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Market power and inter-temporal behavior in tradable permits systems

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Abstract: Banking and borrowing (BB) systems have been developed gradually in tradable permits markets to serve as an environmental management tool. This paper mainly explores the conditions for intertemporal efficiency in the context of market power on tradable permits when considering the output market. We examine the welfare performance of different systems (with or without BB systems) with different initial allocation policies (emissions budget and production planning). The initial allocation conditions for efficiency solutions are derived, which is different from the case without the output market. The total emissions of each firm remain the same with or without BB systems. The welfare gains are higher with BB systems due to less efficiency loss. The welfare performance in two initial allocation policies depends upon the value of total marginal benefits of tradable permits over the horizon given

that the firms have the same emissions budget.

Keywords: banking and borrowing; market power; intertemporal trading; efficiency; initial allocation

JEL Codes: Q40; Q50

1. Introduction

It is well known that the carbon market is the cost-effective approach to the CO_2 reduction in the fight against climate change (Balint et al., 2017). The lowest emission abatement costs are attainable in a competitive tradable permit market. However, the efficiency includes twofold when considering intertemporal trading: efficiency across firms and time. Banking and borrowing (BB) systems enable the firms to transfer permits across time freely. Permits banking means saving some permits in one period to use or trade in the later periods, and permits borrowing means using more in one period than the current standard amounts and paying them back in the future (Kling and Rubin, 1997). Banking was initially introduced into the acid rain program in the United States. The EU ETS allowed banking but no borrowing in phase I (2005-2007) and II (2008-2012), and allowed both banking and borrowing across the year in phase III (2013-2020) (Jia et al., 2016). The Chinese pilot carbon markets allow banking but rule out borrowing (Fan and Todorova, 2017). More studies pay increasing attention to the relationships between BB system and efficiency of intertemporal carbon market (Ellerman et al., 2015; Hintermann et al., 2016). With considering output market, we are mainly concerned in how initial allocation affects intertemporal efficiency and welfare performance in the context of market power in the carbon market.

The study on permits banking or borrowing is started by Cronshaw and Kruse (1996), Rubin (1996). They demonstrate that a competitive tradable permit market with banking can lead to the least cost. Some studies propose analysis on the impacts of the uncertainty on the permits price and behavior of banking. The uncertainty is embodied in several cases, such as demand (Schennach, 2000), abatement cost technologies (Maeda, 2004; Feng and Zhao, 2006; Fell et al., 2012) and forward trading (Newell et al., 2005). The efficiency and welfare analysis in an intertemporally tradable system are also examined. Cason and Gangadharan (2004) find that the banking can reduce the price volatility arising from the imperfect emissions control, but result in more emissions. On the contrary, Bosetti et al. (2009) show that BB system can not only improve welfare but also reduce more emissions in short term. Färe et al. (2013) also reveal that compared with command-and-control and tradable market without intertemporal trading, intertemporal trading harvests the most gains. Chaton et al. (2015) identify the condition for the allocation efficiency of the tradable permit market. The condition depends on the initial allocation and on the output market fundamentals as well, including market size in output market, production costs, and emission parameters. All these papers above present quite profound insights, but none of them have focused on examining the market power on tradable permits markets.

Hahn (1984) firstly considers the market power in tradable permit market. Westskog (1996), Egteren and Weber (1996) and Maeda (2003) likewise examine the cost efficiency in various cases based on Hahn. Recently, more papers investigate the cost efficiency and behavior of the firms by integrating the output market with the tradable permit market (Sartzetakis，1997a, 1997b；Eshel，2005；Hatcher，2012；Hintermann，2015，Jiang et al.，2016). Nevertheless, these papers confine themselves to the static analysis, which does not consider banking or borrowing. Hagem and Westskog (1998) examine the market power in the intertemporal trading market by using a discrete-time model, and they show that both BB system and durable system incur cost inefficiency, because the former makes the suboptimal allocation of abatement across firms, and the latter makes the suboptimal allocation of abatement across periods. While the durable system can alleviate the market power, it is not clear which one can lead to the lowest abatement cost. The following study (Hagem and Westskog, 2008) demonstrates that the market power results in inefficient allocation of permits across periods if the market allows banking but rules out borrowing. Consequently, the Hotelling rule does not imply an efficient allocation anymore. Dormady (2014) provides an experimental analysis of the energy-emissions market with market power. They find that the firms with market power can use energy-emissions market linkages to simultaneously inflate energy price and suppress carbon price. If the firm receives a stock allocation in a dynamic model, a large seller can extend its market power sufficiently but the large buyer has great difficulties in exercising market power. (Liski and Montero, 2011; Montero, 2009). This is different from the Hahn's results and they do not consider the output market as well. However, we think that the stock allocation at beginning of some planning horizon does not fit the real world very well, such as EU ETS and Chinese pilot carbon market, in which only flow allocation (allocation in each year) is considered in the horizon.

