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Free emission quotas, capital mobility and international environmental problems

by

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Abstract

This paper brings together two important questions in environmental policy. The first question is how to solve international environmental problems in a world where environmental policies are implemented by governments at the national level. The second is the question of how the government should allocate emission permits to private agents when environmental objectives are achieved through a system of tradable emission permits.

It is shown that when international environmental problems are attempted solved through uncoordinated policies between countries, free emission quotas should be allocated based on domestic capital use in order to prevent leakage effects through international capital movements. The desirability of free emission quotas might however be reduced if there is ample opportunity to employ the capital in non-polluting activities. It is also shown that it may be desirable to allocate a negative number of free emission quotas per unit of labour in the polluting sector, and that increased domestic abatement is no

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substitute for policies that deal with the leakage problem more directly, such as subsidies to internationally mobile production factors.

1 Introduction

This paper brings together two important questions in environmental policy. The first question is how to solve international environmental problems in a world where environmental policies are implemented by governments at the national level. The second is the question of how the government should allocate emission permits to private agents when environmental objectives are achieved through a system of tradable emission permits.

Tradable emission permits seem to be gaining political acceptance as a useful policy instrument in environmental policy making. A few tradable emission schemes are already in place (e.g., the SO2 trading scheme in the US). In the wake of the Kyoto Protocol, several countries are considering to reach their emission targets through systems of tradable emission permits (e.g., Norway and the EU countries).

The use of tradable emission permits in environmental policy raises some important and difficult questions. One question is whether the government should auction the emission permits or distrubute the permits free of charge. There are several reasons why this is not merely a question about income distribution. First, to give free emission quotas may imply a loss of government revenue. This leads to efficiency costs if public expenditure is financed by distortionary taxes (e.g., Goulder et.al (1997), Parry and Williams III (1999), Goulder et.al (1999)). But, as shown in Mæstad (2000), free emission quotas will not necessarily reduce public income. For instance, if free emission quotas attract capital form abroad, the price of emission permits may increase so much that it more than outweighs the initial revenue loss from having fewer permits to sell in the market. It is therefore not entirely obvious how the existence of distortionary taxes affects the desirability of free emission quotas.

Secondly, free emission quotas may in itself affect the resource allocation. The exact effect will depend on the allocation criteria used. Some allocation rules will not affect the real economy at all, such as "grandfathering" based on historical emissions. But other conceivable allocation rules will surely have real effects, for instance when free emission quotas are distributed on the basis of the actual level of production or the level of capital or labour used. As we shall see below, some of these real effects may be desirable while others are not. The question is therefore how free emission permits should be allocated in the most efficient way.

The fact that free emission quotas may have real effects is particularly interesting in the case when tradable emission permits are used to solve an international environmental problem, such as the climate problem. The fundamental problem when trying to come to grips with the climate problem is that individual countries have incentives to act as free riders. Therefore, coordinated policies, including all affected parties, may be difficult to achieve. However, it may still be possible for a limited number of countries to form a stable cooperating coalition in the sense that it is not in the self-interest of any country to break out of the coalition and resort to non-cooperative behaviour (Barrett (1994), Bauer (1993) and Hoel (1992)).

One obvious problem faced by such a cooperating coalition is that policies that reduce pollution within the cooperating countries may cause increased pollution from non-cooperating countries. This is known as the leakage problem. Leakage may occur through several different channels, both through product markets and factor markets. In this paper, we shall focus exclusively on leakage created by international capital movements. If environmental regulations in the cooperating countries reduce the rate of return to capital, and capital is internationally mobile, we may observe capital flight towards the non-cooperating countries. If more capital in the foreign country increases the marginal productivity of polluting inputs, foreign pollution will increase and thus offset emission reductions at home.

Certainly, the home country may take action in order to reduce the leakage through capital markets. One obvious candidate would be to put restrictions on capital movements (Hoel, 1996). Such policies are however difficult to implement in practice, since we are usually not talking about restrictions on capital movements in general, but restrictions on capital movements to particular foreign sectors. Such sector specific restrictions on capital movements would be quite easy to evade.

If capital exports cannot be taxed or otherwise restricted, an alternative policy would be to subsidise the use of capital at home. This possibility has been discussed by Rauscher (1997) and Mæstad (2001), who find that in order to reduce the leakage through the capital market, the home country should combine emission taxes at home with subsidies to capital. Mæstad (2001) shows that when a system of tradable emission quotas rather than emission taxes is used, the desired outcome can be achieved by giving firms a certain number of free emission quotas per unit of capital employed in the home country.

One problem with these studies is that they do not consider more than one productive sector in each country. If more sectors are introduced, and capital is subsidised in only one of the sectors, there will be an additional efficiency loss because too little capital is allocated to the non-subsidised sector. Typically, capital subsidies or free emission quotas to pollution intensive industries will not only prevent them from moving abroad; it will also prevent a desirable restructuring of the economy towards less polluting activities. In this paper we discuss how the introduction of a clean production sector in the home country affects the desirability of giving free emission quotas to a sector with polluting and internationally mobile firms.

