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Intertemporal emissions trading system at international level

Abstract

This paper develops a two-period, two-stage sequential game along with a numerical application to explore countries' interactions in the international emission trading (IET) system. Accounting for the Annex-1 countries' learning-by-doing (LBD) effects on abatement costs reduction in the post-Kyoto period, the authors analyze countries' intertemporal interactions in the shortsighted and farsighted cases. The theoretical result shows that a perfectly competitive IET system in the Kyoto period might not be cost-effective because of the externalities from LBD. As compared with the shortsighted benchmark, the farsighted Annex-1 countries choose fewer permits in the Kyoto period. In addition, the Annex-1 countries having gross LBD advantage choose higher abatements (lower emissions) in the Kyoto period, consequently leading to a lower permit price in the post-Kyoto period. Finally, the numerical result suggests that the Annex-1 countries' farsightedness lowers the total cost in the post-Kyoto period and leads to environmental efficiency of the expanding participation IET.

Keywords: intertemporal emissions trading, international emissions trading, cost effectiveness, environmental efficiency.
JEL Classification: Q54, Q58.

Introduction

International emissions trading (IET) is one of the flexible mechanisms in the Kyoto Protocol which aim to facilitate cost effective abatement. The IET mechanism stems from the idea of "emissions trading" or "cap-and-trade" scheme. In a trading scheme at domestic level, the authority sets a cap on the emissions of pollutants, and allocates permits to emitting entities. The entities trade permits according to their marginal abatement costs. At equilibrium of the trading scheme, the environmental effectiveness is reached (Bohm, 1992; Hoel, 1993); and the cost effectiveness can be also assured if permits are traded in a perfectly competitive market (Dales, 1968; Montgomery, 1972; Tietenberg, 1985).

At international level, in contrast, countries may choose their permits according to self-interest because no central authority has the power to determine emission cap and permit allocation. Helm (2003) develops a sequential game of IET to analyze the implications of self-interest oriented permit choices, and concludes that IET does not necessarily reduce the total emissions. Holtsmark and Sommervoll (2012) extend Helm's (2003) paper by analyzing a game of IET with multiple trading firms in each country, and conclude that IET leads to increased emissions and reduced efficiency. Following Helm (2003), Carbone et al. (2009) construct a sequential game along with a numerical simulation to analyze the stability and environmental outcome of global and sub-global IET coalitions. They show that a stable coalition tends to be sub-global, and a sub-global IET involving developed and developing countries can lead to a lower level of global emissions. This result highlights the significance of the developing countries' participation in IET.

The IET with expanding participation that consists of industrialized and developing countries in the post-Kyoto period has drawn considerable attention after the Conferences of Parties in Copenhagen. Helm and Pichler (2012) construct a non-cooperative IET game to analyze the developed countries' technology transfers effects on participants' permit endowments choice and welfare. Their conclusion shows that welfare is determined by the industrialized countries' technology transfers levels. Greaker and Hagem (2013) construct a non-cooperative sequential game of IET with a numerical example to emphasize the industrialized countries' strategic research and development (R&D) investment in developing countries. They attribute high integrated emissions reduction and welfare in the IET to industrialized countries' strategic investment.

The above literature places a special focus on the interaction among industrialized and developing countries, but neglects the Annex-1 countries' optimal behavior in an intertemporal IET. Committing themselves to the greenhouse gases (GHGs) reductions in the Kyoto Protocol, the Annex-1 countries' abatement experience can help them to abate GHGs more efficiently in the post-Kyoto period, consequently reducing their abatement costs, i.e., the learning-by-doing (LBD) effect. The higher the abatement levels in the Kyoto period, the lower the abatement costs in the post-Kyoto period. Accounting for the intertemporal LBD effect is relevant to the studies on the post-Kyoto climate pact, because this effect is a significant factor determining the equilibrium of IET.

Given the above, this paper aims at analyzing the cost effectiveness and environmental efficiency of an intertemporal IET with the presence of the LBD effect. A two-period, two-stage game is developed. Players in the first period are the Annex-1 countries, and those in period 2 are the Annex-1 and non Annex-1 countries. Similar to Helm (2003), we model an IET scheme in each period using a two-stage game, in which countries joining the IET scheme choose their optimal caps and emissions sequentially so as to minimize their respective total costs. However, unlike the branch literature following Helm (2003), we construct a two-period intertemporal IET with the presence of the LBD effect. In addition, we consider two cases of the Annex-1 countries' objective functions in the first (Kyoto) period. In the farsighted case, the Annex-1 countries minimize the net present-value cost, i.e., the sum of costs in the Kyoto period and discounted costs in the post-Kyoto period. In the shortsighted case, the Annex-1 countries consider only the costs in the Kyoto period.