This paper mainly explores the conditions for intertemporal efficiency in the context of the carbon market and examines the welfare of different systems and initial allocation policies. Specifically, we propose a simple analytic framework of intertemporal carbon market integrated with output market. There are two types of firms regulated in a finite planning horizon. They are both price takers in output markets. The large firm has the market power to manipulate carbon market to its own advantage, and the fringe one is considered as the price taker. The CO_2 emissions are controlled by an exogeneous cap in a finite plan horizon. The permits are allowed for banking and borrowing across periods. Unlike Montero (2009), our model only considers the flow allocation and rules out the initial stock allocation. For simplicity, we only consider the spot trading and one to one intertemporal trading in this paper.

The main contributions are threefold: firstly, the initial allocation conditions for efficiency solutions are derived considering output market, which is different from the case without output market. The well-known principle is that the intertemporal efficiency of the tradable permits market is to achieve the equivalent discounted marginal abatement costs across firms and periods (Rubin, 1996; Hagem and Westskog, 1998). However, it will lead to efficiency loss when the carbon permits are considered as productive resources. Since the efficiency entails the equal discounted marginal productivity of carbon permits instead of marginal abatement costs. Secondly, we demonstrate that the total emissions of each firm in BB system keep the same with that in no BB system, while the welfare gains more in the former one due to less efficiency loss. Thirdly, instead of historical basis (namely grandfathering), we supply new initial allocations method that based on an expected basis, including emissions budgets and production plan allocation. Given that the two firms have no difference in emissions budget, the production plan will be more preferred when the systemwide carbon market has a high value of marginal benefits of permits.

The rest of the paper is organized as follows. The next section proposes an analytic model, which considers a larger firm can exercise its market power to manipulate price in carbon market with BB system, but cannot influence the price in the output market. The fringe firm is considered as the price taker. Section 3 presents the efficient solutions for welfare maximization. Section 4 characterizes the behaviors of the firm with market power and identifies the condition for intertemporally efficient allocation. Welfare in different cases is examined in Section 5, including welfare comparison in BB system and no BB system, welfare comparison in the cases of emissions budget allocation and production plan allocation. Section 6 concludes.

2. The model

Suppose that there are two firms, $i = F, M$, in the output market and carbon market. The firms produce the same production (such as electricity) with discharging CO_2. They are both considered as price takers in the output market due to price regulation by some regulator[1]. However, in the carbon market, the firm M has the market power (or called strategic firm) such that it can manipulate the trading price. The firm F is the fringe considered as the price taker. The regulator curbs CO_2 emissions by setting an emission cap L for a planning horizon of T periods, $j = 1, 2, \cdots, T$, without loss of generality, T can be flexible in long or short time. L_{ij} are free permits allocated to the firm i in the period j before trading, and $L = \sum_{j=1}^{T}\left(L_{Fj} + L_{Mj}\right)$, $L_i = \sum_{j=1}^{T} L_{ij}$. A one-unit permit allows for one-unit emission. p_j is the output price regulated to increase at the rate of interest: $p = \delta^{j-1} p_j$, where p is the present value of the regulated price, and δ is the discounted rate. The output, q_{ij}, is assumed to be a linear function of carbon emissions e_{ij}, $q_{ij} = \mu_i e_{ij}$, where μ_i is carbon productivity. For simplicity, we do not consider the other production costs.

[1] This assumption isn't unreasonable at all. For example, the electric power sector is the largest CO_2 emitter in the region, and the price of electricity is almost regulated by the government.

The emission abatement costs function is $C^{ij}(e_{ij})$. Specified by quadratic form:

$$C^{ij}(e_{ij}) = \begin{cases} \frac{1}{2}(s_{ij} - e_{ij})^2, & if\ 0 < e_{ij} < s_{ij} \\ 0, & if\ s_{ij} \le e_{ij} \end{cases}$$

where s_{ij} is the emissions of business as usual (i.e. unrestricted emissions). The costs will be zero if the emissions are not below s_{ij}. Otherwise, the compliance costs will strictly increase with the emissions reduction but decrease with the emissions. Thus, the marginal abatement costs, $-C_e^{ij}$, will decrease with the emissions. Moreover, the cap L is ultimately binding such that $L < S_F + S_M$, where $S_F = \sum_{j=1}^{T} s_{Fj}, S_M = \sum_{j=1}^{T} s_{Mj}$. The agents have perfect information on cost functions with each other.

