The Effects of Unilateral Reduction of Greenhouse Gas Emissions on the U.S. Agriculture

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Abstract

This study analyses potential adverse effects of unilateral increase in GHG emission standards. The single good two regions partial equilibrium model of international trade is used to derive and interpret the conditions under which such an increase will lead to a reduction in a total level of GHG emission. We found that improvement in the global GHG emission level will be observed if the response of the home country abatement level is more elastic than that of the foreign country by the factor of the ratio of initial foreign to domestic marginal emission intensities. It is also shown that in the large industry case, the appropriate factor is adjusted by the measure of the relative market influence of two industries. The study concludes that a unilateral reduction in GHG emissions will unlikely lead to the reduction in the total GHG emissions level and may worsen the environmental situation in other regions. An appropriate multilateral agreement that involves producers from the major emitting countries is required to achieve the goal.

1 Introduction

Since the Kyoto Protocol was negotiated and signed in 1997, 191 nations ratified the agreement committing to a different extent to reduce the greenhouse gas (GHG) emissions over the defined period of time. However, despite of the international efforts, the global level of GHG emissions continued to increase to 29.38 billion tonnes of CO_2 equivalent in 2008 in comparison with 20.34 billion tonnes of CO_2 equivalent in 1990

(International Energy Agency 2010). Only about 27% of the world GHG emissions are contributed by the Annex I Kyoto parties and this share is decreasing at a persistent rate of approximately 1% per year, while the combined share of China and India grew from 14% to approximately 27% over 1990 – 2008. The U.S. remain one of the biggest pollutant despite the success in reducing the GHG emission intensity from 0.69 to 0.48 kg of CO_2 equivalent per $1 of GDP (see Fig. 3(b)) under its unilateral effort.

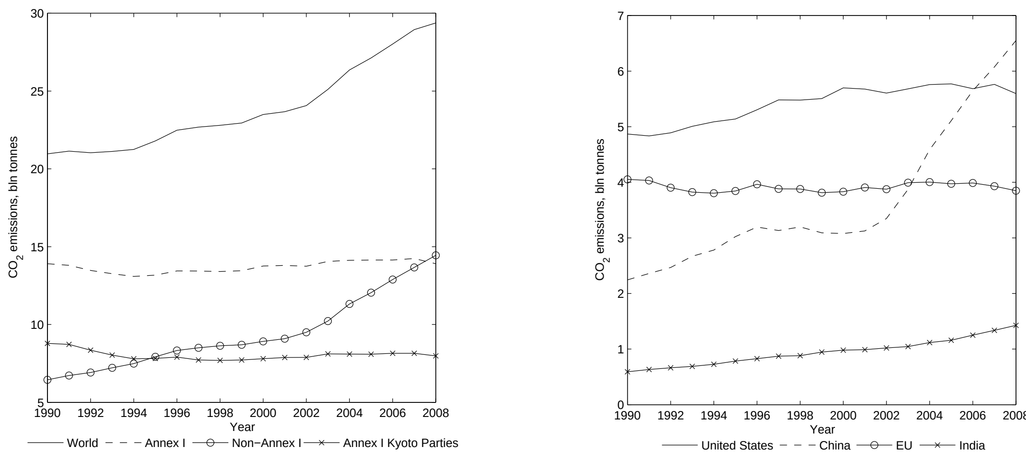

Figure 1: CO_2 emissions by various parties.

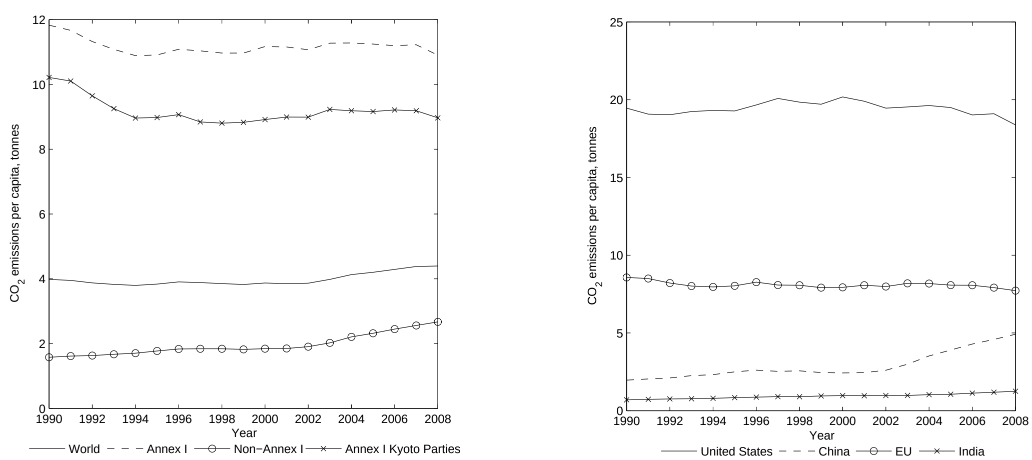

Figure 2: CO_2 emissions per capita by various parties.

