A Study on Carbon Asset Management Models under the Global Sustainable Development Context

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Abstract. Against the increasingly urgent backdrop of global climate change and sustainable development, carbon emissions have become a key indicator for assessing the greening level of economic activities. As a scarce resource and a market-oriented instrument, carbon emission rights have been incorporated into national governance systems and corporate balance sheets. Based on the theoretical framework of sustainable development, ecological economics, and environmental finance, this paper analyzes the evolution, institutional differences, and practical challenges of global carbon asset management (CAM). It further proposes a carbon asset management model grounded in life cycle assessment (LCA) and dynamic optimization. By integrating four modules—carbon accounting, carbon pricing, carbon investment, and carbon performance evaluation—the model achieves systematic management of carbon assets and supports the realization of global carbon reduction goals.

1 Introduction

Global climate change has emerged as one of the most critical systemic risks facing humanity in the 21st century[1]. According to the Intergovernmental Panel on Climate Change (IPCC), if global warming exceeds 1.5°C, the ecological and socioeconomic systems will suffer irreversible damage[2]. Behind these risks, excessive greenhouse gas emissions, particularly carbon dioxide, are the primary driver of global warming. With ongoing industrialization, urbanization, and global economic expansion, carbon emissions from human activities have continued to rise, causing atmospheric greenhouse gas concentrations to reach levels unprecedented in millions of years. This trend not only accelerates the rate of global temperature increase but also exacerbates climate system instability. Consequently, controlling carbon emissions has become a critical priority in the global response to climate change. Only by accelerating the energy transition, enhancing energy efficiency, promoting green technological innovation, improving carbon market mechanisms, and advocating sustainable lifestyles can humanity secure a critical time window for the future and avoid irreversible ecological and socio-economic damages caused by global warming. In response, the United Nations adopted the *Paris Agreement*, establishing a timeline for achieving "carbon peaking" and "carbon neutrality," and calling on nations to control greenhouse gas emissions through policy, market, and technological means[3].

In this context, the concept of carbon asset management (CAM) has gradually gained prominence. The central idea is to treat "carbon emission rights" as assets with economic value and to optimize their allocation through scientific management and market mechanisms[4].

In recent years, research on carbon asset management models can be broadly categorized into three types. The first category focuses on scenario-based and contextualized analytical frameworks. The long-term climate scenarios and integrated data platform provided by the Network for Greening the Financial System (NGFS) have become foundational tools for regulatory and institutional stress testing, widely applied to couple policy pathways, economic shocks, and physical impacts in asset-level loss estimation. [5] The second category comprises models that quantify carbon and climate risks as explicit financial risk indicators. Recent studies have extended the Climate Value-at-Risk and assets-at-risk methodologies to assess potential devaluations and tail losses of energy assets and investment portfolios under various temperature-control scenarios, demonstrating that investors face markedly different impairment magnitudes across delayed, disorderly, and orderly transition pathways. [6] The third category involves enterprise-level optimization and management models. The latest work proposes a carbon asset management mode selection and optimization model for capital-constrained enterprises—covering compliance, autonomous management, and custody modes—by formulating a mathematical programming model integrating benefit, cost, and custody components to support quantitative decision-making for optimal management pathways. [7] Moreover, recent research is promoting a conceptual shift from stranded assets to a broader assets-at-risk framework, which integrates industrial distribution, ownership structures,

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and macroeconomic shocks to enhance the identification of systemic spillover effects within the financial sector. [8]

Thus, carbon assets are no longer merely environmental liabilities but measurable, tradable, and value-appreciating resources. However, the global CAM landscape still faces challenges such as disparities in carbon market standards and accounting systems across countries, incomplete management mechanisms, and volatile carbon pricing[9,10]. Therefore, constructing a scientifically sound carbon asset management model that balances environmental objectives with economic incentives has become a critical pathway toward sustainable development.

2 Model Framework

The objective of carbon asset management is to maximize economic benefits while adhering to environmental constraints. It encompasses carbon accounting, carbon pricing, optimal carbon allocation, and carbon performance feedback. This closed-loop process constitutes the lifecycle management system of carbon assets, as illustrated in Figure 1. Enterprises continuously improve emission reduction efficiency and asset return rates through investment optimization driven by dynamic data feedback.

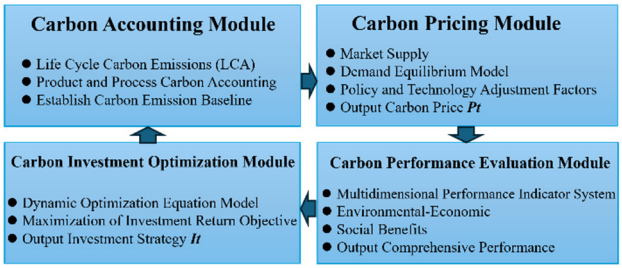

Fig. 1. Carbon asset management model framework.

