Chapter 9
Efficiency and Distribution in Computable Models of Carbon Emission Abatement

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9.1 Introduction

Although much uncertainty surrounds the precise links between carbon emissions and their effect on climate, the risks involved are by now considered sufficiently large for the global community to have started discussing active policy measures. In this context special attention is being paid to the reduction of carbon emissions from the use of fossil fuels. The need for abatement action being generally recognized, the search is on for "efficient" policy instruments, that is, instruments that achieve a given abatement objective at minimum cost. In this context uniform global emission taxes and tradable emission quotas have been suggested as policy instruments of choice.

The initial consensus relating to the efficiency characteristics of a uniform global carbon tax and/or a system of tradable emission quotas has been challenged by Chichilnisky [5] and Chichilnisky and Heal [7], in which the authors (hereafter CH) claim that given the public goods character of emission abatement, a uniform emission tax or tradable emission quotas do not necessarily (in fact not usually) lead to Pareto-efficient outcomes, and that in the context of emission abatement policy efficiency and income distribution issues are intertwined; that is, the fundamental proposition of welfare economics that equity and efficiency are "orthogonal" (i.e., independent of each other) does not

The opinions expressed here are those of the authors and cannot be held to represent the views of the OECD or the IMF.

apply. The nonseparability of equity and efficiency issues is claimed to have important implications for the design of global carbon abatement policies and the choice of instruments to enforce it.

The separability of efficiency and equity is an underlying assumption in most of the computable general equilibrium (CGE) models that have hitherto been used to assess the economic costs of international agreements to reduce carbon emissions. For this reason the results obtained by CH have generated a debate on both the analytical correctness of the argument and its precise policy implications. This chapter aims at clarifying the analytical issues that determine cost efficiency in usual CGE abatement models. In this context some simulation results obtained with the OECD GREEN model are provided. Then it is shown under what conditions the equalization of marginal abatement costs across regions is not a necessary condition for achieving a Pareto-efficient allocation of scarce world resources and in what sense equity and efficiency issues cannot be separated. The consequences of these results for policy are briefly discussed.

9.2 Abatement Cost Models

This section recalls the efficiency conditions in the CGE models that do not embody environmental assets in the utility function (e.g., the OECD's GREEN model).[1] These models were designed with one specific aim: to assess the economic costs of reducing carbon emissions by a given amount determined exogenously. They are not concerned with the joint optimization of output and carbon emission abatement. In particular, they were not intended to evaluate the benefits from a reduction of carbon emissions.

9.2.1 Marginal Abatement Costs — To replicate in a simple way the typical structure of a CGE model, we assume two goods in a given economy: a carbon-free good C and a carbon-based good F, say, fossil fuels, which generates emissions of carbon dioxide E when consumed. The optimization problem of maximizing welfare under a given emission constraint can be formulated as follows:

$$\left.\begin{array}{c} \max \; U(C, F) \\ \text{subject to} \quad g(C, F) = 0, \\ h(F) = E \leq \overline{E} \end{array}\right\}, \tag{9.1}$$

[1] See Burniaux, Nicoletti, and Oliveira Martins [3].

where $g(\cdot)$ represents the production frontier and $h(\cdot)$ is the emission generation function associated with fossil-fuel consumption (with $h'(\cdot) > 0$) and $\overline{E}$ is the emission constraint. Under the normal convexity-concavity assumptions, the first-order conditions characterize the optimum:

$$\frac{\partial U}{\partial C} = \theta \cdot \frac{\partial g}{\partial C} \tag{9.2}$$

and

$$\frac{\partial U}{\partial F} = \theta \frac{\partial g}{\partial F} + [\lambda \cdot h'] = p_F + t_F, \tag{9.3}$$

where θ and λ are, respectively, the Lagrange multipliers associated with the resource and the emission constraint. Relation (9.3) says that the marginal social valuation (or the "correct" price) of F is equal to the competitive market price[2] (p_F) plus a term reflecting the valuation of the emission externality. In this expression the second right-hand term (in brackets) can be interpreted as the excise tax on fossil-fuels (t_F) needed to bring the private cost of F to its social cost. The excise tax t_E to be levied on carbon emissions is then equal to[3]

