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A Game-Theoretic Analysis of Incentive Effects for AgriBiomass Power Generation Supply Chain in China

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Abstract: The undersupplies of feedstock and high costs have hindered the development of China's biomass power generation. In this paper, the noncooperative game, farmer–broker cooperative game, and broker–biomass power plant cooperative game, under government incentives, are constructed and analyzed. The optimal decision strategies and profits for these three cases are obtained, while numerical examples and sensitivity analysis are conducted, aiming at illustrating some specific features of the games. It is shown that the government plays a critical role in the development of utilizing agriBiomass for power generation and can work better in cooperative games. In addition, both agriBiomass supply quantity and profits of supply chain members are higher in cooperative than in noncooperative game. Meanwhile, farmers can get the maximum profit in the broker–biomass power plant cooperative game, while biomass power plant makes the maximum profit in the farmer–broker cooperative game. To guide the healthy development of the industry, there is an urgent need for further exploration of the biomass supply chain management and coordination issue. Specifically, the cooperative game for establishing optimal feedstock price subsidy policy will be done by way of adjusting government incentives and alliance profit distribution.

Keywords: governmental incentive; game-theoretic analysis; agriBiomass power generation; supply chain; cooperative game; noncooperative game



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1. Introduction

As rich and sustainable renewable transportation energy, agriBiomass has gained wide attention in the recent past due to its advantages. Because of its abundant yield and that it can be used to generate heat, electricity, biofuels, biogas, or a combination of them, agriBiomass has been considered as a promising alternative to fossil fuels [1,2]. Reports and researches have shown that the heating value of a ton of agriBiomass is equivalent to the heating value of 0.5 tons standard coal, but the average sulfur content is only 0.38%, compared with coal with a sulfur content of about 1%, which has good economic, environmental, and social benefits [3,4]. From an economic perspective, it can promote employment in rural areas, increase farmers' income, and improve farmers' quality of life. From an environmental perspective, it can improve energy security, effectively reduce greenhouse gas (GHG) emissions and pollution, and improve rural sanitation. From a social perspective, it can improve the energy structure dominated by coal, and better build a resource-saving and environment-friendly harmonious society [5–7]. If agriBiomass can be effectively utilized, we can not only protect the environment, but also realize the recycling of resources and achieve sustainable development. Therefore, more and more scholars are committed to developing advanced technologies to convert agriBiomass to energy and fuel.

As a way to efficiently use biomass energy, agribiomass power generation could be a good substitute for coal-fired power generation, which can alleviate the power supply shortage and reduce environmental pollution [8,9]. Denmark was a leading country to use agribiomass to generate electricity, followed by the United States and European countries [10]. Nowadays, the utilization of agribiomass for power generation is getting more and more popular in the world. China has great development potential due to abundant agribiomass resources. Supported by a series of policies, the agribiomass power generation industry has experienced rapid growth since the year 2006 [11]; by the end of 2017, more than 270 straw power generation projects with a total installed capacity of 7000 MW had been put into operation in China [12,13].

However, most of the biomass power plants were under financial deficits in China due to immaturity in technology, economic, environment, and policy [11,14,15]. Related to technology, crucial issues were the lack of core technologies and experience. Related to environmental, crucial issues were negative impacts on the environment in the process of feedstock transportation. Related to policy, a crucial issue was the government subsidies mechanism. Related to economics, crucial issues were insufficient supplies of feedstock and high costs, which are not because of resource shortage, but lack of biomass supply chain management and coordination [16–18]. Unlike America and European countries, China implements a household responsibility system in agriculture. The collection of agribiomass is faced with scattered small-scale farmers who have much less enthusiasm to collect and supply the feedstock due to the shortage of manpower during the busy harvesting seasons, which makes off-field application difficult [19,20]. Consequently, on the one hand, China's biomass power industry has been suffering from feedstock deficiency. On the other hand, farmers, as the owner of agribiomass, have no choice but to burn or discard it directly [21].

To solve the problems, the broker appears as an intermediary connecting the farmer with the biomass power plant to take charge of intermediate activities, which include collecting, storing, processing, and transporting. The participation of the broker not only frees the farmer from the tedious work of collecting agribiomass, but also provides the biomass power plant with standard forms of feedstock to reduce their burden. However, the broker often arbitrarily increases the agribiomass selling price to the biomass power plant for the best benefit due to the lack of unified management, resulting in high feedstock collection costs [22].

In the light of these problems, many studies have focused on proposing a game-theoretic approach to analyze the players in the biomass power generation supply chain and the process of utilizing biomass for power generation. Nasiri and Zaccour [23] were the first to propose a sequential game considering the farmer, the developer, and the electric utility to model and analyze a biomass electricity generation supply chain in 2009. Then, Sun et al. [24] built a simple game model of a supply chain that consisted of one upstream supplier and two downstream industrial buyers to explore optimal managerial strategies and the total equilibrium profit, and evaluate the impact of the model parameters on game equilibrium. From the perspective of risk, Liu et al. [15] explored the reasons for the current operational dilemma that the biomass power generation industry chain may face in China. By summarizing and discussing the risks in different segments of the biomass supply chain, it is concluded that joint effort of the Government and the biomass power industry is an effective measure to come out of the difficulties. Further, Zhang et al. [25] took the lead in incorporating the formal official organization of villagers' committees into biomass supply model. The biomass supply model considered the players' immaterial utility and the villagers' committees' impact on farmers' behavior, which is different from the previous biomass supply patterns. To overcome the difficulty in collection of feedstock for biomass power plant, Wang et al. [26] proposed a Stackelberg game approach in designing incentive scenarios under perceived risk for the biomass supply chain. They focused on optimizing government incentives for players in the biomass supply chain to demonstrate the impacts of such incentives on farmers and brokers. Using the game-theoretic approach similarly, Ye et al. [27] explored decision-making behavior within a cassava-based bioethanol industry

under the condition of high yield uncertainty, as well as developed a production cost sharing contract to enhance the supply of cassava and the utility of supply chain. In view of the difficulties in high utilization costs and undersupply of straw, Wen et al. [28] applied game theory to design an applicable straw acquisition mode and concluded that the mixed acquisition mode can better guide the straw power plant run in a better condition. Based on that, the government was introduced into the biomass supply chain to adopt price incentives on straw transactions to evaluate the effect of local governmental incentives and explore possible ways to maximize the potential positive impacts [29].