Given that the number of countries are effectively outside of the Kyoto agreement or not committed to GHG reduction, the assessing the effects of an unilateral policy

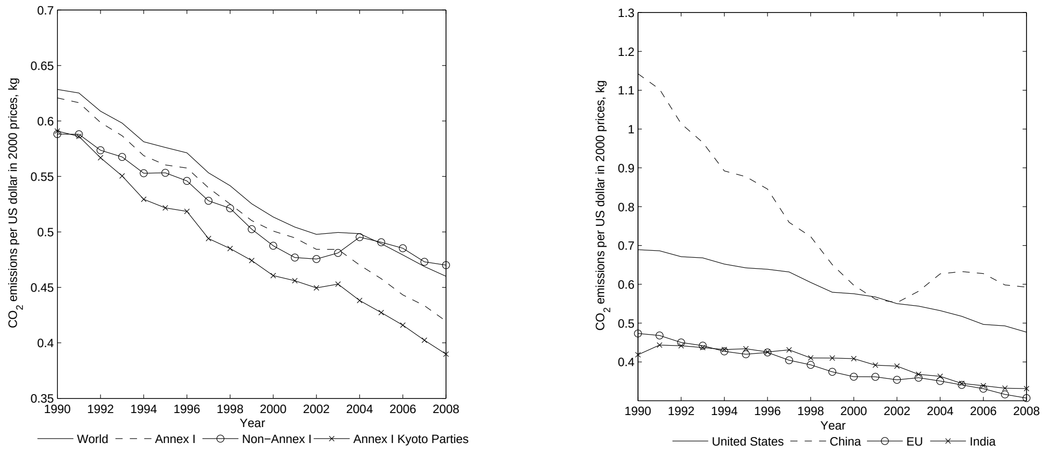

Figure 3: CO_2 emissions per US dollar of GDP by various parties.

of regulating GHG emissions remains an important issue in terms of carbon leakage and global emission level.

Using the general equilibrium model of international trade Copeland and Taylor (2005) found that in an open economy setting the country's best response to the emission reduction in the rest of the world is not defined due to a carbon leakage and depends on the relative strength of free-riding, substitution and income effects. They concluded that it is thus possible for domestic emissions cuts to be an optimal strategy in case of unilateral decrease in foreign emission level.

The recent literature on economics of GHG emissions regulation has strong focus on effects of technology change on production and abatement decisions under globalized trade environment. Assuming that abatement decisions are endogenous, Golombek and Hoel (2004) model research and development activities as a part of environmental policy, which is designed to minimize the total abatement costs. In a static two-country one-product model framework they demonstrate that in a presence of international technology spillovers the effect of a carbon leakage is not necessarily observed. The study demonstrates that it is possible for an increased environmental concern in one country might lead to lower emissions in both countries. Di Maria and van der Werf (2008) suggest that the degree of carbon leakage reported in the current economic literature may be overestimated as it does not take into account the offsetting induced-technology effect created by the incentives to innovate, which reduces carbon leakage.

The studies depend significantly on a variety of underlying assumptions such as the specification of the GHG emission level within the consumer utility function and the mechanism of the spillovers effects that often yields ambiguous conclusions, some of which are sensitive to particular assumption choices made by the authors. Our research is focused on a more general problem of a feasibility of a success of a unilateral policy by concentrating on the industry's production, abatement and trade decisions. We examine, within the proposed model framework, conditions under which the unilateral domestic GHG emission regulation can successfully lead to a global GHG level reduction. Specific questions such as an optimal environmental tax choice and the mechanism of such a choice as well as the particular consumer preferences are beyond the scope of this study as the more specific assumptions are only expected to render the probability of success but not the general rules.

2 The Model

Consider the market for a single good produced in two regions, domestic and foreign, indexed as $i = 1, 2$ correspondingly. Both regions adopt the constant returns to scale technologies that simultaneously generate two types of output: the desired good in quantity q_i and the undesired emissions e_i. To model the possibility of abatement we follow the approach suggested in Copeland and Taylor (2003) and denote $0 \leq \theta_i \leq 1$ to be endogenous fraction of potential production q_i allocated to the abatement activities by the industry in each region and thus foregone from the market. Within the proposed model framework the effect of the choice of θ_i on reduction of emission levels e_i is described as follows:

$$e_i = \varphi_i(\theta_i)q_i \quad i = 1, 2 \tag{1}$$

where $\varphi'(\theta) < 0$, $\varphi''(\theta) > 0$. A higher level of θ reduces the emission intensity $\varphi(\theta)$, however it does so at a decreasing rate making abatement less efficient as more potential output is used. Copeland and Taylor (2003) suggest the choice of abatement function such that $\varphi(0) = 1$ and $\varphi(1) = 0$. The emission function (1) can itself be seen as the production function for the undesired good e_i that requires q_i and θ_i as inputs, implying that q_i can also be treated as the intermediate good. The slope of the isoquant curve can be evaluated by finding the total differential of (1) and setting $de_i = 0$ so that

$$\frac{d\theta_i}{dq_i} = -\frac{\varphi_i}{\varphi_i' q_i} > 0 \tag{2}$$

Assume that $g_i(q_i)$ is the associated cost function, such that $g'(q) > 0$, $g''(q) > 0$. For further analysis each industry profit π_i is defined in terms of the intermediate output q_i as

$$\pi_i = px_i - g_i(q_i) - \tau_i e_i(q_i, \theta_i) \quad i = 1, 2 \tag{3}$$

where $x_i = (1 - \theta_i)q_i$ is the net production level and τ_i is per unit emission tax set exogenously by the government in each nation. Similarly to (1) $x(\theta_i, q_i)$ can be approached as the production function for the final product x_i, where intermediate product q_i and the abatement level θ_i are the complementary inputs as defined by the isoquant slope

$$\frac{d\theta_i}{dq_i} = \frac{1 - \theta_i}{q_i} > 0 \tag{4}$$

The world price p is defined by the aggregate demand function

$$p = p(x_1 + x_2) \tag{5}$$

such that $p(x)' < 0$ and $p(x)'' > 0$, that serves as the market clearing condition and closes the model. Given the market size constraint, each nations's industry seeks to maximize its profit by choosing the level of production q_i and abatement activities θ_i conditional on the emission reduction effect defined by the abatement technology function $\varphi_i(\theta_i)$. We assume that the emissions taxation level is not prohibitive, and $q_1 > 0$ and $q_2 > 0$ for any feasible change in the values of the exogenous parameters of the model. Since we are only interested in interior solutions for production levels, the corresponding optimal conditions for profit maximization can be obtained from (3) as

$$(1-\theta_i)(p'x_i + p) - g_i' - \tau_i\varphi_i = 0 \quad \text{for} \quad x_i > 0 \qquad i = 1, 2 \tag{6}$$

Because the abatement parameters θ_1 and θ_2 are constrained, the optimal conditions for optimal abatement decisions can be obtained by solving the corresponding mixed complementarity optimization problem in (3) that yields the following set of equations:

$$q_i(p'x_i + p) + \tau_i\varphi_i' q_i \leq 0 \perp \theta_i = 1 \tag{7a}$$

$$q_i(p'x_i + p) + \tau_i\varphi_i' q_i = 0 \perp 0 \leq \theta_i \leq 1 \tag{7b}$$

$$q_i(p'x_i + p) + \tau_i\varphi_i' q_i \geq 0 \perp \theta_i = 0 \tag{7c}$$

The term g_i' captures indirect effect of abatement activities on the production costs of the net output x_i, which is negative in case of increase in θ_i. Even though the abatement decision does not enter the intermediate product cost function g_i directly, an increase in the proportion of the potential output $\theta_i q_i$ that is used for abatement activities and thus diverted from the market makes production of the every additional unit of the final good more expensive since it requires a larger quantity of the intermediate good as an input. In terms of the intermediate output q_i, the adverse effect of an increase in θ_i is reflected in the decrease in the potential marginal market revenue measured as $p\theta_i$ which is equivalent to the increase in the marginal opportunity cost. The indirect effect of the abatement decision on the production costs is balanced by the change in the emission costs burden through the change in the intensity of emission demonstrated by the expression $\tau_i \varphi_i' \propto d(\varphi_i)$.

For sufficiently small τ_i the complementarity condition (7c) suggests that the optimal level of coefficient θ_i is equal to zero, implying that there is no incentive to comply with the regulation since the marginal costs of running the abatement activities exceed the marginal benefits from the corresponding emission tax payment reduction. When no regulation is enforced, $\tau_i = 0$, (7c) is guaranteed to hold. On contrary, according to (7a) as τ_i grows the regulation of industrial emissions reaches eventually its prohibitive level leaving no incentive to stay on the market since all the resources are diverted to the abatement activities. If both regions enforce their emission regulations by choosing the emission taxation level $0 < \tau_i \ll \infty$ the proportion of net output q_i used for abatement activities will lie within the unit interval $(0, 1)$ since there is no incentive to neither avoid reducing the emissions completely nor to stop the production. In this case only condition (7b) is effective for each region.

