Analysis of Low-Carbon Electricity Investment Opportunities Based on the Supply Chain

Lichong Cui*[1,a], Huayu Chu[1,b], Yanyang Fu[1,c], Enguang Chen[1,d], Yuqing Sun[2,e]

Email: 183150@qq.com[a], 814225237@qq.com[b], 516950924@qq.com[c], 15733019978@163.com[d], 1137487513@qq.com[e]

[1]State Grid Hebei Electric Power Co., Ltd. Materials Branch, Shijiazhuang Hebei 050081, China
[2]Beijing CHINA-POWER INFORMATION Technology Co., Ltd. Beijing 100083, China

Abstract. In the context of the electricity market and carbon trading market, considering the uncertainty of carbon trading prices, this study utilizes real options theory to calculate the option value of low-carbon technology investment timing and establishes a decision-making model for the optimal timing of low-carbon investments for a single enterprise. Based on this, a two-tier supply chain model for investing in low-carbon technology by power generation companies and grid companies is constructed. The study employs an option game approach to investigate the optimal investment timing for low-carbon technology in the power supply chain. The influencing factors of the optimal investment timing are analyzed through a case study. The results indicate that government low-carbon subsidy coefficients, carbon trading price volatility, and carbon emission reduction levels impact the threshold for low-carbon technology investment. Power companies should comprehensively consider the influence of various factors and scientifically choose the optimal investment timing. Governments should establish reasonable low-carbon subsidy coefficients to encourage power companies to invest in low-carbon technology, achieving a harmonious development of the economy and the environment.

Keywords: power supply chain; low-carbon technology; option game; optimal investment timing.

1 Introduction

Faced with severe energy crises, global climate change, and the existential threats posed by ecological degradation, the pursuit of a low-carbon economy has become a focal point for countries worldwide. As the largest carbon-emitting nation globally, China committed as early as November 2009 to a reduction of 40% to 45% in carbon emissions per unit of GDP by 2020 compared to 2005 levels. To achieve this goal, the power industry is under immense pressure to reduce emissions. Electricity production, being a major contributor to carbon emissions in China, accounts for 40% of the national total, and this situation is unlikely to change fundamentally in the short term.

Research on the power supply chain has primarily been conducted in the context of a fully marketized environment. In reference [1], the equilibrium results of fuel and electricity in the power supply chain were solved, and the impact of carbon tax policies under equilibrium conditions was discussed. Reference [2] transformed the equilibrium problem of the power

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supply chain network into a transportation network equilibrium problem, analyzing the influence of a carbon tax policy on the equilibrium. Reference [3] constructed a two-tier power supply chain revenue-sharing contract model, verifying that the model effectively coordinates the operation of the power supply chain. Reference [4] built a power supply chain model involving fuel, electricity generation, and carbon emission trading, using heuristic algorithms to solve the equilibrium of fuel, electricity, and emissions in the supply chain system. Reference [5] established a three-tier power supply chain involving power plants, power service providers, and users. Based on supply chain equilibrium conditions, the design problem of emissions trading policies was investigated. Reference [6] elucidated the essence of power logistics supply chains, constructed a model for incentive mechanisms among power logistics supply chain members, and confirmed that the profitability of a single-tier supply chain is superior to a two-tier supply chain. The above studies, operating under the premise of power supply chain operational decisions, aimed to maximize the individual profits of supply chain members while exploring equilibrium results.

Option games in the context of overall investment timing decisions in the supply chain have received widespread attention from scholars both domestically and internationally. Reference [7] established a duopoly competition model based on option games, where supply chain enterprises adopt a new technology, incurring investment costs and reducing production costs, leading to the conclusion that the diffusion of new technology has a "spillover" effect. Reference [8], using the real options approach, developed investment models for single enterprises, two enterprises, and multi-enterprise collaborations, determining the optimal investment timing for supply chain enterprises to invest in climate-friendly projects under various scenarios. Reference [9] conducted research and analysis on option game theory, outlining the general research framework of this method. Reference [10] explored investment timing choices in uncertain and competitive environments, discussing both complete information and incomplete information option game models based on stochastic optimal stopping problems. Reference [11] argued that option game investment strategies can maximize the value of enterprise investments, proposing the application ideas and steps of real options and option game investment strategy analysis. Relevant studies indicate that option game theory is an effective tool for addressing the timing decision issues of supply chain enterprises investing in low-carbon technologies.

In summary, there is currently limited literature that focuses on studying the optimal timing of low-carbon investments in the power sector from the perspective of the power supply chain. This paper aims to expand on this topic, incorporating the principles of option games and considering factors such as carbon emission trading prices and government subsidy coefficients from the power supply chain perspective. The goal is to explore the decision-making problem of low-carbon technology investments throughout the entire power supply chain.

