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Carbon emissions, technology upgradation and financing risk of the green supply chain competition

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ABSTRACT

The major obstacle to reducing carbon emissions is the high cost of adopting clean energy, which reduces the market competitiveness of companies using clean energy. In this paper, we study the asymmetric duopoly models of two competing supply chains with different carbon emission technology. The financing risk of the supply chain's carbon emission technology investment could be available as complete or incomplete information to its competitor. We find that the financing risk of carbon emission technology upgradation does not affect either chain's choices of equilibrium quantities and prices in the complete information case. If this information is incomplete for the traditional supply chain, financing risk plays an important role in determining optimal quantities and optimal prices. To encourage the use of clean energy technology to reduce carbon emissions, government should use the per-product carbon emission tax to encourage the traditional supply chain to upgrade its carbon emission technology, and should encourage financial institutions to provide preferential loans to the supply chain that has carbon emission technology disadvantage in the market.

1. Introduction

In practice, many manufacturing or retailing firms in the supply chains that adopting cleaner technology always struggle in the cost disadvantage, which reduces their market competitiveness and impede the reduction of carbon emissions. More often, those supply chains normally have the difficulties in getting sufficient funds to upgrade their carbon emission technology, which restricts the realization of the scale effect of adopting cleaner technology; on the other side, financial institutions lack the incentives to lend loans to those supply chains with new carbon emission technology, because of their cost disadvantage in market competition. The vicious circle may cause green supply chains to disappear in those intensively competitive markets, and chains may be left with no incentive to adopt environmentally friendly technologies. To promote the use of clean energy technology to reduce carbon emissions, government should consider imposing some policies to supply chains.

In the existing literature, a significant amount of studies have been done in the areas of operations and environmental science on the topic of green (or sustainable) supply chain management. Some literatures focus on the theory of green supply chain design and management (Beamon, 1999; Srivastava, 2007; Carter and Rogers, 2008; Seuring and Müller, 2008; Sarkis et al., 2011; Seuring, 2013; Eskandarpour et al., 2015). Zhu et al. (2005, 2008), , Lee (2011); Varsei and Polyakovskiy (2017) provide the evaluation of green supply chain management in the contexts of China, South Korea and Australia. On the literature of financing cleaner technology in the supply chain competition, Yu and Lo (2015), Jung et al., (2018), Tang et al., (2012), Cao and Yu (2018) study different strategies to finance the adoption of carbon emission reduction technology.

However, only a few of studies construct mathematical models, even the optimal strategy for green supply chain development and the effects of government policies are been easily derived in models. Badole et al. (2013) reviews those theoretical literatures. McGuire and Staelin (1983) are the pioneers to analyze the Bertrand competition of two supply chains in a game model, and find that both manufacturers prefer a decentralized equilibrium if products are highly substitutable. Moorthy (1988), and Bonanno and Vickers (1988) find similar results in the extended Bertrand competition model. Rather than using Bertrand model to study the price competition of supply chains, Wu et al., (2009) includes demand uncertainty in the Cournot competition of supply chains. The Cournot competition model with supply uncertainty is given by Fang and Shou (2015). Besides demand and supply uncertainties, there are still many possible risks in supply chain competition (Olson and Wu, 2010, 2017; Heckmann et al., 2015; Cao et al., 2019). However, neither of the above-mentioned studies uses the

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Cournot competition model to analyze the upgradation of carbon emission technology and its related financing risk in supply chain competition.

The main contribution of our paper can be seen as to link and extend the above works by considering the financing risk of carbon emission technology upgradation in a Cournot competition model of supply chains. This stylistic setting allows us to gain insight into the differences between various supply chain strategies when some chain needs financing aid for carbon emission technology investment to become green supply chain. In this paper, we first introduce the asymmetric duopoly model of competing supply chains as benchmark, and discuss the effect of a per-product carbon emission tax on supply chains with different carbon emission technology. Based on the benchmark model, we study supply chain competition with asymmetric financing risk. The financing risk of one supply chain's carbon emission technology upgradation could be available as complete or incomplete information for the other. By analyzing and comparing the optimal quantities, optimal prices, and optimal expected profits in both cases, we find the effects of carbon emission technology investment and asymmetric information of financing risk on the competition equilibria. Some policy implications on promoting the development of green supply chain are also provided based on the results of theoretical analysis.

The paper is organized as follows. Section 2 presents the benchmark model of asymmetric supply chains in the sense of their carbon emission technology. Section 3 analyzes the Cournot competition model of supply chains with asymmetric financing risk, in the cases of complete and incomplete information on financing risk of carbon emission technology investment. Finally, Section 4 concludes.

2. Supply chain competition model

2.1. Cournot competition of supply chains with carbon emissions

In this section, following Wu et al. (2019), we first consider a Cournot game of competing supply chains with carbon emissions in which each chain is composed of a manufacturer servicing a single retailer. The timing of game is as follows:

1 The manufacturers and the retailers in two supply chains bargain simultaneously on the wholesale price, w_i, $i = 1, 2$.
2 The manufacturers and the retailers in the two supply chains agree simultaneously on the desired retailer's order quantity, q_i, $i = 1, 2$. Thereafter, the quantities of q_i are fully produced and delivered by the manufacturer.
3 The retailing prices p_i, $i = 1, 2$, are determined by market demand, and sales take place.