We consider such a dynamic setting system in which firms are allowed to transfer permits across time by banking and borrowing, as long as its cumulative emissions in the whole horizon do not exceed the total permits it holds. B_{ij} is the number of permits banked or borrowed. $B_{ij} \ge 0$ implies banking, inversely borrowing. We assume that each firm has no bankable permits at the beginning. Specifically, B_{ij} can be given by

$$B_{Fj} = L_{Fj} + x_j - e_{Fj},\ B_{Mj} = L_{Mj} - x_j - e_{Mj} \tag{1}$$

where x_j is the trading volume. $x_j < 0 (> 0)$ implies sale (purchase) for the firm F. No one is willing to reserve any permit in the terminal period T as the marginal abatement costs are strictly positive. Therefore,

$$B_{iT} = 0 \qquad i = F, M \tag{2}$$

Then the simultaneous Eq. (1) and (2) yield

$$\sum_{j=1}^{T} e_{Fj} = L_F + X \tag{3}$$

$$\sum_{j=1}^{T} e_{Mj} = L_M - X \tag{4}$$

where $X = \sum_{j=1}^{T} x_j$, which denotes the total trading volume over all periods. It can be seen that in the dynamic setting system the accumulative emissions of firms should exactly equal the permits held over the whole horizon.

3. Problem of the Regulator

We assume that the regulator owns the perfect information on the cost functions of each firm and is able to completely control the output price. The regulator's maximization problem is specified as: which paths of the emissions and outputs in each time should be to maximize the welfare subjects to the emissions cap L. The welfare is defined to be the present value of total revenue net of compliance costs. Therefore, the optimization problem will be:

$$\max_{q_i, e_i} W = \sum_{j=1}^{T} \left(p(\mu_F e_{Fj} + \mu_M e_{Mj}) - \delta^{j-1}(C^{Fj}(e_{Fj}) + C^{Mi}(e_{Mi})) \right) \tag{5}$$

$$s.t. \ \sum_{j=1}^{T}(e_{Fj}+e_{Mj})=L$$

where W is welfare function, and it is concave. The constraint condition is that the total emissions in the horizon should equal the emissions cap. The necessary conditions for the optimal solutions will be:

$$\begin{aligned} &\delta^{m-1}(s_{im}-e_{im})=\delta^{n-1}(s_{in}-e_{in}), \qquad \forall m,n=1,2,\cdots,T, \text{ and } m\neq n, \\ &p\mu_F+\delta^{j-1}(s_{Fj}-e_{Fj})=p\mu_M+\delta^{j-1}(s_{Mj}-e_{Mj}), \qquad \forall j=1,2,\cdots,T \end{aligned} \tag{6}$$

Eq. (6) implies that the welfare maximization calls for: the first equation in (6) demands equal discounted marginal abatement costs across periods for each firm, and the second equation ensures equal marginal productivity of carbon permit across firms in each period. Otherwise, the efficient solutions cannot be obtained.

4. Banking and borrowing system

We first consider the optimization problem of the fringe firm and then move back to that of the strategic firm. It is well known that the equilibrium permits price in such dynamic system will follow the non-arbitrary condition (Rubin, 1996; Hagem and Westskog, 1998): $\beta=\delta^{j-1}\beta_{ij}, j=1,2,\cdots,T$, where β is the present value of permit price in equilibrium. Hence, it is only the total trading volume (X) over all periods rather than the periodic one (x_j) that affects the firms' profits. The fringe firm maximizes the total discounted profits by distributing the emissions across periods, and deciding the total trading volume over the horizon under the constraint that its total emissions cannot exceed the permits held:

$$\max_{e_{Fj},X}\left\{p\mu_F e_{Fj}-\sum_{j=1}^{T}\delta^{j-1}C^{Fj}(e_{Fj})-\beta X\right\} \text{ subjects to (3)}$$