The results derived from our game-theoretic analysis are summarized as follows. First, in the farsighted case, the cost effectiveness of IET in the Kyoto period will not be reached even under a perfectly competitive market structure, and the main reason is the externalities from LBD effects. This conclusion is different from the current works which indicate that a perfectly competitive market structure can ensure the cost effectiveness of IET (e.g. Criqui et al., 1999; Weyant, 1999; Evans, 2003; Helm, 2003; Amato and Valentini, 2011, Holtsmark and Sommervoll, 2012; Habla and Winkler, 2013; Greaker and Hagem, 2013). Second, the Annex-1 countries' abatement decisions in the Kyoto period can affect the permit price in the post-Kyoto period. If an Annex-1 country has higher abatements (lower emissions) in the Kyoto period, then she enjoys significant cost reduction from LBD. Hence in the post-Kyoto period, the country will have lower permit demand, consequently leading to a lower permit price. The potential for a reduction in the permit price is also shown in Greaker and Hagem (2013), but the cause for such a reduction in their work is the R&D investment in the industrialized countries. Finally, as compared with the shortsighted benchmark, the farsighted Annex-1 countries that enjoy gross LBD advantage have incentive to abate more in the Kyoto period.

To obtain more concrete insights into global emissions and countries' costs in each period, a numerical application of our game-theoretical model is conducted. The results show that, as compared with the shortsighted case, the global emissions in the farsighted case are lower. The Annex-1 countries' farsightedness also helps to reduce all countries' costs in the post-Kyoto period.

The remainder of this paper is organized as follows. Section 1 introduces the basic settings of our intertemporal IET model and derives countries' respective optimal behaviors. Section 2 provides a numerical application of the theoretical model. Finally, conclusions are drawn in the last section.

1. Game-theoretical model of intertemporal IET

Consider a partial equilibrium model of global externalities from carbon emissions. Time is divided into two periods, indexed by $t = 1, 2$, i.e., the Kyoto period prior to 2012 (period 1) in which only the Annex-1 countries commit to abatement; and the post-Kyoto period (period 2) in which all countries are required to commit themselves to carbon mitigation. The world economy consists of N countries indexed by $n = 1, \ldots, N$, among which the first I $(< N)$ countries are the Annex-1 countries indexed by $i = 1, ..., I$; and the rest $(N - I)$ countries are non Annex-1 countries indexed by $j = (I+1), \ldots, N$. All countries suffer from damage caused by carbon emissions, and the damage costs differ across countries. Let $D_n(E_t)$ be country n's damage cost associated with total accumulated emission level E_t in period t. The country's marginal damage cost, $D_n'(E_t)$, is positive and non-decreasing, i.e., $D_n'(E_t) > 0$ and $D_n''(E_t) \geq 0$ for $n = 1, \ldots, N$ and all $E_t \geq 0$.

To alleviate the damage from carbon emissions, a climate pact with an IET scheme is developed. Each of the participating countries has to commit to an emission cap. They could meet their respective emission caps by either own abatements or permits trading under price p_t in the IET scheme. Let w_{nt} and C_{nt} respectively be country n's cap and abatement cost in period t, where C_{nt} is a decreasing and convex function of country n's actual emission e_{nt}, i.e., $C_{nt}'(e_{nt}) < 0$ and $C_{nt}''(e_{nt}) > 0$ for $n = 1, \ldots, N$ and all $e_{nt} \geq 0$. If $e_{nt} > (<) w_{nt}$, country n purchases (sells) permits in period t. The permit price in period t (p_t) is determined by the associated market-clearing condition. The total accumulated emissions E_t in period t are equal to the sum of countries' emissions by period t, that is, $E_1 = B_0 + \sum_{i=1}^{I} w_{i1} + \sum_{j=I+1}^{N} \bar{b}_{j1}$ and $E_2 = \sum_{n=1}^{N} w_{n2} + E_1$, where B_0 is the accumulated emissions prior to the Kyoto period, and $\bar{b}_{j1}$ is the non Annex-1 country j' business-as-usual (BAU) emissions in period 1.