As summarized above, most of the research focused on the impact of government incentives on the biomass supply chain members. Exploring the management and coordination incentive mechanism among the players of the biomass power generation supply chain can further enrich the research achievement of a biomass supply chain management. The members of a biomass supply chain have individual behaviors in most cases, so the binding force of the members is still weak. Therefore, this has created a thirst to establish a contractual relationship between biomass supply chain members that would have positive impact on the brokers' behavior to realize efficient management and coordination of the biomass supply chain.

With these considerations in mind, the overall goal of this paper is to apply game theory of incentive effects for agribiomass power generation supply chain in China, and introduce the noncooperative game model, the farmer–broker cooperative game model, and the broker–biomass power plant cooperative game model into the biomass supply chain to analyze how the game modes work, through comparing the decision strategies and the profits of biomass supply chain members change.

The remainder of the paper is organized as follows. Section 2 introduces the main assumptions about agribiomass, and establishes the game theory model among the farmers, the brokers, and the biomass power plant. The equilibrium results in different propositions are characterized and analyzed in Section 3. Section 4 presents computational experiments and sensitivity analysis of several parameters. Section 5 concludes the paper.

2. The Stackelberg Game Model

The Stackelberg game is a typical sequential game that a leader player can anticipate the response of the follower to their strategy. In this game model, the player who makes the decision first is called the leader, while the next player makes the decision based on the leader's decision, which is called the follower. Both players choose their own strategies based on the other's possible strategies to ensure maximizing their interests, so as to achieve the Nash equilibrium.

2.1. The Players of Agribiomass Power Generation Supply Chain

The agribiomass power generation supply chain is a complex dynamic game process, which involves five main components of agribiomass harvesting and collection, preprocessing, storage, transportation, and energy conversion [30,31]. Three players in the biomass supply chain are defined as follows: farmer (player F) represents the agribiomass owner, they are mainly responsible for the work of agribiomass collection and transportation and decides the quantity of agribiomass for sale; broker (player B) stands for the entirety of all those individuals who act between farmer and biomass power plant to take charge of the intermediate activities, which include agribiomass storing, processing, and transporting from the biomass storage station to the biomass power plant; and biomass power plant (player P) is the manufacturer of agribiomass electricity, as well as the agribiomass consumer [32,33]. Finally, the government and the State Grid Corporation of China (SGCC), as the external factors, join the biomass supply chain. The government can influence the agribiomass supply quantity and the profits of the whole biomass supply chain members by providing incentives to the players. The SGCC purchases all agribiomass-based electricity produced by the biomass power plant. The agribiomass power generation supply chain structure is shown in Figure 1.

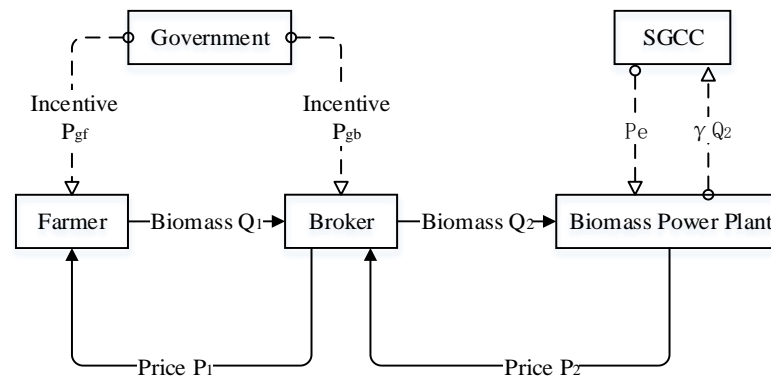


Figure 1. The structure of agribiomass power generation supply chain.

2.2. Assumptions

As stated before, in the proposed game model, the farmer, the broker, and the biomass power plant are assumed as a single game player, respectively. This setting of a single player at each stage is not unrealistic from economy of scale and stability, but it does not affect the main purpose of this paper, that is, to analyze the impacts of such government incentives on biomass power generation supply chain in different game models [23]. In this research, without changing the essence of the research, several assumptions in the biomass supply chain are made, as follows:

1. China implements a household responsibility system in agriculture; the agribiomass holders are thousands of scattered small-scale farmers [19]. For geometrical simplicity, we assume the biomass power plant is in the central position; the biomass storage station is at the center of the agribiomass collection area with radius R [34], as shown in Figure 2. Considering the complexity of the road, tortuosity factor β is introduced to adjust transport distance, so the transportation cost from each supply point to the biomass storage station C_{T1} (CNY) can be calculated by the following integral:

$$C_{T1} = \int_0^R 2\pi r \alpha k \beta r c_{t1} dr = \frac{2}{3} \pi R^3 \alpha k \beta c_{t1}$$

where

$$R = \sqrt{\frac{Q_1}{k\pi\alpha}}$$

If

$$c_q = \beta(k\pi\alpha)^{-\frac{1}{2}} c_{t1}$$

Then, the cost of agribiomass transportation from each supply point to the biomass storage station is given by:

$$C_{T1} = \frac{2}{3} c_q Q_1^{\frac{3}{2}} \quad (1)$$

where c_{t1} (CNY/km·ton) denotes the unit cost of agribiomass transportation from each supply point to the biomass storage station, α represents the agribiomass output in a unit area (ton/km²), and k is the agribiomass collection coefficient. For the ease of subsequent calculations, the unit transportation cost of agribiomass transportation from the biomass storage station to the biomass power plant C_{T2} (CNY/ton) can be calculated as:

$$C_{T2} = c_{t2} \beta L \quad (2)$$

where c_{t2} (CNY/km·ton) denotes the unit cost of agribiomass transportation from the biomass storage station to the biomass power plant, and L (km) represents the average transport distance from the biomass storage station to the biomass power plant.

