Modeling an international market of CO_2 emission permits

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Abstract

Many countries have developed energy models (such as MARKAL-MACRO—MM) to assess their energy policies, in particular concerning the curbing of their carbon dioxide (CO_2) emissions. To integrate national MM models, we propose a multi-regional MARKAL-MACRO (*3*M) model. It enables one to study an international cooperation to curb jointly CO_2 emissions through a market of emission permits (certificate). Furthermore, from a decision support perspective, the *3*M model can be used to integrate aspects of ecological sustainability (in relation to the climate change issue), economic welfare, efficient resource use and technological innovation. To solve *3*M, we have used two alternative mathematical methods. We have implemented both in parallel on a network of independent workstations. As a numerical application, we study the cooperation of three European countries (the Netherlands, Sweden and Switzerland) to curb jointly their CO_2 emissions.

Key words: carbon dioxide emissions, energy-economy modeling, international market of emission permits, economic equilibrium.

1 Introduction

Drastic global climate change, that may be triggered by anthropogenic greenhouse gas (GHG) emissions, is likely to have serious impacts on ecological and socioeconomic systems [11]. To avoid them, the United Nations Framework Convention on Climate Change (UNFCCC) called in 1992 for the "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*". The UNFCCC did not set explicit concentration targets, but stabilizing concentration at a 'safe' level may require significant GHG emission reductions, above all carbon dioxide (CO_2). Reducing CO_2 emissions, that come mostly from the use of fossil fuels, might in turn require extensive changes in energy markets and systems, and seriously affect the world economy. It is therefore important to design effective, such as cost-effective, policies to curb CO_2 emissions.

International cooperation has been advocated by the UNFCCC as an effective option to reduce emissions: "*Parties may implement ... policies and measures* (to curb emissions) *jointly with other Parties*". It allows to take into account differences in national emission reduction costs, due mainly to structural differences of the energy systems. For (industrial) countries committed by an international agreement to reduce their CO_2 emissions by a given level, a suitable strategy is to harmonize (i.e. equalize) their marginal reduction costs. This could be achieved using suitable economic instruments such as a uniform carbon tax or an international market of emission permits where the initial endowments are the original national reduction targets. Notice that the term 'cooperation' is used here in its political meaning, and denotes the situation where the countries implement one of the previous instruments. Economically speaking, however, the trade of emission permits is better described as a competition (on the market) rather than cooperation.

To assess energy policies designed to curb CO_2 emissions, many countries have developed energy models, such as MARKAL [2] and MARKAL-MACRO (MM) [8]. To evaluate the dividends to be gained from cooperating on CO_2 abatement using these tools, one can integrate these models. The coupling of national MARKAL models has been reported in [1] for the case of a uniform carbon tax. This paper is concerned with the integration of national MARKAL-MACRO models, to study an international market of emission permits, and evaluate the economic implications of coordinating abatement policies. Towards that end, national MM models had to be extended by coherent trade and budget relationships in order to model a competitive equilibrium situation.

In this regard, the fundamental role of national MM models as part of a model-base within a decision support framework needs to be addressed. The study of international energy policies and strategies will benefit substantially if a consistent set of national energy models is maintained in a coherent manner, a task currently undertaken (for MARKAL and MM) by a committee (ETSAP) of the International Energy Agency. Having access to these models, we envisage many topics for interregional investigations in energy policies such as efficient resource use, ecological sustainability (in relation to the climate change issue), and technological innovations for example. Even though in our study we still needed the assistance of national MM-experts for consistency in the national models, we believe that the promising results we have obtained will stimulate further standardization on the modeling side, such that these national models can be integrated more easily. The strengths of our approach are as follows:

- to use consistent (MARKAL-MACRO) modeling approach (in terms of economic assumptions and model structure);
- to use regional models that are maintained and developed by national expert teams;
- our integration of regional model approach through mathematical techniques (see below) is general and can be extended to other kinds of models, provided that sufficient consistency is achieved in the regional modeling.

