Chapter 4

Emissions Constraints, Emission Permits, and Marginal Abatement Costs

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4.1 Introduction

Should the marginal cost of emission abatement be equalized across countries? Do markets for tradable emission permits lead to Pareto-efficient patterns of emission abatement? Until recently, the standard answers to both questions were yes. However, Chichilnisky [4] and then, in a more general context, Chichilnisky and Heal [5] proved that the efficient abatement of carbon dioxide (CO_2) emissions does not require the equalization of marginal abatement costs across countries. Equalization is required if and only if it is possible to make unrestricted and free lump-sum redistributions of wealth sufficient to equate the marginal social valuation of consumption in all countries. It follows almost immediately that markets for tradable emission permits do not lead in general to Pareto efficiency, as shown in chapter 3. Chichilnisky, Heal, and Starrett's central result there is that if a market for emission rights is introduced, then the manner in which the emission rights are initially distributed between countries is important for efficiency. To be specific they showed that only a finite number of ways of allocating a given total of emission rights between countries will lead to Pareto-efficient outcomes. Distribution and efficiency are linked in

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competitive economies in which one trades the right to produce privately produced public goods such as carbon dioxide (CO_2) emissions.

Although this point is simple analytically, it has considerable policy implications. For example, prior to this observation it was taken as given that the burden of emission abatement should be borne disproportionately by developing countries by virtue of their supposedly lower marginal abatement costs.[1]

The initial papers (Chichilnisky [4], Chichilnisky and Heal [5], and Chichilnisky, Heal, and Starrett [6]) led to an explosion of interest in these issues. Prat in chapter 6, Heal and Lin in chapter 5, Dwyer [10], Chao and Peck [3], Mäler [12], Mäler and Uzawa [13], Uzawa [16], Manne [14], and Bohm [1] have all subsequently commented on or extended the initial results in various ways. Dwyer, Heal and Lin, and Prat all review issues related to the efficiency of markets for emission permits. Prat looks at the consequences of always distributing permits in a fixed ratio between the participating countries. He shows that, for each set of proportions, there is a total level of emissions such that distributing it in these proportions will lead to Pareto efficiency. Drèze [9] has made a similar observation. Heal and Lin and Dwyer review the implications of strategic behavior in permit markets. The key point here is that in deciding how much to emit in a regime of international emission permits, each country has to make some conjecture about the total levels of emissions produced by all others, as its utility and therefore its demand for permits depends on this. Chichilnisky, Heal, and Starrett (CHS) model a situation in which each country assumes that the total levels of emissions will be that desired by the agency issuing the permits; that is, each country assumes that the international permit regime will be successful in attaining its goals. Heal and Lin and Dwyer look instead at worlds where countries take the emission levels of others as given in the Nash tradition. They show that in these worlds it is more difficult to achieve Pareto efficiency: Heal and Lin show that only a finite number of points on the Pareto frontier can be attained as equilibria with this behavior. Not surprisingly it is easier to attain efficiency if everyone believes that efficiency will be attained and acts accordingly. Chao and Peck and also Manne investigate numerically the interactions between equity and efficiency indicated by the original results of Chichilnisky and Chichilnisky and Heal. Mäler explores the relationship between the CHS results and a Lindahl equilibrium, a more traditional equilibrium concept for market economies with public goods. Many of the counterintuitive results in CHS emerge because a permit market for emissions is a market for a public good but one with uniform prices rather than the individualized prices required in the Lindahl approach. It is therefore an incom-

[1] Much of the rationalization of joint implementation rests on this supposition.

plete market relative to the framework within which Pareto efficiency has been established.

