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Climate, Energy, and Carbon Derivatives: Pricing Mechanisms and Risk Management under Carbon Market Uncertainty

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Abstract. With the development of green finance and the progress of global climate governance, climate-related financial instruments, especially energy and carbon derivatives, have become increasingly important in modern financial markets. This paper examines the pricing mechanisms and risk management of derivatives under uncertainty in the carbon market. By combining literature review with market analysis, this study synthesizes classical derivative pricing models including the Black–Scholes and Heston frameworks, and extends their applicability to the pricing of energy, weather, and carbon derivatives. This paper further analyzes the structural differences across these markets and identifies key sources of risk, including volatility, policy uncertainty, and liquidity constraints. The results indicate that carbon risk has become a key new element in the pricing of derivatives and in portfolio management. This study finds that effective carbon risk mitigation can be realized via integrated strategies including cross-hedging, asset diversification, and scenario-based stress testing. This paper contributes to the literature on climate finance by offering a systematic framework for understanding derivative pricing and risk management under carbon market uncertainty.

Keywords: Climate finance, Carbon derivatives, Energy derivatives, Risk management, Pricing models

1. Introduction

With the increasing urgency of climate change, green finance and environmental markets are developing rapidly. In particular, climate, energy and carbon emission derivatives have attracted widespread academic and industrial attention in recent years, owing to their critical role in risk hedging, risk transfer and price discovery..

Carbon markets are organized systems in which emission allowances and carbon credits are bought and sold, encompassing instruments such as spot trading, futures contracts, and options on carbon allowances. The European Union Emissions Trading System (EU ETS), for example, covers power generation, industrial production, and aviation sectors within its regulatory scope. These markets feature substantial uncertainty driven by policy regulation shifts, macroeconomic volatility, and low-carbon technological transitions. Pricing and risk management are thus particularly challenging in this context [1, 2].

While traditional derivative pricing theories are well-established, their direct application to climate-related markets remains limited. This paper aims to fill this gap by addressing the following research questions: How can classical pricing models be adapted to climate, energy, and carbon derivatives? What are the key differences in market structures across these derivative classes? How can market participants effectively manage risks under carbon market uncertainty? This study offers both theoretical and practical contributions by constructing a systematic structured analytical framework for emerging climate-linked financial derivative instruments..

2. Literature review

2.1. Classical derivative pricing models

The Black-Scholes model, proposed by Black and Scholes in 1973, provides the foundational framework for option pricing under the assumptions of constant volatility, no-arbitrage, and log-normally distributed asset prices. Its core inputs consist of the risk-free rate, underlying asset price, time to maturity and volatility, and the model has been extensively adopted for pricing equity options and interest rate derivatives across mature financial markets [3].

Nevertheless, empirical evidence demonstrates that asset returns exhibit stochastic volatility, prompting the development of extended models. The Heston model, introduced by Heston in 1993, addresses this limitation by incorporating a mean-reverting stochastic volatility process governed by a set of parameters including the long-run variance, the speed of mean reversion, the volatility of volatility, and the correlation between asset price and variance shocks. The Heston model is commonly employed in pricing equity and foreign exchange options, and has since been adapted to price energy and commodity derivatives [4].

These models have been extensively applied in financial derivatives. However, for non-conventional underlying assets such as weather indices or carbon allowances, significant modifications are required to capture the distinct characteristics of these instruments.

2.2. Energy derivatives and commodity markets

Energy derivatives, including futures and options for oil, natural gas and electricity, have been widely examined in academic literature.. Research highlights characteristics such as seasonality, mean reversion, and price spikes, particularly in electricity markets [5]. The role of geopolitical risks and supply-demand imbalances in shaping energy price dynamics has also received substantial scholarly attention [6].

2.3. Weather Derivatives and Climate Finance

Weather derivatives are financial instruments based on meteorological variables such as temperature or rainfall.Unlike traditional assets, their underlying variables are non-tradable—a factor that complicates their pricing. Index-based models and actuarial approaches are commonly used, often supplemented by statistical simulations [7].

2.4. Carbon derivatives and environmental policy

Carbon derivatives are closely tied to regulatory frameworks. Research demonstrates that carbon prices are sensitive to policy parameters such as emission caps and the distribution of allowances [1]. Existing scholarship has also documented market inefficiencies in carbon trading systems, including low market liquidity and policy-induced volatility, which further complicate conventional pricing approaches [2, 8]

3. Climate, energy and carbon derivatives: financial hedging system of multidimensional environmental risks

3.1. Climate derivatives (weather-based)

Weather derivatives are financial instruments designed to hedge financial losses caused by unexpected climate variability, including temperature, precipitation, wind, frost, and other meteorological indicators. They are widely used in agriculture, energy, tourism, and insurance industries to offset revenue volatility arising from adverse weather conditions. Unlike traditional insurance, weather derivatives are triggered by objective meteorological indices rather than actual losses, with transactions typically conducted over the counter (OTC). The high degree of contract customization allows these instruments to align with the specific risk exposures of individual industries, providing a flexible and effective means of managing climate-related financial risk.