2. As byproduct of the regular crops, the agribiomass was acquired by farmers unintentionally. If the agribiomass cannot be collected, it is likely to be discarded directly in field. Thus, opportunity cost need not to be considered in the analysis.
3. This study assumes that different type of agribiomass has no impact on the agribiomass price, collection, transportation, and storage.
4. This study assumes that agribiomass production and supply are all calculated on yearly basis; seasonal and climate factors are neglected for convenience in calculation.
5. This study assumes that the total amount of agribiomass in the collection area is sufficient. In order to prevent vicious competition for feedstock, there is only one biomass power plant in the research area [9].
6. Considering Chinese policy, this study assumes that all electricity generated from agribiomass has been purchased by SGCC at a price P_e [11]. It is true that no overproduction exists within several years in China [29].

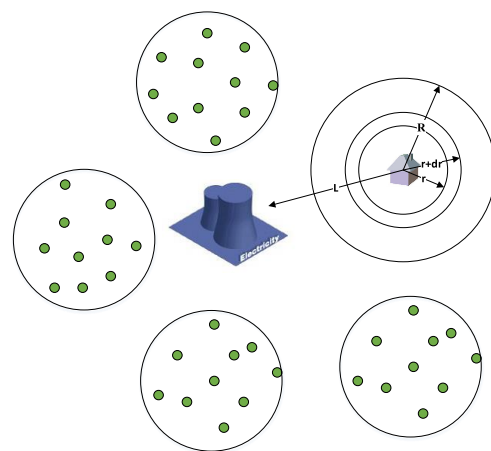


Figure 2. Collection area, facility location, and transportation distance.

2.3. Payoff Functions

2.3.1. The Noncooperative Game Formulation

In this section, we will consider the interaction among the farmer, the broker, and the biomass power plant as a Stackelberg game. The biomass power plant as the predominant player occupies the leading position, followed by the broker, and then the farmer. All of the players in the biomass supply chain seek to maximize their own profits. The profit functions for the players of the game are as follows:

Farmer (Player F): Each farmer decides the quantity of agribiomass that he wants to provide. The farmer pays for the agribiomass collection and transportation costs [35]. So, the farmer's profit maximization function is defined as:

$$\max_{Q_1 \geq 0} \mu_F(Q_1) = (P_1 + P_{gf})Q_1 - \frac{2}{3}c_q Q_1^{\frac{3}{2}} \quad (3)$$

where P_1 (CNY/ton) represents the unit price that the broker offers to the farmer, P_{gf} (CNY/ton) denotes the farmer's unit selling incentive from government, and Q_1 (ton) denotes the quantity of agribiomass supplied by the farmer.

Broker (Player B): The total costs paid by the broker include the price that the broker offers to the farmer, storage cost, and transportation cost. So, the broker's profit maximization function can be expressed as:

$$\max_{P_1 \geq 0} \pi_B(P_1) = P_2 Q_2 + P_{gb} Q_1 - (P_1 Q_1 + C_S Q_1 + C_{T2} Q_2) \quad (4)$$

where

$$Q_2 = (1 - \theta)Q_1$$

denotes P_2 (CNY/ton) the unit price that the biomass power plant offers to the broker, P_{gb} (CNY/ton) the broker's unit purchasing incentive from government, Q_2 (ton) the quantity of agribiomass provided by the broker, C_S (CNY/ton) the unit agribiomass storage cost, C_{T2} (CNY/ton) the unit agribiomass transportation cost, and θ the loss ratio caused by storage in the biomass storage station.

Biomass power plant (player P): The total costs of the biomass power plant include the price that the biomass power plant offers to the broker, the operation cost, and the fixed investment cost. Government incentive to the biomass power plant is reflected in preferential feed-in-tariff. So, the profit maximization function of the biomass power plant is given by:

$$\max_{P_2 \geq 0} \pi_P(P_2) = (P_e - P_{OC})\gamma Q_2 - (P_2 Q_2 + C_{SP}) \quad (5)$$

denotes P_e (CNY/kWh) the electricity purchasing price by the SGCC, P_{OC} (CNY/kWh) the biomass power plant operation cost of generated unit electricity, γ (kWh/ton) the conversion ratio of agribiomass to electricity, and C_{SP} (CNY) the investment cost of biomass power plant.

Additionally, the sum profit of all biomass supply chain members' objective function is expressed as:

$$\pi = \mu_F + \pi_B + \pi_P \quad (6)$$

The sum profit of farmer's and broker's objective function is presented as:

$$\pi_X = \mu_F + \pi_B \quad (7)$$

The sum profit of broker's and biomass power plant's objective function is presented as:

$$\pi_Y = \pi_B + \pi_P \quad (8)$$

2.3.2. The Cooperative Game Formulation

In this section, a farmer–broker cooperative structure and a broker–biomass power plant cooperative structure are applied in the biomass supply chain to determine whether both players can obtain optimal decision strategy and increase their profit if they form an alliance. We will analyze how such cooperation structures carry out through optimization of the alliances' profit functions.

1. The farmer–broker cooperative game

In the farmer–broker cooperative structure, the alliance and the biomass power plant continue the Stackelberg game. First, the biomass power plant decides the price that the biomass power plant offers to the broker. Then, the farmer and the broker work together to determine the farmer's optimal agribiomass supply quantity q_1 and the price that broker offers to farmer p_1 . The improved profit function would be $\hat{\pi}_X - \pi_X$, which is shared by farmer and broker with ratio $(1 - \lambda_1) : \lambda_1$, where $0 < \lambda_1 < 1$. The profit function of the alliance can be characterized by:

$$\begin{cases} \hat{\mu}_F^1 = \mu_F + (1 - \lambda_1)(\hat{\pi}_X - \pi_X) \\ \hat{\pi}_B^1 = \pi_B + \lambda_1(\hat{\pi}_X - \pi_X) \end{cases} \quad (9)$$

2. The broker–biomass power plant cooperative game

Similarly, in the broker–biomass power plant cooperative structure, the farmer and the alliance continue the Stackelberg game, the broker and the biomass power plant work together to determine the price that broker offers to farmer p_1 and the price that the biomass power plant offers to the broker p_2 . The improved profit function would be $\hat{\pi}_Y - \pi_Y$, which is shared by broker and biomass power plant with ratio $(1 - \lambda_2) : \lambda_2$, where $0 < \lambda_2 < 1$.