The Annex-1 countries' abatement activities in period 1 yield LBD effects that reduce their respective abatement costs in period 2. Let $R_i(e_{i1})$ capture the direct effect of cost reduction from LBD, where $0 < R_i(e_{i1}) < 1$. Accordingly, each Annex-1 country i's abatement cost in period 2 is given by $C_{i2}(e_{i2})R_i(e_{i1})$. The higher the abatement levels (lower emissions) in period 1, the lower the abatement cost in period 2. Hence assume that $R_i'(e_{i1}) > 0$. Assume that each of the countries has the objective to minimize her cost associated with carbon emissions, which consists of damage cost, abatement cost and permit-trading expenditure. For Annex-1 country i, the cost pertained to period t $(t=1, 2)$ is $TC_{it} = D_i(E_t) + A_{it}(e_{it}) + p_t\,(e_{it} - w_{it})$, where $A_{it}(e_{it})$ is the abatement cost with $AC_{i1}(e_{i1}) = C_{i1}(e_{i1})$ and $AC_{i2}(e_{i2}) = C_{i2}(e_{i2})R_i(e_{i1})$. For non Annex-1 country j, the cost in period 2 is $TC_{j2} = D_j(E_2) + C_{j2}(e_{j2}) + p_2\,(e_{j2} - w_{j2})$.

Our intertemporal IET game proceeds as follows. In the Kyoto period, the Annex-1 countries respectively decide permits in stages 1 and emissions in stage 2. The equilibrium permit price is then determined based on market-clearing condition. In this period, two cases of the Annex-1 countries' objective functions are considered. In the farsighted case, each Annex-1 country i selects her caps and emissions sequentially to minimize the net present-value cost, i.e., the sum of cost in period 1 and discounted cost in period 2, $TC_{i1} + \delta \cdot TC_{i2}$, where $\delta \in (0, 1)$ is the discount factor. In the shortsighted case, each Annex-1 country i consider only the cost in the Kyoto period, TC_{i1}. Next, in the post-Kyoto period of expanding participation, both of the Annex-1 and non Annex-1 countries join the IET system. Each country n determine permits in stages 1 and emissions in stage 2 to minimize her cost TC_{n2}. The equilibrium permit price is then solved using the market-clearing condition. Table 1 summarizes countries' objective functions and choice variables. The sub-game perfect equilibrium (hereafter SPE) of this game is derived by backward induction as follows.

Table 1. Countries' objective functions and choice variables in the IET game

Period and stage	Countries making decisions	Objective functions		Choice variables
		Farsighted case	Shortsighted case	
Period 1 Stage 1	Annex-1 countries	$TC_{i1} + \delta \cdot TC_{i2}$	TC_{i1}	w_{i1}
Period 1 Stage 2	Annex-1 countries	$TC_{i1} + \delta \cdot TC_{i2}$	TC_{i1}	e_{i1}
Period 2 Stage 1	Annex-1 countries and non Annex-1 countries	TC_{n2}	TC_{n2}	w_{n2}
Period 2 Stage 2	Annex-1 countries and non Annex-1 countries	TC_{n2}	TC_{n2}	e_{n2}

Now begin with the game in period 2 where all countries interact strategically in an IET scheme. The second stage regarding the optimal choice of emissions is firstly solved. In this stage, all countries have chosen their emission caps $\{w_{12},..., w_{N2}\}$, and the associated damage to country n is fixed at $D_n(E_2)$. Given permit price p_2, emission caps $\{w_{12},..., w_{N2}\}$, and emissions $\{e_{11},..., e_{I1}\}$ in period 1, each Annex-1 country i chooses optimal emissions e_{i2}^* to minimize her cost:

$$\min_{e_{i2}\geq 0}\ D_i(E_2) + C_{i2}(e_{i2})R_i(e_{i1}) + p_2\,(e_{i2} - w_{i2}),\quad i = 1,\ldots,I. \tag{1}$$

The first-order conditions for interior solutions e_{i2}^* are

$$-C_{i2}'(e_{i2}^*)R_i(e_{i1}) = p_2,\ i = 1,\ldots,I. \tag{2}$$

Each non Annex-1 country j has an objective function like (1) except the absence of the cost reduction effects from LBD. The associated first-order conditions for interior solutions e_{j2}^* are

$$-C_{j2}'(e_{j2}^*) = p_2,\ j = (I+1),\ldots,N. \tag{3}$$

The second-order conditions hold because $C_{n2}''(e_{n2}) > 0$ for $n = 1,.., N$ and all $e_{n2} \geq 0$. Equations (2) and (3) suggest that both types of countries adjust their respective emissions until marginal abatement cost equals permit price. The equations are referred to as the global cost effective conditions. The equations implicitly define individual countries' demand functions for permits, which are negatively sloped, i.e., $e_{i2}^* = e_{i2}^*(p_2, e_{i1}) =$ $= [-1/C_{i2}''(e_{i2}^*)R_i(e_{i1})] < 0$ with $\partial e_{i2}^*/\partial p_2$, and $e_{j2}^* = e_{j2}^*(p_2)$ with $\partial e_{j2}^*/\partial p_2 = [-1/C_{j2}''(e_{j2}^*)] < 0$.