To integrate national MM models, two approaches which are connected by dual relations can be followed. The first one is a cutting plane method, based on pseudo-monotonicity conditions [6, 10, 4]. The second is a fixed point approach, originally suggested by Negishi [9], and made tractable by decomposing the resulting optimization problems. For both algorithms, the regional subproblems are solved in parallel on different computers. This is not only necessary for the tractability of solving equilibrium problems with many countries, but it could be used to leave all regional models on their original site, where the modeling and solving knowledge is located.

This paper is organized as follows. Section 2 reports on the coupling of national MM models. And in Section 3, we present a numerical application concerning the cooperation of three European countries for curbing jointly CO_2 emissions.

2 Methodology

2.1 MARKAL-MACRO

MARKAL-MACRO (MM) is a link of two sub-models: MARKAL, a bottom-up engineering model of the energy system and MACRO, a top-down macro-economic growth model. MM enables to study equilibrium on national energy markets. Its specificity is the following. First, it contains through rich technological details a sophisticated description of the energy sector (MARKAL), from primary sources to energy services. Second, it uses an aggregate production function for the rest of the economy (MACRO). The overall structure of MARKAL-MACRO is given in Figure 1, which relates primary economic inputs (capital, labor and energy) to the use of economic outputs for consumption, investment and the payment of energy costs.

In this paper we discuss only those relations of MM which are relevant for incorporating trade of CO_2 permits, that is, the complete MM-model is much larger. The mathematical formulation of MM is cast as a convex nonlinear optimization problem, where equilibrium on energy markets is determined by a single optimization. The model maximizes a utility function U, defined as the integral over a time horizon T of the discounted logarithm of consumption C_t. This integral is approximated as follows:

$$U = \sum_{t=1}^{T} \beta_t \log C_t, \tag{1}$$

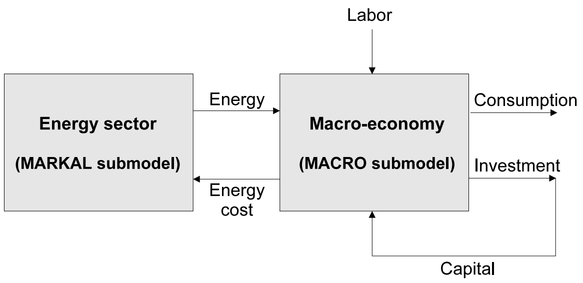


Figure 1: Overview of MARKAL-MACRO

where β_t is the utility discount factor for the period of time t. The production function, which performs the linkage between the MARKAL and MACRO sub-models, is a nested constant elasticity of substitution function. It relates economic output Y_t to the primary inputs capital K_t, labor L_t and energy services $D_{k,t}$ (k are the categories of energy services):

$$Y_t = \left(aK_t^{\rho\alpha} L_t^{\rho(1-\alpha)} + \sum\nolimits_k b_k D_{k,t}^{\rho}\right)^{1/\rho}, \tag{2}$$

where a and b_k are scaling factors, and α is the optimal value share of capital. The production function allows substitution between the pair capital-labor and energy services, when the relative prices change. The elasticity of substitution (ESUB) is given by $\frac{1}{1-\rho}$. Labor L_t is an exogenous parameter. Accumulation of capital K_t depends on new investments I_t and on depreciation of existing capital. Finally, demands for energy services $D_{k,t}$ are primarily determined by economic output (MACRO), prices of energy services (MARKAL) and exogenous parameters (ESUB and a parameter representing energy efficiency improvement independent of price changes). Economic output is distributed between consumption, investment and the payment of energy costs EC_t (computed by MARKAL so as to include the cost of curbing pollutant emissions), as follows:

$$Y_t = C_t + I_t + EC_t. \tag{3}$$

2.2 Multi-regional MARKAL-MACRO

Let us suppose that a group of R regions (e.g. countries) decides to cooperate to curb their CO_2 emissions, by harmonizing their emission reduction efforts. This cooperation is implemented through a market of emission permits, so as to reach overall reduction targets. In addition to these permits, the regions exchange other tradable goods. To study these markets, we propose a multiregional MARKAL-MACRO ($\mathit{3}$M) model, whose general structure is given in Figure 2.