Several commentators have enquired whether equivalent results hold in a framework in which the total level of abatement, instead of being selected as part of an efficient allocation, is imposed arbitrarily by a political authority. Their motivation is a feeling that any global carbon emission targets ultimately selected will reflect political compromise rather than rational economic analysis, so that the relevant policy question is the attainment of efficiency subject to this constraint. We analyze such a situation here. Assuming that an arbitrary level of emission abatement is imposed on the world economy, we ask again the questions with which this chapter opened: Should the marginal cost of emission abatement be equalized across countries? Do markets for tradable emission permits lead to efficient patterns of emission abatement? However, we now ask them in the context of a concept of constrained, or second-best, efficiency.

The answers are exactly as in the previous chapter: Equalization of marginal costs is necessary for constrained efficiency if and only if it is possible to make unrestricted lump-sum transfers of wealth between countries on a scale sufficient to equalize the marginal social valuation of consumption in all countries, and, as a direct consequence, only certain distributions of emission permits are compatible with the attainment of constrained efficiency by way of permit markets. This is an unusual case of first-best results continuing essentially unchanged in a second-best framework.

4.2 The Model

The model and notation are identical to those in Chichilnisky and Heal [5]. The world economy consists of I regions, $I \geq 2$, indexed by $i = 1, ..., I$. Each has a utility function u_i, which depends on its consumption of a vector of m private goods $c_i \in \Re^M$ and on the quality of the world's atmosphere, a, which is a public good. Formally, $u_i(c_i, a)$ measures welfare, where $u_i : R^{M+1} \to R$ is a continuous, strictly concave function and $\partial u_i / \partial c_{i,m} > 0$, $\partial u_i / \partial a > 0$. The quality of the atmosphere, a, is measured by, for example, the reciprocal or the negative of its concentration of CO_2. Let y_i be a vector in R^M giving the production levels of the M private goods in country i. Then the concentration of CO_2 is affected by production:

$$a = \sum_{i=1}^{I} a_i, \; a_i = \Phi_i(y_i) \quad \text{for each country } i = 1, ..., I, \quad \text{and}$$

$$\frac{\partial \Phi_i}{\partial y_{i,m}} < 0 \qquad \forall i \text{ and } m, \qquad (4.1)$$

where a is a measure of atmospheric quality overall and a_i is an index of the abatement carried out by country i. The production functions Φ_i are continuous and show the trade-off between abatement or quality of the atmosphere and the output of consumption goods. An allocation of consumption and abatement across all countries is a vector

$$(c_1, a_1, ..., c_I, a_I) \in \Re^{(M+1)I},$$

as for each of the I regions there are M private goods and one level of abatement. An allocation is feasible if it satisfies constraint (4.1) and the condition that the total consumption of each private good worldwide be equal to the total production, that is,

$$\sum_{i=1,...,I} c_i = \sum_{i=1,...,I} y_i \tag{4.2}$$

Constraint (4.2) allows private goods to be transferred freely between regions; that is, it allows unrestricted lump-sum international redistributions.

An allocation is called feasible with lump-sum transfers if it satisfies the constraints (4.1) and (4.2). It is feasible without lump-sum transfers if it satisfies

$$c_i = y_i \forall i. \tag{4.3}$$

Each region i faces a constraint in terms of allocating total endowments into either consumption c_i or atmospheric quality a_i, represented by the function Φ_i. Then a Pareto-efficient allocation is described by a solution to the problem:

$$\max\ W(c_1, ..., c_i, a) = \sum_{i=1}^{I} \lambda_i u_i(c_i, a), \tag{4.4}$$

$$a = \sum_{i=1}^{I} a_i,\ a_i = \Phi_i(y_i), \quad \text{for each country } i = 1, ..., I, \quad \text{and}$$

$$\sum_{i=1,...,I} c_i = \sum_{i=1,...,I} y_i. \tag{4.5}$$

Note that the marginal cost of abatement in region i in terms of good m is just the reciprocal of the marginal productivity with respect to m of the function Φ_i:

$$MC_{i,m}(a_i) = -1/\frac{\partial \Phi_i}{\partial y_{i,m}}. \tag{4.6}$$

4.3 Emission-Constrained Efficiency

In this section we introduce the concept of constrained efficiency that we work with here and then establish results about the relationship between equalization of marginal abatement costs and efficiency in this sense.