Equilibrium permit price p_2^* can be solved by substituting $e_{i2}^* = e_{i2}^*(p_2, e_{i1})$ and $e_{j2}^* = e_{j2}^*(p_2)$ into the market-clearing condition. That is,

$$\sum_{i=1}^{I} e_{i2}^*(p_2^*, e_{i1}) + \sum_{j=I+1}^{N} e_{j2}^*(p_2^*) = \sum_{n=1}^{N} w_{n2}. \tag{4}$$

Equation (4) indicates that equilibrium permit price p_2^* is affected by the Annex-1 countries' emissions in period 1 $\{e_{11},..., e_{I1}\}$ and all countries' emission caps in period 2 $\{w_{12},..., w_{N2}\}$, i.e., $p_2^* = p_2^*(e_{11},..., e_{I1}; w_{12},..., w_{N2})$ with $\frac{\partial p_2^*}{\partial w_{n2}} < 0$, and $\frac{\partial p_2^*}{\partial e_{i1}} > 0$, $i = 1,\ldots,I$, and

$$n = 1,\ldots, N\,. \tag{5}$$

Accordingly, country n's optimal emissions in period 2 can be expressed as $e^*_{n2} = e^*_{n2}(e_{11},\ldots,e_{I1}; w_{12},\ldots,w_{N2})$ with

$$\frac{\partial e^*_{i2}}{\partial e_{i1}} > 0 \text{ and } \frac{\partial e^*_{n2}}{\partial e_{i1}} < 0,\ n = 1,\ldots, I,,\ n = 1,\ldots, N$$

$$\text{and } n \neq i\,. \tag{6}$$

Proof of (5) and (6) is in the Appendix. The first term in (5) indicates that a higher supply of permits leads to a lower equilibrium permit price. The implications of the other three terms in (5) and (6) are as follows. If Annex-1 country i has lower abatement amounts in period 1 (i.e., higher e_{i1}), the country would have higher abatement costs in period 2 due to a smaller cost reduction effect from LBD. Hence her permit demand in period 2 is higher. Consequently, the equilibrium price increases and other countries' permit demand decreases.

Lemma 1. The Annex-1 countries' abatement levels in the Kyoto period can affect the permit price in the post-Kyoto period. If an Annex-1 country has lower abatement levels (higher emissions) in the Kyoto period, then her permit demand in the subsequent period will increase, consequently leading to a higher permit price.

Next, given e^*_{i2}, all N countries simultaneously and independently choose optimal permits to minimize their respective total costs. The objective functions of the Annex-1 and non Annex-1 countries are respectively

$$\min_{w_{i2} \geq 0}\ D_i(E_2) + C_{i2}(e^*_{i2}) R_i(e_{i1}) + p^*_2\ (e^*_{i2} - w_{i2}),$$
$$i = 1,\ldots, I\text{, and} \tag{7}$$

$$\min_{w_{j2} \geq 0}\ D_j(E_2) + C_{j2}(e^*_{j2}) + p^*_2\,(e^*_{j2} - w_{j2}),$$
$$j = (I+1),\ldots, N\,. \tag{8}$$

Both types of countries have the same equilibrium conditions

$$\frac{\partial p^*_2}{\partial w_{n2}}(e^*_{n2} - w^*_{n2}) - p^*_2 + D'_n(E^*_2) = 0,\ n = 1,\ldots, N\,. \tag{9}$$

Suppose that the second-order conditions hold. Define countries with $D'_n(E^*_2) > p^*_2$ as high-damage countries and $D'_n(E^*_2) < p^*_2$ as low-damage countries. Following (5) and (9), high-damage countries are permit buyers and low-damage countries are permit sellers. The result is consistent with Helm (2003).

Now turn to the game of the Annex-1 countries in period 1. As mentioned before, shortsighted and farsighted cases are explored. In the shortsighted case, the Annex-1 countries consider only the costs in period 1 and neglect the intertemporal LBD effects when choosing permits and emissions. Hence the game in this period is similar to that in period 2. The equilibrium conditions and implications are similar to those in equations (3) and (9).