An additional novelty of this paper is that we introduce a second factor of production (labour). We discuss how this will affect the desirability of giving free emission quotas to capital. We also discuss whether it would be desirable to allocate some free emission quotas per unit of labour rather than per unit of capital. Since free emission quotas to capital introduce distortions in the economy, it might be desirable to use more than one instrument in order to achieve the desired outcome.

The paper is organsied as follows. Sections 2 and 3 present the basic model and the welfare function, respectively. In section 4, the optimal number of free emission permits is characterised in different variants of the basic model. Both the case wih an exogenously defined emission limit and the case with an optimally chosen emission limit are discussed. Section 5 concludes..

2 The basic model

We consider a model with two regions, named the home country and the foreign country. There are three production sectors; a polluting sector (h) in the home country, a clean sector (c) in the home country and a polluting sector (f) in the foreign country. Output in sector i (y^i) is produced by (a subset of) the three factors - capital (k), labour (l) and a pollutant (e). Technology is defined by the production functions

$$y^h = F^h(k^h, l^h, e^h), \tag{1}$$

$$y^c = F^c(k^c, l^c), \tag{2}$$

$$y^f = F^f(k^f, e^f)\ . \tag{3}$$

Marginal products are assumed to be positive and decreasing $(F_j^i > 0,\ F_{jj}^i < 0)$. We also assume non-increasing returns to scale and that the marginal product of factor j increases with the use of the other factors m $(F_{jm}^i > 0)$.

Demand is infinitely elastic in all the three production sectors, and all product prices are normalised to 1. These assumptions about the structure of demand serve the purpose of ruling out leakage through the product markets. As shown in Mæstad (1998, 2001), such leakage should be handled through trade provisions and not through capital subsidies or the like.

Factor prices of capital, labour and the pollutant in sector i are denoted r^i, w^i, and z^i, respectively. Firms take factor prices as exogenously given. Profit maximisation then implies that marginal products equal factor prices

$$F_k^i = r^i, \tag{4}$$

$$F_l^i = w^i, \tag{5}$$

$$F_e^i = z^i. \tag{6}$$

These conditions define factor demand as function of technology and factor prices; $k^i = k^i(r^i, w^i, z^i)$, $l^i = l^i(r^i, w^i, z^i)$, and $e^i = e^i(r^i, w^i, z^i)$.

There is a given total stock of capital, $\bar{K}$, which is freely mobile both nationally and internationally. Labour is not internationally mobile, but is freely mobile between sectors within the home country. The total stock of labour in the home country is $\bar{L}$. Equilibrium conditions in the capital and labour markets are

$$\sum_{h,c,f} k^i(r^i, w^i, z^i) = \bar{K}, \tag{7}$$

$$\sum_{h,c} l^i(r^i, w^i, z^i) = \bar{L}, \tag{8}$$

The pollutant is sold in the world market at an exogenous price Z. The use of the pollutant causes emissions. For simplicity, we normalise the emission factor to 1. Hence, total emissions are $e^h + e^f$.

We assume that the home country is committed to keeping domestic emissions below a certain threshold $e^h \leq \bar{E}$. At the outset, we shall assume an arbitrary, but binding, level of $\bar{E}$. Later, we shall let the home country choose $\bar{E}$ optimally. The emission target is achieved through a system of tradable emission permits in the home country. The government sells the permits to domestic firms at the price p. The consumer price of the pollutant in the home country is then $z^h = Z + p$. The price of emission permits is the equilibrium price in the market for emission permits, as defined by

$$e^h(r^h, w^h, Z + p) = \bar{E} \tag{9}$$

The environmental policy will reduce profitability in the pollutant intensive h-sector, and this may cause capital movements to the foreign country, leading to more foreign pollution. In order to reduce this problem, the government of the home country may consider to allocate some of the emission permits to the h-sector free of charge. In order to affect location decisions, the number of free emission quotas must be an increasing function of the "activity level" in the home country. The activity level can be measured either in terms of output or in terms of inputs used. We shall assume that input quantities are used to measure the activity level in the home country. Now, let q_k be the number of free emission permits per unit of capital in sector h. Similarly, let q_l be the number of free emission permits per unit of labour.[1]

[1]To give free emission permits per unit of actual emissions is not a viable policy alternative because that would be counteracted by an increase in the market price of emission permits in order to keep emissions below the emission target.

Since emission permits have a market value, free emission quotas allocated in this way are equivalent to subsidies on the use of capital and labour in the h-sector.

Let R be the international rate of return to capital, and let W be the domestic wage rate. R and W are determined by the equilibrium conditions Eqs. (7) and (8). The factor prices in the home country are

$$r^h = R - pq_k, \tag{10}$$
$$r^c = R, \tag{11}$$
$$w^h = W - pq_l, \tag{12}$$
$$w^c = W. \tag{13}$$

By inserting the equilibrium conditions for the capital market, the labour market and the market for emission permits (Eqs. (7)-(9)) directly in the first order conditions for profit maximisation, the model can be summarised in the following equations

$$F_k^h(k^h, l^h, \bar{E}) - R + pq_k = 0, \tag{14}$$
$$F_l^h(k^h, l^h, \bar{E}) - W + pq_l = 0, \tag{15}$$
$$F_e^h(k^h, l^h, \bar{E}) - Z - p = 0, \tag{16}$$
$$F_k^c(k^c, \bar{L} - l^h) - R = 0, \tag{17}$$
$$F_l^c(k^c, \bar{L} - l^h) - W = 0, \tag{18}$$
$$F_k^f(\bar{K} - k^h - k^c, e^f) - R = 0, \tag{19}$$
$$F_e^f(\bar{K} - k^h - k^c, e^f) - Z = 0. \tag{20}$$

These equations determine the seven endogenous variables k^h, k^c, l^h, e^f, R, W, and p. Several variants of this model will be considered as we go along.