Then, the farmer decides the quantity of agribiomass that he wants to provide. The profit function of the alliance can be characterized by:

$$\pi_Y = \pi_B + \pi_P \quad (10)$$

3. Equilibrium

Note that the Proposition 1–3 (proof in Appendix A) below illustrate the optimal equilibrium solutions of the noncooperative game, the farmer–broker cooperative game, and the broker–biomass power plant cooperative game, respectively.

3.1. Equilibrium of the Noncooperative Game

As described before, the game is played sequentially. The optimal equilibrium solutions can be solved by backward induction. Thus, in our analysis, we start from the farmer's problem to identify their optimal quantity of agribiomass to be supplied to broker, then, the broker determines agribiomass purchasing price to farmer, and, finally, the biomass power plant determines agribiomass purchasing price to broker.

Proposition 1. *In the noncooperative game, the decision strategies of the farmer's optimal agribiomass supplying quantity, agribiomass price that broker offers to farmer, and agribiomass price that biomass power plant offers to broker are as follows:*

$$\begin{pmatrix} Q_1^* \\ P_1^* \\ P_2^* \end{pmatrix} = \begin{pmatrix} \frac{16[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb}]^2}{81c_q^2} \\ \frac{4[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) - \frac{5}{4}p_{gf} + p_{gb}]}{9} \\ \frac{2(p_e - p_{OC})\gamma(1-\theta) + C_S + C_{T2}(1-\theta) - p_{gf} - p_{gb}}{3(1-\theta)} \end{pmatrix} \quad (11)$$

It can be observed from the decision strategies that the optimal agribiomass quantity that the farmer wants to provide Q_1^* increases with the electricity purchasing price p_e and the government incentives for farmer p_{gf} and broker p_{gb} . This quantity rises by $16[p_e\gamma(1-\theta) + p_{gf} + p_{gb}]^2/81c_q^2$. Furthermore, as expected, this quantity decreases with the unit storage cost C_S and the unit transportation cost C_{T2} . In addition, both the government incentives for farmer and broker can reduce biomass power plant's purchase price P_2^* , the price drops by $(p_{gf} + p_{gb})/3(1-\theta)$, while the government incentive for biomass power plant increases it, the price raises by $2\gamma(1-\theta)p_e/3(1-\theta)$. The results imply that biomass power plant may get higher agribiomass quantity with lower price if farmer and broker get the government incentives. Similarly, broker's purchase price P_1^* are positively related to the governmental incentives for broker and biomass power plant, and negatively related to the government incentive for farmer. At the same time, the price increases by $4[\gamma(1-\theta)p_e + p_{gb}]/9$, while drops by $5p_{gf}/9$.

Based on that, the optimal profits of biomass supply chain members are calculated by substituting the decision strategies into Equations (3)–(5):

$$\begin{pmatrix} \mu_F^* \\ \pi_B^* \\ \pi_P^* \end{pmatrix} = \begin{pmatrix} \frac{64[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb}]^3}{2187c_q^2} \\ \frac{32[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb}]^3}{729c_q^2} \\ \frac{16[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb}]^3}{729c_q^2} - C_{SP} \end{pmatrix} \quad (12)$$

In addition, the total profit of all biomass supply chain members, the sum profit of farmer and broker, and the sum profit of broker and biomass power plant are presented as:

$$\pi^* = \frac{208 \left[(p_e - p_{OC})\gamma(1-\theta) - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} - C_{SP} \quad (13)$$

$$\pi_{\chi}^* = \frac{160 \left[(p_e - p_{OC})\gamma(1-\theta) - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} \quad (14)$$

$$\pi_Y^* = \frac{144 \left[(p_e - p_{OC})\gamma(1-\theta) - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} - C_{SP} \quad (15)$$

The above results indicate that the profit of the farmer, the broker, and the biomass power plant are all positively related to the governmental incentives. As expected, the total profits of the supply chain members and the sum profit of the alliance are also positively related to the governmental incentives. The above results also indicate that government incentives on any of the three players can increase the agribiomass supply quantity and promote the stakeholders' profit.

3.2. Equilibrium of the Cooperative Game

In the cooperative game, the alliance gets decision strategies first to maximize the sum profit of the alliance, and then they share the profits from the cooperative. In this section, we will analyze whether all players can get better decision strategies and increase their profit through comparing the equilibrium solutions that change in the cooperation and the noncooperation game. Proposition 2 and Proposition 3 provide the decision strategies and the optimal profit of the farmer–broker cooperative game and the broker–biomass power plant cooperative game.

3.2.1. The Farmer–Broker Cooperative Game

Proposition 2. *In the farmer–broker cooperative game, the decision strategies of the farmer's optimal agribiomass supplying quantity, agribiomass price that broker offers to farmer, agribiomass price that biomass power plant offers to broker, the optimal profits of biomass supply chain members, the total profit of all biomass supply chain members, and the sum profit of farmer and broker are given by:*

$$\begin{pmatrix} \hat{Q}_1^{1*} \\ \hat{P}_1^{1*} \\ \hat{P}_2^{1*} \end{pmatrix} = \begin{pmatrix} \frac{4 \left[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^2}{9c_q^2} \\ \frac{(138 - 14\lambda_1) \left[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]}{243} - p_{gf} \\ \frac{2(p_e - p_{OC})\gamma(1-\theta) + C_S + C_{T2}(1-\theta) - p_{gf} - p_{gb}}{3(1-\theta)} \end{pmatrix} \quad (16)$$

$$\begin{pmatrix} \hat{\mu}_F^{1*} \\ \hat{\pi}_B^{1*} \\ \hat{\pi}_P^{1*} \end{pmatrix} = \begin{pmatrix} \frac{(120 - 56\lambda_1) \left[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} \\ \frac{(96 + 56\lambda_1) \left[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} \\ \frac{4 \left[(p_e - p_{OC})\gamma(1-\theta) - C_S - C_{T2}(1-\theta) + p_{gf} + p_{gb} \right]^3}{27c_q^2} - C_{SP} \end{pmatrix} \quad (17)$$

$$\hat{\pi}_1^{1*} \frac{540 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} - C_{SP} \tag{18}$$

$$\hat{\pi}_X^{1*} \frac{216 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} \tag{19}$$

