MARKAL/TIMES Modeling of Greenhouse Gas Abatement Strategies: Canadian Case Study and World Coalition Analysis

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Abstract

Global climate change issue raises two basic questions: What to do to guarantee the long-term efficiency (or the least collective cost) of international greenhouse gas control policies? Who pays for abatement and adaptation so that equity among countries is promoted and action of all countries is guaranteed? This paper presents how technical-economic MARKAL and its multi-region advanced version TIMES compute optimal energy and technology decisions under environmental constraint. A Canadian case study points out typical results calculated by MARKAL (e.g. marginal costs, total costs, technology choices, etc.) and it emphasizes critical assumptions influencing computed results, such as optimization assumption, system-effects under local perturbations, end-use elasticities etc. Finally, the paper proposes to use game theory approaches combined to MARKAL/TIMES modeling to calculate transfers among countries that would guarantee that all countries' individual welfare are better off under the international cooperation case compared to the no-cooperation case (Nash equilibrium).

Keywords: MARKAL / TIMES, technical-economic optimization, energy, climate change, game theory, cooperation, non-cooperation

Résumé

La question des changements climatiques soulève deux questions fondamentales : Que faire pour garantir l'efficacité (c'est à dire le moindre coût social) à long terme des stratégies internationales de réduction des gaz à effet de serre? Qui doit payer pour les coûts d'adaptation et de contrôle, en vue de respecter le principe d'équité entre pays et de garantir l'action de tous les pays? Le présent article présente comment le modèle technico-économique MARKAL, ainsi que TIMES, sa version avancée et multi-régionale, permettent de calculer des choix optimaux en matière d'énergie et de technologie, sous contrainte environnementale. Une étude de cas canadienne illustre les résultats fournis par MARKAL (par exemple : coût marginal, coût total, choix technologiques, etc.) et met en évidence les hypothèses critiques pouvant influencer les résultats obtenus par MARKAL (par exemple : hypothèse de base d'optimisation du système, effets de système sous l'effet de perturbations locales, élasticités des demandes finales, etc.). Finalement, l'article propose de combiner les principes de théorie des jeux à la modélisation MARKAL/TIMES pour calculer les transferts entre pays qui garantiront que le bien-être individuel de chaque pays est supérieur dans les cas de coopération avec transfert, par rapport à la non coopération telle que représentée par l'équilibre de Nash.

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1 Introduction

The Third Assessment Report of the Intergovernmental Panel on Climate Change concludes that « *there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities* [and that] *anthropogenic climate change will persist for many centuries* » (IPCC, 2001). Scientific evidence linking anthropogenic greenhouse gas (GHG) emissions with the risk of global climate change is now generally accepted.

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (KP) aim at proposing a GHG emissions control framework. They define legally binding reduction commitments for OECD countries and for Eastern European and Former Soviet Union countries. They also recognize and define principles of actions such as common but differentiated responsibilities, specific needs of developing countries, promotion of sustainable development and integration of actions with national development programs. They finally propose flexible international mechanisms (joint implementation, clean development mechanism and emissions trading) to facilitate efficient GHG reductions.

The UNFCCC and the KP raise two basic questions at the heart of the current international negotiations on climate change:

- What to do? i.e. How and where should GHG emissions be reduced in order to guarantee the long-term efficiency (or the least collective cost) of international GHG control policies?
- Who pays for abatement and adaptation? i.e. How benefits and costs of GHG control should be distributed among countries to promote equity and common but differentiated responsibilities on the one hand, and to guarantee participation and action of all countries on the other hand?

Many recent papers have provided some answers to the policy questions related to national and international efficient options (« What to do ») and more recently from the perspective of equity-based options (« Who pays ») (Rose and Stevens, 2000; Weyant, 2000). This paper presents an approach based on technical-economic modeling and on game theory to deal with both efficiency and equity issues of climate change. It focuses on some methodological and practical aspects of using technical-economic MARKAL model as an integrated decision-aid tool to assess energy and technology choices and to build efficient GHG abatement policies (« What to do » debate). Discussion on the use of game theory as a complementary tool is also provided (« Who pays » debate). It must be noted that this paper is not mathematics oriented but rather methodology and case study emphasized. While the first section points out some MARKAL modeling principles, the second section presents a case study to illustrate how MARKAL optimization can be used to analyze GHG control policies and to emphasize critical assumptions influencing results computed by MARKAL. The last section introduces the advanced world TIMES model and its possible integration with game theory approaches which are proposed to guarantee that all countries' individual welfare are better off under the international cooperation case compared to the no-cooperation case.

