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Research on Energy Trading Mechanism Based on Individual Level Carbon Quota

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Abstract: High economic growth is accompanied by substantial consumption of fossil energy and significant negative externalities on the ecological environment. The global warming effect resulting from environmental pollution caused by energy has brought energy carbon emissions into the forefront of social attention. Establishing a carbon trading market is an essential measure to achieve the "double carbon" goal, with individual and household carbon emissions accounting for 70% of China's total emissions. Constructing an individual-level carbon trading market will facilitate the efficient realization of this goal. However, addressing the challenge of handling vast amounts of data and network congestion in relation to frequent but small-scale individual carbon trading has become an urgent issue that needs to be resolved. In light of this, the present study designs a digital technology-based framework for the carbon market trading system and proposes an individual carbon asset price-based model for carbon market trading, aiming to establish a research framework for the carbon quota market. Furthermore, blockchain technology is employed as the underlying technology in the proposed carbon trading market model to cater to individual-level carbon trading services and achieve optimal matching between carbon quota suppliers, thereby enhancing profitability of the carbon trading platform. The numerical results obtained from the model demonstrate that in absence of government subsidy mechanisms, individual-level carbon trading can effectively reduce total consumer emissions. The present study successfully overcomes the carbon lock-in effect of consumer groups and achieves the generation and trading of individual carbon assets despite capital constraints. This study facilitates accumulation and trade of individual carbon resources, reduces overall consumer emissions, enhances environmental benefits at societal level, and provides a foundation for governmental decision-making.

Keywords: energy trading; carbon trading platform; carbon quota; blockchain technology

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1. Introduction

Energy is the material basis of human production activities, which is directly related to social and economic development and the quality of people's life. The deepening of Chinese society and the rapid economic growth have led to the continuous growth of total energy demand. According to the preliminary calculation of the National Bureau of Statistics, in 2020, China's total annual energy consumption was 5.24 billion tons of standard coal, an increase of 5.2% over the previous year. There is no denying that the demand for fossil fuels is the main source of carbon emissions in China.

At the 75th session of the UN General Assembly, China pledged to peak its carbon dioxide emissions by 2030 and become carbon neutral by 2060. From the perspective of the national institutional framework, the Central Economic Work Conference proposed to correctly grasp carbon to achieve peak carbon neutrality, accelerate the construction of carbon emission rights trading market, and accelerate the formation of incentive and constraint mechanisms for reducing pollution and carbon. In July 2021, China launched a national unified carbon market on the basis of the original seven regional pilot carbon markets, striving to cover eight key high-energy consumption industries during the "14th Five-Year Plan" carbon market.

At the individual level, individuals and households are directly or indirectly responsible for about 72% of global carbon emissions (Hertwich and Peters, 2009) [1]. Relevant statistics show that about 80% of the total carbon emissions in the United States are generated by the living behaviors of residents (Jones and Kammen, 2014) [2]. About 25% of Singapore's carbon emissions are attributed to consumer demand (Su et al., 2017) [3]. As one of the fastest growing emerging economies in the world, China is experiencing a phase of rapid growth in personal and household carbon emissions. Studies show that 35% of China's carbon footprint is related to household carbon consumption behavior (Tian et al., 2014) [4]. According to statistics (Xu, 2019) [5], carbon emissions from Chinese households rose to 379.5 million tons in 2016, an increase of 433% over 1996. In 2017, after a series of scientific, systematic, and quantitative studies, the research group "China's Carbon Emissions: Peak as soon as possible" showed that adjusting consumption demand is the most important way to achieve China's low-carbon development at the individual level. In 2022, the National Development and Reform Commission and other seven ministries jointly issued the "Implementation Plan for Promoting Green Consumption", proposed a green consumption point system, explored the implementation of a global green consumption point system, and moved to incentivize green consumption by issuing green consumption vouchers, green points, direct subsidies, price cuts, and interest rates. Encouraging industry associations, platforming enterprises, manufacturing enterprises, circulation enterprises, etc., to jointly launch green consumption action plans, and launch a wealth of green low-carbon products and green consumption scenarios were also part of this initiative.

However, changing consumer behavior is a long-term task, extending from the production of low-carbon products by enterprises to the participation of consumer behavior to change the final destination of products, which runs through the entire life cycle of products. Today, we urgently need to explore how to increase individual and household carbon reduction. Building a unified and efficient carbon emission rights trading market and promoting a carbon emission reduction model based on individual level carbon emission rights trading is one of the important ways to efficiently complete the "carbon neutral carbon peak" by 2030. Individual level carbon trading is a form of carbon market trading that quantifies individual carbon emissions and trades them to achieve emissions reductions downstream from energy consumption in a "bottom-up" way. Low-carbon users with efficient emission reduction will sell their idle surplus carbon emission allowances, known as surplus carbon allowances, to high-carbon users through carbon trading platforms.

At present, some local governments and enterprises in China have initially explored some forms of individual-level carbon trading, mostly in the form of regional projects. These include Guangdong Province's "carbon inclusive" project and Luzhou City's "Green bud integral" project. The Green Bud Points project quantifies green behaviors in daily life in the form of "green points" that can be exchanged for daily necessities such as soap and rice. Since the implementation of the "Green Bud Points" project in 2018, it has integrated more than 60 local enterprises, 7 universities, and 5 social groups to participate in it, registered more than 70,000 people, and accumulated 37.2 tons of emission reduction.