DEFINITION 1 An allocation is emission-constrained efficient if it maximizes a weighted sum of utilities (4.4) subject to the feasibility constraint either (4.5) (for the case of lump-sum transfers) or (4.3) (for the alternate case) and if in addition it satisfies a constraint on total abatement

$$a = a^* \tag{4.7}$$

specifying a given total abatement level a^*.[2]

4.3.1 Without Lump-Sum Transfers — Chichilnisky [4] and Chichilnisky and Heal [5] established the following proposition concerning first-best Pareto-efficient allocations:

PROPOSITION 1 At a Pareto-efficient allocation $(c_1^*, a_1^*, \ldots, c_I, a_I^*)$, the marginal cost of abatement in terms of good m in each country, $MC_{i,m}(a_i^*)$, is inversely proportional to the marginal valuation of the private good $c_{i,m}$, $\lambda_i \partial u_i / \partial c_{i,m}$. In particular, the marginal costs will be equal across countries if and only if the marginal valuations of the private good are equal; that is, $\lambda_i \partial u_i / \partial c_{i,m}$ is independent of i.

We now establish a result exactly equivalent to this for the case of emission-constrained efficiency. The only difference in the propositions lies in the replacement of the words "Pareto efficient" by "emission-constrained efficient."

PROPOSITION 2 At an allocation $(c_1^*, a_1^*, \ldots, c_I^*, a_I^*)$ which is emission-constrained efficient, the marginal cost of abatement in each country in terms of good m, $MC_{i,m}(a_i^*)$, is inversely proportional to the marginal valuation of the private good $c_{i,m}$, $\lambda_i \partial u_i / \partial c_{i,m}$. In particular, the marginal costs will be equal across countries if and only if the marginal valuations of the private good are equal; that is, $\lambda_i \partial u_i / \partial c_{i,m}$ is independent of i.

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[2] This is formulated as an equality. The results would be unchanged if instead we specified an inequality $a \geq a^*$ with a lower bound for abatement.

PROOF. An emission-constrained efficient allocation, being the solution to the maximization of (4.4) subject to (4.3) and (4.7), must be a stationary point of the Lagrangian

$$L = \sum_k \lambda_k u_k\left(c_k, \sum_k \Phi_k(c_k)\right) + \gamma\left(\sum_k \Phi_k(c_k) - a^*\right),$$

where γ is the shadow price associated with constraint (4.7) on total emissions and so must satisfy the first-order conditions

$$\lambda_i(\partial u_i/\partial c_{i,m}) = -\gamma \frac{\partial \Phi_i}{\partial y_{i,m}} - \frac{\partial \Phi_i}{\partial y_{i,m}} \sum_k \lambda_k(\partial u_k/\partial a) \tag{4.8}$$

for each country $i = 1, ..., I$. Because $MC_{i,m}(a_i^*) = -1/(\partial\Phi_i/\partial y_{i,m})$, the allocation satisfying (4.8) is characterized by

$$MC_{i,m}(a_i^*) = \frac{\gamma + \Sigma_k \lambda_k(\partial u_k/\partial a)}{\lambda_i \partial u_i/\partial c_i}, \tag{4.9}$$