This yields the first order condition:

$$\beta=\delta^{j-1}(s_{Fj}-e_{Fj})+p\mu_F \tag{7}$$

The right term of the equation is the discounted marginal productivity of carbon in the period j. Eq. (7) merely implies that in any period the fringe firm will adjust intertemporally the emissions to make discounted marginal productivity of carbon equal the discounted carbon price. Then Eq. (3) and (7) give

$$X^*=-\theta\beta+\theta p\mu_F+(S_F-L_F) \tag{8}$$

where $\theta=\sum_{j=1}^{T}\delta^{1-j}$, and $S_F=\sum_{j=1}^{T}s_{Fj}$. Actually, Eq. (8) expresses twofold implicit meanings. If the fringe firm is a net buyer, X^* should be positive. Its demand for carbon permits decreases with the carbon price and increases with output price. On the contrary, if it is a net seller, X^* should be negative, then the permits supply of the fringe firm will increase with the carbon price and decrease with the output price. Inasmuch as the fringe firm is the price taker, it has to pick an optimal X^* given that carbon price is decided by the strategic firm.

Note that the firm M has power to fully manipulate the carbon price, which is endogenous due to the fixed cap over the horizon. The firm M therefore faces downward demand (when it is the net buyer) or upward supply function (when it is the net seller) of permits characterized by Eq. (7). Similarly, it maximizes the total discounted profits by adjusting the emissions across periods and selecting a carbon price given that the total emissions cannot exceed the permits held over the horizon:

$$\max_{e_{Mj},\beta}\left\{p\mu_i e_{Mj}-\sum_{j=1}^{T}\delta^{j-1}C^{Mj}(e_{Mj})+\beta X\right\} \text{ subjects to (4)}$$

and the first order condition:

$$\beta - X^*/\theta = p\mu_M + \delta^{j-1}(s_{Mj}-e_{Mj}),\ j=1,2,\cdots,T \tag{9}$$

If the firm M is the net buyer ($X^*<0$), the left term of the equation will exceed the carbon price. Inversely, if it is the net seller ($X^*>0$), it will be below the carbon price. According to Eq. (6), both cases will be inefficiency. If and only if $X^*=0$, the efficiency solution will be attainable. This means that the efficiency is achieved in the situation in which the total initial permits allocated to the strategic firm such that move it away from the carbon market. Specifically, this gives rise to the proposition as follows:

Proposition 1: *Assume that there is one market power firm with the fringe firm in the carbon market and they are all price takers in the output market. The decentralized behavior enables the efficient solutions attainable in the system with banking and borrowing, if the total initially allocated permits satisfy that* $\Delta_\mu\theta p=\Delta_L-\Delta_S$ *, where* $\Delta_\mu=\mu_F-\mu_M$, $\Delta_L=L_F-L_M$, $\Delta_S=S_F-S_M$.

Proof: Eq. (8) can be rewritten as

$$\beta=\theta^{-1}(-X^*+\theta p\mu_F+S_F-L_F) \tag{10}$$

Substituting this to (9) gives

$$\theta^{-1}\delta^{1-j}(-2X^*+\theta p\mu_F+S_F-L_F)=p\mu_M\delta^{1-j}+s_{Mj}-e_{Mj},\ j=1,2,\cdots T \tag{11}$$

Actually, Eq. (17) contains T equations, and adding them yields:

$$(-2X^*+\theta p\mu_F+S_F-L_F)=\theta p\mu_M+S_M-L_F+X^*$$

Then the total trading volume in equilibrium with BB system will be:

$$X^*=\frac{1}{3}\left(L_M-L_F+\theta p(\mu_F-\mu_M)+S_F-S_M\right) \tag{12}$$

Efficiency across periods can be harvested in banking and borrowing system, as each firm strategically adjust intertemporal behavior to keep equal discounted marginal productivity of carbon permits across periods. The efficiency across firms, which characterized by the second equation in (5), entails that

$$\beta-X^*/\theta=\beta$$

making

$$0=X^*=\frac{1}{3}\left(L_M-L_F+\theta p(\mu_F-\mu_M)+S_F-S_M\right)$$

Thus,

$$\Delta_{\mu}\theta p = \Delta_L - \Delta_S \quad \blacksquare$$

The proposition describes the necessary conditions of efficiency solutions in case of market power with a dynamic view and considering the output market. It is the basic extension result of the existing studies, which do not formally consider the output market (Hahn, 1984; Hagem and Westskog, 1998, 2008; Liski and Montero, 2006, 2011). The efficiency in the regular case should satisfy that: $\Delta_L - \Delta_S = 0$. Since in the proposed framework, the efficient solutions call for equal marginal productivity rather than marginal abatement costs. Therefore, once carbon is deemed as input factor, the distribution distortion arising from market power cannot be eliminated yet if only concerning on carbon market but ignore the linkages between the output market and carbon market.