Compared with the noncooperation game, the farmer–broker cooperative game brings a higher broker’s purchase price \hat{P}_1^{1*} , and leads to a large agribiomass supply quantity \hat{Q}_1^{1*} with incremental as $20 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^2 / 81c_q^2$. Furthermore, it could improve the allied total profit $\hat{\pi}_X^{1*}$ with incremental as $56 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3 / 2187c_q^2$. As the price that biomass power plant offers to broker \hat{P}_2^{1*} remains unchanged, but the agribiomass supply quantity increases, so, it brings a higher profit to the biomass power plant $\hat{\pi}_P^{1*}$, and the profit incremental is $92 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3 / 729c_q^2$.

3.2.2. The Broker–Biomass Supply Chain Cooperative Game

Proposition 3. *In the broker–biomass power plant cooperative game, the decision strategies of the farmer’s optimal agribiomass supplying quantity, agribiomass price that broker offers to farmer, agribiomass price that biomass power plant offers to broker, the optimal profits of the farmer, the broker, and the biomass power plant, the total profit of all biomass supply chain members, and the sum profit of broker and biomass power plant are presented as:*

$$\begin{pmatrix} \hat{Q}_1^{2*} \\ \hat{P}_1^{2*} \\ \hat{P}_2^{2*} \end{pmatrix} = \begin{pmatrix} \frac{4 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^2}{9c_q^2} \\ \frac{2 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) - \frac{1}{2}p_{gf} + p_{gb} \right]}{3} \\ (p_e - p_{OC})\gamma - \frac{(4 + 15\lambda_2) \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]}{81(1 - \theta)} \end{pmatrix} \tag{20}$$

$$\begin{pmatrix} \hat{\mu}_F^{2*} \\ \hat{\pi}_B^{2*} \\ \hat{\pi}_P^{2*} \end{pmatrix} = \begin{pmatrix} \frac{8 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{81c_q^2} \\ \frac{(92 - 60\lambda_2) \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{729c_q^2} \\ \frac{(16 + 60\lambda_2) \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{729c_q^2} - C_{SP} \end{pmatrix} \tag{21}$$

$$\hat{\pi}^{2*} \frac{540 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} - C_{SP} \tag{22}$$

$$\hat{\pi}_Y^{2*} \frac{324 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3}{2187c_q^2} - C_{SP} \tag{23}$$

Similarly, compared with the noncooperation game, the farmer is willing to provide more agribiomass supply quantity and the quantity rises by $20 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^2 / 81c_q^2$ in the broker–biomass power plant cooperative game. In addition, the governmental incentives have similar positive impact on the profits of the farmer, the broker, and the biomass power plant to the noncooperation game, but have obtained higher profits to all biomass supply chain members, with the farmer’s and the allied total profits incrementally are $152 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3 / 2187c_q^2$, and $60 \left[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb} \right]^3 / 729c_q^2$, respectively. It is worth to note that the coefficients of the optimal price that broker offers to farmer changes from $(4p_{gb} - 5p_{gf})/9$ in the noncooperation game to $(2p_{gb} - p_{gf})/3$ in the broker–biomass power plant cooperation game. This change indicates that the farmer’s bargaining power may have markedly improved in the broker–biomass power plant cooperative game. Additionally, we can obtain: $\pi^* < \hat{\pi}^{1*} = \hat{\pi}^{2*}$, $\pi_X^* < \hat{\pi}_X^{1*}$, $\pi_Y^* < \hat{\pi}_Y^{2*}$ the results indicate that both the cooperative games can bring the same higher total profits of the supply chain members, and compared with the noncooperation game, both the sum profits of the alliance have increased.

4. Numerical Examples

4.1. Case Description and Results

Numerical examples are performed in this section to illustrate some specific features of the games in above sections. Take one biomass power generation project with installed capacity of 30 MW and annual agribiomass consumption of 250 thousand tons in Shandong Province as an example. Data have been obtained through investigation and related literatures. The investment cost of the investigated biomass power plant (C_{SP}) is 10 million CNY, and the current preferential feed-in-tariff level of the biomass power plant (p_e) is 0.75 CNY/kWh under government subsidy. Additionally, the unit cost of agribiomass transportation from each supply point to the biomass storage station (c_{t1}) is 2 CNY/km·ton, the unit cost of agribiomass transportation from the biomass storage station to the biomass power plant (c_{t2}) is 1.5 CNY/km·ton, and the unit agribiomass storage cost (C_S) is 50 CNY/ton. The detailed parameter values used in the numerical examples are shown in Table 1.

Table 1. Parameter values for the numerical examples.

Parameters	Values	Parameters	Values
β	1.5	k	0.3
c_{t1} (CNY/km·ton)	2	α (ton/km ²)	153
c_{t2} (CNY/km·ton)	1.5	L (km)	20
θ	0.1	C_S (CNY/Ton)	50
P_{OC} (CNY/kWh)	0.32	P_e (CNY/kWh)	0.75
C_{SP} (million CNY)	10	γ (kWh/ton)	800

Take the noncooperative game with the government incentive p_{gf} and p_{gb} of 0 CNY/ton as the baseline case. Substituting the parameter values into the Equations (11) and (12) to determine the optimal decision strategies and the profits of biomass supply chain members:

$$\begin{pmatrix} Q_1^* \\ P_1^* \\ P_2^* \end{pmatrix} = \begin{pmatrix} 105360.35 \\ 97.38 \\ 262.85 \end{pmatrix} \tag{24}$$

$$\begin{pmatrix} \mu_F^* \\ \pi_B^* \\ \pi_P^* \end{pmatrix} = \begin{pmatrix} 3419919 \\ 5129878.4 \\ -3435061 \end{pmatrix} \quad (25)$$

The results can approximate reflect the reality of the biomass power plants in China. $\pi_P^* = -3,435,061 < 0$ and $Q_1^* = 105,360.35 < 250,000$. The above results indicate that the agribiomass supply quantity cannot maintain the normal operation of the biomass power plant, and the biomass power plant was under financial deficits without taking any measures.