3 Welfare

Welfare of the home country is a function of income I and the level of pollution P;

$$U = U(I, P), \quad U_I > 0, \ U_P < 0. \tag{21}$$

Let γ denote the degree to which foreign emissions affect the level of pollution in the home country, $\gamma \in [0,1]$. Hence, $P = e^h + \gamma e^f$. In the case of local pollution $\gamma = 0$, while a pure collective bad, such as the climate problem, implies $\gamma = 1$. With a binding emission limit in the home country, the level of pollution in the home country will be the domestic emission limit plus any pollution received from abroad, i.e., $P = \bar{E} + \gamma e^f$.

Income is the sum of producer surplus (including the value of free emission quotas), government income, and the difference between the return on capital invested abroad less the rent payed to foreign capital invested in the home country.[2] Let α be the share of the capital stock owned by the home country. The net foreign assets of the home country are then $\alpha\bar{K} - k^h - k^c$, and the net financial return for the home country is $R(\alpha\bar{K} - k^h - k^c)$. Wages do not affect welfare, since wages are pure transfers from domestic firms to domestic employees. The income of the home country can now be written

$$\begin{aligned} I &= F^h\left(k^h, l^h, e^h\right) + F^c(k^c, l^c) - (Z + p)e^h + pq_k k^h + pq_l l^h \\ &\quad + R(\alpha\bar{K} - k^h - k^c) + p(\bar{E} - q_k k^h - q_l l^h) \\ &= F^h\left(k^h, l^h, e^h\right) + F^c(k^c, l^c) - Ze^h + R(\alpha\bar{K} - k^h - k^c). \end{aligned} \tag{22}$$

Welfare is then

$$U = U\left[F^h\left(k^h, l^h, e^h\right) + F^c(k^c, l^c) - Ze^h + R(\alpha\bar{K} - k^h - k^c), (\bar{E} + \gamma e^f)\right]. \tag{23}$$

4 The optimal number of free emission permits

The government of the home country chooses q_k and q_l so as to maximise welfare. The optimal number of free emission quotas is given by the following first order conditions:

$$U_I \left[\begin{array}{c} (F_k^h - R)\frac{\partial k^h}{\partial q_j} + (F_k^c - R)\frac{\partial k^c}{\partial q_j} + F_l^h \frac{\partial l^h}{\partial q_j} + F_l^c \frac{\partial l^c}{\partial q_j} \\ +(F_e^h - Z)\frac{\partial e^h}{\partial q_j} + \frac{\partial R}{\partial q_j}\left(\alpha\bar{K} - k^h - k^c\right) \end{array} \right] + U_P \left[\gamma \frac{\partial e^f}{\partial q_j}\right] = 0, \quad j = k, l. \tag{24}$$

[2] There is no consumer surplus in this model since demand is perfectly elastic.

By utilising the factor price equations and the equilibrium conditions in the factor markets (Eqs.(4)-(9)) , the first order conditions can be simplified to

$$U_I\left[-pq_k\frac{\partial k^h}{\partial q_j}-pq_l\frac{\partial l^h}{\partial q_j}+\frac{\partial R}{\partial q_j}\left(\alpha\bar{K}-k^h-k^c\right)\right]+U_P\left[\gamma\frac{\partial e^f}{\partial q_j}\right]=0,\quad j=k,l. \quad (25)$$

To give free emission quotas to the polluting sector distorts the domestic allocation of capital and labour, leading to lower income. This income loss should be balanced against the achievements of free emission quotas in terms of reduced pollution from abroad. In addition, there may be gains or losses due to terms of trade changes in the capital market. A capital exporting (importing) country will gain from higher (lower) interest rates.

In the following, we consider several variants of the general model. Our reference case is a model without labour and with only two production sectors, one polluting sector in the home country and one polluting sector in the foreign country. This model resembles the models discussed by Rauscher (1997) and Mæstad (2000), where it is shown that it may be optimal to subsidise the use of capital in the home country in order to reduce pollution from abroad (for instance, by allocating free emissions on the basis of the amount of capital used). We then consider how this result is affected by introducing a clean sector in the home country and by introducing labour in the model.

