Unclassified **ECO/WKP(98)5**

Organisation de Coopération et de Développement Economiques
Organisation for Economic Co-operation and Development

OLIS : 19-Mar-1998
Dist. : 27-Mar-1998

English text only

ECONOMICS DEPARTMENT

ECO/WKP(98)5
Unclassified

EFFICIENCY AND DISTRIBUTION IN COMPUTABLE MODELS OF CARBON EMISSION ABATEMENT : ECONOMICS DEPARTMENT WORKING PAPERS NO. 192

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ABSTRACT/RÉSUMÉ

The separability between efficiency and equity is an underlying assumption in most computable general equilibrium (CGE) models used to assess the costs of carbon abatement. Chichilnisky and Heal (1994) have generated a debate on both the analytical correctness of this hypothesis as well as its precise policy implications. This technical note aims to clarify the determinants of cost efficiency in standard CGE abatement models. Some simulations are provided illustrating the separability property between an efficient outcome and the distribution of income across countries. In the context of an optimal abatement model, it is also shown under which conditions equity and efficiency are not separable anymore.

* * *

La séparabilité entre équité et efficacité économique est l'hypothèse de base dans la plupart des modèles d'équilibre général calculable (MEGC) utilisés pour évaluer les coûts de réduction des émissions de carbone. Chichilnisky et Heal (1994) ont provoqué un débat à la fois sur l'exactitude de cette hypothèse et ses implications pour la politique économique. Cette note cherche à clarifier les déterminants de l'efficacité économique dans les MEGC destinés à évaluer les coûts de réduction des émissions de carbone. Des simulations numériques sont fournies à fin d'illustrer la propriété de séparabilité entre efficacité et la distribution des revenus. L'étude montre aussi dans le contexte d'un modèle de réduction optimale des émissions, sous quelles conditions équité et efficacité ne sont plus séparables.

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EFFICIENCY AND DISTRIBUTION IN COMPUTABLE MODELS OF CARBON EMISSION ABATEMENT

Joaquim Oliveira Martins and Peter Sturm[1]

I. Introduction

Though 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 recognised, the search has been on for "efficient" policy instruments, i.e. 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 (1994) and Chichilnisky and Heal (1994), 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 policies efficiency and income distribution issues are intertwined, i.e. the fundamental proposition of welfare economics that equity and efficiency are "orthogonal" (i.e. independent of each other) does not apply. The alleged non-separability 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 between 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 as well as its precise policy implications. This note aims at clarifying the analytical issues, which 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 equalisation 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.

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1. Joaquim Oliveira Martins, OECD Economics Department; Peter Sturm, OECD Economics Department and (former) Massey University, New Zealand. This paper was presented at the American Economic Association meeting, San Francisco, January 1996 and the European Economic Association Annual Congress, Istanbul, September 1996. We benefited from helpful comments by G. Chichilnisky, L. Gilotte, G. Heal, J.-C. Hourcade, A. Prat, R. Stavins and H. Tulkens. The opinions expressed in this paper are those of the authors and cannot be held to represent the views of the OECD or its Member countries.

II. 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[2]). These models were designed to assess the economic costs of reducing carbon emissions by a given amount determined exogenously rather than through the joint optimisation of output and carbon emission abatement.

A. Marginal Abatement Costs

In order 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 optimisation problem of maximising welfare under a given emission constraint can be formulated as follows:

$$\text{(1)}\qquad \begin{aligned} &\text{Max}\;\; U(C,F) \\ &\text{s.t.}\;\;\; g(C,F)=0 \\ &\qquad\;\; h(F)=E \le \bar{E} \end{aligned}$$

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

$$\text{(2)}\qquad \frac{\partial U}{\partial C} = \theta \cdot \frac{\partial g}{\partial C}$$

$$\text{(3)}\qquad \frac{\partial U}{\partial F} = \theta \cdot \frac{\partial g}{\partial F} + (\lambda \cdot h') = p_F + t_F$$

where θ and λ are respectively the Lagrange multipliers associated with the resource and the emission constraint, respectively. Relation (3) says that the marginal social valuation (or the "correct" price) of *F* is equal to the competitive market price[3] (p_F) plus a term reflecting the valuation of the emission externality. In this expression, the second RHS 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[4]:

$$\text{(4)}\qquad t_E = t_F \cdot \frac{1}{h'} = \lambda$$

Therefore the carbon tax is equal to the multiplier associated to the carbon constraint and can be interpreted as the marginal (dis)utility of emissions which at the social optimum will equal the marginal

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2. See Burniaux, Nicoletti and Oliveira Martins (1992).