Before describing $\mathit{3}$M, let us introduce some additional notations. In order to support future extensions of the set of traded goods, we denote by $w_{g,r,t}$ the initial endowment of good $g \in G$ for region $r \in R$ in period $t \in T$. Similarly $x_{g,r,t}$ is the net export or exchange of g by region r in period t. By dropping indices for w and x, we mean the corresponding vector, like $x_{g,r} = (x_{g,r})_T$ which contains all time-related components. Currently, our model considers only two goods: good 0, an aggregate good in monetary unit (numéraire good); and good 1, the CO_2 emission permits. Let us further denote p_g the market price of good g. Notice finally that $w_{0,r}$ is 0 and that p_0 is a price index. To take interregional trade into account, regional MM models are modified as follows. First, the economic output of each region r can be used for export:

$$Y_{r,t} = C_{r,t} + I_{r,t} + EC_{r,t} + x_{0,r,t}. \tag{4}$$

And second, each region cannot emit more CO_2 (emission variable $EM_{r,t}$) than the amount of permits it possesses (initial endowment minus net export of permits):

$$EM_{r,t} \leq w_{1,r,t} - x_{1,r,t}. \tag{5}$$

The multi-regional MARKAL-MACRO model can then be formulated following two equivalent alternatives.

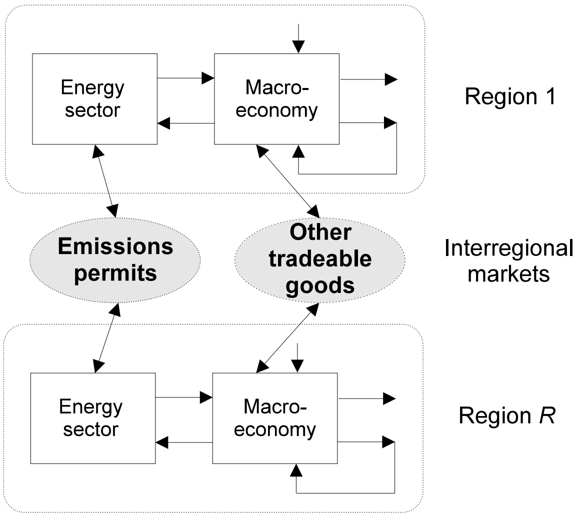


Figure 2: Overview of a MARKAL-MACRO model with R regions

2.2.1 Formulation with market equilibrium conditions

In this formulation, a budget constraint is first added to each regional MM model:

$$p_0^T x_{0,r} + p_1^T x_{1,r} \geq 0, \tag{6}$$

to ensure that, for each region r, trade accounts are balanced over the model time horizon. Let now $p^* = (p_0^*, p_1^*)$ denote market equilibrium prices. A competitive equilibrium of $\mathfrak{Z}$M can then be characterized by the following three conditions (E1)–(E3):

(E1) At $p = p^*$ each region r maximizes its utility U_r under the conditions (2), (4), (5), (6), plus all remaining constraints of MM not presented in this paper.

(E2) Equilibrium prices are feasible: $p^* \geq 0$.

(E3) At the markets equilibrium there is an excess of supply over demand $e(p^*)^T = \left(\sum_{r=1}^R x_{0,r}(p^*),\, \sum_{r=1}^R x_{1,r}(p^*)\right) \geq 0$, and we have complementarity with the price: $p_i^* e_i(p^*) = 0,\ i = 1, \ldots, 2T$.

The complementarity condition in (E3) described the economic fact that prices for free goods (goods in strict excess at the markets equilibrium) are zero. Starting from this formulation, $\mathfrak{Z}$M is first written as a variational inequality problem before being solved, see Appendix A.