$$t_E = t_F \cdot \frac{1}{h'} = \lambda. \tag{9.4}$$

Therefore, the carbon tax is equal to the multiplier associated with the carbon constraint and can be interpreted as the marginal social (dis)utility of emissions. Under certain conditions at the social optimum this will equal the marginal abatement cost (MAC).[4] Bohm [2] suggested that marginal abatement costs should be defined in this way; CH have used another definition that might have created some confusion in the interpretation of their results.[5] They define the MAC as the opportunity cost of a unit of abatement in terms of consump-

[2]The competitive price of each good is equal to the shadow price of the resource constraint times the opportunity cost of production (see Varian [22]).

[3]Note that, by definition, $t_F \cdot dF = t_E \cdot dE$.

[4]By the envelope theorem, $dU/d\overline{E} = \lambda$.

[5]However, for reasons that will become clear shortly, the framework set up by Bohm [2] did not really clarify the debate because it is equivalent to the CH model with unlimited transfers among regions, implying the equalization of MACs under both CH and the standard definitions (see Chichilnisky and Heal [6]).

tion forgone. In our framework the CH definition of MAC would correspond to the trade-off between the consumption of the carbon-based good consumption and carbon abatement:[6]

$$\frac{dF}{d(-E)} = -\frac{1}{h'}. \tag{9.5}$$

Formulation (9.5) does not correspond to the standard definition of marginal abatement costs embodied in CGE models, even if, for presentational purposes, average abatement costs are often expressed in terms of gross domestic product (GDP) or consumption losses for a given level of abatement. Moreover, the emission generation functions h are typically different for each country (e.g., each fossil fuel mix has a different carbon content per unit of energy). The functions h would therefore have to be adjusted before there was any presumption that these opportunity costs should be equalized for Pareto efficiency.

9.2.2 Abatement Efficiency and Pareto Efficiency — Assume that there is a group of countries $i = 1, ..., n$, each applying an emission constraint such that

$$\sum_i \overline{E}_i = \overline{E}_W. \tag{9.6}$$

Therefore, the global emission target is reached by an emission constraint in each country. For example, the stabilization of carbon emissions in the OECD group is attained by stabilizing emissions in each country individually. Within this framework the question of cost-effectiveness can be raised; that is, is there a way of achieving the same global abatement at a lower cost? To simplify assume that two countries j and k are similar in every respect except for the emission generation function. Also suppose that country k generates (at the margin) more emissions per unit of energy than country i, that is,

$$h'_i < h'_k. \tag{9.7}$$

It is obvious that for the same excise tax on fossil fuels the induced marginal reduction in emissions is higher in country k than in country i. Therefore, instead of reducing consumption of fossil fuels at home, country i (the "high-cost/low-carbon" country) will be better-off to "buy" the corresponding amount of emission abatement in country k (the "low-cost/high-carbon" coun-

[6]Note that the CH model has only one consumption good.

try) and compensate this country for the costs incurred up to the point at which marginal abatement costs are equalized in the two countries. This efficiency gain could be extended to n countries, and from that it can be derived that in a cost-effective scheme, marginal abatement costs should be equalized.[7] The most simple way to implement this principle is to impose a global carbon emission constraint. It is precisely in this way that "cost-efficient" agreements are implemented in CGE models:

$$\begin{aligned} &\max\ U_i(C_i,\ F_i) \qquad\qquad \text{for } i = 1, \ldots, n, \\ &\text{subject to } g_i(C_i,\ F_i) = 0 \text{ and } \Sigma\, h_j(F_j) \leq \overline{E}_W. \end{aligned} \tag{9.8}$$

It follows immediately from the first-order conditions of this problem that

$$\frac{t_{F_1}}{h_1'} = \frac{t_{F_2}}{h_2'} = \ldots \frac{t_{F_n}}{h_n'} = \lambda, \tag{9.9}$$

where λ is the Lagrange multiplier associated with the (common) carbon constraint. As previously, this multiplier can be interpreted as the marginal abatement costs or the uniform tax levied on emissions in all countries. Whereas the tax on carbon emissions is equalized across countries, the excise taxes on consumption of F are country specific because they are tied to the characteristics of the emission generation functions, which can and do vary across countries.