4.1 The reference case

Our reference case is a model with two polluting production sectors, one in the home country and one in the foreign country. Both sectors use two factors of production, capital (k) and a pollutant (e). By modifying the model equations (14)-(20), the reference model can be written as

$$\begin{aligned} F_k^h(k^h,\bar{E})-R+pq_k &= 0, & (26)\\ F_e^h(k^h,\bar{E})-Z-p &= 0, & (27)\\ F_k^f(\bar{K}-k^h,e^f)-R &= 0, & (28)\\ F_e^f(\bar{K}-k^h,e^f)-Z &= 0. & (29)\end{aligned}$$

In this model, the first order condition for the optimal number of free emission quotas to capital will be (cf. Eq. (25))

$$U_I\left[-pq_k\frac{\partial k^h}{\partial q_k}+\frac{\partial R}{\partial q_k}\left(\alpha\bar{K}-k^h\right)\right]+U_P\left[\gamma\frac{\partial e^f}{\partial q_k}\right]=0. \tag{30}$$

The equilibrium effects of changes in q_k are derived in the Appendix. By using Eqs. (54)-(56), the first order condition can be written as

$$pq_k=\frac{U_P}{U_I}\gamma\frac{F^f_{ke}}{F^f_{ee}}-\frac{\theta^f}{F^f_{ee}}\left(\alpha\bar{K}-k^h\right), \tag{31}$$

where $\theta^i\equiv F^i_{kk}F^i_{ee}-(F^i_{ke})^2$.[3]

The optimal number of free emission quotas per unit of capital is determined by two factors; (1) the ability of free emission quotas to reduce the welfare loss caused by the leakage effect, and (2) the impact of free emission quotas on the rate of return in the capital market. The latter is a terms of trade effect which is positive (negative) if the home country is a net capital exporter (importer). The terms of trade argument vanishes if the net foreign assets are zero in equilibrium ($\alpha\bar{K}-k^h=0$) and/or if there are constant returns to scale in the foreign country ($\theta^f=0$). In that case, the optimal number of free emission quotas to capital will be unambiguously positive. This is the result established by Rauscher (1997) and Mæstad (2000) (see also Mæstad (2001)).

4.2 A three sector model

Consider next how the desirability of free emission quotas is affected by the existence of a non-polluting sector in the home country. Let the clean sector produce with capital as the only input. This model can be written as

$$F^h_k(k^h,\bar{E})-R+pq_k = 0, \tag{32}$$

$$F^h_e(k^h,\bar{E})-Z-p = 0, \tag{33}$$

$$F^c_k(k^c)-R = 0, \tag{34}$$

$$F^f_k(\bar{K}-k^h-k^c,e^f)-R = 0, \tag{35}$$

$$F^f_e(\bar{K}-k^h-k^c,e^f)-Z = 0. \tag{36}$$

[3]The assumption of non-increasing returns to scale implies that $\theta^i\geq 0$.

The first order condition for the optimal number of free emission quotas is identical to Eq. (30), except that we need to replace $\left(\alpha\bar{K} - k^h\right)$ with $\left(\alpha\bar{K} - k^h - k^c\right)$. The effect of free emission quotas on equilibrium variables is however not the same as before, as shown in the Appendix. By utilising Eqs. (58)-(60), the first order condition for the three sector model without labour can be written

$$pq_k = \frac{U_P}{U_I}\gamma\frac{F^f_{ke}F^c_{kk}}{F^f_{ee}F^c_{kk} + \theta^f} - \frac{\theta^f F^c_{kk}}{F^f_{ee}F^c_{kk} + \theta^f}\left(\alpha\bar{K} - k^h - k^c\right). \tag{37}$$

Proposition 1 *The inclusion of a clean production sector in the home country has no effect on the desirability of free emission quotas if there are constant returns to scale in the foreign country ($\theta^f = 0$). If there are decreasing returns ($\theta^f > 0$), the existence of a clean production sector will make free emission quotas less desirable both for the purpose of reducing leakage and for the purpose of improving terms of trade in the international capital market.*

It is not possible to directly compare the optimal number of free emission quotas between the models, because equilibrium values of the variables may differ. We therefore confine our attention to the qualitative differences between the formulas for the optimal number of free emissions quotas. By comparing Eqs. (31) and (37), we first observe that there is no qualitative difference between the formulas when there are constant returns to scale in the foreign country ($\theta^f = 0$). Constant returns in the foreign sector imply that the international rate of return R is not affected by the policies of the home country. Since R is the rental price of capital in the clean sector as well, free emission quotas will then not influence the amount of capital used in the c-sector. The flip side of this fact is that in this case, free emission quotas are relatively effective in attracting capital from the foreign country (or preventing capital outflow to the foreign country).

The value of the free emission permits (pq_k) should increase with F^f_{ke}. This variable reflects the extent to which capital outflow to the foreign country stimulates foreign emissions. If capital outflow does not increase the marginal productivity of foreign emissions ($F^f_{ke} = 0$), the level of foreign emission will be unaffected by environmental policies in the home country. In that case, the use of free emission permits cannot be justified by reference of leakage effects.

Turning to the case of decreasing returns in the foreign country ($\theta^f > 0$), Eq. (37) shows that both the terms of trade argument and the leakage argument have been weakened by including a clean production sector. The reason is that the increase in capital demand in the h-sector now will increase the rental price of capital R. Then, free emission quotas will not only reduce capital movements to the foreign country, but also lead to an inefficient allocation of capital between the h-sector and the c-sector.