and the proposition follows. ■

Equation (4.9) is identical to the equivalent equation, $MC_i(a_i^*) = \Sigma_k \lambda_k(\partial u_k/\partial a)/(\lambda_i \partial u_i/\partial c_i)$ on page 446 of Chichilnisky and Heal [5] and page 130 of this volume, except for the presence of the term γ reflecting the constraint (4.7). The result is qualitatively the same as in the previous case because, being the shadow price on the provision of a public good, γ is common across all countries.[3] Proposition 2 shows that the product of the marginal valuation of private consumption and the marginal cost of abatement in terms of consumption is equal across countries. Following Chichilnisky and Heal, we write this product as $\lambda_i \partial u_i/\partial c_i \cdot \partial c_i/\partial a$ and note that it can be interpreted as the marginal cost of abatement in country i measured in utility terms, that is, in terms of its contribution to the social maximand $\Sigma_j \lambda_j u_j(c_j, a)$. Equation (4.9) therefore tells us that the marginal cost of abatement in this generalized sense must equal the sum of the marginal valuations of abatement across all countries plus an amount reflecting the shadow price of the abatement constraint. An immediate implication is that in countries that place a high marginal valuation on consumption of the private good (typically low-income countries), the mar-

[3] Of course, if (4.7) is not binding, then $\gamma = 0$, and this condition is precisely the first-order condition characterizing full Pareto efficiency in Chichilnisky and Heal [5]. This will occur only if the specified abatement level a^* is Pareto efficient.

ginal cost of abatement at an efficient allocation will be lower than in other countries. If we assume an increasing marginal cost of abatement (diminishing returns to abatement), then this of course implies lower levels of abatements in poor countries than in rich countries.

Note that these results would be completely unchanged if we were to replace the equality constraint $a = a^*$ by the inequality $a \geq a^*$, placing a lower bound on the acceptable level of abatement. In this case the previous Lagrangean would be unaltered, but the shadow price γ associated with the abatement constraint would satisfy a complementary slackness condition, indicating that it would be zero if the abatement constraint were satisfied with strict inequality. When $\gamma = 0$, we have precisely the results of the previous papers.

4.3.2 With Lump-Sum Transfers — Under what conditions can we recover the conventional wisdom that marginal abatement costs should be equalized across countries? The answer is as in Chichilnisky and Heal [5]: We need to equate the terms $\lambda_i \partial u_i / \partial c_i$ across countries. This could be done by assumption. However, given the enormous discrepancies between the income levels in OECD countries and countries such as India and China and the need for all of them to be involved in an abatement program, such a value judgment seems most unattractive.

There is an alternative possibility. Modify the problem to allow unrestricted transfers of private goods between countries, so that efficiency is defined by maximization of (4.4) subject to the feasibility condition (4.5):

$$\max\ W(c_1, c_2, c_i, \ldots, a) = \sum_i \lambda_i u_i(c_i, a) \quad \text{subject to}$$

$$a_i = \Phi_i(y_i),\ a = \sum a_i,\ \sum y_i = \sum c_i, \quad \text{and} \quad a = a^*. \tag{4.10}$$

We now require the sum of the consumptions across countries to equal the sum of the productions—$\Sigma\, y_i = \Sigma\, c_i$—instead of having these equal on a country-by-country basis. By this modification we are allowing the transfer of goods between countries; that is, we are allowing lump-sum transfers. Note that this is not a model of international trade, which would require the imposition of balance-of-trade constraints.[4] Clearly, the first-order conditions again require that

$$MC_i = \frac{\Sigma_k \lambda_k (\partial u_k / \partial a) + \gamma}{\lambda_i (\partial u_i / \partial c_i)}, \tag{4.11}$$

[4]See the discussion of this in CHS [6].

but in addition we now require that

$$\lambda_i(\partial u_i/\partial c_i) = \mu \ \forall i. \tag{4.12}$$

Therefore, we now have equalization of marginal abatement costs across countries at the ratio

$$\frac{\Sigma_k \lambda_k(\partial u_k/\partial a) + \gamma}{\mu},$$

where, as before, γ is the shadow price on the total emission (abatement) constraint and μ is that on the constraint equating total output of the private good to consumption. Therfore, if we solve an optimization problem that allows unrestricted transfers between countries and we can and do make the transfers that are needed to solve this problem, it will then be efficient to equate marginal abatement costs, with or without an arbitrary constraint on total abatement. The imposition of an arbitrary constraint on abatement, forcing us into the world of second best, makes no difference to the appropriate relationship between marginal abatement costs. This is because the first-order condition in this case, as in the previous case without lump-sum transfers, differs from that without an arbitrary abatement constraint only in the presence of the shadow price γ in the expression for marginal cost.