2 Investment Timing Model

2.1 Background Description

This paper assumes that the power supply chain consists of power generation companies and grid companies. Power generation companies are responsible for the production and supply of electricity, while grid companies focus on the consumer market and engage in sales, establishing an integrated enterprise model and a second-tier power supply chain model.

The majority of carbon emissions in the power supply chain come from the power generation process. Under the combined influence of the carbon trading market and carbon quotas, power generation companies actively invest in low-carbon technologies to achieve both economic and environmental benefits. The power supply chain model is illustrated in Figure 1.

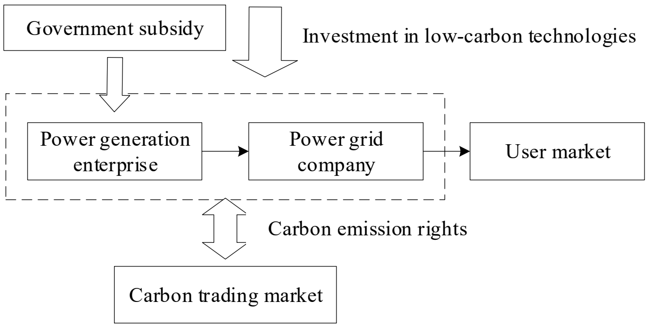

Fig.1 The Second-Tier Power Supply Chain Model

2.2 Theoretical Assumptions

Without altering the essence of the problem, the following assumptions are made in the paper:

(1) The price of one unit of carbon emission rights is denoted as $p(t)$. The value of $p(t)$ is influenced by various uncertainties in the carbon trading market. Here, it is assumed that the carbon emission rights price follows a geometric Brownian motion, as shown in equation (1).

$$d(p) = \mu p(t)dt + \sigma p(t)dz, p(0) = p_0 \tag{1}$$

Where, μ represents the instantaneous expected growth rate of carbon trading prices, with $0 \leq \mu < r$ (where r is the risk-free interest rate); σ is the volatility, and $\sigma \in R^+$; dz is the increment of the standard Wiener process, following a normal distribution with a mean of 0 and a standard deviation of 1.

(2) In the low-carbon era, the government provides subsidies to green electricity in the form of feed-in tariffs. The increase in electricity prices is determined by the carbon emission reduction Δe. It is assumed that for each unit increase in emission reduction, the government increases the feed-in tariff by k.

(3) Influenced by government low-carbon policies, power generation companies actively invest in low-carbon technologies, resulting in a reduction Δe in the carbon emissions per unit of electricity produced, aiming to reduce the overall emissions during the power generation process.

(4) Considering a second-tier power supply chain consisting of a single power generation company and a single grid company, the total electricity generation is denoted as D, and all of it is used for consumption by end-users.

2.3 Low-Carbon Investment Timing Model

Due to the fact that the majority of carbon emissions in the power supply chain originate from power generation companies, upstream enterprises actively respond to national policy calls, engaging in low-carbon technology investments to achieve the goals of a low-carbon supply chain. In low-carbon emission reduction investments, power generation companies play a central role and act as the leading enterprises. Low-carbon technology investments require the participation of all supply chain members. If it is profitable, the grid company chooses to cooperate and provides cost support for low-carbon technology investments. Otherwise, cooperation is not pursued. If cooperation is chosen, the optimal investment timing is determined based on maximizing individual interests. The return on investment in low-carbon technology in the second-tier power supply chain is evidently influenced by carbon trading prices, government low-carbon subsidy coefficients, and factors related to cooperation among enterprises within the supply chain. It is apparent that intra-chain games are played based on the decisions of adjacent enterprises, determining the optimal investment timing to ultimately maximize individual interests. The expected net present value of the profit for the power generation company is given by:

$$\pi_M(t) = \frac{\Delta eDp(t)}{r-\mu}(1-\xi) + \frac{k\Delta eD}{r} - \frac{1}{2}m\Delta e^2(1-\theta-\varphi) \tag{2}$$

The expected net present value of profit for the grid company is:

$$\pi_R(t) = \frac{\Delta eDp(t)}{r-\mu}\xi - \frac{1}{2}m\Delta e^2\varphi \tag{3}$$

In the supply chain, the grid company can choose to invest or not invest. The backward induction method is employed to solve the game equilibrium. First, calculate the investment threshold for the grid company, and then determine the transfer benefit ratio for the power generation company.