5. Welfare analysis

In the following, welfare analysis is carried out in two perspectives: (1) BB system and no BB system; (2) initial allocation based on emissions budget and production plan.

5.1 BB system and no BB system

In this subsection, we will analyze differentiation in two cases: BB system and no BB system. In the latter case, either banking or borrowing is illegal. No firms are willing to store any permit, and they will use up all permits they hold in each period as the marginal abatement costs are strictly positive. Therefore,

$$e_{Fj} = L_{Fj} + x_j \tag{13}$$

$$e_{Mj} = L_{Mj} - x_j \tag{14}$$

The discounted carbon price across periods may not be equivalent since firms disable to smooth the emissions across periods anymore, so the trading volume in each period should have an impact on the total costs. The fringe optimization problem is to maximize the discounted profit in each period by deciding the emissions and trading volume in the respective period given that its emissions do not exceed the permits held:

$$\delta^{j-1}\sum_{j=1}^{T}\max_{e_{Fj},x_j}\left\{p_j\mu_i e_{Fj} - C^{Fj}(e_{Fj}) - \beta_j x_j\right\} \text{ subjects to (13)} \tag{15}$$

The first order condition of this problem is

$$\beta_j = p_j\mu_F + s_{Fj} - e_{Fj} \tag{16}$$

Eq. (6) merely implies that in any period the fringe firm will adjust the emissions to make the marginal productivity equal to the carbon price. As can be seen from (13) and (16) that:

$$x_j^{**} = -\beta_j + p_j\mu_F + (s_{Fj} - L_{Fj}) \tag{17}$$

The variable with the superscript of two stars denotes the equilibrium in no BB system, and the same hereafter. Apparently, if the fringe firm is a buyer, its demand for carbon permits will decrease with the carbon price and increase with the output price. On the contrary, the supply will increase with the carbon price and decrease with the output price. Similarly, the firm M maximizes the discounted profits by deciding the emissions and picking a carbon price in each period given that the total emissions either do not exceed the permits held in the respective period:

$$\delta^{j-1}\sum_{j=1}^{T}\max_{e_{Mj},x_j}\left\{p_j\mu_M e_{Mj} - C^{Mj}(e_{Mj}) + \beta_j x_j\right\} \quad \text{subjects to (14)} \tag{18}$$

the first order condition:

$$\beta_j - x_j^{**} = p_j\mu_M + s_{Mj} - e_{Mj},\ j = 1,2,\cdots,T \tag{19}$$

Eq. (19) implies that in each period the net marginal abatement costs of the firm M will not be equal to the carbon price as long as the trading volume of permits is not zero, which implies the efficiency loss across firms. What's more, the efficiency across periods will not be held either as the carbon prices across periods may not be equivalent. Although the BB system results in inefficiency across firms, it can make the efficient allocation of permits across time. Because BB system disables to segment the carbon markets in two periods, the firm with market power fails to make an independent distorting price in each period in BB system. Consequentially, it can only make a uniform distorting price, which leads to inefficiency across firms but efficiency across time. Therefore, the distortion arising from the market power cannot be eliminated completely, but can be effectively alleviated by BB system compared with no BB system.

The next logical problem is what the difference exists between the behavior and welfare of BB system and no BB system. The result is shown in the proposition as follows.

Proposition 2: *If the initial allocation keeps the same in two systems, then* $X^* = X^{**}$, $\sum_{j=1}^{T} e_{ij}^* = \sum_{j=1}^{T} e_{ij}^{**},\ i = F, M$ *, and* $W^* > W^{**}$.

Proof: The total emissions of firms in equilibrium in BB system will be

$$\sum_{j=1}^{T} e_{Fj}^* = L_F + X^* = \frac{1}{3}\left(2L_F + L_M + \theta p(\mu_F - \mu_M) + S_F - S_M\right)$$

$$\sum_{j=1}^{T} e_{Mj}^* = L_M - X^* = \frac{1}{3}\left(2L_M + L_F + \theta p(\mu_M - \mu_F) + S_M - S_F\right)$$

Combining (17) and (19) yields the optimal periodic trading volume in no BB system:

$$x_j^{**} = \frac{1}{3}\left(L_{Mj} - L_{Fj} + p_j(\mu_F - \mu_M) + s_{Fj} - s_{Mj}\right),\ j = 1,2,\cdots T$$