On the other hand, in the farsighted case, the Annex-1 country i's objective is to minimize the net present-value cost, i.e., the sum of cost in period 1 and discounted cost in period 2, $TC_{i1} + \delta \cdot TC_{i2}$. Again, in this stage, total emissions are fixed, so are damage costs. Thus, an Annex-1 country i's objective function is

$$\min_{e_{i1} \geq 0}\ C_{i1}(e_{i1}) + p_1\,(e_{i1} - w_{i1}) + \delta \cdot TC_{i2},$$
$$i = 1,\ldots, I\,. \tag{10}$$

The corresponding first-order conditions are

$$-C'_{i1}(e^*_{i1}) - \delta \cdot \frac{\partial TC_{i2}(e^*_{11},\ldots,e^*_{I1})}{\partial e_{i1}} = p_1,$$
$$i = 1,\ldots, I\,. \tag{11}$$

Suppose that the second-order conditions hold. Accounting for the intertemporal LBD effects $\delta \cdot \partial TC_{i2}(e^*_{11},\ldots,e^*_{I1}) / \partial e_{i1}$ in the farsighted case, each Annex-1 country i will not follow the cost effective condition of (3) when choosing their optimal emissions. The externality from intertemporal LBD effects distorts the perfectly competitive emissions trading market.

Proposition 1. Intertemporal LBD effect yields externalities that distort the IET market, hence a perfectly competitive IET scheme in the first commitment period might not be cost-effective.

Define countries with $\partial TC_{i2}(e^*_{11},\ldots,e^*_{I1}) / \partial e_{i1} > 0$ as those having gross LBD advantage, and countries with $\partial TC_{i2}(e^*_{11},\ldots,e^*_{I1}) / \partial e_{i1} < 0$ as those having gross LBD disadvantage. Countries with $-C'_{i1}(e^*_{i1}) > p_1$ are defined as high abatement cost countries, and countries with $-C'_{i1}(e^*_{i1}) < p_1$ are defined as low abatement cost countries. Given convexity of the abatement cost function and other things being equal, a country with high abatement costs has higher abatement levels (fewer emissions), and a country with low abatement costs has lower abatement levels (more emissions). Then following (11), countries with gross LBD advantage abate more, and countries with gross LBD disadvantage abate less.

Lemma 2. In the first commitment period, the farsighted Annex-1 countries with gross LBD advantage will abate more.

Equilibrium permit price p_1^* can be solved by substituting $e_{i1}^* = e_{i1}^*(p_1)$ into the market-clearing condition $\sum_{i=1}^{I} e_{i1}^*(p_1^*) = \sum_{i=1}^{I} w_{i1}$. The equilibrium permit price decreases if there is a higher supply of permits, i.e., $\partial p_1^* / \partial w_{i1} < 0$.

Finally, turn to the first stage in period 1. Given e_{i1}^* and permit price p_1^*, each farsighted country i selects optimal permit w_{i1}^* to minimize her total cost. That is,

$$\min_{w_{i1} \geq 0} \; D_i(E_1) + C_{i1}(e_{i1}^*) + p_1^* \; (e_{i1}^* - w_{i1}) + \delta \cdot TC_{i2}. \quad (12)$$

Using (11), the first-order condition of the above problem can be written as

$$\frac{\partial p_1^*}{\partial w_{i1}}(e_{i1}^* - w_{i1}^*) - p_1^* + D_i'(E_1^*) + \delta D_i'(E_2^*) = 0,$$
$$i = 1, \ldots, I. \quad (13)$$

Assume that the second-order conditions hold. Define farsighted countries with $D_i'(E_1^*) + \delta D_i'(E_2^*) > p_1^*$ as high-damage countries and countries with $D_i'(E_1^*) + \delta D_i'(E_2^*) < p_1^*$ as low-damage countries. Then following (13) and $\partial p_1^* / \partial w_{i1} < 0$, high-damage countries are permit buyers and low-damage countries are permit sellers. Because the farsighted Annex-1 countries consider the damage cost in two periods, they are more likely to be high-damage countries and hence permit buyers, ceteris paribus.

Lemma 3. The farsighted Annex-1 countries choose lower permits in the Kyoto period and are more likely to be permit buyers.

3. Numerical application

In the domestic emissions trading system, there is an authority to allocate the permits, hence the abatement target can be assured. At the international level, in contrast, countries choose permits in light of their self interests, and the environmental outcome of the IET scheme is uncertain (Helm, 2003). This section aims at exploring the environmental efficiency of IET by providing a numerical application of our game-theoretical model. In what follows, the settings and data are firstly introduced. Then the global emissions and total costs in the shortsighted and farsighted cases are reported. The associated implications are drawn accordingly.