The option value function for the grid company's low-carbon technology investment is:

$$F_R(p(t)) = \max E\left\{\frac{\Delta eDp(t)\xi}{r-\mu} - \frac{1}{2}m\Delta e^2\varphi, 0\right\} \tag{4}$$

The option value for the grid company low-carbon emission reduction investment is obtained as:

$$F_R(p(t)) = \begin{cases} \left(\frac{\Delta eDp_\xi}{r-\mu} - \frac{1}{2}m\Delta e^2\varphi\right)\left(\frac{p_t}{p_\xi}\right)^{T_t}, & p_t < p_\xi \\ \frac{\Delta eDp_t}{r-\mu} - \frac{1}{2}m\Delta e^2\varphi, & p_\xi > p_t \end{cases} \tag{5}$$

The optimal timing for the grid company low-carbon technology investment is:

$$T_R = \inf\left(t \geq 0 \middle| p(t) > p_\xi\right) \tag{6}$$

In order to effectively facilitate cooperation with the grid company, the power generation company, before determining the transfer benefit ratio ξ, thoroughly considers the decision-making of the grid company. Therefore, based on P_ξ, the power generation company selects a smaller ξ that maximizes its own interests. The option value function for the power generation company low-carbon investment is:

$$F_M(p(t)) = \max_{\xi\in(0,1)} E\left\{\frac{\Delta eDp_\xi(1-\xi)}{r-\mu} + \frac{k\Delta eD}{r} - \frac{1}{2}m\Delta e^2(1-\theta-\varphi), 0\right\} \tag{7}$$

In conclusion, the total option value for the second-tier power supply chain is $F_s(p_t) = F_M(p(t)) + F_R(p(t))$, and the threshold for low-carbon technology investment is

$$P_\xi = \frac{T_1}{T_1-1}\frac{m\Delta e(r-\mu)}{2D}\left(1-\theta-\frac{2kD}{rm\Delta e}+\frac{\varphi}{T_1-1}\right) \tag{8}$$

And,

$$P_T = \frac{T_1}{T_1-1}\frac{m\Delta e(r-\mu)}{2D}\left(1-\theta-\frac{2kD}{rm\Delta e}\right) \tag{9}$$

Easily proven is $P_\xi > P_T$, indicating that the low-carbon technology investment, when completed by both upstream and downstream enterprises in the power supply chain, is associated with a higher investment threshold compared to when undertaken by a single enterprise alone.

3 Case Study Analysis

MATLAB was employed as the computational tool to solve and analyze the formulas. The analysis focuses on the impact of variations in carbon price volatility, government low-carbon subsidy coefficients, and profit transfer coefficients on the optimal investment threshold. The goal is to obtain beneficial conclusions for policy formulation by government authorities and investment decision-making by supply chain enterprises. The parameters in the model are set as follows: m=4000, D=1000, μ=0.03, r=0.5, k=1.

(1) Assuming a one-time transfer payment cost coefficient φ=0.3, volatility σ=0.1, and Δe=4, the relationship between government low-carbon subsidy coefficient and the optimal investment threshold is obtained, as shown in Figure 2.

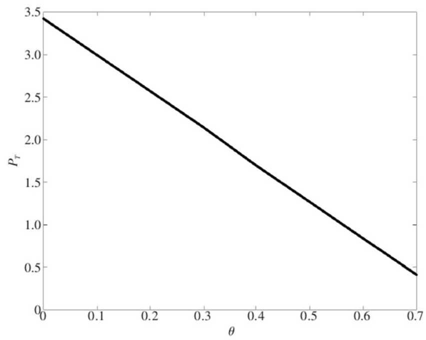

Fig.2 The relationship between the optimal investment threshold and the government subsidy coefficient

Since in the case of supply chain investment, $0<\theta<1-\varphi$, it is obtained that when the one-time transfer payment cost coefficient is 0.3, the government low-carbon subsidy coefficient takes values in the range (0, 0.7).

From Figure 2, it can be observed that the optimal investment threshold decreases with an increase in the government subsidy coefficient, indicating a negative correlation between the two.

(2) Assuming a one-time transfer payment cost coefficient φ=0.3, θ=0.1, and Δe=4, the relationship between the optimal investment threshold for the grid company and the transfer benefit ratio ξ is obtained for different volatilities, as shown in Figure 3. Additionally, the calculation reveals that under the supply chain cooperative game with σ=0.1, the optimal investment threshold (ξ, P_ξ) is (0.5141, 2.9936).

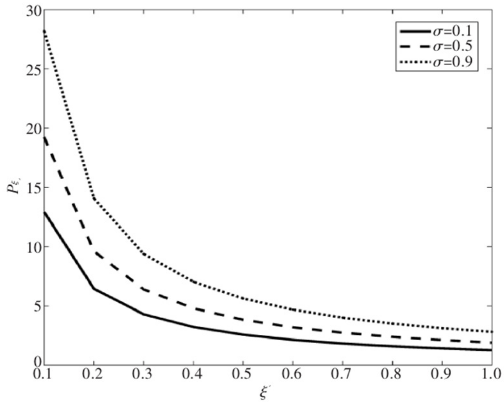

Fig.3 The relationship between the optimal investment threshold and the transfer benefit ratio.