4.2. Sensitivity Analysis

In order to get insights on the impacts of government incentives on the decision strategies and the profits of biomass supply chain members, we will also conduct sensitivity analysis of several parameters in the three game models. Scenarios 1–3 represent the noncooperative game, the farmer–broker cooperative game, and the broker–biomass power plant cooperative game under government incentives, respectively.

The government incentives for farmer and broker have the same incentive effect on the equilibrium solutions except for the broker's purchase price. Therefore, in this section, the changing trends of the equilibrium results are shown under different government incentive for farmer p_{gf} in the noncooperative game, the farmer–broker cooperative game, and the broker–biomass power plant game. The changing trend of the broker's purchase price P_1^* is also shown under different government incentive for broker p_{gb} since the government incentive for farmer p_{gf} and government incentive for broker p_{gb} have different effects on it. Figure 3a–g represent the optimal decision strategies and the profits of Q_1 , P_1 under government incentive for farmer, P_1 under government incentive for broker, P_2 , μ_F , π_B , and π_P , respectively. Since the values of λ_1 and λ_2 are unknown, the shaded part in the figure is the variation range of the equilibrium solutions in a certain scenario.

The sensitivity analysis coincides with above results that the government plays an important role in the development of utilizing agribiomass for power generation and can work better in the cooperative games. Specifically, government incentives can increase the agribiomass supply quantity and the biomass supply chain members' profit, and reduce the biomass power plant's purchase price. Meanwhile, the broker's purchase price P_1^* is positively related to the governmental incentive for broker, and negatively related to the government incentive for farmer. The three game models have similar trends under the government incentives. Both the cooperative game models can optimize the equilibrium results. In addition, according to the above analysis, several conclusions are obtained as follows:

- (1) $Q_1^* < \hat{Q}_1^{1*} = \hat{Q}_1^{2*}$, both the cooperative game models can bring the same higher agribiomass supply quantity. The agribiomass supply quantity will meet the demand of the biomass power plant under certain government incentives and cooperative structures.
- (2) $P_1^* < \hat{P}_1^{1*} < \hat{P}_1^{2*}$, and $P_2^* = \hat{P}_2^{1*} < \hat{P}_2^{2*}$, both the broker and the biomass power plant pay the highest purchase price in the broker–biomass power plant cooperative game. Although they will provide a higher price to purchase agribiomass in two cooperative game models, the profits of all biomass supply chain members have increased.
- (3) $\hat{\mu}_F^{1*} < \hat{\mu}_F^{1*} < \hat{\mu}_F^{2*}$, $\pi_B^* < \hat{\pi}_B^{1*}$, $\pi_B^* < \hat{\pi}_B^{2*}$, $\pi_P^* < \hat{\pi}_P^{2*} < \hat{\pi}_P^{1*}$ the optimal profit of farmer, broker, and biomass power plant have all increased in both cooperative game models, and the biomass power plant will turn loss into gain under certain circumstances. Meanwhile, the farmer can get the maximum profit in the broker–biomass power plant cooperative game, while the biomass power plant makes the maximum profit in the farmer–broker cooperative game. The possible reasons may be that cooperation of some parties would often result in the maximum benefit of the isolated party. The broker's maximum profit is determined by λ_1 and λ_2 .

To be summarized, the agribiomass power generation supply chain would prefer the cooperative game models with government incentives to the noncooperative one because they can gain more agribiomass supply quantity and the profits from the former game models. Specifically, which method of the cooperation game model to choose would be worthy for further research. In addition, whether there are any other measures, such as cooperation between supply chain members and mutual cooperation among farmers, rather than government incentives, could have similar effects, it is worthy of broader discussion in future research.