3 Analysis of unilateral domestic policy change

Assume that the region 1 makes a commitment to reduce the industrial emissions by increasing the emission taxation level by an amount $d\tau_1$, while policy remains the same in the region 2. If the domestic industry is too small to influence the world price then the unilateral change in τ_1 will lead to no change in the aggregate demand x^* since the world price remains effectively fixed. Under $dp = 0$ the demand constrained requires that $dx_1 = -dx_2$. Assuming both regions enforce their environmental policy on some non prohibitive level, such that $0 < \tau_1 \ll \infty$ and $0 < \tau_2 \ll \infty$, the model equilibrium can be described by using equations (6) and (7b) along with the demand constraint and collecting the terms as

$$g_1' - p(1-\theta_1) + \tau_1\varphi_1 = 0 \tag{8}$$

$$p + \tau_1\varphi_1' = 0 \tag{9}$$

$$x_1 + x_2 = x^* \tag{10}$$

$$p'x_2 + p + \tau_2\varphi_2' = 0 \tag{11}$$

To facilitate the further analysis the total differentials of equations (8) and (9) with respect to q_1, θ_1 and τ_1 are obtained as:

$$g_1''dq_1 + (p + \tau_1\varphi_1')d\theta_1 = -\varphi_1 d\tau_1 \tag{12}$$

$$\tau_1\varphi_1''d\theta_1 = -\varphi_1' d\tau_1 \tag{13}$$

Due to a price taking behaviour of the home country, equation (13) can be directly solved for appropriate multiplier that describes the effect of unilateral change in τ_1

on domestic abatement decision θ_1 in a small open economy

$$\frac{d\theta_1}{d\tau_1} = -\frac{\varphi_1'}{\tau_1\varphi_1''} > 0 \tag{14}$$

Note that the effect of $d\theta_1$ is zeroed out in (12) due to optimality requirement (9), implying the independence of production and abatement decisions under small industry assumption within the proposed model framework, since $\frac{\partial^2\pi_1}{\partial q_1\partial\theta_1} = \frac{\partial^2\pi_1}{\partial\theta_1\partial q_1} = 0$. Therefore (12) can as well be directly solved for dq_1 to get

$$\frac{dq_1}{d\tau_1} = -\frac{\varphi_1}{g_1''} < 0 \tag{15}$$

Using the definition of the net production level x the corresponding change in the domestic market output level is

$$dx_1 = (1-\theta_1)dq_1 - q_1 d\theta_1 = \frac{q_1\varphi_1' g_1'' - (1-\theta_1)\tau_1\varphi_1\varphi_1''}{\tau_1\varphi_1'' g_1''} < 0 \tag{16}$$

Note that although the home country equilibrium change is completely described by the changes in domestic supply and abatement activities and the small country assumption can't influence the world price, the demand restriction (11) implies that the appropriate reduction in x_1 has to be compensated by an increase in the net output for region 2, since $dx_2 = -dx_1$. In this situation the foreign industry may also have an incentive to adjust it's own abatement ratio θ_2, reflecting an indirect effect of $d\tau_1 > 0$ that can be evaluated using the total differentials of the optimality conditions (10) and (11) as

$$\frac{d\theta_2}{d\tau_1} = \frac{(p''x_2 + 2p')}{\tau_2\varphi_2''}\frac{\partial x_1}{\partial\tau_1} > 0 \tag{17}$$

However, since the change in x_2 is insignificant, $p''x_2 + 2p' \simeq 0$ and therefore $\frac{d\theta_2}{d\tau_1} = 0$ (which is equal to zero if region 2 industry is also small). Indeed, since both marginal costs and marginal benefits of foreign abatement activities (estimated per unit of potential output q_i) remain unchanged due to the constant price and no change in foreign GHG emission regulation, there is no incentive to neither increase nor decrease θ_2. Hence $dx_2 = dq_2 > 0$.

Let ψ denote the emission intensity per unit of market output x, so that

$$\psi_i = \frac{\varphi_i}{1-\theta_i} > 0 \quad \text{and} \quad d\psi_i = \frac{1}{(1-\theta_i)^2}(\varphi_i + \varphi_i'(1-\theta_i))d\theta_i \tag{18}$$

where $\varphi_i + \varphi_i'(1-\theta_i) \leq 0$ by convexity of φ_i. Note, that an improvement in abatement technology used by the industry implies that the same marginal emission level φ can be achieved at a lower level of abatement activities requiring smaller portion of the potential output due to the higher curvature of the new abatement function φ_i^*. In this case,

$$\frac{\varphi_i^*(\theta_i^*)}{1-\theta_i^*} < \frac{\varphi_i^o(\theta_i^o)}{1-\theta_i^o} \tag{19}$$

where $\varphi_i^*(\theta_i^*) = \varphi_i^o(\theta_i^o)$ and $\theta_i^* < \theta_i^o$. By the definition of the net output emission intensity (18) we have $\psi_i^* < \psi_i^o$ implying that an abatement technology improvement leads to reducing the level of marginal level of net output emissions ψ.