However, the current carbon trading practice is mainly focused on scenarios such as travel that do not require product intervention but only consumer participation. There are difficulties in terms of uneven distribution and monitoring implementation. Although these projects have played a certain role in promoting individual carbon emission reduction, they mainly encourage green consumption by exchanging goods and discounts, and they lack unified standards and applicable methodologies. More importantly, there is a Nash equilibrium between the current individual level carbon trading and green projects, that is, the government pays for high-carbon consumer behavior, which will lower the efficiency of resource allocation and lead to the decline of total social welfare. Therefore, how to encourage more users to participate in low-carbon consumption without increasing the burden of government funds has become the focus of carbon trading reform in the future and is also one of the problems to be solved in this paper. In addition, limited public acceptance is a problem that cannot be ignored at the individual level of carbon trading. Carbon reduction is not only a public environmental activity, but also a cost and tradeable product. As the main participants in emission reduction, consumers will pay the corresponding low carbon costs. How to make up for the lack of material incentives between costs and benefits and how to crack the carbon locking effect of consumer groups is also an urgent barrier to break through.

Considering the above carbon trading dilemma, how to ensure that users participate in carbon trading without government subsidies has become an urgent problem to be solved. Therefore, this paper introduces a carbon trading mechanism to ensure that low carbon emission users can still get a positive return without government involvement. The commercialization of carbon emission reduction through the trading of surplus carbon allowances between low carbon consumers and high carbon consumers will effectively stimulate consumers' enthusiasm for low-carbon consumption. In order to ensure the authenticity and effectiveness of the remaining carbon quota trading information and prevent data fraud, this paper builds a decentralized trading carbon account trading system based on the transparency and openness of the data of blockchain technology to reduce opportunistic behavior. In addition, emission reduction behavior is inseparable from people's lives, such as taking subways and buses to work instead of driving fuel cars to work, not using non-degradable shopping bags, and so on. The above low-carbon behaviors appear in all aspects of life and can happen anytime and anywhere. Therefore, individual-level carbon trading is characterized by small amounts and high frequency. It is tedious work to count the transactions of individual carbon allowances and carbon credits, and the trading system needs to be expanded on the basis of the original blockchain to meet the technical needs of the remaining carbon quota transactions. Ensuring that users can trade surplus carbon allowances without government subsidies will help ease the financial pressure on the government and realize the Pareto optimal state of government: low carbon users, high carbon users, and social welfare.

The main contributions of this paper are reflected in the following two aspects: (1) On the premise of not considering government subsidies, in the face of consumer personal carbon quota projects with both public welfare and commercialization, the trading mechanism of surplus carbon quota based on carbon trading platform is proposed. It breaks through the carbon locking effect of consumer groups and realizes the generation and trading of individual carbon assets under the condition of financial constraints. (2) Based on the guarantee of individual carbon trading service level, this paper constructs a carbon trading market system based on blockchain technology. It establishes an individual carbon account trading model under the price driving mechanism of individual carbon assets and analyzes the issuance and management of individual carbon credits. We analyze the influencing factors of individual carbon asset price and explore the multi-agent incentive model of consumers' low-carbon behavior. This paper is expected to provide suggestions for the macro-policy control of government departments. (3) The profitability of the carbon trading platform is contingent upon the service sensitivity exhibited by both parties involved. Furthermore, the societal compounded interest derived from adopting blockchain technology surpasses the social welfare obtained from abstaining its adoption.

2. Literature Review

2.1. The Impact of Carbon Quota Trading on Carbon Emissions

Carbon emission trading is an effective mechanism for achieving carbon neutrality [6]. In this process, carbon emissions are treated as a tradable commodity, and government departments allocate carbon allowances to firms based on predetermined guidelines [7]. If a firm's actual carbon emissions exceed the initial quota allocated by the government, it must obtain additional allowances through the carbon trading market [8]. Conversely, if a firm's actual carbon emissions are lower than the allocated amount, it can sell excess carbon quotas for profit. Through this market-based approach, carbon quota trading effectively reduces emissions and promotes low-carbon and sustainable development. Yang C. et al. (2023) [9] conducted a study on the mechanism of carbon emission quota trading using an agent negotiation model with negotiator preferences and Bayesian algorithms, resulting in a win-win situation for all parties involved in the trading process. An Q. et al. (2023) [10] adopted the two-stage data envelopment analysis method to explore the resource allocation in the carbon emission system and proposed the two-stage research structure of the carbon trading process.

As a market mechanism, carbon quota trading promotes the reduction of global CO_2 emissions [11]. While carbon quota trading has been gradually implemented in the European Union and China, it still faces several challenges. Qi X. et al. (2022) [12] argue that the imbalance between supply and demand of carbon quotas could hinder the development of the carbon market, with factors such as marginal production profit, marginal emission reduction cost, and purchasing carbon quotas through carbon trading jointly influencing portfolio effects. The utilization of digital technology facilitates the trading process by abstracting buyers and sellers into distinct nodes. Moreover, incorporating big data and artificial intelligence technologies into carbon emission trading can enhance efficiency while achieving win-win outcomes through accurate matching. Based on China's experience with its pilot program for carbon trading, Shi B. et al. (2022) [13] demonstrate that policy implementation not only reduces regional carbon emissions but also curbs per capita CO_2 emissions. However, it is important to note that the effectiveness of these measures depends on environmental regulations' stringency as they may limit the full potential of market-based mechanisms like carbon quotas.