During the process of manufacturing, the byproduct of carbon emission e_i also occurs with every product and the per-product tax for carbon emission is t, which is determined and charged by the government. Hence the carbon emission tax of per-unit production is te_i. We assume that the Manufacturer 2 has the disadvantage on carbon emission technology, $0 < e_1 < e_2$. In the next section, we will consider the possibilities that the Manufacturer 2 adopts some green technology and try to reduce carbon emissions. Let π_i^{SC}, π_i^M, and π_i^R denote the profit of the supply chain as a whole, the manufacturer's profit, and the retailer's profit, respectively. We can write these profit functions as follows:

$$\pi_i^{SC} = q_i(p_i - c_i - te_i),\ \ i = 1, 2; \tag{1}$$

$$\pi_i^M = q_i(w_i - c_i - te_i),\ \ i = 1, 2; \tag{2}$$

$$\pi_i^R = q_i(p_i - w_i),\ \ i = 1, 2. \tag{3}$$

One can find that $\pi_i^{SC} = \pi_i^M + \pi_i^R$, $i = 1, 2$, which implies that the supply chain profit is the sum of the manufacturer's and retailer's profit.

The manufacturers and retailers in the two supply chains bargain on the wholesale price, w_i, $i = 1, 2$, to determine their respective shares of profit. We formulate the bargaining model on the wholesale price between the manufacturer and the retailer as a Nash Bargaining game.[1] In the bargaining stage, for simplicity, we let $\alpha = 1/2$ be the bargaining power, and $\Phi_i(w)$ denote the Nash bargaining product. Then, the Nash Bargaining Product model for a manufacturer and a retailer choosing a wholesale price w_i, $i = 1, 2$ is:

$$Max_w\{\Phi_i(w_i)\} = Max_w\{(\pi_i^M)^{1/2}(\pi_i^R)^{1/2}\},\ \ i = 1, 2. \tag{4}$$

Then we can derive that $w_i = \frac{p_i - c_i}{2}$, $\pi_i^M = \pi_i^R = \frac{\pi_i^{SC}}{2}$, $i = 1, 2$, i.e., the manufacturer and the retailer divide the chain profit equally because their bargaining powers are equally distributed.

To keep things simple and tractable, we consider the additive inverse demand function where the ith retailer's price, p_i, depends on two elements: its own quantity of product, q_i, and the competitor's quantity of product, q_j $(j \neq i)$, through a substituting coefficient $b_i \in (0, 1)$:

$$p_i = a_i - q_i - b_i q_j,\ \ i = 1, 2;\ j = 3 - i. \tag{5}$$

As reflected in (5), $b_i = 0$ implies that the chains are independent of each other, and they can behave as the monopoly firm in each chain; while $b_i = 1$ implies that the products of two chains are homogenous and they will face the most intensive competition. To simplify the expressions, we assume that $a_1 = a_2 \equiv a$, which implies that the highest possible quantity of demand of the two supply chains are identical; $b_1 = b_2 \equiv b$, which implies that the substitution effects between the final products of two chains are symmetric; $c_1 = c_2 = c$, which implies that two manufacturers have the same production cost. Two chains are still asymmetric in the sense of carbon emission technology, $e_2 > e_1 > 0$.

In the benchmark model, we assume that manufacturers have sufficient capacity, we can ensure that $d_i = q_i$, and we therefore rewrite the profit functions of supply chains as follows:

$$\pi_i^{SC} = q_i(a - q_i - bq_j - c - te_i),\ \ i = 1, 2;\ j = 3 - i. \tag{6}$$

By taking the first order derivatives with respect to q_i, we have the First Order Conditions (FOC):

$$\frac{\partial \pi_i^{SC}}{\partial q_i} = a - 2q_i - bq_j - c - te_i = 0,\ \ i = 1, 2;\ j = 3 - i. \tag{7}$$

By solving two equations in (7), we have the best reaction functions of two supply chains:

$$q_i^* = \frac{a - c - te_i - bq_j}{2},\ \ i = 1, 2;\ j = 3 - i. \tag{8}$$

Rearranging equations in (8), the optimal quantities of two chains are given:

$$q_i^* = \frac{a - c}{2 + b} - \frac{2e_i - be_j}{4 - b^2}t,\ \ i = 1, 2;\ j = 3 - i. \tag{9}$$

Substituting the optimal quantities of (9) into (5), the optimal prices are solved as:

$$p_i^* = \frac{a + c + bc}{2 + b} + \frac{(2 - b^2)e_i + be_j}{4 - b^2}t,\ \ i = 1, 2;\ j = 3 - i. \tag{10}$$

By calculating the optimal profits of the two supply chains, we can derive the following proposition of the benchmark model:

Proposition 1. *In the Sub-game Perfect Equilibrium (SPE) of the asymmetric Cournot competition model of supply chains, the optimal profits of chains, manufacturers, and retailers are:*

$$\pi_i^{SC*} = \left[\frac{a - c}{2 + b} - \frac{2e_i - be_j}{4 - b^2}t\right]^2,\ \ i = 1;\ j = 3 - i. \tag{11}$$

[1] The Nash Bargaining game is initiated by Nash (1950), and then developed by Kalai and Smordinsky (1975) and Binmore et al. (1986).

$$\pi_i^{M^*} = \pi_i^{R^*} = \frac{1}{2}\cdot\left[\frac{a-c}{2+b} - \frac{2e_i - be_j}{4-b^2}t\right]^2, \ i = 1; \ j = 3-i. \tag{12}$$

We denote the carbon emission technology difference as $\Delta e \equiv e_2 - e_1 > 0$ and the profit difference as $\Delta\pi^{SC^*} \equiv \pi_1^{SC^*} - \pi_2^{SC^*}$. Recall (9) and (10), then we can derive that $p_1^* < p_2^*$, and $q_1^* > q_2^*$. Similarly, we can define the price difference and the quantity difference in the equilibrium as $\Delta p^* \equiv p_2^* - p_1^* > 0$ and $\Delta q^* \equiv q_1^* - q_2^* > 0$, respectively. Because Supply Chain 1 has the cost advantage, it can supply the final product in a lower price and snatch more market share in the competition with Supply Chain 2. Some properties related to those differences can be summarized in the following lemma:

Lemma 1. *In the SPE of the asymmetric Cournot competition model of supply chains, as the carbon emission technology difference Δe increases, the price difference, Δp^*, the quantity difference, Δq^*, and the profit difference, $\Delta\pi^{SC^*}$, increases.*

Proof: Employing the equations in 10, (9) and (11), we can derive the expressions of three difference functions, respectively:

$$\Delta p^* = \frac{(2-b-b^2)t}{4-b^2}\Delta e,$$

$$\Delta q^* = \frac{t}{2+b}\Delta e,$$

$$\Delta\pi^{SC^*} = \left[\frac{2(a-c)}{2+b} - \frac{p_e(2e_1+\Delta e)}{2+b}\right]\frac{t\Delta e}{2+b}.$$

Taking the first order derivatives of Δp^*, Δq^*, and $\Delta\pi^{SC^*}$with respect to Δe, respectively, we have:

$$\frac{\partial\Delta p^*}{\partial\Delta e} = \frac{(2-b-b^2)t}{4-b^2} > 0,$$

$$\frac{\partial\Delta q^*}{\partial\Delta e} = \frac{t}{2+b} > 0,$$

$$\frac{\partial\Delta\pi^{SC^*}}{\partial\Delta e} = \left[\frac{2(a-c)}{2+b} - \frac{t(2e_1+\Delta e)}{2+b}\right]\frac{t}{2+b} - \frac{t}{2+b}\frac{t\Delta e}{2+b} = \frac{2t(a-c-te_2)}{(2+b)^2} > 0.$$

Given that $b \in (0, 1)$, $t > 0$ and $q_i^* > 0$ in Eq. (8). ■

From Lemma 1, we notice that—regardless of a decrease in e_1 or an increase in e_2, which result in an increase in Δe—as the carbon emission technology become more asymmetric, Supply Chain 2 will suffer the lower optimal price, lower optimal quantity, and lower optimal profit.

Repeat the similar procedures as the proof of Lemma 1, we can derive the following lemma in relation to the carbon emission tax of per-unit production t:

Lemma 2. *In the SPE of the asymmetric Cournot competition model of supply chains, as the carbon emission tax of per-unit production t increases, the price difference, Δp^*, the quantity difference, Δq^*, and the profit difference, $\Delta\pi^{SC^*}$increases.*

Supply Chain 2 will suffer the lower optimal price, lower optimal quantity, and lower optimal profit when the carbon emission tax of per-unit production t becomes higher. Hence, the incentive of Supply Chain 2 to upgrade its carbon emission technology increases as the carbon emission tax increases. However, the traditional supply chain in a weak market position may lack the funding of carbon emission technology upgradation. To encourage the development of the green supply chain, government may need to consider some policy measures to reduce this carbon emission technology difference.

3. The model with financing risk and technology upgrading

3.1. Financing risk on the investment of technology upgrading

In this section, we consider the case where only Supply Chain 2 faces the manufacturing carbon emission technology restriction and needs to borrow from the financial institution to invest in carbon emission technology to become a green supply chain. Recall that $e_2 > e_1 > 0$, to reduce the carbon emission taxation and gain more profit as the green supply chain, Supply Chain 2 considers to update its carbon emission technology and reduce the per-product carbon emission by Δe_2, and ask the financial institution for a loan $l(\Delta e_2)$, where l is an concave function of Δe_2, which satisfies the Inada Condition, i.e., $l(\Delta e_2 = 0) = 0$, $l'(\Delta e_2) > 0$, $l''(\Delta e_2) < 0$. The financial institution agrees to lend the loan $l(\Delta e_2)$ with an exogenous probability $u \in (0, 1)$, and the interest rate of the loan is $r \in (0, 1)$.