3.2. Energy derivatives

Energy derivatives represent one of the most mature and liquid derivative markets globally, covering crude oil, natural gas, electricity, coal, and other bulk energy products. These instruments—primarily standardized futures, options, and swaps—are mainly traded on formal exchanges [5, 6] Energy derivatives play a critical role in hedging price fluctuations caused by supply-demand imbalances, geopolitical risks, and policy changes. They enable producers, consumers, and traders to stabilize costs and revenues, improve market transparency and efficiency, and support the stable operation of the global energy system.

3.3. Carbon derivatives

Carbon derivatives are financial contracts based on carbon emission allowances and carbon credits, encompassing carbon futures, options, swaps, and other structured products. These instruments serve as important tools for market participants to hedge carbon price risks, reduce emission reduction costs, and achieve carbon neutrality targets [1]. The EU Emissions Trading System (EU ETS) is the world's largest and most mature carbon market, characterized by comprehensive trading rules, high liquidity, and robust price discovery capabilities. It serves as the benchmark for global carbon pricing and a replicable market mechanism for worldwide carbon emission governance [2].

4. Risk management

4.1. Sources of risk

In the risk analysis framework of the environmental derivatives market, three core categories of risk pose systematic challenges [7, 8] The first is volatility risk, driven by supply-demand imbalances, macroeconomic cyclical fluctuations, and structural shocks in energy markets. This risk manifests as nonlinear and sharp price fluctuations in energy, carbon emission allowances, and weather derivatives, directly impacting the stability of asset valuations and the reliability of market participants' cash flow forecasts. The second is policy risk, arising from dynamic adjustments to regulatory frameworks (such as revisions to carbon tax rates and the reset of emission ceilings), the evolution of climate policy objectives (such as updates to carbon neutrality pathways), and changes in market access rules. Such institutional shifts may lead to market rule reconstruction, contraction of trading scope, or revaluation of carbon assets, generating structural uncertainty. The third is liquidity risk, which is particularly acute in emerging carbon and climate derivative markets. Its characteristics include inadequate market depth due to insufficient trading volume, buy-sell imbalances caused by investor homogeneity, and gaps in contract varieties due to low standardization—ultimately leading to high transaction costs, exacerbated price slippage, and difficulties in position liquidation. These risk sources interact through price transmission, regulatory change, and market microstructure deficiencies, posing multidimensional challenges for market participants in strategy design, portfolio optimization, and long-term business decision-making, and require systematic evaluation and proactive management through quantitative methods such as dynamic monitoring, scenario simulation, and stress testing.

4.2. Hedging strategies

Three principal hedging strategies are employed in environmental derivative markets. Cross-hedging involves employing highly correlated liquid assets such as energy futures, power contracts, or commodity derivatives to offset price exposures in carbon or climate markets where direct hedging instruments are inadequate. Diversification entails allocating capital across energy products, carbon instruments, weather derivatives, and traditional financial assets to reduce concentration risk and smooth overall portfolio volatility. Delta hedging involves dynamic portfolio adjustment through the calculation and offsetting of price sensitivity (delta), thereby enabling real-time risk balancing against small fluctuations in underlying asset prices [3, 5].

4.3. Scenario analysis and stress testing

Scenario analysis is utilized to quantify the potential impacts of plausible extreme events (e.g., sudden policy tightening, energy supply crises, climate disasters, or macroeconomic shocks). Stress testing simulates severe tail risks to assess capital adequacy, earnings stability, and solvency, thereby building risk resilience and supporting sound decision-making under conditions of high uncertainty [6, 8].

4.4. Industry case

Integrated risk management frameworks incorporating energy derivatives and carbon instruments are widely adopted by energy-intensive enterprises, power producers, and industrial emitters. By coordinating hedging strategies against price volatility and regulatory risk, firms minimize operating costs, meet emission constraints, stabilize profitability, and enhance sustainability—all while operating under the dual pressures of market fluctuations and climate governance requirements [1, 2].

5. Empirical insight

The findings carry important implications across multiple stakeholder groups. For investors, incorporating carbon risk into portfolio allocation is essential for maintaining competitive and resilient portfolios. For firms, integrated risk management that combines energy and carbon instruments significantly improves operational resilience. For regulators, striking a balance between market efficiency and environmental goals is critical to the long-term effectiveness of climate finance mechanisms.

The convergence of energy and carbon markets points to a future trend toward integrated climate financial systems, where pricing signals, risk management tools, and policy incentives are becoming increasingly interconnected [7, 8].

6. Conclusion

This paper provides a comprehensive analysis of pricing mechanisms and risk management strategies for climate, energy, and carbon derivatives under market uncertainty.

Key contributions include: extending classical pricing models to climate finance contexts [3, 4]; identifying carbon risk as a core pricing factor in derivative valuation [1, 2]; and proposing integrated risk management frameworks that address the interconnected nature of volatility, policy, and liquidity risks in environmental derivative markets.

Three policy directions are recommended on the basis of this study's findings. First, carbon market transparency should be enhanced to support better-informed pricing and risk assessment.Second, market liquidity should be improved through deliberate market design and expanded investor participation. Third, the development of standardized derivative products should be promoted to lower transaction costs and enhance market accessibility.

Future studies may focus on empirical modeling of carbon risk premia, the application of machine learning methods to climate derivative pricing, and cross-market integration analysis across energy, carbon, and weather derivative markets.

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