4.4 Emission Permits and Emission Constraints

How would the imposition of emission constraints as discussed previously affect the results of the previous chapter on efficiency and the distribution of emission rights? As one might expect, they all carry through again. An immediate implication of the competitive trading of emission permits at a uniform price is the equalization of marginal emission costs, narrowly defined, and if the equality of these marginal costs does not characterize efficiency except for particular distributions of wealth, then the trading of emission permits can be expected to lead to efficiency only for those same particular distributions. Another intuition that leads to the same conclusion was mentioned before: Efficiency in markets for public goods in general requires Lindahl markets with as many prices as there are agents. In the absence of these markets, one cannot expect efficiency, constrained or otherwise.

Formally, let each country be given an allocation E_i of emission rights, where $\Sigma_i E_i = E^*$ and E^* is the agreed total level of emissions worldwide. They can trade these as price takers in a market in which there is a single price

p_e for the right to emit one unit. Countries therefore maximize utility subject to the budget constraint

$$\sum_l c_{i,l} p_l = \sum_l y_{i,l} p_l - p_e(E_i + a_i). \tag{4.13}$$

The interpretation of the right-hand side of this budget constraint is as in the previous chapter: The difference between actual emissions e_i and target emissions E_i is $e_i - E_i = e_i^N - a_i - E_i$, where e_i^N is the emission level of region i when abatement is zero. For simplicity we have dropped the constant terms in e_i^N. This budget constraint requires that for each country the value of consumption equal the value of production plus the net revenue from the sale of permits. Note that (4.13) can be rewritten as

$$\left(\sum_l c_{i,l} p_l - \sum_l y_{i,l} p_l\right) = -p_e(E_i + a_i). \tag{4.14}$$

Here the left-hand side is the difference between the value of domestic consumption and production, that is, the balance of trade. A surplus of consumption over production (i.e., a position of net imports) is funded by the revenue generated by sales of permits in international markets. Conversely, a net purchase of permits in international markets has to be matched by a surplus of production over consumption and therefore a net export position. This interpretation of the budget constraint makes it clear that controlling the initial endowments of emission rights acts as a substitute for lump-sum transfers.

Each country seeks to maximize its utility $u_i(c_i, a)$ subject to the budget constraint (4.13) and to the production relations given in (4.1). We assume that in so doing it supposes the total level of emissions to be fixed at E^*, the desired total level. This in effect implies the existence of a credible intergovernment agency that sets and implements global emission targets. An alternative (explored by Heal and Lin in the next chapter) is to look for a Nash equilibrium in countries' abatement levels.

In the case of a total level of emissions taken by all countries to be E^*, each country chooses consumption levels and abatement or emission levels to satisfy

$$\overbrace{\frac{\dfrac{\partial u_i}{\partial c_{i,l}}}{\dfrac{\partial u_i}{\partial c_{i,m}}} = \frac{p_l}{p_m}}^{\text{mrs} = \text{price ratio}} \tag{4.15}$$

and

$$\overbrace{\frac{\partial \Phi_i}{\partial y_{i,m}} = -\frac{p_m}{p_e}}^{\text{mrt = price ratio}}. \tag{4.16}$$

These are standard conditions: (4.15) requires only that marginal rates of substitution between goods be equated to their price rations, and (4.16) requires tangency between the production possibility frontier and an isoprofit hyperplane. The latter implies in particular that, for given prices, levels of production (and therefore also of emission) are determined independently of the utility function. (Of course, in equilibrium the prices will depend on preferences.)

