificate Transaction Cost (10,000 yuan)	Carbon Public Welfare Transaction Cost (10,000 yuan)
1	33,218	29	29	0	0
2	29,664	7	2	5	0
3	31,557	27	16	0	11
4	27,450	1	-15	5	11

As shown in Table 9, according to the evaluation results of the development and absorption potential of green certificates and carbon public welfare, the carbon-emitting regulated enterprises within the power supply company can fully absorb the green certificates with development potential of non-carbon-emitting regulated enterprises and residents, and partially absorb the carbon public welfare emission reduction potential with development potential. Specifically, 1,661 tons of carbon public welfare emission reduction can be absorbed, accounting for 58% of the total development potential.

Table 9. Calculation Results of Environmental Rights Development and Absorption Potential

Development Potential Calculation	Carbon Public Welfare Emission Reduction (tons of CO_2)	Green Certificate Development Potential (pieces)
Enterprise Users	2,325	2,663
Residential Users	555	-
Total Development Potential	2,881	2,663
Absorption Potential Calculation	Carbon Public Welfare Emission Reduction (tons of CO_2)	Green Certificate Development Potential (pieces)
Carbon-Emitting Regulated Enterprises	1,661	8,463

Combined with the evaluation results of green certificate and carbon public welfare development potential, the transaction costs of carbon-emitting regulated enterprises under the 4 scenarios are shown in Figure 3.

Figure 3. Environmental Rights Transaction Costs under the Mutual Recognition Mechanism

As the benchmark group without a coordination mechanism, Scenario 1 has a total carbon emission of 33,218 tons of CO_2 and a comprehensive transaction cost of 290,000 yuan, with the cost entirely composed of carbon quota transactions. Compared with Scenario 1, after introducing green certificate trading, Scenario 2 reduced the total carbon emissions to 32,099 tons of CO_2, a decrease of 3.4%, and the comprehensive transaction cost to 220,000 yuan, a decrease of 24.1%, including 210,000 yuan for carbon quota transactions and 20,000 yuan for green certificate transactions. The total carbon emissions of Scenario 3 were 31,557 tons of CO_2, a decrease of 5.0% compared with Scenario 1. The comprehensive transaction cost of Scenario 3 was 270,000 yuan, a decrease of 6.9% compared with Scenario 1, with a cost structure of 160,000 yuan for carbon quota transactions and 110,000 yuan for carbon public welfare transactions. As the core scenario of multi-market coordination, Scenario 4 had the best data performance: the total carbon emissions were 30,264 tons of CO_2, a decrease of 9.0% compared with Scenario 1, and the comprehensive transaction cost was 190,000 yuan, a decrease of 34.5% compared with Scenario 1, with a cost structure of 70,000 yuan for carbon quota transactions, 20,000 yuan for green certificate transactions, and 110,000 yuan for carbon public welfare transactions.

Based on the environmental rights development potential calculation model established with State Grid data and combined with the relevant data provided by the power supply company, the annual total power generation of distributed photovoltaic projects eligible for the development of Shanghai carbon public welfare assets in the region in 2024-2025 was 6,858,885 kWh, with a total emission reduction of about 2,881 tons of CO_2, and 2,881 tons of Class I Shanghai carbon public welfare assets could be developed. Distributed photovoltaic projects with an installed capacity of more than 1MW in the region are not suitable for the development of Shanghai carbon public welfare assets but can apply for green certificates. Their grid-connected electricity was 2,663,832 kWh, and the number of green certificates that could be applied for was about 2,663. The income evaluation of green certificates and carbon public welfare under different scenarios is shown in Figure 4.

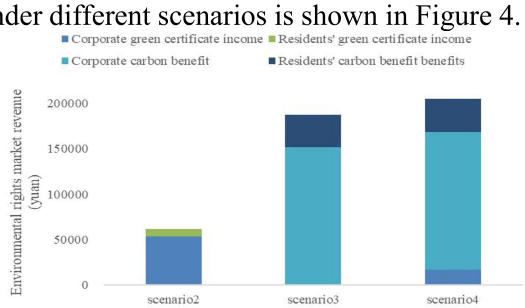

Figure 4. Income Evaluation of Green Certificates and Carbon Public Welfare under Different Scenarios