In this Cournot competition model of supply chains with asymmetric financing risk in manufacturing carbon emission technology investment, the timing of the game becomes:

1 Manufacturer 2 in Supply Chain 2, who faces the opportunity of technology upgrade, asks the financial institution for a loan, $l(\Delta e_2)$, to reduce its per-product carbon emission by Δe_2. The financial institution approves the loan application with probability $u \in (0, 1)$. If the loan is approved, Manufacturer 2 will receive the full loan amount with an interest rate $r \in (0, 1)$.
2 The manufacturers and retailers in the two supply chains bargain simultaneously and decide wholesale prices, w_i, $i = 1, 2$.
3 The manufacturers and the retailers in the two supply chains simultaneously agree on the desired retailer order quantity, q_i, $i = 1, 2$. Thereafter, the quantities of q_i are fully produced and delivered by the manufacturers.
4 The retailing prices p_i, $i = 1, 2$, are determined by market demand, and sales take place. Manufacturer 2 pays interest, $rl(\Delta e_2)$, to the financial institution and every player receives its payoff.

We start our analysis with the complete information case, in which Manufacturer 1 is able to observe the result of the loan application of Supply Chain 2. There are two possible outcomes of loan application in this model: if Supply Chain 2 has received the loan and makes an investment, its carbon emission technology updates to a higher level; we denote the quantity and the price as q_i^h and p_i^h, respectively; similarly, let q_i^l and p_i^l denote the quantity and price if the loan application has been rejected and the carbon emission technology of Manufacturer 2 remains the same low level. Both manufacturers can choose different levels of production given different outcomes of loan application, in the case of complete information.

The expected profit functions of Supply Chain 2 are the following:

$$\pi_2^{SC} = u[q_2^h(p_2^h - c - t(e_2 - \Delta e_2)) - rl(\Delta e_2)] + (1-u)q_2^l(p_2^l - c - te_2). \tag{13}$$

In this section, financing behavior constitutes complete information and every player in the game observes the outcome of the loan application. The financing risk is resolved before a retail price p_i is chosen.

However, Manufacturer 1 does not consider updating its technology and the expected profit functions of Supply Chain 1 are the following:

$$\pi_1^{SC} = uq_1^h(p_1^h - c - te_1) + (1-u)q_1^l(p_1^l - c - te_1). \tag{14}$$

Taking the first order derivatives with respect to q_1^l, q_1^h, q_2^l and q_2^h, we have four FOCs:

$$\frac{\partial\pi_1^{SC}}{\partial q_1^l} = a - 2q_1^l - bq_2^l - c - te_1 = 0,$$

$$\frac{\partial \pi_1^{SC}}{\partial q_1^h} = a - 2q_1^h - bq_2^h - c - te_1 = 0,$$

$$\frac{\partial \pi_2^{SC}}{\partial q_2^l} = a - 2q_2^l - bq_1^l - c - te_2 = 0,$$

$$\frac{\partial \pi_2^{SC}}{\partial q_2^h} = a - 2q_2^h - bq_1^h - c - t(e_2 - \Delta e_2) = 0.$$

Rearranging equations, we can derive the following best reaction functions:

$$q_1^{l^*} = \frac{a - c - te_1 - bq_2^l}{2}, \tag{15}$$

$$q_1^{h^*} = \frac{a - c - te_1 - bq_2^h}{2}, \tag{16}$$

$$q_2^{l^*} = \frac{a - c - te_2 - bq_1^l}{2}, \tag{17}$$

$$q_2^{h^*} = \frac{a - c - t(e_2 - \Delta e_2) - bq_1^h}{2}. \tag{18}$$

Solving Eqs. (15) and (17), the optimal quantities of two chains when Manufacturer 2 has not increased its carbon emission technology are:

$$q_1^{l^*} = \frac{a-c}{2+b} - \frac{2e_1 - be_2}{4-b^2}t, \tag{19}$$

$$q_2^{l^*} = \frac{a-c}{2+b} - \frac{2e_2 - be_1}{4-b^2}t. \tag{20}$$

The two optimal quantities of production are exactly the same as the benchmark model in the previous section, because the model remains the same as the benchmark model if Manufacturer 2 fails the loan application.