2 MARKAL Modeling: Some Principles

MARKAL (MARKet ALlocation) was developed in a cooperative multinational project over a period of more than two decades by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency. The model has a long and rich history of methodological developments and applications to energy and environmental issues within Canada and more than 35 countries around the world[1] (Canada, United States, European Union, Germany, Belgium, China, Italy, Mexico, etc.).

Supply/demand equilibrium

MARKAL is a dynamic linear programming (LP) model of the production, trading, transformation, and end-uses of various energy forms and some materials that affect GHG emissions (Fishbone et Abilock, 1981). Its paradigm is the computation of a local (one country or one region) or multi-regional equilibrium based on the long term least-total-cost for providing the externally defined energy services demands and exports for the entire system over a 30 to 45-year time horizon (1995-2040).

As an equilibrium model, MARKAL implements an economic equilibrium on energy markets, which means that a MARKAL solution is guaranteed to respect the balance of each energy form used, at a price that is endogenously adjusted as quantities used vary. In practice, the selection of technologies in all sectors, at all periods (energy substitution, new technology penetration, industry processes replacement), and the computation of energy prices, occur simultaneously in the model. In MARKAL, the simultaneous double adjustment, which is the essence of a computable equilibrium, is made possible by the use of optimization: MARKAL minimizes the total discounted cost of the system over the long term, by satisfying any externally imposed constraint such as emissions limits. Cost of the system includes: investment and operating costs of all sectors, plus (optionally) the cost of lost demand, when demand elasticities are provided.

The basic LP MARKAL model is of the general sort (Fishbone et Abilock, 1981):

$$\min imize\left(\sum_{i} c_i X_i\right) \qquad \text{subject to } \sum_{i} a_{ji} X_i \leq \text{ or } \geq b_j$$

where coefficients c_i (objective function), a_{ji} and b_i (constraint functions) are known parameters and vectors X_i are the solution of the problem. MARKAL objective function relates to the total discounted cost of the system. Constraints include among others:

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[1] MARKAL teams around the world belong to the international consortium of Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). GERAD (Groupe d'études et de recherche en analyse des décisions) is composed of researchers from École des Hautes Études Commerciales, École Polytechnique, McGill University and Université du Québec à Montréal. GERAD researchers have been prime developers of MARKAL in its modern form, and continue to be leading expert modelers within ETSAP. It developed multi-regional Canadian MARKAL and contributes to the development of the world advanced version TIMES.

- *satisfaction of demand* (at each time period, each region, each time-slice) where demand can itself be elastic to price (see below):

  $$\sum_{k} \mathrm{ACTIVITY}(k,t,r,s) = \mathrm{DEMAND}(t,r,s)$$

- *capacity transfer from one period to the next*:

  $$\mathrm{CAPACITY}(k,t,r) = \sum_{t',\, t-t'<\mathrm{LIFE}(k)} \mathrm{INVESTMENT}(k,t',r) + \mathrm{RESIDUAL\ CAPACITY}(k,t)$$

- *use of capacity (depending on availability factor AF)*:

  $$\mathrm{ACTIVITY}(k,t,r,s) \le \mathrm{AF}(k,t,r,s) * \mathrm{CAPACITY}(k,t,r)$$

- *energy-carrier balance* (production, exports and imports of energy-carrier must at least equal consumption),
- *peak-load electricity reserves*,
- *emission constraints*, etc.

with k technology

t time period

r region

s time-slice

Elastic end-use demands

Identified as a bottom-up or engineering model, MARKAL is configured to reflect the changes in end-use demands resulting from changes in the costs (and therefore the prices) of supplying those demands (Kanudia and Loulou, 1997). In other words, end-use demands are elastic to their endogenously computed own price. Consequently, due to feedback effects among sectors, a GHG scenario in MARKAL will result in the alteration of end-use demands throughout the economy. Conversely, changes in end-use demands also feedback into the energy supply chain and have investment, operation and emission consequences for those sectors. MARKAL goes therefore beyond the conventional bottom-up models, while still relying on the typical detailed technico-economic data[2].