How do the first-order conditions (4.15) and (4.16) chosen by the country compare with the conditions (4.11) and (4.12), which describe allocations that are efficient subject to an emission constraint? Clearly, (4.16) is the same as (4.11) provided that

$$\frac{p_m}{p_e} = \frac{\dfrac{\partial u_i}{\partial c_{i,m}}}{\gamma + \Sigma_k \lambda_k \dfrac{\partial u_k}{\partial a}} = \frac{\lambda_k \dfrac{\partial u_k}{\partial c_{k,l}}}{\gamma + \Sigma_k \lambda_k \dfrac{\partial u_k}{\partial a}} \qquad \forall k \neq i. \tag{4.17}$$

This condition can only hold if $\partial u_i/\partial c_{i,m}$ and $\lambda_k(\partial u_k/\partial c_{k,l})$ are independent of i and k. Condition (4.12), required for emission-constrained efficiency, automatically implies this. However, there is nothing equivalent in the countries' utility maximization conditions: Condition (4.15) does not imply equalization of marginal valuations.

Therefore, utility maximization subject to the budget constraint (4.13) does not lead to the conditions needed for efficiency. There is an additional requirement represented by (4.12), namely, that $\partial u_i/\partial c_{i,m} = \lambda_k \partial u_k/\partial c_{k,l}$ $\forall l$, $\forall k \neq i$. This condition would of course be satisfied if there were policy instruments available to redistribute resources without restriction across countries—if, for example, lump-sum redistributions were possible. In the absence of such instruments, what is required to ensure that (4.12) is met and that constrained efficiency is attained in the permit market?

Condition (4.12) requires that, for each good, its marginal social valuation be equal for every country. This is a condition with which we are familiar from the previous chapter. As there we note that this is a condition on the distribution of income or wealth. The same arguments as in that chapter can now be applied. We look in more detail at the determinants of the terms $\partial u_i/\partial c_{i,m}$. As $u_i = u_i(c_i, E^*)$, where E^* is fixed, the derivatives of u_i with respect to consumption can depend only on consumption levels. These in turn depend, by means of the budget constraint (4.13), on prices p_l, production levels $y_{i,m}$, abatement levels a_i, and initial endowments of emission rights E_i. Once prices are given, production and abatement levels are fully determined by (4.16). In the absence of policy instruments that can effect unrestricted redistributions across countries, the only variables then available for ensuring that marginal social valuations of consumption are equalized across countries are therefore the initial allocations of permits, and only those initial permit allocations that ensure that (4.12) is satisfied will lead to emission-constrained efficient allocations. We formalize this in the following and show that very few initial allocations satisfy this condition.

PROPOSITION 3 Let E^* be the level of total emissions at an emission-constrained efficient allocation of resources in the economy. Assume that countries maximize utility subject to the budget constraint (4.13) given by the ability to trade emission permits. Assume furthermore that a regularity condition defined below is satisfied. Then, of all possible ways of allocating the total emission E^* among countries as initial endowments, only a subset of measure zero will lead to market equilibria that are emission-constrained efficient. If the inequality $(I - 1) + M \leq (I - 1) \times M$ holds, then only a finite number of ways of allocating the emission rights lead to efficiency.

REMARK 1 Strict concavity and the regularity assumption are needed for this result. Otherwise, one can construct counterexamples. For example, with quasi-linear preferences of the form $u_i(a) + \alpha_i c_i$, $\alpha_i > 0$, there might be infinitely many allocations of permits that will lead to efficient outcomes.