From Figure 3, it can be observed that, with volatility remaining constant, the optimal investment threshold and the transfer benefit ratio are inversely proportional. When the transfer benefit ratio approaches 0, the investment threshold may become infinite. This implies that when the grid company chooses cooperative investment, but the power generation company decides to solely enjoy the benefits of low-carbon investments or only shares a minimal proportion of the benefits with the grid company, the waiting time for low-carbon investment becomes longer. When the transfer benefit ratio is greater than 0.3, the reduction in the investment threshold is very gradual.

4 Conclusion

This paper explores the timing of low-carbon technology investments in the power industry, starting from the perspective of the power supply chain system. Considering the environment of the carbon trading market and the power market, the study uses the option game method to investigate the timing of low-carbon technology investments by power supply chain enterprises, constructing a model of a second-tier power supply chain composed of grid companies. The case study analysis focuses on the impact of government low-carbon subsidy coefficients, carbon trading price volatility, and carbon emission reduction on the optimal investment timing decisions of power supply chain members. From the analysis results, it is evident that the optimal investment threshold decreases with an increase in the government subsidy coefficient. This is because an increase in government financial support for low-carbon technology investments in the power supply chain lowers the investment threshold, shortening the waiting time for supply chain enterprises to invest in low-carbon technology. The higher the transfer benefit ratio for power generation companies, the more likely it is to prompt grid companies to invest earlier. However, a higher transfer benefit ratio also leads to a reduction in the interests of power generation companies. To facilitate cooperation, power generation companies and grid companies often choose to invest based on the optimal investment threshold in cooperative games

References

[1] Lumen Technologies: A Promising Investment Opportunity with Growth Potential - Follow Antonio Velardo's Call on (META)[J]. M2 Presswire, 2023,

[2] Firmansyah Amrie, Arham Amardianto, Qadri Resi Ariyasa, Wibowo Puji, Irawan Ferry, Kustiani Nur Aisyah, Wijaya Suparna, Andriani Arifah Fibri, Arfiansyah Zef, Kurniawati Lestari, Mabrur Azas, Dinarjito Agung, Kusumawati Rahayu, Mahrus Moh. Luthfi. Political connections, investment opportunity sets, tax avoidance: does corporate social responsibility disclosure in Indonesia have a role?[J]. Heliyon, 2022, 8 (8): e10155-e10155.

[3] Ohlendorf Nils, Flachsland Christian, Nemet Gregory F., Steckel Jan Christoph. Carbon price floors and low-carbon investment: A survey of German firms[J]. Energy Policy, 2022, 169

[4] Yang Ang, Meng Xiangyu, He He, Wang Liang, Gao Jing. Towards Optimized ARMGs' Low-Carbon Transition Investment Decision Based on Real Options[J]. Energies, 2022, 15 (14): 5153-5153.

[5] Song Yazhi, Li Yin, Liu Tiansen. Carbon asset remolding and potential benefit measurement of machinery products in the light of lean production and low-carbon investment[J]. Technological Forecasting & Social Change, 2023, 186 (PB).

[6] EngelCox Jill A., Geocaris Madeline. Future Low-Carbon Technology Options for a 100 Percent Decarbonized Power Sector[J]. Climate and Energy, 2023, 39 (8): 1-10.

[7] Chowdhury A.F.M. Kamal, Deshmukh Ranjit, Wu Grace C., Uppal Anagha, Mileva Ana, Curry Tiana, Armstrong Les, Galelli Stefano, Ndhlukula Kudakwashe. Enabling a low-carbon electricity system for Southern Africa[J]. Joule, 2022, 6 (8): 1826-1844.

[8] Keppler Jan Horst, Quemin Simon, Saguan Marcelo. Why the sustainable provision of low-carbon electricity needs hybrid markets[J]. Energy Policy, 2022, 171

[9] Seward William, Qadrdan Meysam, Jenkins Nick. Corrigendum to Quantifying the value of distributed battery storage to the operation of a low carbon power system[J]. Applied Energy, 2023, 331

[10] AlvarezHerault MarieCécile, Dib JeanPierre, Ionescu Oana, Raison Bertrand. Long-Term Planning of Electrical Distribution Grids: How Load Uncertainty and Flexibility Affect the Investment Timing[J]. Energies, 2022, 15 (16): 6084-6084.

[11] Zhu Qing, Lu Kai, Liu Shan, Ruan Yinglin, Wang Lin, Yang Sung-Byung. Can low-carbon value bring high returns? Novel quantitative trading from portfolio-of-investment targets in a new-energy market[J]. Economic Analysis and Policy, 2022, 76 755-769.