This overall efficiency improvement might entail an extremely uneven distribution of the burden sharing across countries. This point is illustrated in table 9.1, which provides the simulation results with the OECD GREEN model of an international agreement to reduce world emissions by an amount corresponding to the stabilization of carbon emissions in the so-called Annex 1 group (i.e., OECD, eastern Europe, and the former Soviet Union). The comparison between the first and the second column in the table shows the efficiency gains from imposing an OECD-wide uniform carbon tax instead of a country- or region-specific tax. The average income losses in the OECD are reduced by roughly 0.1 percentage points over the period 1990–2050. At the world level the change in income losses is in the same order of magnitude. However, if the agreement is enlarged to the group of the so-called major emitters (i.e., Annex 1 plus China and India), the same global level of abatement can be achieved with a much lower world income loss (0.22% instead of

[7] Note again that this does not imply that the marginal productivity of abatement, h', needs to be equalized across countries.

Table 9.1
Distribution of gains and losses under different agreements.
Abatement scenario: reduction of world emissions corresponding to the stabilization of missions in Annex 1 countries at their 1990 levels.

Regions	**Unilateral taxes in OECD**	**Uniform tax: OECD**	**Uniform tax: Annex 1 + China + India**
OECD	−0.85	−0.76	−0.25
Annex 1	−0.86	−0.77	−0.20
China	−0.52	−0.47	−1.19
India	−0.07	−0.07	−0.74
Energy exporters	−3.62	−3.32	0.07
World	−1.07	−0.97	−0.22

Note: Average annual real income losses for the period 1990–2050 (as a percentage of deviation relative to the baseline scenario).
Source: GREEN model (OECD [17]).

0.97%). From table 9.1 it can be seen that this overall improvement leads to a disproportionate increase of the burden borne by "low-cost" countries (i.e., China and India). Interestingly, the major gainers from this abatement efficiency improvement are the energy-exporting countries.[8]

To secure the transfer of the emission abatement effort from high- to low-abatement-cost countries, it might be necessary to make transfers that compensate the latter for their incremental costs. Nonetheless, provided that the emission constraint is applied at the global level, it can be shown that abatement efficiency ensures Pareto efficiency and reciprocally.[9] In this context the issues of efficiency and equity are perfectly separable. This point is especially important for the design of a system of tradable permits,[10] as it implies that any initial distribution of allocation of permits will achieve efficiency. The considerations

[8] The intuition behind this result is the following: Because the overall resource allocation is optimized, there is a lower decrease of world energy consumption per unit of abatement. In addition, at the world level there is a shift from high-carbon domestic energy sources (typically coal) toward lower carbon imported ones (oil and gas). The lower reduction in energy demand and the substitution effect tend to increase the revenues of the energy-exporting countries.

[9] Indeed, a Pareto-efficient outcome will be characterized by the following program:

$$\max\ U_i(C_i,\ F_i)$$
$$\text{subject to}\quad U_k(C_k,\ F_k) \geq \overline{U}_k \quad \text{for } k,\ i = 1,\ \ldots,\ n \quad \text{and} \quad k \neq 1 \quad \text{and} \quad f_k(C_k,\ F_k) = 0$$
$$\text{and} \quad \sum_j h_j(F_j) \leq \overline{E_W}.$$

This would yield similar results to (9.8).

[10] Abstracting from uncertainty or transaction costs considerations.

Table 9.2
Distribution of gains and losses under different permit allocation rules.
Abatement scenario: reduction of world emissions corresponding to the stabilization of emissions in Annex 1 countries at their 1990 levels.