2.2. Individual Carbon Credits for Consumers

Individual carbon credits were first proposed by David Miliband, the then UK Environment Secretary, to allocate carbon credits to individuals in order to control individual carbon emissions. Individual carbon credit, as a direct measure of carbon emission reduction on the consumption side, is gradually becoming another novel attempt to reduce household carbon emissions in various countries. Scholars have also applied exhaust gas temperature (EGT) to strategic interaction analysis among multi-stakeholders in green projects. Some scholars have discussed the impact of carbon taxes and carbon subsidies on the diffusion efficiency of green manufacturing technologies (Zhang et al., 2019) [14]. Individual level carbon trading is not a futuristic concept and is one of the effective ways to achieve high quality carbon reduction (Fawcett, 2010) [15]. Relevant studies have pointed out that although the average distribution of individual carbon emission credits under the individual-level carbon trading policy is somewhat unfair (Burgess, 2016) [16]; however, it can effectively change individual behavioral decision-making and improve low-carbon awareness (Li et al., 2018) [17]. A case study conducted in China shows that individual and household participation in carbon markets can reduce carbon emissions in rural areas by 45.5% and urban areas by 28.1%, respectively, and save carbon emission reduction costs by 13.60~14.01% (An et al., 2021) [18]. Although existing research has explored the theoretical feasibility of individual carbon trading, there are still some key research gaps that need to be addressed. Most individual carbon trading designs mainly focus on resident participation incentives due to the large amount of carbon emissions data available for individuals and households in a country [19].

Due to the huge potential of individual-level carbon trading, a number of government agencies and related enterprises have initiated a number of carbon inclusive practice projects in combination with China's national conditions, such as the "carbon inclusive" project in Guangdong Province and Alipay Ant Forest [20]. Such programs bypass some of the barriers to mandatory individual-level carbon trading by encouraging citizens to participate voluntarily in the carbon market, mainly in the form of monetary or honor incentives [21,22]. However, most of the cities or companies implementing carbon inclusive pilot projects are aimed at green travel scenarios. Due to data limitations, it is difficult to cover the whole scene of residents' lives, and most of the projects in good running condition introduce external incentive mechanisms in the market. The model of converting low-carbon behavior data into carbon credits for trading profits in the carbon trading market runs better than the model of policy guidance or coupon issuance alone [23], which confirms the positive role of market incentive feedback [24]. In addition, the case of Ant Forest shows that citizens have a strong desire for low-carbon behavior [25]. Under the premise that data can be automatically collected through the platform, such a huge user base and significant emission reduction effect can be achieved only through reasonable honor incentives. According to the actual pilot situation of local governments and enterprises, there are still some problems in the promotion of carbon Generalized System of Preference (GSP) [26].

2.3. The Application of Blockchain Technology in Carbon Trading

In the actual operation of the individual carbon market, there are some problems, such as the design of incentive mode, the protection of user privacy, and the sharing of data assets of different merchants. Zhang T. (2023) and other scholars have pointed out that there is insufficient transparency in all aspects of current carbon trading, as well as risks associated with centralized data operations and mutual trust issues [27]. Liu Y. et al. (2022) argue that information asymmetry in carbon trading slows down the process and increases transaction costs [28]. Among them, the main obstacle restricting the national promotion of individual-level carbon trading is the management cost of massive personal carbon asset data. The rapidly developing blockchain technology provides a new way to solve the above problems. Blockchain can record the whole process data of carbon quota issuance, reporting, and compliance, and its immutable and traceable characteristics will reduce the probability of enterprises concealing emissions, individuals or data management agencies tampering with data, reduce the possibility of false data and false transactions, and greatly reduce the verification cost of government departments. The programmable feature of blockchain, that is, smart contracts, can meet the implementation of carbon inclusive policies in different regions and different scenarios. A perfect smart contract can run automatically and without maintenance, which will greatly reduce the management cost of data statistics and carbon credits issuance and recovery in the process of carbon inclusive construction (Ji Bin et al., 2021) [29]. Through the side chain expansion technology of blockchain, it is also possible to organically integrate the individual-level carbon market built from the bottom up into a unified carbon market.

Reviewing the existing literature, we draw the following conclusions:

First, existing studies focus on exploring the low-carbon strategic interaction between the government and enterprises, while there is little analysis on the incentive mechanism of consumers' low-carbon behavior. Second, individual carbon credit, as a practical measure of carbon emission reduction on the consumption side, is still in the stage of feasibility theoretical analysis. It is necessary to build a multi-participation incentive mechanism based on actual cases to improve consumers' willingness to participate. Third, the data scale is too large, and data authenticity, security, and traceability need to be enhanced. It is difficult to grasp the scale of the authenticity and privacy of the data, and it is difficult to trace the data. Fourth, individual behavior big data of different enterprises is difficult to share, and there is a problem of "data islands". In the era of big data, enterprise user data is the core asset of enterprises. If the data cannot be shared under the premise of security and reliability, it will be difficult to comprehensively and conveniently quantify low-carbon behavior data. Therefore, how to deal with the above problems is the key to the promotion of the carbon GSP.