2.2.2 Formulation with an aggregated utility function

This alternative approach consists in aggregating, with appropriate weights η_r ($r \in R$) called Negishi weights [9], the regional utility functions into a global welfare function. $\mathfrak{Z}$M is then formulated as follows:

$$\left\{ \begin{array}{ll} \max & \sum_{r=1}^R \eta_r U_r \\ \text{s.t.} & \\ & \left(\sum_{r=1}^R x_{0,r},\, \sum_{r=1}^R x_{1,r}\right) \geq 0 \\ & (2),\ (4) \text{ and } (5), \quad \forall r \in R. \end{array} \right. \tag{7}$$

The first constraint of problem (7) corresponds to a global excess constraint. Let $p = (p_0, p_1)$ denote the dual variables associated with it for a given Negishi weights vector $(\eta)_R$. Then $(\eta)_R^*$

corresponds to an equilibrium if and only if the budget constraint holds for each region $r \in R$, namely if ${p_0^*}^T x_{0,r} + {p_1^*}^T x_{1,r} = 0, \ \forall r \in R$.

We will explicit in Appendix B how we solve this alternative formulation.

3 Trade of CO_2 emission permits among three European countries

The numerical application concerns the cooperation of the Netherlands (NL), Sweden (SW) and Switzerland (CH) to curb jointly their CO_2 emissions through a competitive market of emission permits. These three countries have high living standards. For instance, the 1993 gross domestic product (GDP) per capita was (in thousand US$) 20.9 for NL, 24.7 for SW and 35.7 for CH [5]. However, the structure and efficiency in terms of CO_2 emissions of their energy systems is rather different [7].

NL is a major exporter of natural gas, and its own energy system relies heavily on it. In 1993, 98% of all houses were connected to the natural gas grid, and around 50% of electricity production was based on natural gas and 40% on coal. Furthermore, fossil fuels accounted in 1990 for 97% of the total primary energy use (TPE) resulting in CO_2 emissions of 161.3 million tones, that is 10.8 tones per capita.

In CH, electricity production is mainly from hydro (60%) and nuclear (38%) power stations. Under the current nuclear moratorium (valid until 2000), nuclear capacity is not allowed to increase. Fossil fuels accounted in 1990 for 54% of the TPE, but the use of coal is very low. In 1990, CO_2 emissions from energy combustion were 43 million tones with 6.4 tones emitted per capita. The main contributors of CO_2 were transportation and heating activities.

SW has large hydroelectric resources. Its electricity production is primarily based on hydro-power (52%) and nuclear power (42%), the rest is mainly produced from fossil fuels. This situation is due to change, as the Swedish Parliament has decided in 1980 to phase-out nuclear energy by the year 2010, starting in 1995. Fossil fuels accounted in 1990 for only 34% of the TPE, resulting in CO_2 emissions of 54 million tones, that is 6.3 tones emitted per capita.

These differences lead to significant variations of CO_2 abatement costs among the countries (see below). They constitute an incentive for cooperating on CO_2 emission abatement by harmonizing reduction efforts. This Section evaluates the consequences and benefits to be gained by these three countries, when they reach jointly different reduction targets through an international market of emissions permits.

3.1 CO_2 emission control scenarios

We consider four scenarios related to CO_2 emissions. The first one is a reference or 'Business as Usual' (BaU) scenario, where no CO_2 emission reduction is requested. This situation is simulated with the 𝔐M model, when the countries trade only the numéraire—namely, when emissions are free, that is $p_1 = 0$ (or equivalently $w_{1,r} = +\infty$ and $x_{1,r} = 0$ for all country r). The reason for doing so is that trade of the numéraire influences significantly the results. It would then be misleading to take as reference the situation where the countries are completely isolated. The resulting CO_2 emissions are given in Table 1.

Country	2000	2010	2020	2030	2040
CH	42.9	49.6	51.1	54.1	56.2
NL	162.9	177.4	176.8	178.0	197.2
SW	64.9	102.1	124.6	156.9	178.9

Table 1: *Reference CO_2 emissions (Mt/year)*

The other three scenarios correspond to CO_2 control cases: stabilization, 20% and 40% reduction. They are relative to 1990 levels (approximately 42 million tones for CH, 62 for SW and 160 for NL). In the stabilization scenario, emissions between 2000 and 2040 are kept constant at their 1990 levels (0% scenario). The 20% and 40% reduction targets are to be reached by 2040, starting in 2000 from the 1990 levels, with a linear decrease between 2000 and 2040. For illustration purposes, Table 2 gives the CO_2 control targets for CH.