3. The competitive price of each good is equal to the multiplier of the resource constraint times the opportunity cost of production (see Varian, 1994).

4. Note that by definition: $t_E.dE = t_F.dF$

abatement cost (*MAC*)[5]. As pointed out by Bohm (1993), marginal abatement costs should be defined in this way. CH have used another definition which, in fact, created some confusion in the interpretation of their results[6]. They define the *MAC* as the opportunity cost of a unit of abatement in terms of consumption foregone. In our framework, the CH definition of *MAC* would correspond to the trade-off between the consumption of the carbon-based good consumption and emissions[7]:

$$\frac{dF}{dE} = \frac{1}{h'} \tag{5}$$

Formulation (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 GDP or consumption losses for a given level of abatement. Moreover, due to the fact that 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) there is no reason why these opportunity costs should be equalised for Pareto efficiency.

B. Abatement efficiency and Pareto efficiency

Assume that there is a group of countries *i=1,...,n* each applying an emission constraint such that:

$$\sum_i \overline{E}_i = \overline{E}_W \tag{6}$$

Thus, the global emission target is reached by an emission constraint in each country. For example, the stabilisation of carbon emissions in the OECD group is attained by stabilising emissions in each country individually. Within this framework, the question of cost effectiveness can be raised, i.e. 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 *j*, i.e:

$$h'_j < h'_k \tag{7}$$

It is obvious that for the same excise tax on fossil-fuels the induced marginal reduction in emissions is larger country *k* than in country *j*. Therefore, instead of reducing consumption of fossil-fuels at home, country *j* (the "high-abatement cost/low-carbon" country) will be better-off to "buy" the corresponding amount of emission abatement in country *k* (the "low-abatement cost/high-carbon" country) and compensate this country for the costs incurred up to the point where marginal abatement costs are equalised in the two countries. This Pareto improvement could be extended to *n* countries, and it follows

5. By the envelope theorem $dU / d\overline{E} = \lambda$.

6. However, for the reasons that will become clear below, the framework set up by Bohm (1993) did not really clarify the debate because it is equivalent to the CH model with unlimited transfers among regions which implies the equalisation of *MACs* under both CH and the standard definition of the carbon tax (see Chichilnisky and Heal, 1993).

7. Note that the CH model has only one consumption good.

that in a cost-effective scheme, marginal abatement costs should be equalised[8]. The simplest 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:

$$(8) \quad \begin{array}{l} \text{Max} \;\; U_i(C_i, F_i) \\ \text{s.t.} \;\; g_i(C_i, F_i) = 0 \end{array} \qquad \text{for } i=1,\ldots,n$$

$$\text{and} \quad \sum_j h_j(F_i) \leq \overline{E}_W$$

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

$$(9) \quad \frac{t_{F_1}}{h'_1} = \frac{t_{F_2}}{h'_2} = \ldots = \frac{t_{F_n}}{h'_n} = \lambda$$

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. While the tax on carbon emissions is equalised 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 usually do- differ between countries.

The overall efficiency improvement achieved by equalising the marginal costs of emission reduction may entail an extremely uneven distribution of the overall costs of (or income reductions due to) world emission reduction. This point is illustrated in Table 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 stabilisation of carbon emissions in the so-called Annex-1 group (i.e. OECD, Eastern Europe and 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 0.97 per cent). From Table 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[9].

8. Note again that this does not imply that the marginal productivity of abatement, *h'*, needs to be equalised across countries.

9. The intuition behind this result is the following: because the overall resource allocation is optimised, 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) towards lower carbon imported ones (oil and gas). The lower reduction in energy demand and the substitution effect tend to increase the revenues of the oil exporting countries.