3.1. The settings and data. Suppose that country n has a quadratic abatement cost function in period t

$$C_{nt}(e_{nt}) = (1/2)\alpha_n(\bar{b}_{nt} - e_{nt})^2, \; n = 1, \ldots, N,$$
$$t = 1, 2, \quad (14)$$

where $\alpha_n > 0$ describes the technological parameter; $\bar{b}_{nt}$ is country n's baseline emission level in period t; and $(\bar{b}_{nt} - e_{nt})$ is country n's abatement level in period t. An Annex-1 country i has direct cost reduction effects from LBD, which is captured by the term $R_i(e_{i1}) = 1/(\bar{b}_{i1} - e_{i1})$. Following the assumption of damage function (i.e., $D_n'(E_t) > 0$ and $D_n''(E_t) \geq 0$) in section 1 and Kennedy and Laplante (2000), we assume that country n's damage function is of linear form, i.e., $D_n(E_t) = \theta_n E_t$, where $\theta_n > 0$ describes the damage parameter and E_t is the accumulated emissions by period t.

In order to highlight the significance of countries/regions in the post-Kyoto period, the world economy is divided into six countries/regions, consisting of Japan, the European Union (EU), the former Soviet Union (FSU), the United States (US), China and the rest of the world (ROW). Among these countries, Japan, the EU and the FSU are the Annex-1 countries; and the US, China and ROW are non Annex-1 countries.

Table 2 summarizes the data adopted in the numerical simulations. Values of the damage parameter θ_n are calibrated based on Carbone et al. (2009). The EU has the highest willingness-to-pay (WTP) for emission reductions, while China has the lowest one. Values of the technological parameter α_n are estimated based on the GTAP-E model (Burniaux and Truong, 2002). The period 1 baseline emission levels $\bar{b}_{n1}$ are taken from the GTAP-E model. The period 2 baseline emission levels $\bar{b}_{n2}$ are computed by multiplying the period 1 baseline emissions levels by the carbon emission growth rate in Dagoumas et al. (2006). These emission levels are measured in millions tons of carbon (MtC).

Table 2. Data used in the numerical analysis

Countries/ regions	θ_n	α_n	$\bar{b}_{n1}$ (MtC)	Growth rate in 10 years (%)	$\bar{b}_{n2}$ (MtC)
Japan	7.50	1.58	304	9.40	332.58
EU	15.00	0.64	932	10.50	1,029.86
FSU	2.50	0.97	588	-11.80	544.49
US	7.50	0.18	1,489	13.80	1,694.48
China	0.20	0.08	753	44.00	1,084.32
ROW	0.50	0.69	2,137	44.00	3,077.28

3.2. Numerical results. Table 3 summarizes countries' abatement levels in the farsighted and the shortsighted cases in period 1. As compared with the shortsighted case, the Annex-1 countries choose higher abatement levels in the farsighted case. The EU, which is the Annex-1 region with the lowest α_n, has the greatest difference in abatement levels between the farsighted case and shortsighted cases.

Table 3 The Annex-1 countries' abatement levels in period 1

Countries/ regions	Abatements (MtC)	
	Farsighted case	Shortsighted case
Japan	6.23	5.27
EU	16.49	13.02
FSU	10.46	8.59
Total amounts	33.18	26.89

Observation 1. All farsighted Annex-1 countries enjoy gross LBD advantage and choose higher abatement levels in the Kyoto period.

Countries' decisions in each period in each case are summarized in Table 4. The emissions and allowances are measured in millions tons of carbon (MtC) and the permit prices are measured in US dollars per ton of carbon. As compared with the shortsighted case, the farsighted Annex-1 countries choose fewer emission allowances in period 1, hence global emissions are lower. In period 2, the countries with lower marginal damage costs choose more emission allowances; while countries with higher marginal damage costs choose fewer. The overall global emission in the farsighted case is much lower than that in the shortsighted case. The above result indicates that countries' farsightedness leads to environmental efficiency of IET in both periods.

Observation 2. The Annex-1 countries' farsightedness leads to environmental efficiency of IET in each period.