3. Basic Assumption

The paper establishes an evolutionary game model that encompasses the carbon trading platform, the carbon quota supplier, and the carbon quota demander in order to analyze participants' decision-making choices. Factors such as carbon trading price, users' willingness to participate, and service level are examined for their impact.

We define the carbon quota, establish a fixed total for social carbon emissions, and assign each user their individual maximum carbon allowance. During the same period, users with low carbon consumption will have a surplus portion of their carbon quota, while users with high carbon consumption will not have any surplus or may even exceed their allocated limit. As demanders of excess carbon allowances, users with high carbon emissions seek to purchase additional quotas from the carbon trading platform. Through the trading of surplus carbon allowances, we aim to enable low-carbon consumers to receive tangible rewards while maintaining unchanged total social carbon emissions. High-carbon consumers can acquire extra allowances and avoid penalties for excessive emissions by utilizing the proposed model for trading in carbon quotas, thereby achieving Pareto optimality among participants in the market.

This paper considers four types of nodes: government nodes, low carbon emission users, carbon trading platforms, and high carbon emission users. Among them, low-carbon users can sell the remaining carbon emissions to the nodes of the carbon trading platform at a certain price, or they can be retained as personal carbon assets. High-carbon users purchase carbon emission rights through carbon trading platforms, which are used to offset excessive emissions that have already occurred. All nodes want to maximize utility. In addition, how to price the remaining carbon allowances in order to attract more users to participate is particularly important. Based on this, this paper analyzes the decision-making of the carbon trading platform, low carbon individuals, and high carbon individual. According to the problem description, the symbols mentioned in this paper are shown in Table 1.

Table 1. Description of symbols.

Symbol	Implication
α	Sensitivity coefficient of users to the service level of carbon trading platform
q	Service level of carbon trading platform
c	Carbon allowances A price that suppliers place on their remaining carbon emissions
k	Service level coefficient of carbon trading platform
v	Fixed utility for users joining the platform
f	Registration fees charged by carbon trading platforms to users
p	A fixed transaction fee charged by a carbon trading platform to users
U	The utility function of the user, U_m represents the financial utility, U_e represents the carbon reduction utility
N	The scale function of users joining the carbon trading platform
π	Profit function of carbon trading platform
S	The user's residual function
E	Total carbon reduction utility function
s	Surplus carbon quota suppliers
d	Surplus carbon quota demand side

A carbon trading platform is the trading of individual carbon emission rights. From the perspective of supply and demand of surplus carbon allowances, this paper divides users of carbon trading platform into low-carbon users, that is, suppliers of surplus carbon allowances, and high carbon users, that is, those who need the remaining carbon quota. The individual level carbon trading system is shown in Figure 1.

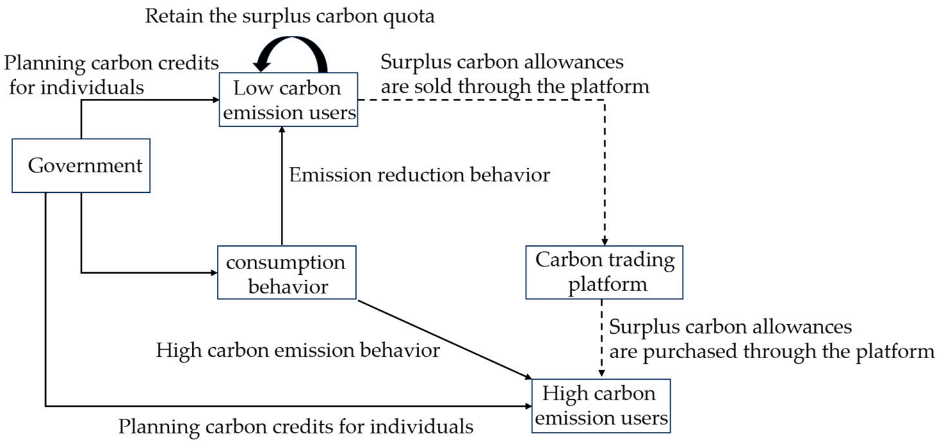

Figure 1. Carbon trading system for individual carbon allowances.

Government decisions:

Determine the total carbon emission N within a certain region and determine the unit price P of the remaining carbon quota in the carbon trading market. The state sets a ratio of δ that can be offset with the surplus carbon credits purchased. The government will control the total carbon emission to ensure the total welfare of society. Consumers have individual caps on carbon credits, and there are two types of consumers: low carbon users and high carbon users.