Solving Eqs. (16) and (18), the optimal quantities of two chains when Manufacturer 2 has increased its carbon emission technology are:

$$q_1^{h^*} = \frac{a-c}{2+b} - \frac{2e_1 - b(e_2 - \Delta e_2)}{4-b^2}t, \tag{21}$$

$$q_2^{h^*} = \frac{a-c}{2+b} - \frac{2(e_2 - \Delta e_2) - be_1}{4-b^2}t. \tag{22}$$

By comparing (19) and (21), we have $q_1^{l^*} > q_1^{h^*} > 0$, and by comparing (20) and (22), we have $q_2^{h^*} > q_2^{l^*} > 0$, which implies that the asymmetricity of optimal quantities between two supply chains will be mitigated if Manufacturer 2 can receive the loan successfully and reduce its carbon emission by $\Delta e_2 > 0$

Substituting (19)–(22) into (5), we can derive the optimal prices of two chains in two possible situations:

$$p_1^{l^*} = \frac{a + c + bc}{2+b} + \frac{(2-b^2)e_1 + be_2}{4-b^2}t, \tag{23}$$

$$p_2^{l^*} = \frac{a + c + bc}{2+b} + \frac{(2-b^2)e_2 + be_1}{4-b^2}t, \tag{24}$$

$$p_1^{h^*} = \frac{a + c + bc}{2+b} + \frac{(2-b^2)e_1 + b(e_2 - \Delta e_2)}{4-b^2}t, \tag{25}$$

$$p_2^{h^*} = \frac{a + c + bc}{2+b} + \frac{(2-b^2)(e_2 - \Delta e_2) + be_1}{4-b^2}t. \tag{26}$$

We can derive that $p_1^{l^*} > p_1^{h^*} > 0$, and $p_2^{l^*} > p_2^{h^*} > 0$, implies that two supply chains will face more intensive price competition when their carbon emission technology become more symmetric. Note that the financing risk u is not included in all expressions of optimal quantities (19)–(22), or in all expressions of optimal prices (23)–(26). This follows because in this complete information case, each player observes the outcome of the loan application before the optimal quantities and prices are determined. The game can be reduced into two sub-games of complete information. By calculating the optimal profits of the two supply chains, we can derive the following proposition of the complete information model:

Proposition 2. *In the SPE of the Cournot competition model of supply chains with asymmetric financing risk in manufacturing carbon emission technology, the optimal expected profits are:*

$$\pi_1^{SC^*} = u\left[\frac{a-c}{2+b} - \frac{2e_1 - b(e_2 - \Delta e_2)}{4-b^2}t\right]^2 + (1-u)\left[\frac{a-c}{2+b} - \frac{2e_1 - be_2}{4-b^2}t\right]^2, \tag{27}$$

$$\pi_2^{SC^*} = u\left\{\left[\frac{a-c}{2+b} - \frac{2(e_2 - \Delta e_2) - be_1}{4-b^2}t\right]^2 - rl(\Delta e_2)\right\} + (1-u)\left[\frac{a-c}{2+b} - \frac{2e_2 - be_1}{4-b^2}t\right]^2 \tag{28}$$

Comparing the optimal profits of supply chains in the benchmark model in (11), the optimal expected profit of Supply Chain 1, $\pi_1^{SC^*}$, decreases and the optimal expected profit of Supply Chain 2, $\pi_2^{SC^*}$, increases as the Supply Chain 2 has the opportunity to upgrade its carbon emission technology. Some properties related to the financing risk of carbon emission technology upgradation u can be summarized in the following lemma:

Lemma 3. *In the SPE of the Cournot competition model of supply chains with asymmetric financing risk in terms of manufacturing carbon emission technology, as the financing risk of Supply Chain 2, u, increases, the optimal profit of Supply Chain 1 decreases and the optimal profit of Supply Chain 2 increases.*

Proof: Taking the first order derivatives of $\pi_1^{SC^*}$in (27) with respect to u, respectively, we have:

$$\frac{\partial \pi_1^{SC^*}}{\partial u} = \left[\frac{a-c}{2+b} - \frac{2e_1 - b(e_2 - \Delta e_2)}{4-b^2}p_e\right]^2 - \left[\frac{a-c}{2+b} - \frac{2e_1 - be_2}{4-b^2}p_e\right]^2$$

$$= \left[\frac{2(a-c)}{2+b} - \frac{4e_1 - b(2e_2 - \Delta e_2)}{4-b^2}p_e\right]\left[-\frac{\Delta e_2}{4-b^2}p_e\right].$$

Because $q_1^{l^*} > q_1^{h^*} > 0$, we can derive that $\frac{2(a-c)}{2+b} - \frac{4e_1 - b(2e_2 - \Delta e_2)}{4-b^2}p_e > 0$. Hence, we can derive that $\frac{\partial \pi_1^{SC^*}}{\partial u} < 0$.

By taking the similar procedure and apply the inequality (28), we can also derive that $\frac{\partial \pi_2^{SC^*}}{\partial u} > 0$. ■

Lemma 3 shows that a preferential policy to provide more financing opportunities to the supply chain will encourage its development on adopting green carbon emission technology. By increasing the probability of getting the loan, Supply Chain 2 will be better off if its corporate finance risk reduces. However, does this result still hold when the financing risk represents incomplete information to Supply Chain 1?

3.2. Asymmetric competition of incomplete information

If the financing risk represents incomplete (or asymmetric) information to Supply Chain 1, Manufacturer 1cannot obtains the outcome of loan application of Manufacturer 2, and there is no more information available to Manufacturer 1 to distinguish the different situations. Hence, Supply Chain 1 has to choose the only level of production, q_1, to maximize its expected profit.