Consider the first-order conditions for efficiency:

$$\frac{\partial u_i}{\partial c_{i,l}} - \lambda_k \frac{\partial u_k}{\partial c_{k,l}} = 0. \tag{4.18}$$

Define the function Ω from $\Re^{(I-1)+M}$ to $\Re^{(I-1)\times M}$. Its arguments are those of (4.8), namely, E_i, $i = 1, ..., I$ and p_l, $l = 1, ..., M$ and e. Now, as the E_i are nonnegative and sum to a fixed number and there are only M relative prices, Ω is defined on $\Re^{(I-1)+M}$:

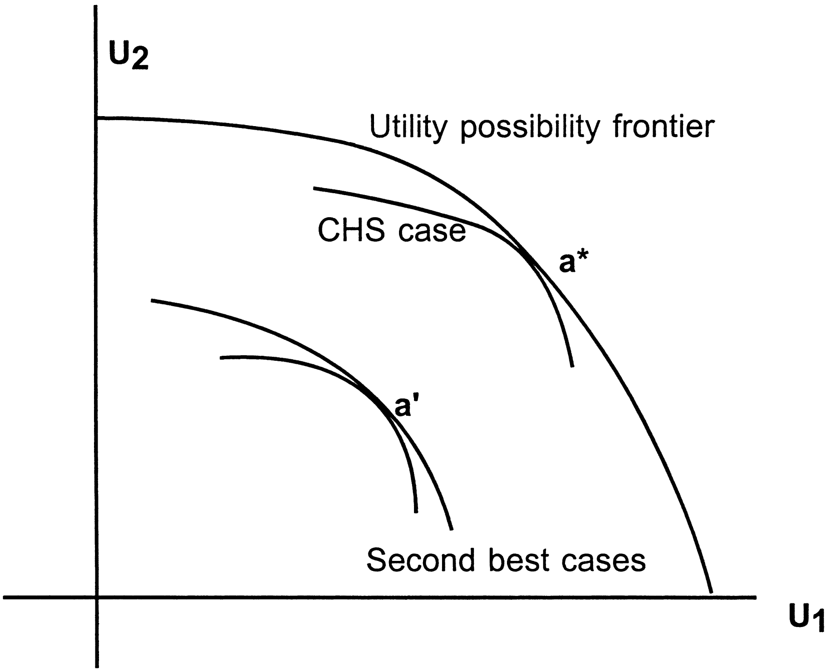

FIGURE 4.1. The frontiers corresponding to different allocations of an arbitrary emission total with with and without lump-sum transfers.

$$\Omega\colon \Re^{(I-1)+M} \to \Re^{(I-1)\times M},\ \Omega(x) = \frac{\partial u_i(x)}{\partial c_{i,l}} - \lambda_k \frac{\partial u_k(x)}{\partial c_{k,l}},$$

where $x \in \Re^{(I-1)\times M}$. Proposition 3 uses the following regularity condition, which essentially states that the first-order conditions for efficiency change smoothly as prices and permit allocations change:

Regularity condition. The matrix of first partial derivatives of the function Ω has full rank.

PROOF. The proof copies exactly that in the previous chapter. ■

How does the intuition behind this result relate to the equivalent result in the previous chapter? It can be explained by a very similar diagram (see figure 4.1). The figure repeats figure 3.2 of chapter 3 with additions. It shows the utility possibility frontier of a two-person economy and the utility vectors that emerge from trading permits corresponding to a total level of emissions associated with an efficient equilibrium. The point a′ shows the utility levels at an arbitrary inefficient equilibrium, associated with which is a total level of emissions, say, E_X. The two frontiers through a′ show the utility levels attained by trading emission rights totaling $E_{a'}$ under two different conditions. The outer frontier corresponds to the case in which lump-sum transfers ensure that conditions (4.12) is satisfied, namely, that the marginal valuations of consumption are equal across countries. The inner one corresponds to the case in which this does not happen. Utility vectors on the outer frontier through a′ are constrained Pareto efficient. Those on the other frontier are not, except at the point at which the two frontiers touch. At this point the distribution of emission rights is consistent with constrained efficiency, and no redistribution is needed.