2.1. Carbon Accounting

Carbon accounting, based on the Life Cycle Assessment (LCA) method, quantifies carbon emissions throughout the entire life cycle of a product or project—from raw material acquisition, production, and transportation to usage and disposal[11,12]. The total life-cycle carbon emissions can be expressed as:

$$C_{total}=\sum_{i=1}^{n}(C_{raw,i}+C_{prod,i}+C_{trans,i}+C_{use,i}+C_{waste,i}) \quad (1)$$

Where:

C_{total} : Total carbon emissions over the product or project life cycle (tons of CO_2-equivalent).

$C_{raw,i}$: Emissions from raw material extraction or procurement at stage i.

$C_{prod,i}$: Emissions from production and manufacturing at stage i.

$C_{trans,i}$: Emissions from transportation and logistics at stage i.

$C_{use,i}$: Emissions from product use at stage i.

$C_{waste,i}$: Emissions from disposal and recycling at stage i.

The output of this module provides a data foundation for initial carbon asset accounting and subsequent management.

2.2 Carbon Pricing

Carbon prices are jointly influenced by market supply and demand, policy interventions, and technological progress. The dynamic evolution of carbon prices can be represented by the following functional relationship:

$$P_t=P_0[1+\alpha(D_t-S_t)]+\beta T_t+\gamma N_t \quad (2)$$

$$N_t \sim \mathrm{N}(0,\sigma^2) \quad (3)$$

Where:

P_t: Carbon price at period t (USD/ton CO_2).

P_0: Baseline or initial market price.

D_t ,S_t: Market demand and supply of carbon allowances, respectively.

α: Sensitivity coefficient reflecting price elasticity to market imbalances.

T_t: Technological progress index (0–1), representing the degree of low-carbon technology diffusion.

β: Response coefficient of carbon price to technological progress (typically negative, indicating that faster innovation reduces carbon prices).

N_t: Represents the stochastic disturbance term of the market, reflecting the short-term impacts of policy expectation changes, investor sentiment, and unexpected events on carbon prices.

γ: The volatility response parameter, characterizing the sensitivity of carbon prices to market uncertainty.

2.3 Carbon Investment Optimization Module

At the enterprise level, the objective of carbon asset management is to maximize economic benefits through emission reduction investments and carbon trading. The dynamic optimization model is formulated as:

$$max\sum_{t=1}^{T}\delta^t(P_tR_t-I_t-C_t) \quad (4)$$

Subject to:

$$E_t\le E_{max}, R_t=f(I_t) \quad (5)$$

Where:

t: Time period (1, 2, …, T).

δ: Discount factor ($\delta=\frac{1}{1+r}$), reflecting the present value of future returns.

P_t: Carbon price (from the pricing module).

R_t: Emission reduction volume relative to the baseline (tons of CO_2).

I_t: Investment in emission reduction (USD).

C_t : Carbon-related costs (including allowance purchases, penalties, etc.).

E_{max}: Regulatory or industry-imposed emission cap.

This model achieves dynamic optimization in carbon asset investment decisions, balancing the trade-off between abatement costs and market gains.

2.4 Dynamic Evolution of Carbon Assets

To depict the temporal variation of carbon asset values, the following dynamic evolution equation is introduced:

$$V_{t+1} = V_t + S_t - I_t + \phi R_t \quad (6)$$

Where:

V_t: Carbon asset book value at period t (USD).

S_t : Value appreciation from emission reduction.

I_t: Investment cost during period t.

R_t: Government subsidies or carbon incentives (e.g., green finance or carbon funds).

ϕ: Policy incentive coefficient representing the impact of fiscal and policy support on asset growth.

This equation illustrates the growth trajectory of carbon assets through iterative cycles of investment and returns.

2.5 Carbon Performance Evaluation

To comprehensively evaluate carbon asset management performance—for use by governments or investors in assessing corporate green performance—a multidimensional performance index is constructed as:

$$PI = w_1 E_{env} + w_2 E_{eco} + w_3 E_{soc} \quad (7)$$

Subject to:

$$w_1 + w_2 + w_3 = 1 \quad (8)$$

Where:

PI: Composite Carbon Performance Index.

E_{env}: Environmental performance indicator (e.g., carbon reduction rate per output unit, energy efficiency).

E_{eco}: Economic performance indicator (e.g., investment return rate, carbon asset yield).

E_{soc}: Social performance indicator (e.g., employment growth, ESG rating improvement).

w_i: Weighting coefficients reflecting the relative importance of each dimension.

This multidimensional framework supports quantitative evaluation and cross-enterprise comparison of carbon management effectiveness.