Carbon trading platform decision:

Carbon trading platform is an intermediary platform that provides a trading venue and matching and scheduling services for carbon quota bilateral users who need to trade by charging registration fees or commissions. According to the supply of carbon allowances, the node of the carbon trading platform determines the price P_{ph} of the remaining carbon emission reduction per unit for repurchasing low-carbon emission individuals, and the price P_c for selling to high-carbon emission users. The unit operating cost of setting up carbon trading platform is represented by c. Considering the satisfaction of users, as well as the matching rate and fit of carbon quotas, the carbon trading platform introduces blockchain technology to ensure the level of operational service and attract more users to participate in carbon quota trading. The improvement of service level will also increase the cost of carbon trading platform, so under the use of blockchain technology, the unit cost is c_b. The improvement of service level will increase the cost of the carbon trading platform, so the platform needs to consider how to reasonably customize pricing strategies on the premise of coordinating service level, cost, and effectiveness. When individual abaters join the carbon trading market, the operating income π of the carbon trading platform is:

$$\pi\left(P_{ph}\right) = \left(P_c - P_{ph} - c - c_b\right)D_{all} = \frac{DW}{e}\left(P_c - P_{ph} - c - c_b\right)P_{ph} \quad (1)$$

Low carbon emission user decision:

Low-carbon emission users who purchase green products and services provided by low-carbon enterprises can obtain corresponding green points and have the remaining carbon quota. Suppose that the probability that the user chooses to sell the remaining carbon quota is $x \in [0,1]$ and the probability that the user chooses to retain the remaining carbon quota is $1 - x$. When the user chooses the former, the individual utility $P_{ph}D_i$ is obtained. In addition, because carbon trading platforms are profitable, carbon quota providers who participate in carbon trading are required to pay a commission. The individual utility of low-carbon emission users is u_i, that is:

$$u_i = \left(P_{ph} - \theta_i e\right) D_i x \tag{2}$$

where θ_i is the individual perception coefficient, subject to uniform distribution, that is, $\theta_i \sim U(0,1)$. The use of low-carbon services or products will cost more than the use of high-carbon services or products. Therefore, let e be the value measure of the cost paid by an individual to obtain a unit carbon credit, and D_i is the individual carbon emission reduction. If, then individual carbon abaters join the carbon trading market, namely:

$$\theta \le \theta^* \triangleq \frac{P_{ph}}{e} \tag{3}$$

High carbon emission user decision: The remaining carbon quota customers are mainly high-carbon emission consumers under the quota emission constraint. The main purpose of high-carbon consumers participating in carbon trading is to purchase carbon emission rights from low-carbon users through carbon trading platforms. Therefore, high carbon emission users have a strong incentive to trade carbon. Suppose that the potential number of carbon demanders is normalized to 1. High carbon emission users need to pay a certain fee, and the nodes of the carbon trading platform sell carbon emission rights to high carbon emission users for carbon emission offsetting. In addition, additional potential costs arising from differences in demand for carbon credits trading among high-carbon consumers need to be considered.

3.1. Equilibrium Analysis

Carbon trading market supply and demand balance, $D_{all} = N\delta$, where D_{all} is the total amount of individual tradeable carbon credits in the ecology. The total number of individuals is W and the average emission reduction of all individuals is D, then the total emission reduction D_{all} in the ecology is:

$$D_{all} = \sum_{i=0}^{W} W \int_0^{\theta^*} D d\theta = \frac{P_{ph}}{e} DW \tag{4}$$

When individual abaters join the market, the operating income π of the carbon trading platform is:

$$\pi\left(P_{ph}\right) = \left(P_c - P_{ph} - c\right) D_{all} = \frac{DW}{e}\left(P_c - P_{ph} - c\right) P_{ph} \tag{5}$$

where c is the unit operating cost of the carbon trading platform. The carbon trading platform adjusts the circulating carbon credits price P_{ph} to maximize the operating income, that is, to solve:

$$\max_{P_{ph}} \frac{DW}{e}\left(P_c - P_{ph} - c\right) P_{ph} \tag{6}$$

Solve this optimization problem and combine the results with Formulas (3) and (4) to get Proposition 1.

Proposition 1. *The optimal price* ${P_{ph}}^*$ *and the corresponding* P_c *for maximizing the operating profit of the carbon trading platform are:*

$${P_{ph}}^* = \frac{1}{2}(P_c - c), \quad P_c = \frac{2N\delta e}{DW} + c \tag{7}$$

It can be seen from Proposition 1 that according to carbon market conditions and individual emission reduction effectiveness, the country can adjust the market price by setting the offset ratio δ, thus adjusting the price of carbon credits. DW reflects the supply of regional carbon inclusive projects, and $N\delta$ delta is the total demand for carbon allowances in the carbon market; the price increases with the increase in demand.

Meanwhile, according to the above hypothesis and Proposition 1, emission reduction utility surplus (8) and social welfare (9) can be obtained.

$$U = \sum_{i=0}^{W} u_i = \int_0^{\theta^*} \left(P_{ph} - \theta e\right) DW d\theta = \frac{eN^2\delta^2}{2DW} \tag{8}$$

$$\pi + U = \frac{3eN^2\delta^2}{2DW} \tag{9}$$

According to the social welfare expression, the greater the offset ratio, the greater the social welfare. However, since the price of carbon allowances in the market is generally higher than the price of remaining carbon allowances, enterprises will prioritize allocation. The larger the offset ratio δ, the lower the welfare utility of enterprises saving carbon allowances through emission reduction. Therefore, the model further considers the benefits of emission reduction enterprises, and Formula (10) is shown below, where c_i pays emission reduction cost for saving carbon allowances per unit. π_b is the social benefit of emission reduction enterprises:

$$\pi_b = (P - c_1)N(1 - \delta) \tag{10}$$

It is assumed that the relationship between the unit emission reduction cost paid by the emission reduction enterprise and the carbon quota saved in the carbon trading market is linear, that is, $kc_1 = N(1 - \delta)$. The larger k is, the easier it is to reduce emissions, and the smaller k is, the more difficult it is to reduce emissions. The total social welfare is:

$$\begin{aligned} \pi_b = \ & \left(P - \tfrac{N(1-\delta)}{k}\right) N(1 - \delta) + \tfrac{3eN^2\delta^2}{2DW} \\ & = \left(\tfrac{3eN^2}{2DW} - \tfrac{N^2}{k}\right)\delta^2 + \left(\tfrac{2N^2}{k} - PN\right)\delta - \tfrac{N^2}{k} + PN \end{aligned} \tag{11}$$

According to Formula (11), the social benefit of the emission reduction enterprise π_b is a quadratic function. Therefore, when certain conditions are met, there will be a local optimal solution between $\delta \in (0, 1)$, namely Proposition 2.

Proposition 2. *Government makers should control the issuance of quotas so that they meet the following conditions:* $k < min\left(\frac{2N}{P}, \frac{2DW}{3ek}\right)$, $N < \frac{DWP}{3e}$.

When $0 < \delta^* < 1$, maximize the welfare of all market nodes. When $\delta^* = 0$, the emission reduction enterprises in the market tend to offset all carbon emissions with carbon quotas. When $\delta^* = 1$, all emissions tend to be offset by the purchase of surplus carbon emissions.

3.2. Analysis of Matching Mode of Carbon Trading Market

3.2.1. Carbon Trading Platform Profit Maximization

The optimal objectives of the matching model of carbon trading market include the maximization of profit π and the maximization of total carbon emission benefit E. Carbon trading platforms need to decide whether to introduce blockchain technology into their pricing models at a service level q. Low carbon users and high carbon users decide whether to join the carbon trading platform according to their possible financial utility U_m and carbon reduction utility U_e. A price that low-carbon users put on their remaining carbon emissions c. The scale of high carbon consumers and low carbon consumers who choose to join the carbon trading platform is N. If the matching probability is assumed to be 1, the scale of users also represents the probability of successful trading of both parties. Users who choose to join the carbon trading platform will get a certain fixed utility v. Users have a certain sensitivity to the service level provided by the platform. Under a certain service sensitivity coefficient α, the higher the service level q of the carbon trading platform, the higher the fixed utility obtained by users. For the carbon trading platform, the improvement of service level will lead to the increase of user scale and service cost, and the service cost is positively correlated with the platform service level cost coefficient k.

The utility function on the demand side is as follows: the fixed utility obtained by the carbon quota demand joining the carbon trading platform, the positive utility $q\beta_d$ brought by the service provided by the platform, the disutility $-cN$ of paying the carbon quota fee, and the fee $-f_d$ paid to the carbon trading platform.

$$U_d = v_d + q\beta_d - cN - f_d \tag{12}$$

If the carbon quota supplier joins the carbon trading platform to obtain fixed utility, the positive utility $q\beta_s$ brought about by the service provided by the platform, and the negative utility $-f_s$ brought about by paying the registration fee of the carbon trading platform, then the utility function of the carbon quota supplier is:

$$U_s = v_s + q\beta_s - f_s \tag{13}$$

For users who participate in carbon trading, they will participate only when their own utility is positive. If $U_d = 0$, the fixed utility of the critical condition on the demand side of carbon quota can be obtained, that is, ${v_d}^* = cN + f_d - q\beta_d$, and the fixed utility of the critical condition on the supply side of carbon quota can be obtained, that is, ${v_s}^* = f_s - q\beta_s$. When $v_d > {v_d}^*$, the demand side will join the carbon trading platform; when $v_s > {v_s}^*$, carbon quota providers will join the carbon trading platform. Since the fixed utility of users joining the platform is $v \sim U[0,1]$, and according to the assumption, the total market size of users of both the supply and demand sides is 1, the scale of users joining the carbon trading platform is:

$$N_d = 1 + P[v_d > {v_d}^*] = 1 + q\beta_d - cN - f_d \tag{14}$$

$$N_s = 1 + P[v_s > {v_s}^*] = 1 + q\beta_s - f_s \tag{15}$$

The carbon trading platform makes profits by charging fees $N_d f_d, N_s f_s$ to bilateral users and generates service cost $\frac{k}{2}q^2$. The profit function of the carbon trading platform is:

$$\pi = N_d f_d + N_s f_s - \frac{k}{2}q^2 \tag{16}$$

It can be obtained that:

$$N_d = \frac{1 - f_d + q\beta_d + c(f_s - q\beta_s)}{1+c}$$

$$N_s = \frac{1 - f_s + q(\beta_s + \beta_d) - f_d}{1+c}$$

N_d, N_s generation into π, and make $\frac{\partial \pi}{\partial f_d} = 0, \frac{\partial \pi}{\partial f_s} = 0$, carbon trading platform can be obtained to maximize profit:

$${f_d}^* = \frac{(c-2)(1+q\beta_d) + c(1+q\beta_s)}{c^2-4} \tag{17}$$

$${f_s}^* = \frac{c(c-1) - 2(1+q\beta_s) - c(1+q\beta_d)}{c^2-4} \tag{18}$$

The π-Hesse matrix is obtained as:

$$H(\pi) = \begin{bmatrix} \frac{-2}{1+c(c-1)} & \frac{c-1}{1+c(c-1)} \\ \frac{c-1}{1+c(c-1)} & \frac{-2}{1+c(c-1)} \end{bmatrix}$$