4.5 Conclusions

Efficient abatement subject to an arbitrarily chosen emission level does not in general require equalization of marginal abatement costs; rather it requires equalization of the marginal social opportunity costs of abatement across countries. Marginal costs in the usual sense are to be equalized only if we can make unrestricted lump-sum transfers between countries, not a very interesting hypothesis.

An implication is that for the attainment of emission-constrained efficiency by the trading of emission permits, the initial distribution of permits (property rights) matters, as only a finite number of initial distributions lead to emission-constrained efficiency. The initial allocation of emission permits may play the role of lump-sum transfers: Certain initial distributions of these permits lead to efficiency because they correspond to the lump-sum transfers, which equate marginal valuations of the consumption good, as required for the equalization of marginal costs. The relationship between efficiency and distribution noted in CHS in chapter 3 for the case of Pareto efficiency continues for the case of emission-constrained efficiency.

References

1. Bohm, P. "Should Marginal Carbon Abatement Costs Be Equalized across Countries?" Mimeograph, Department of Economics, University of Stockholm, August 1993.
2. Brown, D., and G. Heal. "Equity Efficiency and Increasing Returns." *Review of Economic Studies* 46, no. 4 (October 1979): 571–85.
3. Chao, H., and S. Peck. "Pareto Optimal Environmental Control and Income Distribution with Global Climate Change." Working paper, Electric Power Research Institute, Palo Alto, California, July 1994.

4. Chichilnisky, G. "The Abatement of Carbon Emissions in Industrial and Developing Countries." Paper presented at the International Conference on the Economics of Climate Change, OECD/IEA, Paris, June 1993. Published in *The Abatement of Carbon Emissions in Industrial and Developing Countries,* ed. Tom Jones. Paris: OECD, 1994.
5. Chichilnisky, G., and G. Heal. "Who Should Abate Carbon Emissions? An International Viewpoint." *Economics Letters* 44 (spring 1994): 443–49.
6. Chichilnisky, G., G. Heal, and D. Starrett. "The Design of Markets for Emission Permits: Equity and Efficiency Are Not Orthogonal." Working paper, Columbia Business School, Columbia University, and Department of Economics, Stanford University, (chapter 3 of this volume).
7. Coppell, J. "Implementing a Global Abatement Policy: Some Selected Issues." Paper presented at the International Conference on the Economics of Climate Change, OECD/IEA, Paris, June 1993. Published in *The Abatement of Carbon Emissions in Industrial and Developing Countries,* ed. Tom Jones. Paris: OECD, 1994.
8. Dasgupta, P., and G. Heal. *Economic Theory and Exhaustible Resources.* Cambridge: Cambridge University Press, 1979.
9. Drèze, J. Private communication, 1994.
10. Dwyer, D. "Who Should Abate Carbon Emissions? A Comment." Working paper, Department of Economics, Columbia University, fall 1993.
11. Heal, G., and Y. Lin. "Equilibrium and Efficiency in International Permit Markets." Working paper, Columbia Business School, Columbia University, 1994.
12. Mäler, K.-G. Unpublished manuscript, Beijer Institute of Ecological Economics, Royal Swedish Academy of Science, Stockholm, 1994.
13. Mäler, K.-G., and H. Uzawa. "Tradable Emission Permits, Pareto Optimality and Lindahl Equilibrium." Discussion paper, Beijer Institute of Ecological Economics, Royal Swedish Academy of Science, Stockholm.
14. Manne, A. "Greenhouse Gas Abatement: Towards Pareto Optimality in Integrated Assessments." Working paper, Department of Operations Research, Stanford University, 1994.
15. Prat, A. "The Efficiency Properties of a Constant-Ratio Mechanism for the Distribution of Tradable Emission Permits." Working paper, Department of Economics, Stanford University, 1993. (Chapter 6 of this volume.)
16. Uzawa, H. "Pareto Optimality, Competitive Equilibrium and Lindahl Equilibrium." Discussion Paper Series No.9, Japan Development Bank Center on Global Warming, 1995.