Table 5 reports countries' costs in the two cases in each period. Note that the farsighted Annex-1 countries' discounted costs in period 2 are not added in their costs in period 1. As compared with the shortsighted benchmark, the Annex-1 countries' abatement costs in period 1 are much higher in the farsighted case because of higher abatement levels. The higher abatement levels lead to lower accumulated emissions, hence the Annex-1 countries' damage costs are lower than those in the shortsighted case. In period 2, the global total cost and individual countries' damage costs in the farsighted case are lower than those in the shortsighted case.

Observation 3. The Annex-1 countries' farsightedness lowers the total cost associated with global externalities from carbon emissions in the post-Kyoto period.

Conclusions

In this paper we develop a sequential game along with a numerical application to explore the intertemporal interactions among the Annex-1 and non Annex-1 countries in the Kyoto period and the post-Kyoto period. A special attention is paid to the cost reduction effects from LBD. A perfectly competitive IET system in the Kyoto period can be cost-ineffective because of the externalities from LBD. As compared with the shortsighted benchmark, the farsighted Annex-1 countries choose fewer permits in the Kyoto period. In addition, the Annex-1 countries having gross LBD advantage choose higher abatements (lower emissions) in the Kyoto period, consequently leading to a lower permit price in the post-Kyoto period.

Conducting numerical simulation of the intertemporal IET scheme, we obtain further insights into the Annex-1 and non Annex-1 countries' decisions. In the Kyoto period, the Annex-1 countries abate more in the farsighted case than in the shortsighted case. Therefore, they have lower damage costs, and the global emissions are lower. Besides, the Annex-1 countries' farsightedness lowers the total cost in the post-Kyoto period and leads to environmental efficiency of the expanding participation IET.

In our model, we assume that all the Annex-1 countries are unanimously farsighted or shortsighted in the Kyoto period; and that all counties in the world economy participate in an IET scheme in the post-Kyoto period. These assumptions can be relaxed in the future studies by allowing for sub-group farsighted case and sub-group trading in the post-Kyoto period.

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Appendix A

Table 4. Countries’ decisions in each period in each case (Unit: MtC)

Period 1				Period 2		
Farsighted case						
Permit prices	Permit price in period 1: 8.75 ($US/tone)			Permit price in period 2: 5.53 ($US/tone)		
Countries/regions	Emissions	Allowances	Total costs	Emissions	Allowances	Total costs
Japan	298.16	300.98	51,433.49	312.11	198.78	102,803.23
EU	916.46	893.88	103,242.79	895.50	349.99	207,629.15
FSU	578.17	597.93	16,971.02	488.39	663.19	33,227.92
US	-	-	-	1,663.74	1,550.41	102,831.65
China	-	-	-	1,015.15	1,322.48	1,214.09
ROW	-	-	-	3,069.26	3,359.30	5,225.35
Total amounts	1,792.78	1,792.78	1,791.30	7,444.16	7,444.16	452,931.40
Countries/regions	Emissions	Allowances	Total costs	Emissions	Allowances	Total costs
Japan	298.73	300.98	51,433.49	329.08	284.37	103,849.28
EU	918.98	893.88	103,242.79	1,021.21	806.03	208,390.83
FSU	579.41	597.93	16,971.02	538.79	607.74	34,153.69
US	-	-	-	1,663.74	1,619.04	103,932.49
China	-	-	-	1,015.15	1,136.39	2.283.25
ROW	-	-	-	3,069.26	3.183.67	6,295.81
Total amounts	1797.11	1797.11	154,514.88	7,637.23	7.637.23	458,905.35

Table 5. Countries' costs in each period in each case (Unit: million US dollars)

	Period 1 (excluding the costs in period 2)			Period 2		
Farsighted case						
Countries/regions	Damage costs	Trading costs	Abatement costs	Damage costs	Trading costs	Abatement costs
Japan	46,288.36	-24.70	30.67	102,119.56	627.05	56.62
EU	92,576.72	197.61	87.00	204,239.12	3,018.31	371.73
FSU	15,429.45	-172.91	53.08	34,039.85	-967.14	155.21
US	-	-	-	102,119.56	627.04	85.05
China	-	-	-	2,723.19	-1,700.46	191.36
ROW	-	-	-	6,807.97	-1,604.97	22.19
Total amounts	154,294.53	0.00	170.75	452,049.25	0.00	882.16
Shortsighted case						
Japan	46,320.86	-22.40	21.97	103,600.09	247.35	1.84
EU	92,641.71	179.17	54.25	207,200.18	1,190.64	1.84
FSU	15,440.29	-156.77	35.80	34,533.36	-381.51	1.84
US	-	-	-	102,600.09	247.35	85.05
China	-	-	-	2,762.67	-670.78	191.36
ROW	-	-	-	6,906.67	-633.05	22.19
Total amounts	154,402.86	0.00	112.02	458,603.05	0.00	304.11