We can rewrite the following expected profit functions of the two chains:

$$\pi_1^{SC} = uq_1(a - q_1 - bq_2^h - c - te_1) + (1 - u)q_1(a - q_1 - bq_2^l - c - te_1), \tag{29}$$

$$\pi_2^{SC} = u[q_2^h(a - q_2^h - bq_1 - c - t(e_2 - e_2)) - rl(e_2)] + (1 - u)q_2^l(a - q_2^l - bq_1 - c - te_2). \tag{30}$$

Note that there is only a single quantity choice q_1 for Supply Chain 1 because it cannot observe the result of the loan application. Supply Chain 1 has to decide the optimal quantity choice q_1 in dealing with two possible situations, but it is not able to distinguish which situation the chain faces. Taking the first order derivatives with respect to q_1, q_2^h and q_2^l, we have the following FOCs:

$$\frac{\partial \pi_1^{SC}}{\partial q_1} = u(a - 2q_1 - bq_2^h - c - te_1) + (1 - u)(a - 2q_1 - bq_2^l - c - te_1) = 0, \tag{31}$$

$$\frac{\partial \pi_2^{SC}}{\partial q_2^h} = u[a - 2q_2^h - bq_1 - c - t(e_2 - \Delta e_2)] = 0, \tag{32}$$

$$\frac{\partial \pi_2^{SC}}{\partial q_2^l} = (1 - u)(a - 2q_2^l - bq_1 - c - te_2) = 0. \tag{33}$$

We can then solve the best reaction functions:

$$q_1^* = \frac{a - c - te_1 - ubq_2^h - (1 - u)bq_2^l}{2}, \tag{34}$$

$$q_2^{h^*} = \frac{a - c - t(e_2 - \Delta e_2) - bq_1}{2}. \tag{35}$$

$$q_2^{l^*} = \frac{a - c - te_2 - bq_1}{2}. \tag{36}$$

Solving the three equations above, the optimal quantities of the two chains are:

$$q_1^* = \frac{a - c}{2 + b} - \frac{2e_1 - be_2 + ub\Delta e_2}{4 - b^2}t, \tag{37}$$

$$q_2^{h^*} = \frac{a - c}{2 + b} - \frac{2(e_2 - \Delta e_2) - be_1 + \frac{1-u}{2}b^2\Delta e_2}{4 - b^2}t, \tag{38}$$

$$q_2^{l^*} = \frac{a - c}{2 + b} - \frac{2e_2 - be_1 - \frac{u}{2}b^2\Delta e_2}{4 - b^2}t. \tag{39}$$

Note that if $u = 0$, $q_1^* = q_1^{l^*} = \frac{a-c}{2+b} - \frac{2e_1 - be_2}{4-b^2}t$, which is the optimal quantity of Supply Chain 1 given that it receives the information that Manufacturer 2 has not obtained the loan from the financial institution in (19); If $u = 1$, $q_1^* = q_1^{h^*} = \frac{a-c}{2+b} - \frac{2e_1 - b(e_2 - \Delta e_2)}{4-b^2}t$, which is the optimal quantity of Chain 1 given that it receives the information that Manufacturer 2 has obtained the loan and increased the carbon emission technology successfully in (21). We can derive that

$$q_1^* = uq_1^{h^*} + (1 - u)q_1^{l^*}, \tag{40}$$

which implies that the optimal quantity choice of Chain 1 in the incomplete information model is a weighted average of two optimal quantities in the complete information case, by using the financing risk of Chain 2, u, as the weight.

Compared to the model of complete information and given that $u \in (0, 1)$, we can find that the optimal quantity of Manufacturer 2 when it has not received the loan, $q_2^{l^*}$, is higher than that of the complete information model in Eq. (20), because in this case Supply Chain 2 will face less intense competition, in which Supply Chain 1 will under-produce, i.e., $q_1^* < q_1^{l^*}$; similarly, $q_2^{h^*}$, is lower than that of the complete information model in Eq. (22), because in this case Supply Chain 2 will face more intense competition if it has obtained the loan, in which Supply Chain 1 will over-produce, i.e., $q_1^* > q_1^{h^*}$.

Substituting (37)–(39) into (5), we can then calculate the optimal prices of the two chains:

$$p_1^{l^*} = \frac{a + c + bc}{2 + b} + \frac{(2 - b^2)e_1 + be_2 + \frac{u}{2}(2 - b^2)b\Delta e_2}{2 + b}t, \tag{41}$$

$$p_2^{l^*} = \frac{a + c + bc}{2 + b} + \frac{(2 - b^2)e_2 + be_1 + \frac{u}{2}b\Delta e_2}{4 - b^2}t, \tag{42}$$

$$p_1^{h^*} = \frac{a + c + bc}{2 + b} + \frac{(2 - b^2)e_1 + b(e_2 - \Delta e_2) - \frac{1-u}{2}(2 - b^2)b\Delta e_2}{4 - b^2}t, \tag{43}$$

$$p_2^{h^*} = \frac{a + c + bc}{2 + b} + \frac{(2 - b^2)(e_2 - \Delta e_2) + be_1 - \frac{1-u}{2}b^2\Delta e_2}{4 - b^2}t. \tag{44}$$