Scenario	2000	2010	2020	2030	2040
0%	42.0	42.0	42.0	42.0	42.0
-20%	42.0	39.9	37.8	35.7	33.6
-40%	42.0	37.8	33.6	29.4	25.2

Table 2: *CO_2 emission targets for CH (Mt/year)*

Along with these CO_2 control cases, two situations are simulated. The first is when each country curbs separately its CO_2 emissions. It is again evaluated with 3M, when the countries trade only the numéraire. But in this case, the variables $w_{1,r}$ are fixed to the national CO_2 control targets. The second situation is when the same overall targets are obtained at the international level, through an international market of emission permits. This situation is simulated by the full 3M model described in Section 2.2. For each country r, its initial endowment of emission permits ($w_{1,r}$) is set to its original CO_2 control targets; but trade of permits is allowed and the variables $x_{1,r}$ are thus not set to 0.

3.2 Numerical results

Throughout this section numerical results are reported only for 4 periods (of 10 years) from 2000 to 2030. Results for the last period (2040) are not considered to reduce possible misleading effects due to terminal conditions. For the three countries, the incentive to cooperate on CO_2 abatement lies in the differences of their marginal reduction costs (when individually curbing their emissions). Figure 3 gives the undiscounted marginal costs of CO_2 emission reduction, together with the undiscounted market equilibrium prices of CO_2 permits, for our three emission control scenarios.

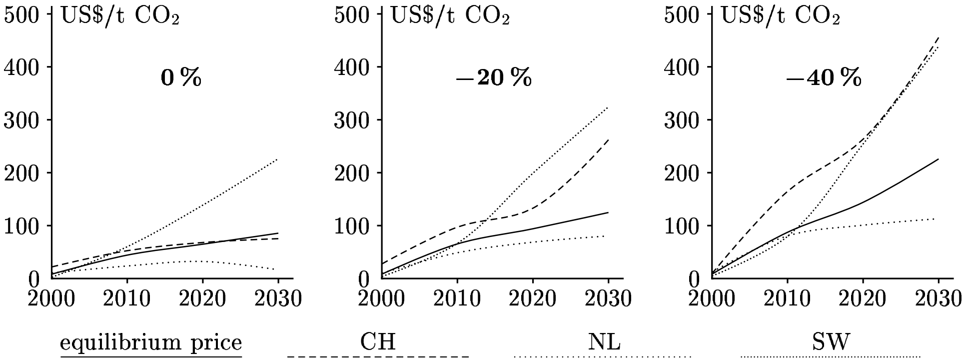


Figure 3: Undiscounted marginal reduction costs and permit prices

Figure 3 shows in particular that the permit prices lie between the lowest and highest national marginal reduction costs. To make a comparison among the periods possible prices have to be discounted to a base year. It turns out that the price-components of the numéraire good can be interpreted as discount rate at the equilibrium, which for all three scenarios is around 4.9 % per year. Table 3 shows then the equilibrium permit prices discounted back to the year 2000. They remain rather modest even in the −40 % scenario. Indeed the highest permit price (55 US\$/t CO_2) is equivalent to 12.6 US cents per liter of gasoline.

Scenario	2010	2020	2030
0%	27.4	24.8	20.3
-20%	40.5	36.0	29.6
-40%	54.1	55.1	53.7

Table 3: *Discounted equilibrium permit prices (US$ /t CO_2), base year 2000*

Countries that have comparatively low marginal reduction costs (when individually curbing their emissions) find it attractive to curb their emissions more than the level of their initial endowments. They can then sell their permit surpluses to countries that have comparatively high marginal reduction costs. For these latter countries, it is indeed more economic to buy permits than curbing the corresponding CO_2 emissions at home. Table 4 gives the net export of CO_2 emission permits for the different emission control scenarios.