Table 1. Distribution of gains and losses under different agreements (1)

Abatement scenario: reduction of world emissions corresponding to the stabilisation of emissions in Annex 1 countries at their 1990 levels.

Regions	Differentiated taxes in OECD countries	Uniform Tax in OECD countries	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

1. Average annual real incomes losses for the period 1990-2050 (in per cent deviations relative to the baseline scenario).

Source: GREEN model, OECD (1995).

To secure the transfer of the emission abatement effort from high to low abatement cost countries it may 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[10]. In this context, the issues of efficiency and equity are perfectly separable. This point is particularly important for the design of a system of tradable permits. Abstracting from uncertainty and transaction costs considerations, it implies that *any* initial distribution of allocation of permits will achieve efficiency. The considerations 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 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:

i) a *grand-fathering* rule, where countries/regions are endowed with emission quotas corresponding to their emissions in 1990;

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10. Indeed, a Pareto-efficient outcome will be characterised by the following program:

$$\operatorname{Max} U_i(C_i, F_i)$$
$$\text{s.t. } U_k(C_k, F_k) \leq \overline{U}_k$$
$$g_k\left(C_k, F_k\right) = 0$$
$$\text{and } \sum_j h_j(F_j) \leq \overline{E}_W$$

that would yield identical results to (8).

ii) an *egalitarian* rule, where quotas are allocated in proportion to country/region population shares in 1990.

Obviously, the second rule is more favourable to countries like 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 may happen, in some cases, that small differences appear between the model simulated 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. It is not the non-separability between equity and efficiency which causes the gap.

Table 2. Distribution of gains and losses under different permit allocation rules

Abatement scenario: reduction of world emissions corresponding to the stabilisation of emissions in Annex 1 countries at their 1990 levels.

Allocation rules	OECD	Annex 1	China and India	World
Initial quotas (1)				
Grand-fathering	56.5	84.7	15.3	100.0
Egalitarian	26.0	38.9	61.1	100.0
Losses/gains (2)				
Grand-fathering	-0.3	-0.1	-1.7	-0.2
Egalitarian	-0.7	-0.7	2.0	-0.2

1. In per cent of world emissions.
2. Average real income losses for the period 1990-2050 (in per cent deviation relative to the baseline scenario).

Source: GREEN model, OECD (1995).

III. Optimal Abatement Models

Ideally, instead of imposing an emission constraint, the level of global carbon emissions should be set at the (global) welfare optimising level. This means that each country or the world community as whole, should determine the likely effective damages of climate change and in this way establish a balance between costs and benefits of policy actions aiming to reduce the risk of climate change. Given the massive 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 world carbon emissions can be viewed as a public "bad" that is produced in a decentralised way by private consumption activities in all countries. This point was highlighted in Chichilnisky (1994) and Chichilnisky and Heal (1994)[12]. Defining an objective function having global emissions (E_w) 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:

$$(10) \quad U_i(C_i, F_i; E_W) \quad \text{with} \quad E_W = \sum_j h_j(F_j)$$

A. The general case: country-specific production frontiers

A Pareto optimum can be obtained by maximising the utility of each country subject to the constraints that there will be no utility losses for any other country, and their *specific* production frontiers. As discussed in the next section, the latter assumption is crucial for the results. Formally, the optimisation programme will be as follows:

$$(11) \quad \begin{array}{ll} \text{Max} & U_i(C_i, F_i; E_W(F_1, F_2, ..., F_n)) \\ \text{s.t.} & U_k(C_k, F_k; E_W) \leq \overline{U}_k \quad \text{for } k \neq i \\ & g_k(C_k, F_k) = 0 \qquad \text{for } k = 1, ..., n \end{array}$$

Using (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:

$$(12) \quad \mu_k \cdot \frac{\partial U_k}{\partial C_k} = \theta_k \cdot \frac{\partial g_k}{\partial C_k}$$

$$(13) \quad \mu_k \cdot \frac{\partial U_k}{\partial F_k} = (\theta_k \cdot \frac{\partial g_k}{\partial F_k}) + \left[\sum_j \mu_j \cdot \frac{\partial U_j}{\partial E_W}\right] \cdot h'_k$$

$$\text{for } k = 1, ..., n \text{ and } \mu_i = 1$$

where the μ_k's are the multipliers associated with the Pareto optimum constraint. Equation (13) can be interpreted much in the same way as the relation (3) above, i.e. in each country the excise tax on fossil-fuel consumption will be equal to second RHS term of equation ($T.h'_k$). Following the same previous reasoning, the tax on carbon emissions T will then be the same in each country and equal to:

11. The first applied models of this kind were built by Nordhaus (1992) and Peck and Teisberg (1992). Several integrated assessment projects are currently under way (see for example, the second-generation model of Edmonds *et al.*, 1993, and more recently, Prinn *et al.*, 1996, and Chichilnisky *et al.*, 1996).

12. See also Chichilnisky, Heal and Starrett (1993), and Hourcade and Gilotte (1994).

$$(14) \quad T = \left[\sum_j \mu_j \cdot \frac{\partial U_j}{\partial E_W} \right]$$

Moreover, from equations (13) and (14) it can also be derived that Pareto efficiency requires that:

$$(15) \quad T = \frac{\mu_k \cdot \dfrac{\partial U_k}{\partial F_k} - (\theta_k \cdot \dfrac{\partial g_k}{\partial F_k})}{h'_k} \quad \text{for} \quad k = 1,\ldots,n$$

The conditions (14)-(15) induce two important departures from the previous results:

First, in the context of an optimal abatement model, the equality between the carbon tax and the marginal disutility of emissions (or marginal abatement costs, i.e. $\partial U_k / \partial E_W$) by country does not hold anymore. Indeed, from (14) the carbon tax corresponds now to a weighted sum of the marginal utilities across regions[13]. In other words, while all countries face the same carbon tax, the marginal rates of substitution between the emissions and the non-carbon consumption good (and -- *a fortiori* -- disutility of emissions) are not equalised across countries[14]. 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. Conversely, the equalisation of marginal utilities across countries would require a system of differentiated carbon taxes, and this would correspond to the so-called Lindhal's solution (see Foley, 1970). It should be stressed that even if the equalisation of marginal abatement utilities is not an objective *per se*, an *uniform* carbon tax is required for achieving cost efficiency. In this respect, our conclusion is different from Chichilnisky and Heal (1994).

Second, the set of relations (14)-(15) provide a system of linear (*n+1*) equations determining *jointly* the optimal carbon tax *T* and the set of *n* multipliers μ_k. Put differently, the optimal tax is associated with only *one* combination of welfare weights. Therefore, the solution would correspond to a Pareto point instead of a Pareto frontier, as is the case in a situation involving only private goods. In this sense, equity and efficiency are not separable anymore[15]. For each simultaneous choice of welfare weights and the corresponding carbon tax -- that could be, for instance, the outcome of an international negotiation process -- there will be an optimal level of global carbon abatement[16].

It should be noted that the optimal solution ($T, \mu_1, \mu_2,..., \mu_n$) depends on the actual preferences, income and production characteristics in each region. Gathering such an information set is clearly a daunting task, but in the context of a CGE model where a utility function similar to (10) is specified, all

13. This correspond to the usual solution of the optimal tax with externalities (see Baumol and Oates, 1988).

14. This is the analogue to the classical case of optimising the output of a public good, where marginal utilities of the public good can differ between individuals (cf. Samuelson, 1954).

15. In more general terms, the distribution of property rights matters for Pareto efficiency in a economy with public goods (Laffont, 1989).

16. The problem can also be reversed. For each level of carbon abatement there is an implicit distribution of welfare weights. Along these lines and in the context of a numerical simulation model, Eyckmans, Proost and Schokkaert (1993) showed that the optimal level of world abatement increases with the degree of aversion for income inequality.

the relevant 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 towards the public good, parameterisation of the production functions, etc. For example, it would be interesting to analyse how the global abatement level depends from the different sets of weights[17].

The question here is what interpretation should be given to the welfare weights. Formally, each weight corresponds to the marginal valuation of the preferences of each country in a world welfare function. Accordingly, for a globally negotiated emission level, the distribution of weights will reflect the bargaining power of each region in the negotiation process. More interestingly, the set of welfare weights could be related to the initial allocations of permits in a system of tradable permits. This interpretation would have quite a strong implication 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.