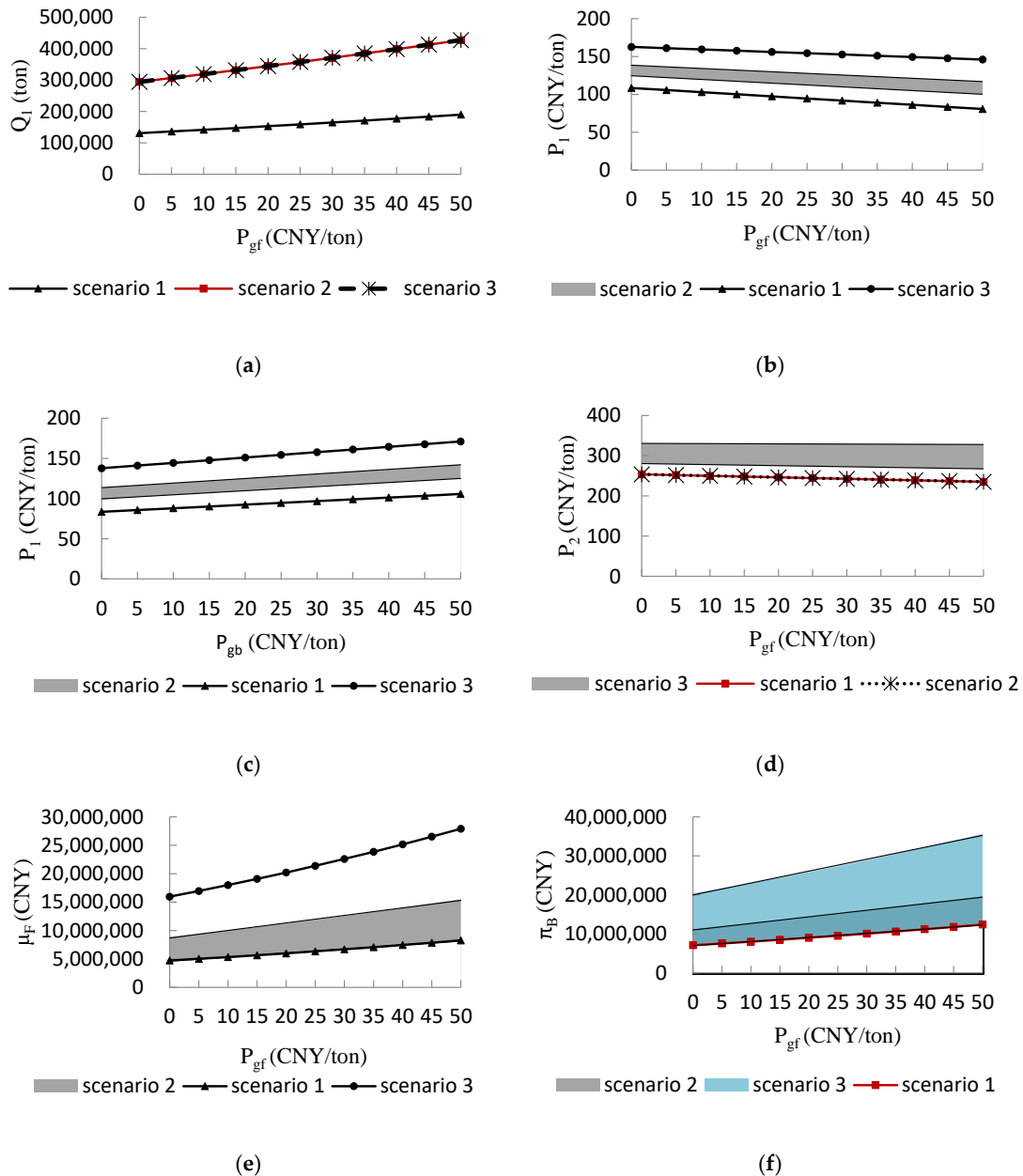
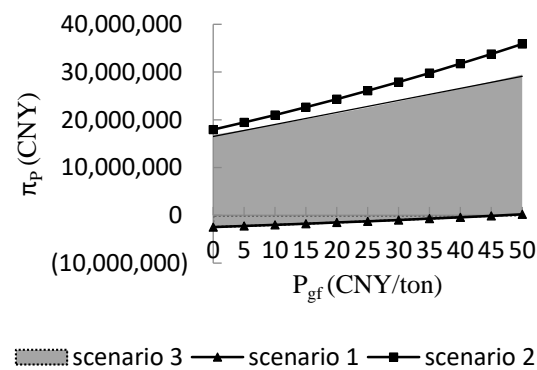


Figure 3. Cont.



(g)

Figure 3. Effect of government incentives on equilibrium solutions in three game models. (a) Represent the optimal decision strategies of Q_1 under government incentive for farmer; (b) Represent the optimal decision strategies of P_1 under government incentive for farmer; (c) Represent the optimal decision strategies of P_1 under government incentive for broker; (d) Represent the optimal decision strategies of P_2 under government incentive for farmer; (e) Represent the optimal profits of μ_F under government incentive for farmer; (f) Represent the optimal profits of π_B under government incentive for farmer; (g) Represent the optimal profits of π_P under government incentive for farmer.

5. Conclusions

The sufficient supply of agribiomass is a requirement in promoting the development of the biomass power industry. However, most of the biomass power plants in China were under insufficient supply of feedstock and high supply costs. In this paper, the noncooperative game, the farmer–broker cooperative game, and the broker–biomass power plant cooperative game under government incentives were constructed and analyzed. Numerical examples and sensitivity analysis of several parameters were conducted which aim at illustrating some specific features of the game models.

The optimal equilibrium solutions for these three scenarios were obtained. The government plays a critical role in the development of utilizing agribiomass for power generation and can work better in the cooperative games. It is shown that both the agribiomass supply quantity and the profits of farmer, broker, and biomass power plant are higher in both the cooperative game models than in the noncooperative game model; consequently, the total profits of the supply chain members and the sum profit of the alliance are expected to be higher under both cooperative structures. Additionally, the farmer can get the maximum profit in the broker–biomass power plant cooperative game, while the biomass power plant makes the maximum profit in the farmer–broker cooperative game. The broker's maximum profit is determined by λ_1 and λ_2 .

To be summarized, the biomass power generation in China is still in its initial stage. It would be of interest to explore how government incentives can affect the decision strategies and the profits of all three players in the biomass supply chain, so as to improve the feedstock supply quantity and the operation of biomass power plants. To guide the healthy development of the power generation industry, there is a need for further exploration of the biomass supply chain management and coordination issue. Specifically, we will work on the cooperative game model to establish optimal feedstock price subsidy policy, by way of adjusting government incentives and the alliance profit distribution.

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Appendix A

Appendix A.1. Proof of Proposition 1

Let $\partial\mu_F(Q_1)/\partial Q_1 = 0$, the farmer's optimal agribiomass supplying quantity is obtained as follows:

$$Q_1^* = (p_1 + p_{gf})^2 / c_q^2$$

Substituting farmer's responding function (Q_1^*) into broker's profit function, the broker's anticipated profit is expressed as:

$$\max_{P_1 \geq 0} \pi_B(P_1) = [P_2(1 - \theta) + P_{gb} - P_1 - C_S - C_{T2}(1 - \theta)] (P_1 + P_{gf})^2 / c_q^2$$

Let $\partial\pi_B(P_1)/\partial P_1 = 0$, the agribiomass price that broker offers to farmer is obtained as follows:

$$P_1^* = \frac{2[P_2(1 - \theta) - C_S - C_{T2}(1 - \theta)] - p_{gf} + 2p_{gb}}{3}$$

Substituting farmer's responding function (Q_1^*) and broker's responding function (P_1^*) into biomass power plant's profit function, the biomass power plant's anticipated profit is expressed as:

$$\max_{P_2 \geq 0} \pi_P(P_2) = [(p_e - p_{OC})\gamma - P_2](1 - \theta) \frac{4[P_2(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^2}{9c_q^2} - C_{SP}$$