Allocation rules	**OECD**	**Annex 1**	**China and India**	**World**
Initial quotas				
Grandfathering	56.5	84.7	15.3	100.0
Egalitarian	26.0	38.9	61.1	100.0
Losses/gains				
Grandfathering	−0.3	−0.1	−1.7	−0.2
Egalitarian	−0.7	−0.7	2.0	−0.2

Note: Initial quotas expressed as percentages of world emissions. For losses/gains, data are average income losses for the period 1990–2050 (as a percentage deviation relative to the baseline scenario).
Source: GREEN model (OECD [16]).

about income distribution can be viewed as a separate problem that can be solved, say, through a negotiation process. A quantified example of this remarkable property is shown in table 9.2. In the simulations presented, the same global abatement target as in the previous experiment is achieved by a system of permit trading with two extreme endowment rules: (1) a grandfathering rule, whereby countries/regions are endowed with emission quotas corresponding to their emissions in 1990, and (2) an egalitarian rule, whereby quotas are allocated in proportion to country/region population shares in 1990. Obviously, the second rule is more favorable to countries such as China and India and results in significant income gains in these countries compared with the losses incurred under the first rule.

Notwithstanding, the average world income losses remain exactly the same whatever the endowment rule is. It might happen in some cases that small differences appear between scenarios having the same abatement target but different permit allocations. This can be caused either by the approximate numerical solution provided by the resolution algorithm or by the different dynamic adjustment paths between scenarios. The nonseparability between equity and efficiency it is not what causes the gap.

9.3 Optimal Abatement Models

Ideally, instead of imposing an emission constraint, the level of global carbon emissions should be set at the (global) welfare-optimizing level. This means that each country or the world community as whole should be able to determine the effective damages of climate change and in this way establish a balance between costs and benefits of a policy action aiming to reduce the risk of global warming. Given the uncertainty surrounding the causal link between emissions, climate change, and its impacts on the economic system, this assessment requires an amount of information that is not currently available. Nonetheless, this is the research agenda of the so-called integrated assessment projects.[11]

The implications of considering the abatement externality directly in the utility function are profound because carbon emissions can be viewed as a public "bad" that is produced in a decentralized way by private consumption activities. This point was highlighted in Chichilnisky [5] and Chichilnisky and Heal [7].[12] Defining an objective function having global emissions as an argument implies that each country's utility function depends on the level of consumption of the carbon-based good in all the other countries:

$$U_i(C_i, F_i; E_w) \quad \text{with } E_w = \sum_j h_j(F_j). \tag{9.10}$$

9.3.1 The General Case: Country-Specific Production Frontiers — A Pareto optimum can be obtained by maximizing the utility of each country subject to the constraints on the utility levels of other countries and their specific production frontiers (as discussed shortly, the latter assumption is especially important):

$$\max\ U_i(C_i, F_i; E_w(F_1, F_2, \ldots, F_n)) \quad \text{subject to} \tag{9.11}$$
$$U_k(C_k, F_k; E_w) \geq \overline{U}_k \quad \text{for } k \neq i \quad \text{and} \quad g_k(C_k, F_k) = 0 \quad \text{for } k = 1, \ldots, n.$$

Using (9.10) and differentiating the corresponding Lagrangian with respect to all C_i and F_i, the first-order conditions for a given country i are

$$\mu_k \frac{\partial U_k}{\partial C_k} = \theta_k \cdot \frac{\partial g_k}{\partial C_k} \tag{9.12}$$

and

$$\mu_k \cdot \frac{\partial U_k}{\partial F_k} = (\theta_k \cdot \frac{\partial g_k}{\partial F_k}) + \left(\sum_j \mu_j \cdot \frac{\partial U_j}{\partial E_w} \right) \cdot h_k' \tag{9.13}$$

for $k = 1, \ldots, n$ and $\mu_i = 1$.