Given the emission function (1) the total change in domestic emission E_1 due to the unilateral increase in the taxation level $d\tau_1$ is

$$dE_1 = \psi_1 dx_1 + \frac{x_1}{(1-\theta_1)^2}(\varphi_1 + \varphi_1'(1-\theta_1))d\theta_1 = \psi_1 dx_1 + x_1 d\psi_1 < 0 \tag{20}$$

Let us denote

$$\eta_i = \frac{d\psi_i}{dx_i}\frac{x_i}{\psi_i} > 0 \tag{21}$$

to be the elasticity of the emission intensity ψ with respect to the net production level x. Then (20) can be expressed in terms of η as

$$dE_1 = \psi_1 dx_1 + x_1 d\psi_1 = \psi_1(1+\eta_1)dx_1 < 0 \tag{22}$$

Note that for region 2, $d\psi_2 = 0$, therefore $\eta_2 = 0$ and

$$dE_2 = \psi_2 dx_2 + x_2 d\psi_2 = \psi_2 dx_2 > 0 \tag{23}$$

Using the definitions provided above the necessary condition for successful reduction in the global level of GHG are described in the form of the following Theorem:

Theorem 3.1 (Necessary Condition) *In small country case a unilateral increase in τ_1 will lead to reduction in total level of GHG emissions if and only if the following holds*

$$1 + \eta_1 \geq \delta \tag{24}$$

where $\delta = \frac{\psi_2}{\psi_1}$.

Proof Under the small industry assumption $dx_1 = -dx_2$. Let us assume that at the initial equilibrium the home country industry employs the technology such that $\delta\psi_1 = \psi_2$ for some $\delta > 0$. Combining this assumption with (22), (23) and the demand restriction yields an equation for the effect of unilateral increase of domestic emission taxation on the aggregate emission level for both regions as

$$\frac{dE}{d\tau_1} = \frac{dE_1}{d\tau_1} + \frac{dE_2}{d\tau_1} = \psi_1(1+\eta_1)\frac{dx_1}{d\tau_1} + \psi_2\frac{dx_2}{d\tau_1} = \psi_1(1+\eta_1-\delta)\frac{dx_1}{d\tau_1} \tag{25}$$

Examining (25) suggests that the total emission level will not increase if and only if the following condition holds

$$1 + \eta_1 \geq \delta \tag{26}$$

for small country case. $\blacksquare$

Intuitively Theorem 3.1 suggests that domestic emission function needs to be elastic enough at the initial equilibrium level of θ_1 to be able to compensate for the corresponding change in the net output and the resulting increase in the foreign GHG emission level given the difference in the initial emission intensities in two regions. In a particular case that $\tau_1 > 0$ and $\tau_2 = 0$ (the foreign industry is not regulated) Theorem 3.1 requires that

$$1 + \eta_1 \geq \delta \quad \text{where} \quad \delta = \frac{1}{\psi_1} \tag{27}$$

for the desired improvement in emission level, since $\theta_2 = 0$ and $\psi_2 = 1$. As discussed in the previous section the absence of GHG regulation or, more specifically, regulation enforcement leaves no incentives to intensify the abatement activities beyond 0 leading to the highest possible emission intensity level ψ_2 and therefore the largest possible difference δ given the domestic abatement level and technology available in both regions. As the result, significantly bigger efforts by domestic industry are required to compensate for increasing foreign GHG emissions to achieve the success.

Here, and in our further analysis of unilateral regulation policy, the relative size of the initial emission intensities as measured by a parameter δ proved to be crucial. The following result based on the particular combinations of the initial values of ψ_1 and ψ_2 provides an important additional insight on the viability of unilateral actions in the area of the GHG emission regulation:

Corollary 3.2 (Sufficient Condition) *Under assumptions of Theorem 3.1* $\psi_1 >$

ψ_2 is the sufficient condition for reduction in total level of GHG emissions in case of the unilateral increase in τ_1. Converse is not necessarily true.