In order to maximise national welfare, environmental policies should provide incentives to move capital out of the dirty sector and into the clean one. One problem with the use of free emission quotas for the purpose of reducing international capital movements is that they at the same time weaken the incentives for a restructuring of the domestic economy. Therefore, the three sector model is less favourable towards the use of free emission quotas than the two sector model. In the case of a fairly constant marginal product of capital in the clean sector (i.e., when $|F_{kk}^c|$ is low), the optimal q_k will be close to zero, because even small changes in the interest rate then have a big impact on the capital stock employed in the clean sector, thus implying high efficiency costs of free emission quotas in the h-sector.

4.3 A three sector model with labour

Consider now the effect of introducing a domestic labour market in the home country. We have seen that the use of free emission quotas to capital in the h-sector will distort the incentives to invest in the clean sector. When we introduce a domestic labour market, we might conceive that the optimal policies might change. Would it for instance be desirable to allocate some of the free emission quotas in the h-sector to labour rather than to capital in order to reduce distortions in the capital market? This is the topic of this section.

We now let the government have the opportunity to allocate free emission quotas to both capital and labour in the h-sector. The relevant model is then the one presented in Eqs. (14)-(20). The first order conditions for the optimal choice of q_k and q_l are given by Eq. (25).

For simplicity, the terms of trade argument will be suppressed in the following by assuming that net foreign investment is zero in equilibrium, i.e., $\alpha\bar{K} - k^h - k^c = 0$. The terms of trade argument is well understood in the literature and does therefore not deserve particular attention in the present context.

By solving Eq. (25) for q_k and q_l, the first order conditions can be written

$$pq_k = -\frac{U_P}{U_I}\gamma\left[\frac{\frac{\partial e^f}{\partial q_k}\frac{\partial l^h}{\partial q_l} - \frac{\partial e^f}{\partial q_l}\frac{\partial l^h}{\partial q_k}}{\frac{\partial k^h}{\partial q_l}\frac{\partial l^h}{\partial q_k} - \frac{\partial k^h}{\partial q_k}\frac{\partial l^h}{\partial q_l}}\right], \tag{38}$$

$$pq_l = -\frac{U_P}{U_I}\gamma\left[\frac{\frac{\partial e^f}{\partial q_l}\frac{\partial k^h}{\partial q_k} - \frac{\partial e^f}{\partial q_k}\frac{\partial k^h}{\partial q_l}}{\frac{\partial k^h}{\partial q_l}\frac{\partial l^h}{\partial q_k} - \frac{\partial k^h}{\partial q_k}\frac{\partial l^h}{\partial q_l}}\right]. \tag{39}$$

In order to proceed, we need to calculate the equilibrium effects of changes in the number of free emission quotas (see Appendix). By using the expressions in Eqs. (62)-(68), Eqs. (38) and (39) take the following form

$$pq_k = -\frac{U_P}{U_I}\gamma F^f_{ke}\frac{A}{C} \tag{40}$$

$$pq_l = -\frac{U_P}{U_I}\gamma F^f_{ke}\frac{B}{C} \tag{41}$$

where

$$A \equiv \left\{ \begin{array}{c} -\left[\theta^c + F^c_{kk}(F^h_{ll} + F^h_{le}q_l) - F^c_{kl}(F^h_{kl} + F^h_{ke}q_l)\right] \\ \left[\theta^f\left(F^c_{kk} + F^h_{kk} + F^h_{ke}q_k\right) + F^c_{kk}F^f_{ee}\left(F^h_{kk} + F^h_{ke}q_k\right)\right] \\ -\left[-F^c_{kk}(F^h_{kl} + F^h_{le}q_k) + F^c_{kl}(F^h_{kk} + F^h_{ke}q_k)\right] \\ \left[\theta^f\left(F^c_{kl} + F^h_{kl} + F^h_{ke}q_l\right) + F^c_{kk}F^f_{ee}\left(F^h_{kl} + F^h_{ke}q_l\right)\right] \end{array} \right. \tag{42}$$

$$B \equiv \left\{ \begin{array}{c} -\left[-F^c_{kk}(F^h_{kl} + F^h_{le}q_k) + F^c_{kl}(F^h_{kk} + F^h_{ke}q_k)\right] \\ \left[\theta^f\left(F^c_{ll} + F^h_{ll} + F^h_{le}q_l\right) + \theta^c F^f_{ee} + F^c_{kk}F^f_{ee}\left(F^h_{ll} + F^h_{le}q_l\right)\right] \\ -\left[\theta^c + F^c_{kk}(F^h_{ll} + F^h_{le}q_l) - F^c_{kl}(F^h_{kl} + F^h_{ke}q_l)\right] \\ \left[\theta^f\left(F^c_{kl} + F^h_{kl} + F^h_{le}q_k\right) + F^c_{kk}F^f_{ee}\left(F^h_{kl} + F^h_{le}q_k\right)\right] \end{array} \right. \tag{43}$$

$$C \equiv \left\{ \begin{array}{c} \left[\theta^f\left(F^c_{kl} + F^h_{kl} + F^h_{le}q_k\right) + F^c_{kk}F^f_{ee}\left(F^h_{kl} + F^h_{le}q_k\right)\right] \\ \left[\theta^f\left(F^c_{kl} + F^h_{kl} + F^h_{ke}q_l\right) + F^c_{kk}F^f_{ee}\left(F^h_{kl} + F^h_{ke}q_l\right)\right] \\ -\left[\theta^f\left(F^c_{ll} + F^h_{ll} + F^h_{le}q_l\right) + \theta^c F^f_{ee} + F^c_{kk}F^f_{ee}\left(F^h_{ll} + F^h_{le}q_l\right)\right] \\ \left[\theta^f\left(F^c_{kk} + F^h_{kk} + F^h_{ke}q_k\right) + F^c_{kk}F^f_{ee}\left(F^h_{kk} + F^h_{ke}q_k\right)\right] \end{array} \right. \tag{44}$$