Scenario	Country	2000	2010	2020	2030
0%	CH	-0.8	-0.5	0.3	0.6
	NL	-0.6	6.4	14.7	26.3
	SW	1.5	-5.8	-15.0	-26.5
-20%	CH	-0.8	-1.5	-1.7	-3.7
	NL	-0.6	4.6	12.2	25.5
	SW	1.4	-3.2	-10.8	-22.2
-40%	CH	-0.8	-2.7	-4.2	-6.6
	NL	-1.4	2.2	14.8	23.2
	SW	1.7	0.6	-10.7	-16.5

Table 4: *Net export of CO_2 emission permits (Mt/year)*

Table 4 shows that NL is the main net seller of permits and SW the main net buyer. The severity of the reduction requested influences the trade of permits in the following way. CH becomes a net buyer, increasing its permits imports, NL sells less permits and SW reduces its buying of permits.

To evaluate economic consequences of the trade of CO_2 permits, we have computed the gross national product (GNP) of each country for the different scenarios. It is defined as the gross domestic product (GDP) plus the net capital (and work) income from abroad. In the stand-alone national MARKAL-MACRO model, it is assumed that the net capital (and work) income from abroad is zero in all time periods. We have then:

$$\mathrm{GNP}_t = \mathrm{GDP}_t = Y_t - EC_t, \quad \forall t \in T.$$

For the *3*M model, one has to take into account international trade. For each country $r \in R$ the GNP can be written as:

$$\mathrm{GNP}_{r,t} = Y_{r,t} - EC_{r,t} + \frac{p_{1,t}}{p_{0,t}} x_{1,r,t}, \quad \forall t \in T.$$

Notice that, following equation (4), the trade of numéraire ($x_{0,r,t}$) is already included in the definition of the production function $Y_{r,t}$. Figure 4 gives aggregated GNP losses, with and without trade of permits, for the different countries and scenarios. The aggregation is done with a discount rate of 2.5 % instead of 4.9 %. This lower discount rate gives a relative higher weight to the later periods where the bigger losses occur. In Figure 4 BaU (origin of x-axis) means 'business as usual' and describes the situation where no CO_2 limitations are imposed but trade of numéraire is allowed; this yields the highest achievable GNP-level giving the reference point for each region (100 %). Thereon the emissions are increasingly reduced along the x-axis down to the -40 %-scenario. The lines marked by a star (*) reflect the outcome when the regions do not trade permits but have to meet the reduction goals individually. Lines without stars mark scenarios where trade of CO_2 permits is allowed. Finally the 'overall' line shows the behavior of the total GNP summed over all regions. Using GNP to measure the benefits of cooperation, it turns out that trading CO_2 permits yields an

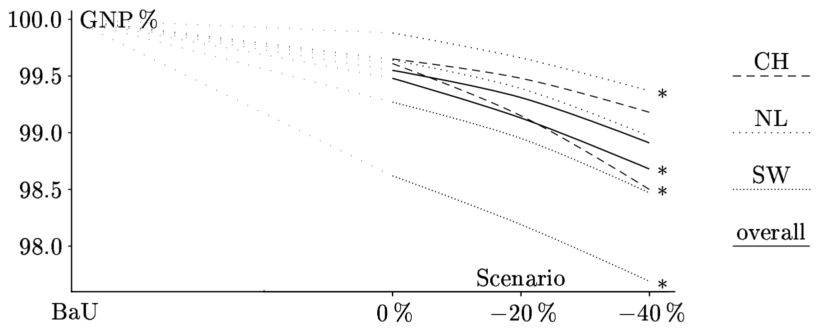


Figure 4: Change of aggregated GNP in %; the $*$-curves depict the non-cooperation cases relative to BaU, whereas the non-$*$-curves relate the cooperative cases to BaU.

overall profit, that is, the overall GNP losses are reduced when trade of permits takes place. But this global benefit is not fairly divided between the three countries: CH and SW are net winners, with reduced GNP losses, whereas NL's GNP losses increase when it cooperates, despite the sell of its permits. Notice that one might have a different allocation of the cooperation benefits if one uses as a measure 'compensating' or 'equivalent variation' instead of GNP. Moreover, this allocation depends on the way the overall initial endowments are distributed among the three countries. Such results could then be used to negotiate initial endowments or fair transfer payments.