By comparing (41)–(44) with (23)–(26), we can derive that both $p_1^{l^*}$ and $p_2^{l^*}$ are higher than that of the complete information model in Eqs. (23) and (24), the price competition between two chains becomes less intensive since Supply Chain 1 will under-produce in the incomplete information case, i.e., $q_1^* < q_1^{l^*}$; meanwhile, $p_1^{h^*}$and $p_2^{h^*}$ are lower than that of the complete information model in Eqs. (25) and (26), the price competition between two chains becomes more intensive since Supply Chain 1 will over-produce in the incomplete information case, i.e., $q_1^* > q_1^{h^*}$.

Summarizing the results above, we can get the following proposition about the optimal quantities and optimal prices in the incomplete information model:

Proposition 3. *In the Perfect Bayesian Equilibrium (PBE) of the Cournot competition model of supply chains with asymmetric financing risk of carbon emission technology upgradation in manufacturing part, for the optimal quantities,* $q_1^* = uq_1^{h^*} + (1 - u)q_1^{l^*}$, *and* $q_1^{h^*} < q_1^* < q_1^{l^*}$; $q_2^{l^*}$ *is higher and* $q_2^{h^*}$*is lower in comparison with the complete information case. For the optimal prices,* $p_1^{l^*}$, $p_2^{l^*}$ *are higher in comparison with the complete information case, and* $p_1^{h^*}$ *and* $p_2^{h^*}$ *are lower in comparison with the complete information case.*

By calculating the optimal profits of the two supply chains, we can derive the following proposition of the incomplete information model:

Proposition 4. *In the PBE of the Cournot competition model of supply chains with asymmetric financing risk in manufacturing carbon emission technology, the optimal expected profits are:*

$$\pi_1^{SC^*} = \left[\frac{a - c}{2 + b} - \frac{2e_1 - be_2 + ub\Delta e_2}{4 - b^2}t\right]^2, \tag{45}$$

$$\pi_2^{SC^*} = u\left\{\left[\frac{a - c}{2 + b} - \frac{2(e_2 - \Delta e_2) - be_1 + \frac{1-u}{2}b^2\Delta e_2}{4 - b^2}t\right]^2 - rl(\Delta e_2)\right\} + (1 - u)\left[\frac{a - c}{2 + b} - \frac{2e_2 - be_1 - \frac{u}{2}b^2\Delta e_2}{4 - b^2}t\right]^2 \tag{46}$$

We can compare the optimal expected profits of two supply chains (45) and (46) in the incomplete information model with the optimal expected profits (27) and (28), but the results of comparisons depend on the coefficient relationship between u and other exogenous variables in the model.

Note that the amount of technology upgradation of Supply Chain 2, Δe_2, is being treated as an exogenous variable in Proposition 4. In fact, Δe_2 is the endogenous variable and by taking the first order derivative of (46) with respect to Δe_2 and rearrange the F.O.C., we have

$$u\left[\frac{a-c}{2+b} - \frac{2(e_2 - \Delta e_2) - be_1 + \frac{1-u}{2}b^2\Delta e_2}{4-b^2}t\right]\frac{4 - b^2 + ub^2}{4 - b^2}t + (1 - u)\left[\frac{a-c}{2+b} - \frac{2e_2 - be_1 - \frac{u}{2}b^2\Delta e_2}{4-b^2}t\right]\frac{ub^2}{4-b^2}t = url'(\Delta e_2). \tag{47}$$

On can find that the two terms on the L.H.S. of (47) are positive and recall that $l(\Delta e_2)$ is a concave function of Δe_2 so that $l'(\Delta e_2) > 0$, we can make sure that a positive optimal amount of carbon emission technology upgradation exists for Supply Chain 2. Then we can summarize the following Lemma:

Lemma 4. *In the Perfect Bayesian Equilibrium (PBE) of the Cournot competition model of supply chains with asymmetric financing risk of carbon emission technology upgradation, the optimal amount of carbon emission technology upgradation for Supply Chain 2 is determined by Eq. (47).*

4. Extensions

4.1. Financing risk on the retailing carbon emission technology upgradation

In this section, we consider the case that only the retailer in Supply Chain 2 needs to collect financing aid from banks to invest in its carbon emission technology. In this model, Retailer 2 needs to increase its carbon emission technology by Δe_2, and ask the financial institution for the loan $l(\Delta e_2)$ with an interest rate r.[2] Similarly, we can write the expected profit functions of Supply Chain 2 when it can receive the loan $l(\Delta e_2)$ with probability u:

$$\pi_2^{SC} = u[q_2^h(p_2^h - c) - t(e_2 - \Delta e_2) - rl(\Delta e_2)] + (1-u)q_2^l(p_2^l - c - te_2),$$

$$\pi_2^M = uq_2^h(w_2^h - c) + (1-u)q_2^l(w_2^l - c),$$

$$\pi_2^R = uq_2^h[p_2^h - w_2^h - t(e_2 - \Delta e_2) - rl(\Delta e_2)] + (1-u)q_2^l(p_2^l - w_2^l - te_2)$$