To guarantee the existence of ${f_d}^*, {f_s}^*$, $H(\pi)$ negative definite must be satisfied, and the equilibrium condition $-2 < c(c-1) < 2$ can be obtained. By substituting ${f_d}^*, {f_s}^*$ back to the original formula, the scale and platform profits of bilateral users joining the carbon trading platform under the equilibrium condition can be obtained:

$$N_d{}^* = \frac{(c-1)(1+q\beta_d) - 2(1+q\beta_s)}{(c-1)^2 - 4}$$

$$N_s{}^* = \frac{(c-1)(1+q\beta_s) - 2(1+q\beta_d)}{(c-1)^2 - 4}$$

$$\pi^* = \frac{(1+q\beta_d)^2 + (1+q\beta_s)^2 + (1-c)(1+q\beta_d)(1+q\beta_s)}{4-(c-1)^2} - \frac{k}{2}q^2$$

To ensure that the number of bilateral users is positive, combined with the equilibrium conditions and the range of parameters themselves, the conditions to be met in the pursuit of profit maximization in the carbon trading platform are $-2 < c(c-1) < 1$.

3.2.2. Social Welfare Maximization

According to the results obtained in Section 3.2.1, the scale of bilateral users joining the carbon trading platform and the platform profits are

$$N_d = \frac{1+q\beta_d - f_d + \delta[f_s - (1+q\beta_d)]}{1+\delta\alpha_s}$$

$$N_s = \frac{1+q\beta_d + (1+q\beta_d)\alpha_s - f_s - f_d\alpha_s}{1+\delta\alpha_s}$$

$$\pi = \frac{f_s[(1+q\beta_s) + \delta f - (1+q\beta_d)] - f_d}{1+\delta\alpha_s} - \frac{k}{2}q^2$$

According to the characteristics of each participant of the carbon trading platform, the social welfare expression can be obtained

$$\pi = S_d + S_S + \pi$$

$$S_d = \int_{v_d{}^*}^{1} (v_d + \alpha_d N_s + q\beta_d - cN_s - f_d) f(v_d) dv_d = \frac{1+q\beta_d - f_d + \delta[f_s(1+q\beta_d)^2]}{2(1+\delta\alpha_s)^2}$$

$$S_S = \int_{v_s{}^*}^{1} (v_s + \alpha_s N_d + q\beta_s - f_s) f(v_s) dv_s = \frac{[f_s + \alpha_s(1+q\beta_s) - (1+q\beta_d)^2]}{2(1+\delta\alpha_s)^2}$$

Let $\frac{\partial W}{\partial f_d} = 0$, $\frac{\partial W}{\partial f_s} = 0$, we can obtain:

$$f_d{}^* = \frac{\alpha_s(\alpha_s - \delta)(1+q\beta_s) + \alpha_s(1+q\beta_d)}{(\alpha_s-\delta)^2 - 1}$$

$$f_s{}^* = \frac{\delta(\alpha_s - \delta)(1+q\beta_d) + (1+q\beta_s)}{1-(\alpha_s-\delta)^2}$$

The W-Hesse matrix is obtained as

$$H(W) = \begin{bmatrix} \frac{{\alpha_s}^2 - 1 - 2\delta\alpha_s}{(1+\delta\alpha_s)^2} & \frac{\delta(\delta-\alpha_s)\alpha_s}{(1+\delta\alpha_s)^2} \\ \frac{\delta(\delta-\alpha_s)\alpha_s}{(1+\delta\alpha_s)^2} & \frac{\delta^2 - 2\delta\alpha_s - 1}{(1+\delta\alpha_s)^2} \end{bmatrix}$$

To ensure the existence of ${f_d}^*, {f_s}^*$, it is necessary to satisfy the negative definite of $H(W)$, and when the equilibrium condition can be obtained, it is added at equilibrium.

The bilateral user scale of the carbon trading platform, the profits of the carbon trading platform, and social welfare are, respectively,

$$N_d{}^* = \frac{(\delta - \alpha_s)(1 + q\beta_s) - (1 + q\beta_d)}{(\alpha_s - \delta)^2 - 1}$$

$$N_s{}^* = \frac{(\delta - \alpha_s)(1 + q\beta_d) - (1 + q\beta_s)}{(\alpha_s - \delta)^2 - 1}$$

$$\pi = \frac{(\delta - \alpha_s)[(\delta - \alpha_s)(1 + q\beta_d) - (1 + q\beta_s)]}{(\alpha_s - 1 - \delta)^2(\alpha_s + 1 - \delta)^2} - \frac{k}{2}q^2$$

$$W^* = \frac{2(\delta - \alpha_s)(1 + q\beta_d)(1 + q\beta_s) - [(1 + q\beta_d) - (1 + q\beta_s)]^2}{2(\alpha_s - \delta)^2 - 2} - \frac{k}{2}q^2$$

4. Result Analysis

Result 1. Taking the profit maximization of the carbon trading platform as the goal, the influence of different parameters on the profit of the carbon trading platform can be obtained when the equilibrium state is reached:

(1) There is a positive correlation between the profit of carbon trading platform and the service sensitivity coefficients β_d, β_s of both parties.