4 Conclusion

Multi-regional energy models can contribute to evaluate the economic implications of international policy coordination for curbing carbon dioxide (CO_2) emissions. The multi-regional MARKAL-MACRO (*3*M) model we propose enables one to study an international market of CO_2 emission permits. It allows in particular an assessment of the benefits of trade for the different countries, and gives insights on the consequences of coordinating CO_2 abatement on national economies and energy systems.

From a decision support perspective, our *3*M model can be used to integrate aspects of ecological sustainability (in relation to the climate change issue), economic welfare, efficient resource use and technological innovation. Furthermore, the specificity of our approach is to use regional models that are developed by national expert teams, but are structurally consistent.

The mathematical methods, namely the VIP and Negishi approaches, we use for integrating regional MM models are general. They can in principle be used to couple other kinds of models into an economic equilibrium framework. The implementation of these methods has been done in parallel on a network of independent workstations. This is a clear advantage for solving large multi-regional models, when the number of countries is large.

A VIP approach

Based on the excess function $e(p)$, the equilibrium conditions (E1)–(E4) can be formulated as a nonlinear complementarity problem (NCP):

$$\begin{cases} \text{find } p^* \in \mathbb{R}^d_+, \text{ such that:} \\ e(p^*) \geq 0, \quad {p^*}^T e(p^*) = 0. \end{cases}$$

This is equivalent to the following variational inequality problem (VIP):

$$\begin{cases} \text{find } p^* \in \mathbb{R}^d_+, \text{ such that:} \\ e(p^*)^T (p - p^*) \geq 0, \quad \forall p \in \mathbb{R}^d_+. \end{cases} \tag{8}$$

Because the excess function is homogeneous of degree zero, the feasible price set can be restricted to $\Delta = \{p \in \mathbb{R}^d_+ : \sum_i p_i = 1\}$ by an appropriate scaling. We suppose that $e(p)$ is pseudo-monotone on Δ, namely that $e(p')^T(p - p') \geq 0$ implies $e(p)^T(p - p') \geq 0$ for all $p, p' \in \Delta$. Given pseudo-monotonicity, the cut set $C_p = \{p' \in \Delta \mid e(p)^T(p - p') \geq 0\}$ contains all solutions of problem (8). If in addition $e(p)$ is continuous, the set $\cap_{p\in\Delta} C_p$ contains *only* the solutions of (8). Pseudo-monotonicity allows therefore the application of a cutting plane method as follows. Starting from the initial set of localization $S^0 = \Delta$, we choose at iteration k a 'center' $p^k \in S^k$, and we compute the set $S^{k+1} = S^k \cap C_{p^k} = \{p \in S^k \mid e(p^k)^T(p^k - p) \geq 0\}$. We continue until $\|e(p^k)\|$ or $|p^{kT} e(p^k)|$ is small enough, or until $\min_{p\in\Delta} e(p^k)^T(p - p^k) > -\varepsilon$, for an $\varepsilon > 0$.

In practice, the excess function for the $\mathfrak{M}$M model is not pseudo-monotone. Nevertheless, this cutting plane algorithm is able to find the equilibrium prices. Indeed, only pseudo-monotonicity in the solution p^* is needed. Moreover, the problems we are solving are in some sense close to pseudo-monotonicity, and we can expect that most cutting planes do not cut away the solution. Among the possible centers we have considered—analytic center, center of gravity and of the largest inscribed sphere—the first one is the most favorable. Finally, let us notice that the computation of the excess function requires only the solving of R independent optimization problems. This can be done in parallel (distributed or parallel computing).

B Negishi approach

The concept described in this Section goes back to Negishi [9]. Let us recall that it consists in solving problem (7) described in Section 2.2.2. To do so, one has to determine the appropriate Negishi weights η_r, taking the budget excess (6) for each region r as the criterion to be checked. This is done through an iterative approach that increases η_r when region r does not use all the wealth it could have ($p^T e_r > 0$), and decreases it otherwise. More precisely, the updating scheme estimates η_r through the inverse of the dual variable μ_r associated with constraint (6). Indeed, at the markets equilibrium, the relation $\eta_r = 1/\mu_r$ holds exactly [9] (up to a normalization). The dual variables μ_r are obtained by solving the regional utility maximization problems (E1).