Fortunately, these expressions can be simplified to

$$pq_k = \frac{U_P}{U_I}\gamma\frac{F^f_{ke}F^c_{kk}}{F^f_{ee}F^c_{kk}+\theta^f} > 0, \tag{45}$$

$$pq_l = \frac{U_P}{U_I}\gamma\frac{F^f_{ke}F^c_{kl}}{F^f_{ee}F^c_{kk}+\theta^f} < 0. \tag{46}$$

Proposition 2 *The inclusion of a domestic labour market does not affect the desirability of giving free emission quotas to capital. However, it is required that the use of labour in the polluting sector is "taxed" through a negative number of free emission quotas per unit of labour.*

First of all, when the terms of trade argument has been suppressed, the use of free emission quotas can only be justified in the case of transboundary pollution, i.e., when γ is strictly positive.

Eq. (45) shows that it is optimal for the home country to allocate a positive number of free emission quotas per unit of capital used in the polluting sector in this model as well. Indeed, the formula is identical to the case without a domestic labour market. This implies for instance that with constant returns to scale in the foreign country, the arguments for using free emission quotas are the same as in the reference case. But the explanation is more subtle here than in the model without labour. In that case, we argued that constant returns in the foreign country would imply no distortions in the use of capital in the clean sector because the international rental price of capital would remain constant. But this is not a sufficient explanation here, because free emission quotas now will affect the factor use in the clean sector through the labour market. In particular, if free emission quotas to capital in the h-sector lead to increased demand for labour, the domestic wage rate will increase, leading to reduced labour demand in the clean sector and to indirect effects on the use of capital in that sector. The analysis shows, however, that such labour market effects are more efficiently handled via q_l than via q_k.

Incidentally, it is not obvious that labour demand increases in the h-sector. Although an increase in q_k will increase the capital stock in the h-sector and by that stimulate labour demand, capital inflows will put an upward pressure on the market price of emission permits. This may in turn weaken the demand for labour. Hence, the effect of free emission quotas on labour demand and wages is indeterminate.

Eq. (46) shows that free emission quotas to capital should come together with a *negative* number of free emission quotas per unit of labour. In other words, the total amount of free emission quotas allocated to the polluting sector should be reduced in proportion to the number of employees within the sector. This result is in stark contrast to the idea of allocating free emission quotas to internationally mobile firms on the basis of employment, which has been launched in the political debate on this issue.

In order to interpret this result, it is useful to bear in mind that in a three sector model where only labour can move between the h- and c-sectors and capital is mobile only between the polluting h- and f-sectors (i.e., capital is sector specific to polluting industries), the optimal q_l would be zero. In other words, it is only when free emission quotas to capital affect k^c that the amount of free emission quotas shouldbe reduced in proportion to labour use. Hence, the purpose of using q_l is to counteract the negative effect of q_k on the use of capital in the clean sector. "Negative" free emission quotas to labour in the h-sector are given in order to reallocate labour from the h-sector to the c-sector. The stronger is the positive impact of higher l^c on the marginal productivity of capital in the clean sector (i.e., at high levels of F^c_{kl}), the more effective are negative free quotas to labour in stimulating capital use in the clean sector. This policy will of course introduce an additional distortion in the labour market, but, as is a well known result in second best theory, two small distortions may well be preferable to one big distortion.

Finally, consider the case where free emission quotas are given to capital only. This case can be studied by forcing q_l to zero. Now, from Eq. (25) the first order condition for the optimal number of free emission quotas is

$$pq_k = \frac{U_P}{U_I}\gamma\frac{\partial e^f/\partial q_k}{\partial k^h/\partial q_k}. \tag{47}$$

By utilising the equilibrium effects calculated above, taking into account that q_l

is zero, we obtain

$$pq_k = \frac{U_P}{U_I}\gamma\frac{F^f_{ke}\left[F^c_{kk}\left(F^h_{ll}+F^c_{ll}\right)-F^c_{kl}\left(F^h_{kl}+F^c_{kl}\right)\right]}{\left(F^f_{ee}F^c_{kk}+\theta^f\right)\left(F^h_{ll}+F^c_{ll}\right)-F^f_{ee}\left(F^c_{kl}\right)^2}. \tag{48}$$

Proposition 3 *In a three sector model with a domestic labour market and with no emission quotas allocated on the basis of labour use, the optimal number of free emission quotas per unit of capital may be either positive or negative.*

Eq. (48) shows that the sign of q_k is ambiguous if q_l is forced to zero. In other words, if free emission permits are not withdrawn on the basis of labour use, it is not obvious that it is optimal to give a positive number of free emission quotas per unit of capital. This contrasts with the two-sector model, where it was always optimal to give free emission quotas to capital (when we ignore the terms of trade effect in the international capital market). Hence, to extend the analytical framework to a three sector model may fundamentally change the policy recommendations unless additional policy instruments are activated.