Adding the T equations gives that

$$X^{**} = \frac{1}{3}\left(L_M - L_F + (\mu_F - \mu_M)\sum_{j=1}^{T} p_j + S_F - S_M\right)$$

Note that $p_j\delta^{j-1} = p$, then $\sum_{j=1}^{T} p_j = \theta p$. Therefore, $X^* = X^{**}$. The total emissions in no BB system will be:

$$\sum_{j=1}^{T} e_{Fj}^{**} = L_F + X^{**} = \sum_{j=1}^{T} e_{Fj}^*$$

$$\sum_{j=1}^{T} e_{Mj}^{**} = L_M - X^{**} = \sum_{j=1}^{T} e_{Mj}^*$$

Therefore, the total revenue should be identical in two systems: $p(\mu_F \sum_{j=1}^{T} e_{Fj}^{**} + \mu_M \sum_{j=1}^{T} e_{Mj}^{**}) = p(\mu_F \sum_{j=1}^{T} e_{Fj}^{*} + \mu_M \sum_{j=1}^{T} e_{Mj}^{*})$. However, as stated above, the no BB system suffers inefficiency across both firms and periods, and the BB system suffers inefficiency only across firms but keeps efficiency across periods. This says that $\sum_{j=1}^{T}\left((C^{Fj}(e_{Fj}^{*}) + C^{Mj}(e_{Mj}^{*})\right) < \sum_{j=1}^{T}\left((C^{Fj}(e_{Fj}^{**}) + C^{Mj}(e_{Mj}^{**})\right)$, thus $W^{*} > W^{**}$.

Although the total emissions at the equilibrium of the firm i in the two systems remain the same, yet the optimal emissions distribution across periods will not be equivalent and thereby affect the social welfare. Actually, the total allocation (L_j) rather than periodic one (L_{ij}) has an impact on periodic emissions and welfare performance in BB system, whereas the periodic allocation will affect them in no BB system. The fringe firm's strategy on settling the permits without BB system is not as flexible as that with BB system. It cannot get any more permits except for purchasing some from the market. Thereby, the monopoly (or monopsony) is able to credibly manipulate the permit price at each time, and results in both inefficient allocations across the firms and time. The BB system provides more choices on distributing the permits such that the firms can transfer the permits across time freely. As a result, the strategic firm can only make a uniform discrimination price on the horizon due to failing to segment the market across time.

5.2 Initial allocations based on emissions budget and production plan

It is necessary to examine the welfare effects in different initial allocation scenarios. Specifically, two types of initial allocation in BB system are examined in this study. One of them is to allocate permits based on emissions budget in BAS, and the other is based on the production plan. As stated above, s_j is the emission of business as usual (BAS) in the future period. It should be noted that s_j is an expected value rather than a historical one at beginning of the planning horizon. s_j is therefore seen as the periodic emissions budget in BAS of firms. The emissions budget is reported by firms and further approved by the authority before carbon permits issuing. Furthermore, given s_j the production plan can be simultaneously exported from the linear production function.

Note that in BB system the periodic initial allocation does not necessarily change welfare performance but the total initial allocation does. Hence, we should examine welfare effect caused by the later instead of the former. substituting Eq. (12) to (11) yields the optimal emissions across periods for the strategic firm in BB system

$$e_{Mj}^{*} = \frac{\delta^{1-j}}{3\theta}\left(2L_M + L_F\right) + \frac{\delta^{1-j}}{3} p(\mu_F - \mu_M) - \frac{\delta^{1-j}}{3\theta}\left(2s_M + s_F\right) + s_{Mj} \tag{20}$$

Similarly, the optimal emissions for the fringe firm in BB system are obtained from the simultaneous equations (7), (8) and (12):

$$e_{Fj}^{*} = \frac{\delta^{1-j}}{3\theta}\left(2L_F + L_M\right) + \frac{\delta^{1-j}}{3} p(\mu_F - \mu_M) - \frac{\delta^{1-j}}{3\theta}\left(2s_F + s_M\right) + s_{Fj} \tag{21}$$