3 Model Application Analysis

A Energy Group Co., Ltd., a company primarily engaged in coal-fired power generation while concurrently developing wind and solar power, is selected as the subject of this analysis. Since 2020, the company has gradually introduced emission reduction technologies and implemented carbon emission management. The data sources include A Energy's annual reports from 2020 to 2024, carbon emission accounting reports, transaction data from the national carbon trading market, and publicly available energy statistics. These datasets are empirically analyzed using the carbon asset management model developed in this study. The calculation results are shown in Table 1.

Table 1. Dynamic data of carbon assets of Company A.

Indicator	2020	2021	2022	2023	2024
ΔC_t (tCO_2)	198400	302700	411500	523800	614600
P_t (USD/tCO_2)	48.6	49.7	51.1	52.4	54.2
I_t ($\times 10^4$ USD)	980	1,180	1,420	1,640	1,830
R_t ($\times 10^4$ USD)	520	510	495	480	470
ΔV_t ($\times 10^4$ USD)	562.9	1342.50	2076.70	3127.20	4312.90
V_t ($\times 10^4$ USD)	562.9	1905.40	3982.10	7109.30	11422.20

From 2020 to 2024, Company A's carbon emission reductions increased steadily, reflecting its continuous progress in technological upgrading and energy efficiency improvement. The average annual growth rate of carbon reduction reached approximately 17.2%. Meanwhile, the carbon price showed a slight upward trend, rising from 48.6USD/tCO_2 in 2020 to 54.2 USD/tCO_2 in 2024, which is consistent with the overall trajectory of the global carbon market. The company's investment expenditure increased from 9.8 million USD to 18.3 million USD, indicating diminishing marginal returns as the scale of technological investment approached its optimal level. The change in carbon asset value exhibited a nonlinear growth pattern, characterized by moderate fluctuations primarily influenced by investment cycles, carbon price sensitivity, and policy incentives.

Overall, the company's cumulative carbon asset value increased significantly—from 5.63 million USD in 2020 to 114.22 million USD in 2024—corresponding to an average annual growth rate of approximately 58.9%. These results demonstrate that, under an integrated framework of investment, pricing, and performance, proactive carbon asset management can substantially enhance asset appreciation. This approach not only supports the achievement of environmental objectives but also strengthens corporate financial performance and long-term competitiveness.

Based on the multi-dimensional performance evaluation model, the comprehensive performance assessment of the carbon emissions of Company A over the past five years is conducted as shown in Table 2.

Table 2. The annual performance evaluation results of Enterprise A.

Indicator	2020	2021	2022	2023	2024
E	0.55	0.63	0.7	0.77	0.83
F	0.42	0.55	0.67	0.72	0.78
S	0.58	0.61	0.65	0.71	0.76
PI	0.5	0.59	0.67	0.73	0.79

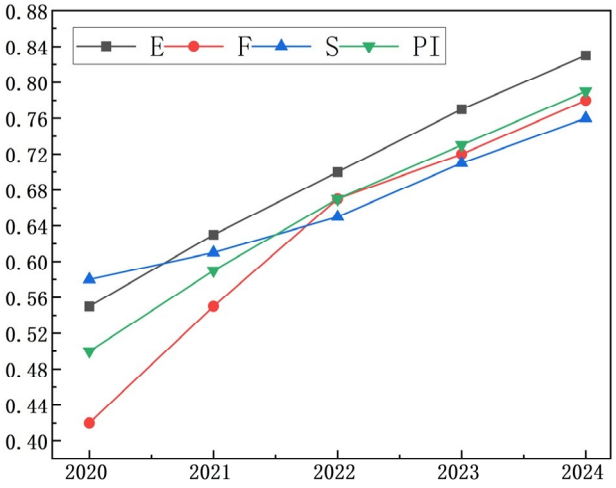

Fig. 2. The performance appraisal trend of Enterprise A.

As shown in Figure 2, The results indicate that after the implementation of carbon management, Company A's Carbon Performance Index (*PI*) increased from 0.50 in 2020 to 0.79 in 2024, representing an overall improvement of approximately 58%. Among the three dimensions, environmental performance exhibited the most significant growth (+51%), suggesting that emission-reduction investments directly enhanced ecological benefits. Meanwhile, both economic and social performance showed continuous improvement, reflecting a synergistic and mutually reinforcing relationship among the three performance dimensions.

4 Conclusion

Carbon asset management represents an important institutional innovation for achieving global sustainable development goals. This paper constructs a carbon asset management model based on life cycle analysis and dynamic optimization, and applies it to an empirical analysis of Company A using relevant data from the past five years. The results indicate that scientific carbon asset management can not only reduce emission costs but also enhance economic returns and corporate social responsibility, thereby achieving a win–win outcome for both the environment and the economy. This model provides a systematic theoretical framework and decision-making tool for participants in the carbon market. Future research should further enhance the model's intelligence and international applicability, promoting the establishment of a unified, efficient, and equitable global carbon asset governance system to contribute to global climate governance and sustainable development.

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