4.4 Choosing the emission limit optimally

So far we have thought of the emission limit as exogenous to the decisions about whether or not to give free emission quotas. This may be an unrealistic assumption, because the possibility to use free emission quotas may affect the optimal emission limit, which again may affect the optimal number of free emission quotas. We will therefore characterise the optimal number of free emission quotas also in the case when the emission limit is optimally chosen.

The first order condition for the optimal emission limit is obtained by partially differentiating the welfare function with respect to $\bar{E}$.

$$U_I\left[p - pq_k\frac{\partial k^h}{\partial \bar{E}} - pq_l\frac{\partial l^h}{\partial \bar{E}} + \frac{\partial R}{\partial \bar{E}}\left(\alpha\bar{K} - k^h - k^c\right)\right] + U_P\left[1+\gamma\frac{\partial e^f}{\partial \bar{E}}\right] = 0. \tag{49}$$

We now want to utilise the first order conditions for the optimal choice of q_k and q_l. We may either use the first order conditions in the full-blown model (Eqs. (45) and (46)), in which case net foreign investment must be forced to zero in Eq. (49).

Alternatively, we may use the first order condition in the three-sector model without labour (Eq. (37)), in which case q_l in Eq. (49) must be zero. Both procedures lead to the same result[4];

$$p = -\frac{U_P}{U_I}. \tag{50}$$

Proposition 4 *The emission limit should be chosen so that the market price of emission quotas equals the marginal rate of substitution between income and pollution.*

Eq. (50) shows that the emission limit should be chosen according to the same principles as in the case of a local environmental problem, i.e., by ensuring that the quota price equals the marginal willingness to pay for increased environmental quality. One implication of this result is that leakage problems should not be dealt with by increasing the level of abatement in the home country. For this purpose, it is more efficient to use free emission quotas in order to reduce capital movements to the foreign country.

A further implication is that none of our previous conclusions are fundamentally affected by the fact that the emission limit is optimally chosen. The optimal number of free emission quotas in the three sector model with labour is now given by

$$q_k = -\gamma \frac{F^f_{ke} F^c_{kk}}{F^f_{ee} F^c_{kk} + \theta^f} > 0, \tag{51}$$

$$q_l = -\gamma \frac{F^f_{ke} F^c_{kl}}{F^f_{ee} F^c_{kk} + \theta^f} < 0. \tag{52}$$

5 Final remarks

We have investigated the desirability of using free emission quotas in order to come to grips with the leakage problems that may arise through international capital movements when one attempts to solve international environmental problems through

[4]The calculations require total differentiation of the respective models with respect to the emission limit $\bar{E}$ and a significant amount of algebraic manipulation. Details can be obtained from the author upon request.

unilateral policies. While previous literature recommends to subsidise domestic use of capital in order to prevent such leakage, e.g., by issuing free emission permits in proportion to the capital stock, this paper shows that the desirability of such policies may be reduced when capital also may be employed in alternative, clean production activities in the home country. The reason is that capital subsidies to the polluting sector will conserve a domestic industry structure that is inefficiently pollution intensive. However, the desirability of free emission quotas to domestic capital will be retained if the international rental price of capital is fixed, because capital use in the clean sector then is unaffected by policies towards the polluting sector. It was also shown that if there is a domestic labour market, a positive number of free emission permits per unit of capital should go together with a negative number of free emission permits per unit of labour. Finally, we demonstrated that when free emission quotas are used, it will not be optimal for the home country to deal with the leakage problem by increasing the domestic level of abatement.

This paper has not dealt with the issues related to the financing of free emission quotas. If the allocation of free emission quotas leads to higher tax rates, there will be additional efficiency costs related to free emission quotas beyond those that have been accounted for here. For a further discussion of this issue, see Mæstad (2000).

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Appendix

This appendix contains the derivation of the equilibrium effects of changes in the number of q_k and q_l in the various models used in the paper.

The reference model

Differentiation of the system (26)-(29) with respect to q_k yields

$$\begin{bmatrix} F^h_{kk} & 0 & -1 & q \\ F^h_{ke} & 0 & 0 & -1 \\ -F^f_{kk} & F^f_{ke} & -1 & 0 \\ -F^f_{ke} & F^f_{ee} & 0 & 0 \end{bmatrix} \begin{bmatrix} dk^h \\ de^f \\ dR \\ dp \end{bmatrix} = \begin{bmatrix} -pdq_k \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{53}$$

By Cramer's rule, we obtain

$$\frac{dk^h}{dq_k} = \frac{pF^f_{ee}}{|H_1|}, \tag{54}$$

$$\frac{de^f}{dq_k} = \frac{pF^f_{ke}}{|H_1|}, \tag{55}$$

$$\frac{dR}{dq_k} = \frac{-p\left(F^f_{kk}F^f_{ee} - \left(F^f_{ke}\right)^2\right)}{|H_1|}, \tag{56}$$

where $|H_1|$ is the Hessian determinant.