In this case of emissions budget, the total permits over the horizon are completely allocated in terms of the share of its budgeting emissions in the total one. Let L_i^E denote the total issued amount of the firm i in emissions budget allocation policy. Thus, L_L^E, L_M^E will be:

$$L_L^E = \frac{S_F L}{S_F + S_M}, \quad L_M^E = \frac{S_M L}{S_F + S_M}$$

In this case of production planning, the total permits over the horizon are completely allocated in terms of the share of its planning outputs in total one. Let L_i^O denote the total issued amount of the firm i in production plan allocation policy. Thus, L_L^O, L_M^O will be:

$$L_F^O = \frac{\mu_F S_F L}{\mu_F S_F + \mu_M S_M}, \quad L_M^O = \frac{\mu_M S_M L}{\mu_F S_F + \mu_M S_M}$$

Then we get the main results as follows:

Proposition 3: *Let W^E, W^O denote the social welfare in case of emissions budget and production plan respectively. Two firms have the same emissions budget $S_F = S_M$. If $\theta p(\mu_F + \mu_M) > \frac{2}{3}L$, then $W^E < W^O$. Inversely, $W^E > W^O$.*

Proof: see the Appendix.

The firms will have the same initial allocated amounts ($L/2$) in emission budget allocation policy given that the firms report the same emissions budget. In this case, the welfare performance depends upon the value of total marginal revenue of carbon permit ($\theta p(\mu_F + \mu_M)$) over the horizon. If this value is large enough (more than $\frac{2}{3}L$), then the production plan allocation policy will be more preferred than emissions budget one. Otherwise, the later should be more preferred.

One of the other cases is $\mu_F = \mu_M$. In this case, the two allocation policies have equal welfare performance. Since the emissions budget allocation policy will be equivalent to the production plan one no matter what the emissions budget will be. However, it is not clear which allocation policy is more preferred given that $S_F \neq S_M$ and $\mu_F \neq \mu_M$, as in this case, it is uncertain which firm has the larger output in the future. Hence the welfare performance is uncertain in two policies as well.

6. Conclusions

When considering the output market, we explore the behaviors of the firms on tradable permits markets with market power in banking and borrowing systems, and examine the welfare in different initial allocation scenarios. The initial allocation conditions for efficiency solutions are derived, which is different from the case without the output market. Once the tradable permits are regarded as an input factor in production, the efficiency does not necessarily entail the equal discounted marginal abatements costs. Instead, it demands the equal discounted marginal productivity of tradable permits across both firms and time in BB systems. It does not affect the total emissions of each firm over the horizon as well as total trading volume whether or not the carbon market allows for BB systems, but the welfare system-wide benefits more from the BB system (compared with no BB system). If both fringe and strategic firms have the identical emission budget, the production plan is preferred if the total marginal revenue of carbon is comparatively large in the system-wide output market.

The main results contain several policy implications. First, it is essential for the regulator that firms may not operate along with the path of lowering compliance costs. The equal marginal abatement costs across firms and time will bring about more welfare loss due to initial distribution distortion of the carbon permits without considering the output market. Hence the initial solution for market power based on the equal marginal productivity. Secondly, banking and borrowing should be a useful instrument to reduce the welfare distortion arising from the market power. In fact, the BB system does not increase any revenue achieving from the output market, but it does decrease the compliance costs compared to no BB system. Finally, the proposed initial allocation approach can be a reference to the authority. If the emissions budget of firms is roughly equivalent, production plan allocation policy is more suitable for tight cap policy while emission budget one is suitable for a slack one. The superiority of the proposed approach is that it vests the autonomy for future emission planning in firms. However, the grandfathering based on historical data does not involve firms' prospection at all.

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Appendix

Proof for ***Proposition 3***:

The welfare in any initial allocation policy will be

$$W^k = p(\mu_F \sum_{j=1}^{T} e_{Fj}^{k*} + \mu_M \sum_{j=1}^{T} e_{Mj}^{k*}) - \frac{1}{2}\sum_{j=1}^{T}\delta^{j-1}(e_F^{k*} - s_{Fj})^2 - \frac{1}{2}\sum_{j=1}^{T}\delta^{j-1}(e_M^{k*} - s_{Mj})^2, k = E, O$$