Appendix B. Proof

In this Appendix, we show the comparative statistic results in equations (5) and (6). Denote J the Hessian matrix of the $N+1$ in equations (2), (3) and the market-clearing condition as

$$J = \left[\begin{array}{cccc|cccc|c} C''_{12} & 0 & \cdots & 0 & 0 & \cdots & \cdots & 0 & 1 \\ 0 & C''_{22} & \cdots & \vdots & \vdots & \cdots & \cdots & \vdots & \vdots \\ \vdots & \cdots & \ddots & 0 & \vdots & \cdots & \cdots & \vdots & \vdots \\ 0 & \cdots & 0 & C''_{I2} & 0 & \cdots & \cdots & 0 & 1 \\ \hline 0 & \cdots & \cdots & 0 & C''_{I+1\,2} & 0 & \cdots & 0 & 1 \\ \vdots & \cdots & \cdots & \vdots & 0 & \ddots & \cdots & \vdots & \vdots \\ \vdots & \cdots & \cdots & \vdots & \vdots & \cdots & \ddots & 0 & \vdots \\ 0 & \cdots & \cdots & 0 & 0 & \cdots & 0 & C''_{N2} & 1 \\ \hline 1 & \cdots & \cdots & 1 & 1 & \cdots & \cdots & 1 & 0 \end{array}\right], \quad \text{(A1)}$$

given $C''_{n2}(e^*_{n2}) > 0$, $n = 1, \dots, N$.

The determinant of the Hessian matrix is $|J| = -\left(\sum_{s=1}^{N} \prod_{n \neq s} C''_{n2}(e^*_{i2})\right) < 0$. Applying Crammer's rule, we acquire the own-effect on emissions,

$$\frac{\partial e^*_{i2}}{\partial e_{i1}} = \left(C'_{i2}(e^*_{i2}) R_i(e_{i1}) + C_{i2}(e^*_{i2}) R'_i(e_{i1})\right) \frac{K_i}{|J|} > 0, \quad \text{(A2)}$$

where $K_i = \left(\sum_{s=1}^{N} \prod_{n \neq s,i} C''_{n2}(e^*_{i2})\right) > 0$, and $C'_{i2}(e^*_{i2}) R_i(e_{i1}) + C_{i2}(e^*_{i2}) R'_i(e_{i1}) < 0$ by assuming that the second period marginal abatement cost dominates marginal LBD effect.

On the other hand, applying Crammer's rule, we obtain the cross-effect on emissions,

$$\frac{\partial e^*_{r2}}{\partial e_{i1}} = \left(C'_{i2}(e^*_{i2}) R_i(e_{i1}) + C_{i2}(e^*_{i2}) R'_i(e_{i1})\right) \frac{K_r}{|J|} < 0, \quad \text{(A3)}$$

where $K_r = (-1)^{2N-1} \prod_{n \neq i,r} C''_{n2}(e^*_{n2})$ and $r \neq i$. Moreover, the impact of the first period emissions on equilibrium permit price is

$$\frac{\partial p_2^*}{\partial e_{i1}} = \left(C'_{i2}(e_{i2}^*) R_i(e_{i1}) + C_{i2}(e_{i2}^*) R'_i(e_{i1}) \right) \frac{K}{|J|} > 0, \tag{A4}$$

where $K = (-1)^{2N+4} \prod_{n \neq i} C''_{n2}(e_{n2}^*)$.

Differentiating the market clearing condition $\sum_{i=1}^{I} e_{i2}^* + \sum_{j=I+1}^{N} e_{j2}^* = \sum_{n=1}^{N} w_{n2}$ with respect to w_{i2} and rearranging yields

$$\frac{\partial p_2^*}{\partial w_{i2}} = \frac{1}{\sum_{u=1}^{I} \frac{\partial e_{u2}^*}{\partial p_2} + \sum_{j=I+1}^{N} \frac{\partial e_{j2}^*}{\partial p_2}} < 0. \tag{A5}$$

Similarly, differentiating the market clearing condition with respect to w_{j2} yields

$$\frac{\partial p_2^*}{\partial w_{j2}} = \frac{1}{\sum_{i=1}^{I} \frac{\partial e_{i2}^*}{\partial p_2} + \sum_{v=I+1}^{N} \frac{\partial e_{v2}^*}{\partial p_2}} < 0. \tag{A6}$$