Proof By definition, $\psi_1 > \psi_2$ implies $\delta < 1$. Using the fact that $\eta \geq 0$ yields the corresponding lower bound for condition for successful reduction in total GHG emission level,

$$1 + \eta_1 \geq 1 \tag{28}$$

Hence (26) is guaranteed if $\psi_1 > \psi_2$. However, the upper bound is always greater or equal 1 and therefore $\psi_1 < \psi_2$ is not sufficient for increase in total level of GHG emissions. ∎

If the abatement technology diffusion is possible, it is expected that the emission intensities in both regions will converge to the level which is lower of the two, as discussed in the previous section. In the light of the Theorem 3.1 such an outcome implies that the assumed gap will decrease so that $\delta = 1$ reducing possible carbon leakage by the factor δ (see eq. (23)) and improving the chance of reducing the global level of GHG emissions. Furthermore, if the abatement technology diffusion is perfect, i.e. $\psi_1 = \psi_2$, the success of the unilateral domestic policy is guaranteed by the conclusion of Corollary 3.2.

When both countries have market power the analysis becomes more complex as both the world price and demand are going to react to the unilateral domestic emission policy change accordingly in order to adjust to the new equilibrium. Differentiating the profit functions for both industries and collecting the terms yields the following set of equations that describe the Cournot type optimality conditions for large country case,

$$g_1' + (1-\theta_1)\tau_1\varphi_1' + \tau_1\varphi_1 = 0 \tag{29}$$

$$p'x_1 + p + \tau_1\varphi_1' = 0 \tag{30}$$

$$g_2' + (1-\theta_2)\tau_2\varphi_2' + \tau_2\varphi_2 = 0 \tag{31}$$

$$p'x_2 + p + \tau_2\varphi_2' = 0 \tag{32}$$

Again the total differentiation of (29) – (32) is required in order to evaluate the effect of $d\tau_1 > 0$ on q_1, θ_1, q_2 and θ_2 given $d\tau_2 = 0$. Let $a_i = p''x_i + 2p' < p''x_i + p' < 0$ and $b_i = \tau_i\phi_i'' > 0$. Then, in the matrix notation, the result can be represented as $\mathbf{A\Gamma} = \lambda$, where

$$\mathbf{A} = \begin{pmatrix} g_1'' & b_1(1-\theta_1) & 0 & 0 \\ (1-\theta_1)a_1 & -q_1a_1 + b_1 & (1-\theta_2)(a_1 - p') & -q_2(a_1 - p') \\ 0 & 0 & g_2'' & b_2(1-\theta_2) \\ (1-\theta_1)(a_2 - p') & -q_1(a_2 - p') & (1-\theta_2)a_2 & -q_2a_2 + b_2 \end{pmatrix}$$

$$\mathbf{\Gamma} = \begin{pmatrix} dq_1 \\ d\theta_1 \\ dq_2 \\ d\theta_2 \end{pmatrix} \quad \text{and} \quad \lambda = \begin{pmatrix} -(\varphi_1 + \varphi_1'(1-\theta_1))d\tau_1 \\ -\varphi_1' d\tau_1 \\ 0 \\ 0 \end{pmatrix}$$

Using the results of appendix A, the effect of the change in emission tax level τ_1 on production and abatement decisions can be evaluated by the Cramer's rule as

$$\frac{dq_1}{d\tau_1} = \frac{\det \mathbf{A}_{q_1}}{\det \mathbf{A}} \lesseqgtr 0 \quad \text{and} \quad \frac{dq_2}{d\tau_1} = \frac{\det \mathbf{A}_{q_2}}{\det \mathbf{A}} > 0 \tag{33}$$

and

$$\frac{d\theta_1}{d\tau_1} = \frac{\det \mathbf{A}_{\theta_1}}{\det \mathbf{A}} > 0 \quad \text{and} \quad \frac{d\theta_2}{d\tau_1} = \frac{\det \mathbf{A}_{\theta_2}}{\det \mathbf{A}} < 0 \tag{34}$$

Equations (33) and (34) indicate that the qualitative effects are similar to the small industry case. However, the effect of increase in domestic tax τ_1 on intermediate production decision of home industry is ambiguous and depends on the relative strength of tax burden and price change prior to the new policy introduction which defines the sign of $b_1 - a_1 q_1$. In the case that the latter quantity is positive, $dq_1 < 0$ since the effect of the tax increase is dominant.

$$\begin{aligned}\frac{dx_1}{d\tau_1} &= \frac{(1-\theta_1)\det \mathbf{A}_{q_1} - q_1 \det \mathbf{A}_{\theta_1}}{\det \mathbf{A}} \\ &= \frac{(\varphi_1' g_1'' q_1 - \varphi_1 b_1 (1-\theta_1))\left[g_2'' b_2 - a_2\left(g_2'' q_2 + b_2(1-\theta_2)^2\right)\right]}{\det \mathbf{A}} < 0\end{aligned} \tag{35}$$

similarly,

$$\begin{aligned}\frac{dx_2}{d\tau_1} &= \frac{(1-\theta_2)\det \mathbf{A}_{q_2} - q_2 \det \mathbf{A}_{\theta_2}}{\det \mathbf{A}} \\ &= \frac{(\varphi_1' g_1'' q_1 - \varphi_1 b_1 (1-\theta_1))(a_2 - p')\left(g_2'' q_2 + b_2(1-\theta_2)^2\right)}{\det \mathbf{A}} > 0\end{aligned} \tag{36}$$