Substituting Eq. (20), (21) and $L = L_F + L_M$ to the welfare function gives that

$$W^k = \frac{p}{3}\left(L_F^k(\mu_F - \mu_M) + L(\mu_F + 2\mu_M) + b\right) - \frac{1}{18}\sum_{j=1}^{T}\delta^{1-j}(\delta^{j-1}(L + L_F^k) + h_{Fj})^2 - \frac{1}{18}\sum_{j=1}^{T}\delta^{1-j}(\delta^{j-1}(2L - L_F^k) + h_{Mj})^2$$

where b, h_{Fj} and h_{Mj} are constants. It can be seen that the welfare is a quadratic function of L_F given L. It has been proved that $\Delta_\mu \theta p = \Delta_L - \Delta_S$ in Proposition 2, so we can get that the efficient initial allocation for fringe firm will be

$$L_F^* = \frac{1}{2}(L + \Delta_S + \Delta_\mu \theta p)$$

Thus, welfare performance in two initial allocation policies can be determined by the comparative magnitude between $|L_F^E - L_F^*|$ and $|L_F^O - L_F^*|$. If $|L_F^E - L_F^*| > |L_F^O - L_F^*|$, then $W^E < W^O$. Inversely, $W^E > W^O$.

(1) If $\mu_F > \mu_M$, then $L_F^E - L_F^O = \frac{(\mu_M - \mu_F)S_F S_M L}{K} < 0$, $L_F^E - L_F^* = -\frac{1}{2}\Delta_\mu \theta p < 0$, where $K = (S_F + S_M)(\mu_F S_F + \mu_M S_M)$.

A. If $\theta p > \frac{L}{\mu_M + \mu_F}$, then $L_F^* - L_F^O = \frac{(\mu_M - \mu_F)L}{\mu_M + \mu_F} + (\mu_F - \mu_M)\theta p > 0$. Thus $L_F^E < L_F^O < L_F^*$, which implies $|L_F^E - L_F^*| > |L_F^O - L_F^*|$. Therefore, $W^E < W^O$.

B. If $\theta p < \frac{L}{\mu_M + \mu_F}$, then $L_F^* - L_F^O = \frac{(\mu_M - \mu_F)L}{\mu_M + \mu_F} + (\mu_F - \mu_M)\theta p < 0$. Thus $L_F^O < L_F^* < L_F^E$.

$\left|L_F^O - L_F^*\right| - \left|L_F^E - L_F^*\right| = (\mu_F - \mu_M)(\frac{L}{\mu_F + \mu_M} - \frac{3}{2}\theta p)$. Obviously, if $0 < \theta p < \frac{2}{3}\frac{L}{\mu_F + \mu_M}$, then $\left|L_F^E - L_F^*\right| < \left|L_F^O - L_F^*\right|$, and therefore, $W^E > W^O$. If $\frac{2}{3}\frac{L}{\mu_F + \mu_M} < \theta p < \frac{L}{\mu_M + \mu_F}$, then $\left|L_F^E - L_F^*\right| > \left|L_F^O - L_F^*\right|$, and $W^E < W^O$.

(2) If $\mu_F < \mu_M$, then $L_F^E - L_F^O > 0$, $L_F^E - L_F^* = -\frac{1}{2}\Delta_\mu \theta p > 0$.

A. If $\theta p > \frac{L}{\mu_M + \mu_F}$, then $L_F^* - L_F^O = \frac{(\mu_M - \mu_F)L}{\mu_M + \mu_F} + (\mu_F - \mu_M)\theta p < 0$. Thus $L_F^* < L_F^O < L_F^E$, which implies $\left|L_F^E - L_F^*\right| > \left|L_F^O - L_F^*\right|$. Therefore, $W^E < W^O$.

B. If $\theta p < \frac{L}{\mu_M + \mu_F}$, then $L_F^* - L_F^O = \frac{(\mu_M - \mu_F)L}{\mu_M + \mu_F} + (\mu_F - \mu_M)\theta p < 0$. Thus $L_F^O < L_F^* < L_F^E$. $\left|L_F^O - L_F^*\right| - \left|L_F^E - L_F^*\right| = (\mu_F - \mu_M)(\frac{L}{\mu_F + \mu_M} - \frac{3}{2}\theta p)$. Obviously, if $\theta p > \frac{2}{3}\frac{L}{\mu_F + \mu_M}$, then $\left|L_F^E - L_F^*\right| > \left|L_F^O - L_F^*\right|$. Thus $W^E < W^O$. If $\frac{2}{3}\frac{L}{\mu_F + \mu_M} < \theta p < \frac{L}{\mu_M + \mu_F}$, then $\left|L_F^E - L_F^*\right| < \left|L_F^O - L_F^*\right|$, and $W^E > W^O$.

Summarizing above, if $\theta p > \frac{2}{3}\frac{L}{\mu_F + \mu_M}$, then $W^E < W^O$. Inversely, $W^E > W^O$.

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