Let $\partial\pi_P(P_2)/\partial P_2 = 0$, the agribiomass price that biomass power plant offers to broker is obtained as follows:

$$P_2^* = \frac{2(p_e - p_{OC})\gamma(1 - \theta) + C_S + C_{T2}(1 - \theta) - p_{gf} - p_{gb}}{3(1 - \theta)}$$

Incorporating biomass power plant's optimal decision (P_2^*) into broker's responding function, the agribiomass price that broker offers to farmer is presented as:

$$P_1^* = \frac{4[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) - \frac{5}{4}p_{gf} + p_{gb}]}{9}$$

Further, by putting the agribiomass price that broker offers to farmer into farmer's responding function, the farmer's optimal agribiomass supplying quantity is presented as:

$$Q_1^* = \frac{16[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^2}{81c_q^2}$$

Appendix A.2. Proof of Proposition 2

The alliance's anticipated profit is expressed as:

$$\pi_X = (P_{gf} + P_{gb})Q_1 + P_2(1 - \theta)Q_1 - \frac{2}{3}c_qQ_1^{\frac{3}{2}} - C_SQ_1 - C_{T2}(1 - \theta)Q_1$$

Let $\partial\pi_X/\partial Q_1 = 0$, the farmer's optimal agribiomass supplying quantity is obtained as follows:

$$\widehat{Q}_1^{1*} = \frac{[p_2(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^2}{c_q^2}$$

Substituting farmer's responding function (\widehat{Q}_1^{1*}) into biomass power plant's profit function, the biomass power plant's anticipated profit is expressed as:

$$\max_{P_2 \geq 0} \pi_P(P_2) = [(p_e - p_{OC})\gamma - P_2](1 - \theta) \frac{[p_2(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^2}{c_q^2} - C_{SP}$$

Let $\partial\pi_P(P_2)/\partial P_2 = 0$, the agribiomass price that biomass power plant offers to broker is obtained as follows:

$$\widehat{P}_2^{1*} = \frac{2(p_e - p_{OC})\gamma(1 - \theta) + C_S + C_{T2}(1 - \theta) - p_{gf} - p_{gb}}{3(1 - \theta)}$$

Incorporating biomass power plant's optimal decision (\widehat{P}_2^{1*}) into farmer's responding function, the farmer's optimal agribiomass supplying quantity is presented as:

$$\widehat{Q}_1^{1*} = \frac{4[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^2}{9c_q^2}$$

Further, substituting farmer's responding function (\widehat{Q}_1^{1*}) and biomass power plant's optimal decision (\widehat{P}_2^{1*}) into the alliance's total profit function, the alliance's anticipated profit is obtained as:

$$\widehat{\pi}_X^{1*} = \frac{216[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^3}{2187c_q^2}$$

The sum profit of farmer and broker in the noncooperative are presented as:

$$\pi_X^* = \frac{160[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^3}{2187c_q^2}$$

Given $\widehat{\pi}_B^1 = \pi_B + \lambda_1(\widehat{\pi}_X - \pi_X)$,

$$\begin{aligned} & \left[P_2(1 - \theta) + p_{gb} - P_1 - C_S - C_{T2}(1 - \theta) \right] \widehat{Q}_1^{1*} \\ &= \frac{32[(p_e - p_{OC})\gamma(1 - \theta) - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^3}{729c_q^2} \\ &+ \frac{56\lambda_1[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]^3}{2187c_q^2} \end{aligned}$$

Then, the agribiomass price that broker offers to farmer is presented as:

$$\widehat{P}_1^{1*} = \frac{(138 - 14\lambda_1)[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + p_{gf} + p_{gb}]}{243} - p_{gf}$$

Appendix A.3. Proof of Proposition 3

Let $\partial\mu_F(Q_1)/\partial Q_1 = 0$, the farmer's optimal agribiomass supplying quantity is obtained as follows:

$$Q_1^* = (p_1 + p_{gf})^2 / c_q^2$$

Substituting farmer's responding function (Q_1^*) into the alliance's total profit function, the alliance's anticipated profit is expressed as:

$$\pi_Y = [(p_e - p_{OC})\gamma(1 - \theta) - P_1 - C_S - C_{T2}(1 - \theta) + P_{gb}] (P_1 + P_{gf})^2 / c_q^2 - C_{SP}$$

Let $\partial\pi_Y/\partial P_1 = 0$, the agribiomass price that broker offers to farmer is obtained as follows:

$$\hat{P}_1^{2*} = \frac{2[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) - \frac{1}{2}P_{gf} + P_{gb}]}{3}$$

By putting broker's responding function (\hat{P}_1^{2*}) into farmer's responding function, the farmer's optimal agribiomass supplying quantity is presented as:

$$\hat{Q}_1^{2*} = \frac{4[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]^2}{9c_q^2}$$

Further, substituting farmer's responding function (\hat{Q}_1^{2*}) and broker's responding function (\hat{P}_1^{2*}) into the alliance's total profit function, the alliance's anticipated profit is obtained as:

$$\hat{Q}_1^{2*} = \frac{4[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]^2}{9c_q^2}$$

The sum profit of broker and biomass power plant in the noncooperative are presented as:

$$\pi_Y^* = \frac{144[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]^3}{2187c_q^2} - C_{SP}$$

$$\text{Given } \hat{\pi}_P^2 = \pi_P + \lambda_2(\hat{\pi}_Y - \pi_Y),$$

$$\begin{aligned} & \left[(p_e - p_{OC})\gamma - P_2(1 - \theta) \frac{4[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]^2}{9c_q^2} - C_{SP} \right. \\ & = \frac{16[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]^3}{729c_q^2} - C_{SP} \\ & \quad \left. + \frac{60\lambda_2[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]^3}{729c_q^2} \right] \end{aligned}$$

Then, the agribiomass price that biomass power plant offers to broker is obtained as follows:

$$\hat{P}_2^{2*} = (p_e - p_{OC})\gamma - \frac{(4 + 15\lambda_2)[(p_e - p_{OC})\gamma(1 - \theta) - C_S - C_{T2}(1 - \theta) + P_{gf} + P_{gb}]}{81(1 - \theta)}$$

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