Note that in general $dx_1 \neq dx_2$, i.e. $dx_2/dx_1 \neq 1$, due to the difference in the response of supply to the price change in each of the regions. However, based on (35) and (36) it can be shown that $-1 \leq dx_2/dx_1 \leq 0$. For convenience, let ϵ denote the elasticity of reaction of region 2 market output to such of region 1

$$\epsilon = -\frac{dx_2}{dx_1}\frac{x_1}{x_2} > 0 \tag{37}$$

As in the small industry case, the necessary conditions for the reduction in the global level of GHG emissions can be stated in the form of the following Theorem:

Theorem 3.3 (Necessary Condition) *In large country case a unilateral increase in τ_1 will lead to reduction in total level of GHG emissions if and only if the following holds*

$$\frac{1+\eta_1}{1+\eta_2} \geq \delta\epsilon\frac{s_2}{s_1} \tag{38}$$

where $\delta = \frac{\psi_2}{\psi_1}$.

Proof Using the definitions (21) and (37) the total change in the emission level due to the unilateral increase in the domestic emission regulation can be calculated as

$$\begin{aligned}\frac{dE}{d\tau_1} = \frac{dE_1}{d\tau_1} + \frac{dE_2}{d\tau_1} &= \psi_1(1+\eta_1)\frac{dx_1}{d\tau_1} - \psi_2(1+\eta_2)\epsilon\frac{s_2}{s_1}\frac{dx_1}{d\tau_1} \\ &= \psi_1(1+\eta_1 - \delta\epsilon\frac{s_2}{s_1}(1+\eta_2))\frac{dx_1}{d\tau_1}\end{aligned} \tag{39}$$

where s_i is the market share for region i production. In this case, the emission level will not increase if the following condition holds

$$\frac{1+\eta_1}{1+\eta_2} \geq \delta\epsilon\frac{s_2}{s_1} \tag{40}$$

for large country case. ∎

The result above is the generalization of the Theorem 3.1 for the large country case. Here the success threshold value is smaller $\delta\epsilon\frac{s_2}{s_1} \leq \delta$ due to the partial adjustment of the market output. However the change in price in response to the production shift may lead to a corresponding decrease in a foreign country abatement activities level ($\eta_2 \neq 0$) and therefore the actual success will depend on the relative size of these effects. In general, it is not possible to derive a large country equivalent of the Corollary (3.2) unless more specific assumptions are made.

4 Concluding remarks

This study examines the feasibility of success of unilateral GHG emission reduction policy in an open economy where abatement decisions of the firms are endogenous in a sense of Copeland and Taylor (2003). The analysis is carried out using a static single good two-country partial equilibrium model with a focus on the production and trade considering both small and large industry assumptions.

The results indicate that unilateral GHG regulation decreases domestic production due to the increased costs associated with the undesired output. An implied additional production costs resulting form of an environmental tax can significantly reduce the competitiveness of the domestic industries under unilateral environmental policies, compared to the foreign regions where producers operate under low or no environmental regulations. It is shown that if the foreign region is not cooperating and remains outside of the GHG emissions regulation agreement the domestic products will be substituted in the international market by the similar foreign goods regardless of the size of both industries, leading to a carbon leakage phenomena.

Our analysis suggests that in the case that the foreign industry uses a significantly inferior abatement technology which assumes higher emission intensity, such a shift in the production under a unilateral policy of regulating GHG emissions can lead to an increase in a global GHG emissions, indicating a failure of the unilateral domestic environmental regulation policy. Moreover, a corresponding higher resource requirements can create an incentive for reducing the level of foreign abatement activities that would further increase an environmental damage in the regions that remain outside of the GHG emission regulation agreement.

Theoretically derived conditions for success of the unilateral domestic GHG emission regulation policy proposed in this study require that the industries abatement response to the tax shock to be significantly higher than that of the foreign region in order to compensate an increase in the overall emission intensity due to the differences in abatement technologies. This task can be achieved by adjusting the industry costs through the direct or indirect measures such as subsidies or border tax adjustments. Both approaches are being favoured to a certain extent however an efficient implementation of such policies is complicated due to their essentially protective nature. In a more general quasi-unilateral case, when "domestic" and "foreign" regions are represented by the industries in the countries that are in or outside of the Kyoto type agreement, respectively, the same logic can be applied, i.e. it is required that the major polluting regions to be an active participants in the global GHG emission regulation thus satisfying the conditions for a success of such an agreement.