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[11] The first applied models of this kind were built by Nordhaus [16] and Peck and Teisberg [18]. Several integrated assessment projects are currently under way (see, e.g., the second-generation model of Edmonds et al. [10] and, more recently, Prinn et al. [20] and Chichilnisky et al. [9]).

[12] See also Chichilnisky, Heal, and Starrett [8], and Hourcade and Gilotte [13].

Equation (9.13) can be interpreted much in the same way as the relation (9.3); that is, in each country the excise tax on fossil fuel consumption will be country specific and equal to $(T \cdot h'_k)$. However, the tax on carbon emissions T will be the same in each country and equal to

$$T = \sum_j \left(\mu_j \cdot \frac{\partial U_j}{\partial A} \right). \tag{9.14}$$

Moreover, from condition (9.13) it can also be shown that Pareto efficiency can be obtained only if

$$\frac{\mu_k \cdot \dfrac{\partial U_k}{\partial F_k} - \left(\theta_k \dfrac{\partial g_k}{\partial F_k} \right)}{h'_k} = T \qquad \text{for } k = 1, \ldots, n. \tag{9.15}$$

The conditions (9.14) and (9.15) entail two important departures from the previous results. First, in this framework the equality between the optimal carbon tax and the marginal abatement costs (or the marginal disutility of emissions) by country does not hold anymore. Indeed, from (9.14) the carbon tax corresponds now to a weighted sum of marginal abatement costs across regions.[13] In other words, although all countries face the same carbon tax, marginal abatement costs are not necessarily equalized across countries. This point was a source of confusion when interpreting the CH results because in their original paper the expression for the carbon tax was never made explicit (they refer only to the nonequalization of the MACs). Conversely, the equalization of marginal abatement costs across countries would require a system of differentiated carbon taxes, and this would correspond to the so-called Lindhal solution (see Foley [12]). It should be stressed that even if the equalization of marginal abatement utilities is not an objective per se, a *uniform* carbon tax is required for achieving cost efficiency. In this respect, our conclusion is different from Chichilnisky and Heal (1994).

Second, one must choose the appropriate set of multipliers or welfare weights in order to verify condition (9.15). Given that countries may differ in their preferences toward abatement and in their production conditions, not all combinations of utility weights will lead to Pareto efficiency. Typically, there

[13]This corresponds to the usual solution of the optimal tax with externalities (see Baumol and Oates [1]).

would be a Pareto point instead of a Pareto frontier, as is the case with only private goods.[14] This implies that the issues of equity and efficiency cannot be separated anymore (see also Laffont [14]).

Consequently, the delicate problem of the appropriate welfare weights becomes crucial for efficiency. For each simultaneous choice of welfare weights and the corresponding carbon tax—which could, for example, be the outcome of an international negotiation process—there will be an optimal level of global carbon abatement.[15]

It should be noted that the optimal solution depends on the actual preferences, income levels, and production characteristics. Gathering such an information set is a daunting task, but in the context of a CGE model, where a utility function similar to (9.10) is used, all the necessary information will be available by assumption. Such a model could then be used to run simulations illustrating how sensitive the results are to different choices of preferences toward the public good, forms of the production functions, and so on. For example, it would be interesting to analyze how the global abatement level depends on the different sets of welfare weights.

There is also a question of what interpretation should be given to the welfare weights. Formally, they correspond to the marginal valuations of the utilities of the different countries in a world welfare function. For a globally negotiated emission level, the weights will reflect the bargaining power of each region in the negotiations. It might also be interesting to relate the weights to the initial allocation of permits in a system of tradable permits. This would have strong implications for the design of a tradable permit scheme, as it would imply that only one initial permit allocation would be Pareto efficient for each level of global emissions.

9.3.2 Special Case: A Global Production Frontier — Chichilnisky and Heal [7] showed that a situation in which marginal abatement costs (in the sense of marginal consumption forgone by unit of abatement) will be equated across countries is one in which lump-sum transfers among countries can be realized without any limitation.[16] In our framework the possibility for unlimited trans-

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[14]The set of relations (9.14)–(9.15) provide a system of linear $(n+1)$ equations determining *jointly* the optimal carbon tax T and the set of n multipliers μ_k.