Three sector model without labour

Differentiation of the system (32)-(36) with respect to q_k yields

$$\begin{bmatrix} F^h_{kk} & 0 & 0 & -1 & q \\ F^h_{ke} & 0 & 0 & 0 & -1 \\ 0 & F^c_{kk} & 0 & -1 & 0 \\ -F^f_{kk} & -F^f_{kk} & F^f_{ke} & -1 & 0 \\ -F^f_{ke} & -F^f_{ke} & F^f_{ee} & 0 & 0 \end{bmatrix} \begin{bmatrix} dk^h \\ dk^c \\ de^f \\ dR \\ dp \end{bmatrix} = \begin{bmatrix} -pdq_k \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{57}$$

By Cramer's rule, we obtain

$$\frac{dk^h}{dq_k} = \frac{-p\left(F^f_{ee}F^c_{kk} + \theta^f\right)}{|H_2|}, \tag{58}$$

$$\frac{de^f}{dq_k} = \frac{-pF^f_{ke}F^c_{kk}}{|H_2|}, \tag{59}$$

$$\frac{dR}{dq_k} = \frac{-p\theta^f F^c_{kk}}{|H_2|}. \tag{60}$$

Three sector model with labour

Differentiation of the system (14)-(20) with respect to q_k and q_l yields

$$\begin{bmatrix} F^h_{kk} & 0 & F^h_{kl} & -1 & 0 & q_k & 0 \\ F^h_{kl} & 0 & F^h_{ll} & 0 & -1 & q_l & 0 \\ F^h_{ke} & 0 & F^h_{le} & 0 & 0 & -1 & 0 \\ 0 & F^c_{kk} & -F^c_{kl} & -1 & 0 & 0 & 0 \\ 0 & F^c_{kl} & -F^c_{ll} & 0 & -1 & 0 & 0 \\ -F^f_{kk} & -F^f_{kk} & 0 & -1 & 0 & 0 & F^f_{ke} \\ -F^f_{ke} & -F^f_{ke} & 0 & 0 & 0 & 0 & F^f_{ee} \end{bmatrix} \begin{bmatrix} dk^h \\ dk^c \\ dl^h \\ dR \\ dW \\ dp \\ de^f \end{bmatrix} = \begin{bmatrix} -pdq_k \\ -pdq_l \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}. \tag{61}$$

Let H_3 denote the Hessian matrix. By Cramer's rule we find that the effect on foreign emissions of free emission quotas is given by

$$\frac{\partial e^f}{\partial q_j} = -\frac{F^f_{ke}}{F^f_{ee}} \frac{\partial k^f}{\partial q_j}, \qquad j = k, l, \tag{62}$$

where the effect of free emission quotas on the use of capital in the foreign country can be written as

$$\frac{\partial k^f}{\partial q_k} = -\frac{\partial k^h}{\partial q_k} - \frac{\partial k^c}{\partial q_k} = \frac{pF^f_{ee}}{|H_3|} \left[\theta^c + F^c_{kk}(F^h_{ll} + F^h_{le}q_l) - F^c_{kl}(F^h_{kl} + F^h_{ke}q_l)\right], \tag{63}$$

$$\frac{\partial k^f}{\partial q_l} = -\frac{\partial k^h}{\partial q_l} - \frac{\partial k^c}{\partial q_l} = \frac{pF^f_{ee}}{|H_3|} \left[-F^c_{kk}(F^h_{kl} + F^h_{le}q_k) + F^c_{kl}(F^h_{kk} + F^h_{ke}q_k)\right]. \tag{64}$$

The effects on capital and labour use in the polluting sector in the home country are

$$\frac{\partial k^h}{\partial q_k} = \frac{-p}{|H_3|} \left[\theta^f \left(F^c_{ll} + F^h_{ll} + F^h_{le}q_l\right) + \theta^c F^f_{ee} + F^c_{kk}F^f_{ee} \left(F^h_{ll} + F^h_{le}q_l\right)\right], \tag{65}$$

$$\frac{\partial k^h}{\partial q_l} = \frac{p}{|H_3|} \left[\theta^f \left(F^c_{kl} + F^h_{kl} + F^h_{le}q_k\right) + F^c_{kk}F^f_{ee} \left(F^h_{kl} + F^h_{le}q_k\right)\right], \tag{66}$$

$$\frac{\partial l^h}{\partial q_k} = \frac{p}{|H_3|} \left[\theta^f \left(F^c_{kl} + F^h_{kl} + F^h_{ke}q_l\right) + F^c_{kk}F^f_{ee} \left(F^h_{kl} + F^h_{ke}q_l\right)\right], \tag{67}$$

$$\frac{\partial l^h}{\partial q_l} = \frac{-p}{|H_3|} \left[\theta^f \left(F^c_{kk} + F^h_{kk} + F^h_{ke}q_k\right) + F^c_{kk}F^f_{ee} \left(F^h_{kk} + F^h_{ke}q_k\right)\right]. \tag{68}$$