From the empirical results of the development path and income level of photovoltaic grid-connected electricity, although Scenario 2 achieved 100% development coverage of distributed photovoltaic grid-connected electricity in the region by virtue of the advantage of no installed capacity limit for green certificates, the total income was only 61,707 yuan due to the significantly lower green certificate price than the carbon public welfare price, and the income conversion efficiency was at a low level limited by the price difference. Scenario 3 achieved a total income of 187,248 yuan relying on the high unit price characteristics of carbon public welfare, an increase of 203.1% compared with Scenario 2, showing the income advantage of high-value environmental rights products. However, restricted by Shanghai's carbon public welfare development rules, distributed photovoltaic projects with an installed capacity of more than 1MW cannot be included in the development system, resulting in 28% of photovoltaic grid-connected electricity not being effectively utilized, with a development coverage rate of only 72%, forming a limitation of "high income - low coverage". Scenario 4, through the differentiated asset matching strategy, not only achieved 100% development coverage of photovoltaic grid-connected electricity, completely solving the utilization gap of Scenario 3, but also realized a comprehensive income of 204,509 yuan by prioritizing the conversion of electricity with an installed capacity of less than 1MW into carbon public welfare to cash in high income and converting electricity with an installed capacity of more than 1MW into green certificates to activate idle rights and interests. This represents an increase of 231.4% compared with Scenario 2 and 9.2% compared with Scenario 3, achieving the dual optimization of development coverage rate and income level. This result indicates that the development of a single environmental rights product has a binary contradiction of "efficiency - coverage" - full green certificate development has comprehensive coverage but low-income efficiency, while full carbon public welfare development has high income but limited coverage. The mixed development model of "green certificates + carbon public welfare" breaks market barriers and optimizes asset allocation, not only providing an all-scenario utilization path for photovoltaic grid-connected electricity but also amplifying the income scale through multi-product coordination, providing a practical paradigm for the value release of photovoltaic environmental rights in Chongming District and even ecologically sensitive regions, further improving the comprehensive efficiency of environmental rights development, and promoting the in-depth integration of the goals of "full development coverage - maximum income".

4. Conclusions

Based on the environmental rights trading market data of Chongming District from 2020 to 2025, this study uses the LMDI method to decompose environmental rights transaction costs from multiple dimensions, constructs a model for the development and absorption potential of environmental rights such as green certificates, green electricity, and carbon public welfare emission reductions, and establishes a "mutual recognition ratio model" to verify the minimum comprehensive carbon transaction cost under multi-market coordination. The main conclusions are as follows:

(1) Carbon cost intensity is the core driving force for cost growth. With a positive contribution of +281,438 yuan, carbon cost intensity drives the growth of environmental rights transaction costs, mainly due to the tightening of quota supply and the increase in carbon market prices.

(2) Carbon emission intensity is an effective inhibitor of cost growth. Carbon emission intensity shows a significant negative contribution of -221,688 yuan, derived from enterprises' reduction in carbon emissions per unit of output value through the introduction of efficient equipment and optimization of energy structure, as well as the full play of the green power substitution effect.

(3) Production efficiency and employment scale present dual-order driving characteristics. The production efficiency level pushes up costs by +91,263 yuan, reflecting fluctuations in management efficiency during capacity recovery; the employment scale effect inhibits costs by -53,018 yuan, derived from automation transformation and optimization of human resources.

(4) Multi-market coordination has a significant cost optimization effect compared with a single market. The cost of a single carbon quota market is 290,000 yuan, which drops to 220,000 yuan

after introducing green certificates, 270,000 yuan after introducing carbon public welfare, and 190,000 yuan under the multi-market mutual recognition mechanism, with a corresponding decrease of 9.0% in total carbon emissions.

(5) Multi-market coordination achieves dual optimization of coverage rate and income. Through the strategy of "prioritizing the development of high-value products", not only 100% development coverage of photovoltaic grid-connected electricity is achieved, but also a comprehensive income of 204,509 yuan is obtained, an increase of 231.4% compared with a single green certificate and 9.2% compared with a single carbon public welfare.

Overall, this study verifies the significant optimization effect of the multi-market coordination mechanism in ecologically sensitive regions by systematically decomposing the multi-dimensional driving mechanism of environmental rights transaction costs. By breaking market barriers and optimizing asset allocation, multi-market coordination provides a new realization path for the full release of environmental rights value. This conclusion indicates that under the dual impetus of ecological civilization construction and the carbon neutrality goal, the establishment of a scientific and systematic multi-market coordination mechanism can not only effectively reduce enterprises' environmental rights transaction costs and fully mobilize their enthusiasm for carbon reduction but also promote the optimal operation of the environmental rights market in ecologically constrained regions such as Chongming District, providing strong support for their green development and high-quality transformation.

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