[15]See Eyckmans, Proost, and Schokkaert [11], who, in the context of a numerical simulation model, showed that the optimal level of world abatement increases with the degree of aversion for income inequality.

[16]Noteworthy, allowing for international trade and especially trade in emission permits would not solve the problem of nonseparability. Indeed, international trade can replicate a situation of an integrated world economy only under first-best conditions.

fers would be equivalent to imposing a unique (global) production frontier in the equation (9.11), as follows:

$$\left.\begin{array}{rl} \max & U_i(C_i, F_i; E_w(F_1, F_2, ..., F_n)) \\ \text{subject to} & U_k(C_k, F_k; E_w) \geq U_k \quad \text{for } k \neq i \\ \text{and} & g_k\left(\sum C_k, \sum F_k\right) = 0 \end{array}\right\}, \tag{9.16}$$

and the first-order conditions for this problem are now

$$\mu_k \frac{\partial U_k}{\partial C_k} = \theta \cdot \frac{\partial g}{\partial C} \tag{9.17}$$

and

$$\mu_k \frac{\partial U_k}{\partial F_k} = \theta \cdot \frac{\partial g}{\partial F} + \left(\sum_j \mu_j \cdot \frac{\partial U_j}{\partial E_w}\right) \cdot h'_k$$
$$\text{for } k = 1, ..., n \quad \text{and} \quad \mu_i = 1, \tag{9.18}$$

where C and F correspond to the total (world) consumption level of the two goods. By replacing the welfare weights derived from (9.17) into (9.18) and simplifying, one gets

$$\frac{1}{n}\sum_k \left[\frac{\frac{\partial U_k}{\partial F_k}}{\frac{\partial U_k}{\partial C_k}}\right] - \frac{1}{n}\sum_j \left[\frac{\frac{\partial U_j}{\partial E_w}}{\frac{\partial U_j}{\partial C_j}}\right] \cdot \sum_k h'_k = \frac{\frac{\partial g}{\partial F}}{\frac{\partial g}{\partial C}}, \tag{9.19}$$

$A_k = -h_k(F_K)$. In this case the multipliers disappear from the optimality conditions. Expression (9.19) corresponds to the usual Lindhal-Bowen-Samuelson condition for the optimum with public goods. The sum of the marginal rates substitution are equal to the marginal rate of transformation between consumption and the carbon-based good.

9.4 Further Research and Conclusions

Contributing to this debate, Manne [15] referred to a case in which the externality (carbon emissions) originates in the production rather than in the utility function. In that case equity and efficiency are separable. Sturm [21] argues that in the context of international negotiations on climate change policies, only the (limited) notion of "efficiency in production" is operationally relevant. He showed that for this concept the distinction between public and private goods is irrelevant as long as there is a well-defined opportunity cost of regional abatement in terms of the private good, equivalent to the definition of marginal rate of transformation between private goods.

Prat [19] suggests that a constant-ratio mechanism (a ratio meaning a proportional division of the total emission quotas between countries) could separate the issues of equity and efficiency; once the ratio is determined, the (unique) optimal level of abatement can be decided by a planner. However, the implementation of decentralized procedure could raise serious practical problems. Another approach was put forward by Chao and Peck [4], who proposed a set of numerical simulations by which it is shown that the world optimal level of carbon abatement is not very sensitive to the income transfers among the countries. It goes without saying that the latter result depends crucially on the parameter calibration of the model.

These approaches adopt a somewhat pragmatic view of the problem that could be justified given the lack of information concerning the impacts of the climate change. Indeed, at this stage the joint optimization of income and emissions seems an exceedingly ambitious objective. Ultimately, the questions of equity have to be dealt with in the context of international negotiations by taking into account both net transfers or emission quota allocations.

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