B. Special case: a global production frontier

Chichilnisky and Heal (1994) showed that a situation where marginal abatement costs (in the sense of marginal consumption foregone by unit of abatement) will be equated across countries is one where lump-sum transfers among countries can be realised without any limitation[18]. In our framework, the possibility for unlimited transfers would be equivalent of imposing a unique (global) production frontier in the program (11), as follows:

$$\text{(16)}\quad \begin{aligned} &\text{Max}\quad U_i(C_i, F_i; E_W(F_1, F_2, \ldots, F_n)) \\ &\text{s.t.}\quad U_k(C_k, F_k; E_W) \le \overline{U}_k \quad \text{for}\quad k \neq i \\ &\qquad g(C, F) = 0 \qquad \text{with}\quad C = \sum_k C_k \quad \text{and} \quad F = \sum_k F_k \end{aligned}$$

and the first-order conditions for this problem are now:

$$\text{(17)}\quad \mu_k \cdot \frac{\partial U_k}{\partial C_k} = \theta \cdot \frac{\partial g}{\partial C}$$

$$\text{(18)}\quad \mu_k \cdot \frac{\partial U_k}{\partial F_k} = (\theta \cdot \frac{\partial g}{\partial F}) + \left[\sum_j \mu_j \cdot \frac{\partial U_j}{\partial E_W}\right] \cdot h'_k = (\theta_k \cdot \frac{\partial g}{\partial F}) + T \cdot h'_k$$

$$\text{for}\quad k = 1, \ldots, n \quad \text{and} \quad \mu_i = 1$$

17. Note that there is not a two-way mapping between the carbon tax and the global abatement level. Different levels of abatement could be compatible with the same carbon tax.

18. Noteworthy, allowing for international trade and, in particular trade in emission permits, would not solve the problem of non-separability between equity and efficiency. Indeed, international trade can only replicate a situation of an integrated world economy under first-best conditions. Permit trade could achieve cost efficiency but the welfare weights would still need to be determined for Pareto efficiency.

where *C* and *F* are world consumption level of the two goods. As above, *T* corresponds to the uniform carbon tax. By replacing the welfare weights derived from (17) into (18), simplifying and summing over *n* regions, one gets:

$$(20) \quad \sum_k \frac{1}{n} \cdot \left[\frac{\frac{\partial U_k}{\partial F_k}}{\frac{\partial U_k}{\partial C_k}} \right] + \sum_j \left[\frac{\frac{\partial U_j}{\partial E_W}}{\frac{\partial U_j}{\partial C_j}} \right] \cdot \sum_k \frac{1}{n} \cdot h'_k = \frac{\frac{\partial g}{\partial F}}{\frac{\partial g}{\partial C}}$$

In this case, the optimality conditions will not depend anymore on the welfare weights. The above equation is the equivalent of the usual Bowen-Lindhal-Samuelson condition for the optimal provision of a public good produced in a centralised way. The sum of the marginal rates of substitution between the consumption goods and public bad is equal to the marginal rate of transformation between the carbon-free and the carbon-based good.

IV. Final remarks

Contributing to the debate of efficiency-equity separability, Manne (1993) referred to a case where the externality (carbon emissions) originate in the production rather than in the utility function. In that case equity and efficiency are separable. Sturm (1995) 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 (1995) suggests that a constant-ratio (a ratio meaning an emission quota) mechanism could separate the issues of equity and efficiency; once the distribution of ratios is determined the (unique) optimal level of abatement can be decided by a planner. The implementation of decentralised procedure could raise serious practical problems, however. Another approach was put forward by Chao and Peck (1995) proposing a set of numerical simulations where it is shown that the world optimal level of carbon abatement is not very sensitive to income transfers between 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, which could be justified given the lack of information concerning the impacts of the climate change. At this stage, the joint optimisation of income and emissions still seems an exceedingly ambitious objective; the progress, however, in the science of climate change could modify this perception (Oliveira Martins, 1998). Ultimately, the questions of equity have to be dealt with in the context of international negotiations by taking into account both expected regional damages from global warming and net transfers or emission quota allocations between regions.

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