Note that the expected profit of Supply Chain 2 π_2^{SC} is exactly the same as Eq. (13) for the main model in Section 3, while the chain profit of π_1^{SC} remains unchanged as Eq. (14). Hence, we can derive the following proposition:

Proposition 5. *In the Perfect Bayesian Equilibrium (PBE) of the Cournot competition model of supply chains with asymmetric financing risk of carbon emission technology upgradation in retailing part, the optimal quantities, optimal prices, and optimal expected profits are the same as Proposition 3.*

The main results of our analysis remain the same in the case of a retailing carbon emission technology investment, because the bargaining powers of the manufacturer and retailer in both supply chains are balanced, i.e., $\alpha = 0.5$. The manufacturing and retailing carbon emission technology investments cause similar effects on the expected profit of chains, which is shared equally by the manufacturer and the retailer.

4.2. The unbalanced bargaining powers

In the previous analysis, we assumed that manufacturers and retailers in both chains share the bargaining power equally, i.e., $\alpha = 0.5$, to simplify the analysis. However, α could be any value within the interval (0, 1). Recall that the Nash Bargaining Product model of choosing a wholesale price w_i in Eq. (4):

$$\text{Max}_{w_i}\{\Phi_i(w_i)\} = \text{Max}_{w_i}\{(\pi_i^M)^\alpha(\pi_i^R)^{1-\alpha}\},\ \ i = 1, 2.$$

Then we can derive the F.O.C. with respect to α,

$$\alpha q_i^\alpha (w_i - c)^{\alpha-1} - (1-\alpha)q_i^{1-\alpha}(p_i - w_i)^{-\alpha} = 0. \tag{48}$$

Rearranging (48), we have

$$\frac{(p_i - w_i^*)^\alpha}{(w_i^* - c)^{1-\alpha}} = \frac{(1-\alpha)}{\alpha}q_i^{1-2\alpha}. \tag{49}$$

Note that as α increases, w_i^* must increase for Eq. (49) being hold. Hence, an increase in the bargaining parameter α will result in an increase in the wholesale price and an increase in the manufacturer's share of total profit. Given any $\alpha \in (0, 1)$, we can still derive consistent properties of market equilibria as in our previous analysis, except that the distributions of profits within a supply chain will be changed. Although the explicit functions of optimal quantities, optimal prices, and optimal expected profits in competing equilibria for the general model cannot be easily solved, we can use some values of $\alpha \in [0, 1]$, other than 0.5, to repeat the whole analysis in Sections 2 and 3. Hence, if the government wants to publish some preferential policies to encourage the adoption of green technology in the supply chain, it should choose the party with higher bargaining power. Either a manufacturer or a retailer who can receive more shares of the total profit has an higher incentive to make the investment in carbon emission technology.

5. Policy implications

From the results of the previous theoretical analysis, we can summarize the policy implications to encourage the use of clean energy technology in supply chains.

First, the per-product carbon emission tax is an efficient tool to encourage the traditional supply chain to upgrade its carbon emission technology, especially when the market power of the traditional supply chain is relatively low in current competition.

Second, government should encourage financial institutions to provide preferential loans to the supply chain that has carbon emission technology disadvantage in the market. The government should pay special attentions on the effects of such a policy to shape the competition between supply chains in practice.

Third, the government should focus on either the manufacturer or the retailer to encourage the carbon emission technology upgradation, depending on which one has a relatively higher bargaining power in the chain.

6. Conclusions

In this paper, we introduced the Cournot competition model of two supply chains with asymmetric carbon emission technology as the benchmark, and discussed the effect of a per-product carbon emission tax to deal with the problem of carbon emission from the traditional supply chains. We then added the financing risk about carbon emission technology investment into the benchmark model. The financing risk of one supply chain's carbon emission technology investment could be available as complete or incomplete information to its competitor. We find that, in the complete information case, the financing risk of carbon emission technology upgradation does not affect the choices of optimal quantities and optimal prices, because both chains can observe the outcome of the loan application. If this information is incomplete, the financing risk plays an important role in the determination of optimal quantities and optimal prices. In either case, the supply chain benefits from the preferential loan, which could increase its probability of getting the loan for carbon emission technology investment.

To encourage the development of green supply chains, government should increase per-product carbon emission tax if some supply chain has lower carbon emission technology and provide the chain with an incentive to upgrade its technology and become a green supply chain. Government should also encourage financial institutions to provide preferential loans to the supply chain if it needs to upgrade its carbon emission technology in the competition with other supply chain.

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[2] We still make the same assumption that the amount of loan $l(\Delta e_2)$ satisfies the Inada Condition.

Author statement

Prof. Tao Wu conducts the entire research, formulates the model, and provides the proofs of the theory. Prof. Chih-Chun Kung collaborates with Prof. Wu by providing insightful suggestions, discussions, and policy implications. Both authors provide financial support to this study.

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