Using restart techniques, this yields a fast and robust convergence of the Negishi algorithm. A practical disadvantage of the Negishi approach lies in the fact that one has to handle a much larger optimization problem. This can imply computational intractability, when the number R of regions to be solved increases. However, by dualizing the global excess constraint, the problem can be decomposed, so as to solve again at each iteration R independent optimization problems. We have implemented this Negishi algorithm using the '*Analytic Center Cutting Plane Method*' (ACCPM) [3, 4].

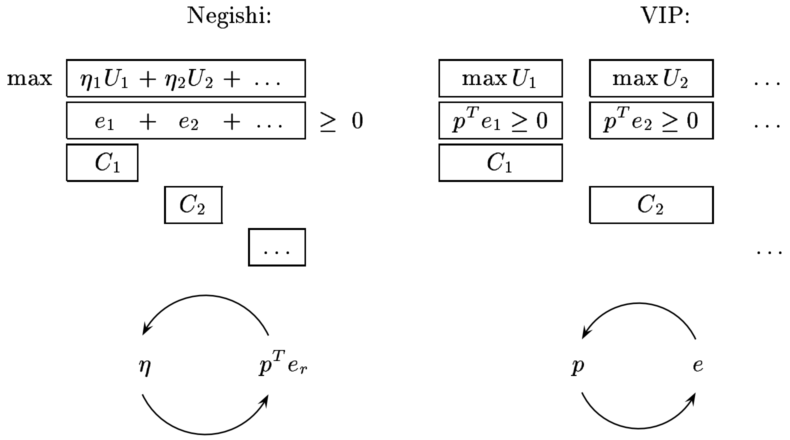
C Comparing both approaches

Figure 5 compares the Negishi and VIP approaches. Notice that C_r denote the set of constraints (2), (4) and (5) for region r.

The formulation with an aggregated utility (Negishi) does not contain explicit prices, and hence budget constraints. However, the dual variables associated with the global excess constraint yield the prices of the traded goods. The Negishi approach consists in modifying the Negishi weights so as to satisfy regional budget constraints in the so-called 'space of consumers'. In the VIP-approach, the overall excess is not directly constrained. But by adjusting the prices, which are exogenous variables, this approach seeks to balance the global excess in the so-called 'space of goods'.

D Implementation issues

The regional models have been made fully consistent (same currency, same emission unit). Furthermore, while the Swiss and Swedish model have a time horizon ranging from 1990 to 2040, the



Negishi: space of consumers

VIP: space of goods

Figure 5: Comparing the Negishi- and the VIP-approaches

Dutch model goes from 2000 to 2040. We have thus restricted the trading period to 2000–2040 and adjusted the models accordingly for the non-trading periods.

The size of the resulting nonlinear models ranges from around 27'000 to 72'000 non-zeros. On our HP-735/125 the solution time for a single region using restart techniques varies between a few minutes (Swiss and Swedish models) to 15-30 minutes (Dutch model), depending on the amount of parameter changes (the prices in case of the VIP-approach, the Negishi weight in the fixed point approach). The computation of an analytic center is very fast, requiring only a few seconds. With the distribution of the regional models on three computers (two different IBM RS6000 and the HP mentioned), about 1 day has been necessary to reach a solution in case of the VIP-approach (100–150 iterations). Based on older databases the solving time for a Negishi-based approach can be estimated to be around 2 days. Notice that computation time can be greatly reduced by an appropriate reduction of the feasible set using a priori information about the solution.

The implementation consists of a small main program in C language, a small GAMS (General Algebraic Modeling System) problem for the computation of the analytic center, and the adjusted regional GAMS models. The distribution of the computation on different computers has been easily done by using some standard UNIX system calls.

Acknowledgment: We are grateful to the ECN (Netherlands Energy Research Foundation, Petten) Policy Studies for receiving the Dutch MARKAL-MACRO model, and to the Division of Energy Systems Technology at Chalmers University of Technology (Gôteborg, Sweden) for the Swedish one.

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