A Comparative statics analysis of unilateral tax increase for large country case

Using Laplace expansion the determinant of $\mathbf{A}$ can be evaluated as

$$\begin{aligned}\det \mathbf{A} &= (A_{11}A_{22} - A_{12}A_{21})(A_{33}A_{44} - A_{43}A_{34}) + (A_{11}A_{42} - A_{12}A_{41})(A_{23}A_{34} - A_{33}A_{24}) \\ &= \left[g_1''b_1 - a_1\left(g_1''q_1 + b_1(1-\theta_1)^2\right)\right]\left[g_2''b_2 - a_2\left(g_2''q_2 + b_2(1-\theta_2)^2\right)\right] \\ &- (a_1 - p')\left(g_1''q_1 + b_1(1-\theta_1)^2\right)(a_2 - p')\left(g_2''q_2 + b_2(1-\theta_2)^2\right) > 0 \qquad (41)\end{aligned}$$

since $[g_i''b_i - a_i\,(g_i''q_i + b_i(1-\theta_i)^2)] > (a_i - p')\,(g_i''q_i + b_i(1-\theta_i)^2)$.

Let $\mathbf{A}_{q_1}$ and $\mathbf{A}_{q_2}$ denote the matrices $\mathbf{A}$ with the columns of the corresponding variables replaced with vector λ. The determinants for such matrices are found to be

$$\begin{aligned}\det \mathbf{A}_{q_1} &= (\lambda_{11}A_{22} - A_{12}\lambda_{21})(A_{33}A_{44} - A_{43}A_{34}) + \lambda_{11}A_{42}(A_{23}A_{34} - A_{33}A_{24}) \\ &= [-\varphi_1 b_1 + a_1 q_1(\varphi_1 + \varphi_1'(1-\theta_1))] \left[g_2'' b_2 - a_2\left(g_2'' q_2 + b_2(1-\theta_2)^2\right)\right] \\ &+ (a_1 - p')q_1\left(\varphi_1 + \varphi_1'(1-\theta_1)\right)(a_2 - p')\left(g_2'' q_2 + b_2(1-\theta_2)^2\right) \lesseqgtr 0 \end{aligned} \tag{42}$$

and

$$\begin{aligned}\det \mathbf{A}_{q_2} &= \lambda_{11}A_{34}(A_{22}A_{41} - A_{21}A_{42}) + \lambda_{22}A_{34}(A_{11}A_{42} - A_{41}A_{12}) \\ &= \varphi_1' b_2(1-\theta_2)(a_2 - p')\left(g_1'' q_1 + b_1(1-\theta_1)^2\right) \\ &- (\varphi_1 + \varphi_1'(1-\theta_1))b_2(1-\theta_2)(1-\theta_1)(a_2 - p')b_1 \\ &= b_2(1-\theta_2)(a_2 - p')(\varphi_1' g_1'' q_1 - \varphi_1(1-\theta_1)b_1) > 0 \end{aligned} \tag{43}$$

By analogy, let $\mathbf{A}_{\theta_1}$ and $\mathbf{A}_{\theta_2}$ denote the matrices $\mathbf{A}$ with the columns of the corresponding variables replaced with vector λ. The determinants for such matrices are found to be

$$\begin{aligned}\det \mathbf{A}_{\theta_1} &= [-\varphi_1' g_1'' + a_1(1-\theta_1)(\varphi_1 + \varphi_1'(1-\theta_1))] \left[g_2'' b_2 - a_2\left(g_2'' q_2 + b_2(1-\theta_2)^2\right)\right] \\ &+ (a_1 - p')(1-\theta_1)\left(\varphi_1 + \varphi_1'(1-\theta_1)\right)(a_2 - p')\left(g_2'' q_2 + b_2(1-\theta_2)^2\right) > 0 \end{aligned} \tag{44}$$

and

$$\det \mathbf{A}_{\theta_2} = \lambda_{11}A_{33}(A_{21}A_{42} - A_{22}A_{41}) + \lambda_{22}A_{33}(A_{12}A_{41} - A_{42}A_{11})$$
$$= (\varphi_1 + \varphi_1'(1-\theta_1))g_2''(1-\theta_1)(a_2 - p')b_1$$
$$- \varphi_1' g_2''(a_2 - p')\left(g_1'' q_1 + b_1(1-\theta_1)^2\right)$$
$$= -g_2''(a_2 - p')(\varphi_1' g_1'' q_1 - \varphi_1(1-\theta_1)b_1) < 0 \tag{45}$$

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