The revenue of the platform mainly comes from the fees of bilateral users, and the increase of the scale of users and the increase of trading volume will increase the profits of the platform. In the operation of the carbon trading platform, in order to obtain greater profits, it is necessary to expand the number of users. For example, in the early stage of the development of the platform, subsidies are an effective means to attract users to join.

The service sensitivity coefficient of both the supply and demand sides reflects the impact of different service levels provided by the platform on the user's utility. When the user's service sensitivity is strong, the user has higher requirements for the service level. To attract customers, the platform will strive to improve the service level and increase the pricing. Because users are more sensitive to the service level, they are more willing to join the carbon trading platform when the service level is improved. The increase in the scale of users and the increase in commission fees will bring greater profits to the platform. Therefore, for the user groups with strong service sensitivity, the platform can appropriately improve the level and pricing to increase profits.

(2) There is a negative correlation between the profit of carbon trading platform and the capacity pricing c of the supply side.

In addition to the fees charged by the carbon trading platform, the demand side of the carbon quota needs to pay the carbon emission fee to the supplier, which is set by the supplier and collected through the platform. The profit of the carbon trading platform is not directly related to it, but the larger the c, the smaller the scale of the demand side will be, and the lower the success rate of the transaction. Therefore, the profits of the carbon trading platform will decrease due to the increase, and the carbon trading platform also needs to control the pricing of carbon quotas on the supply side.

(3) Platform profit is a concave function of platform service level q, which is positively correlated with low service level and negatively correlated with high service level.

The level of service provided by carbon trading platforms for bilateral users can be high or low. When the service level is higher, bilateral users will get greater utility, the scale of users joining the carbon trading platform will expand, and the platform will appropriately increase the registration fee or transaction fee. When the platform service level is low, the cost brought by improving the service level is less than the benefit brought by the expansion of user scale, and the platform profit increases. When the platform service is already at a high level, the benefits to users brought by further improvement of the service level are diminishing, and the additional cost is higher than the benefits brought by the expansion of the user scale. Therefore, blindly improving the service level will lead to lower profits.

Result 2. To maximize social welfare, the size of social welfare is related to the value of the proportion σ that can be offset.

(1) When $\alpha_s - 1 < \sigma < 1$ or $-1 < \sigma < \alpha_s - \sqrt{{\alpha_s}^2 + 1}$, social welfare with blockchain technology is greater than social welfare without blockchain technology.

The value range of σ affects the service level of the platform. Therefore, for different offset ratios, the carbon trading platform needs to intervene in the unit price of the surplus carbon quota to some extent or take measures to affect the network externalities of the supply and demand side of the surplus carbon trading so as to adjust the range and maximize social welfare.

(2) The total carbon emission reduction is positively correlated with the service level q provided by the platform, positively correlated with the service sensitivity coefficient β_d on the demand side, and negatively correlated with the service sensitivity coefficient β_s on the supply side.

5. Research Conclusions

By analyzing the development trend of China's carbon market in the future, this paper points out that building individual carbon trading market is an important way to realize the goal of "double carbon". According to the current construction status of each pilot carbon trading market and the national unified carbon trading market, there are prominent problems in the process of carbon trading, such as difficult supervision and high management costs. At the same time, the pilot projects related to carbon inclusion carried out in some regions also highlight the problems of large data volume, high management costs, and data islands in the process of individual carbon trading. Facing the scenario of big data in the future, this paper proposes a carbon market system design scheme based on blockchain technology. Finally, the price driving mechanism model of carbon price in the side-chain ecology is analyzed, and the analysis results provide a reference for the government departments to conduct macro-policy regulation. The main innovations of this article are:

(1) For the future big data scenario, the carbon market blockchain system architecture design scheme is built. The numerical results obtained from the model demonstrate that in absence of government subsidy mechanisms, individual-level carbon trading can effectively reduce total consumer emissions. The present study successfully overcomes the carbon lock-in effect of consumer groups and achieves the generation and trading of individual carbon assets despite capital constraints. This study facilitates accumulation and trade of individual carbon resources, reduces overall consumer emissions, enhances environmental benefits at societal level, and provides a foundation for governmental decision-making. (2) A price-driven mechanism model is proposed for individual carbon assets circulating in the side chain of the blockchain system. Based on the massive transaction data of the future carbon market, this paper proposes and analyzes the technical solutions of the practical application of blockchain, which promotes the technological transformation of important industries, helps enterprises find new business operation models, and thus contributes to the development of the national economy. (3) On the premise of not considering government subsidies, in the face of consumer personal carbon quota projects with both public welfare and commercialization, the trading mechanism of surplus carbon quota based on carbon trading platform is proposed. It breaks through the carbon locking effect of consumer groups and realizes the generation and trading of individual carbon assets under the condition of financial constraints. This paper is expected to provide suggestions for the macro-policy control of government departments.

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