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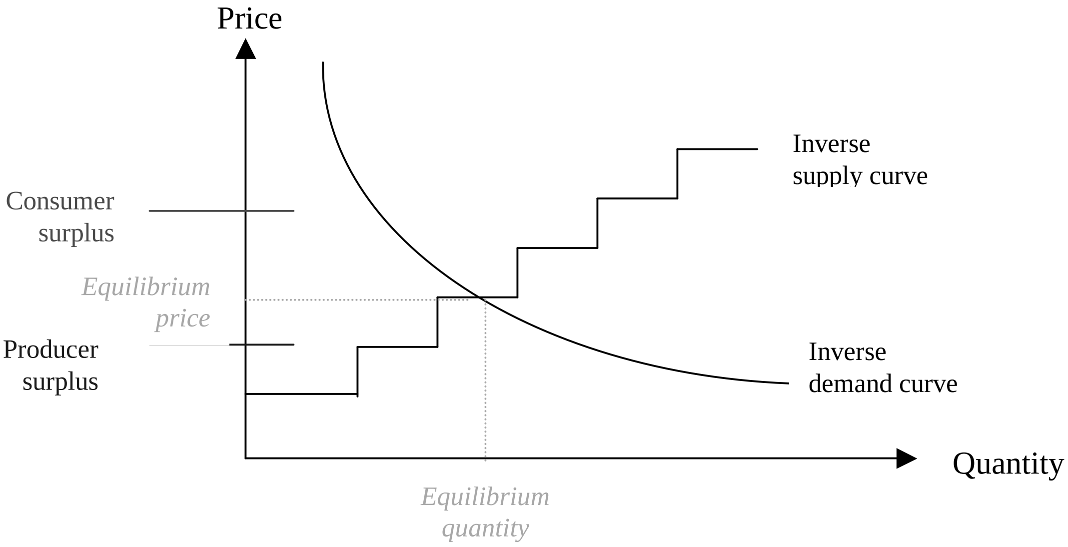
[2] Several classes of long-term integrated assessments methods are used to address the policy issues of climate change. *Bottom-up models* rely on detailed supply and demand technology databases and offer the detailed analysis of technical potential, focusing on the engineering characteristics of technologies such as costs and performance (Bruce, Lee et Haites, 1996). They are generally considered as promoting a prescriptive framework for GHG control. *Top-down models* analyze more aggregated behaviors based on economic indices such as prices and elasticities (Bruce, Lee et Haites, 1996). They are generally considered to promote a descriptive framework for macroeconomic impacts

Also, it is known from the Equivalence Theorem of economic theory that a supply/demand equilibrium is reached when the sum of the producers' and consumers' surpluses is maximized (Kanudia and Loulou, 1997). As illustrated by Figure 1, the supply/demand equilibrium is the point at which the area between the supply and the demand curves is maximized[3]. One consequence of this computational approach is that the model is indifferent to the allocation of costs among economic agents (producers, consumers, provinces). Consequently, MARKAL does not distribute the costs and benefits relating to that response in a unique way neither among producers, nor between producers, consumers and governments (Loulou *et al.*, 2000).

Figure 1: Supply/Demand Equilibrium



A prospective integrated modeling tool

Given the simplifying assumption that the economy will always configure itself in a least-cost way, which is based on a theory of competitive markets, the model assumes that economic

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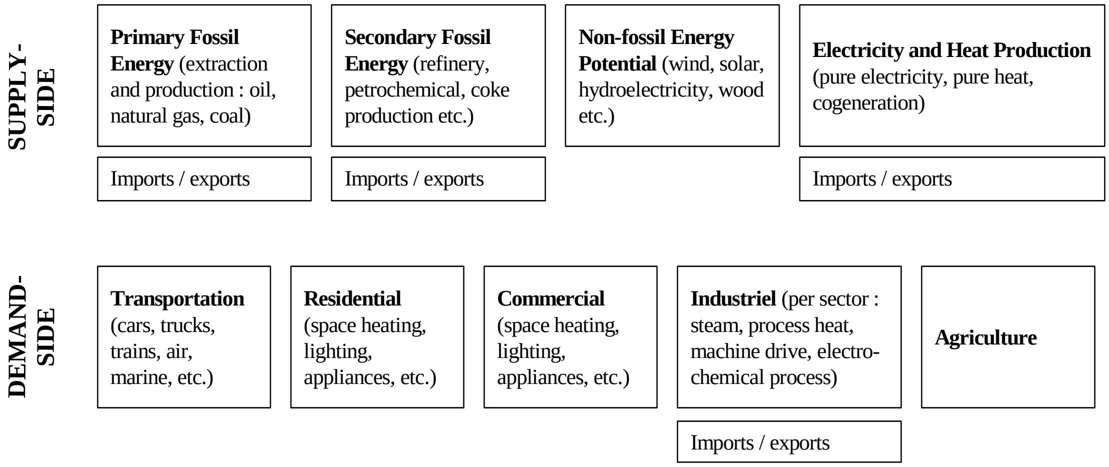
analysis of GHG control. According to the conventional wisdom, top-down studies may be too pessimistic (control costs may be too high), while bottom-up studies may be too optimistic (control costs may be too low) (Krause, 1996). The main reason is the interpretation of the energy efficiency gap, i.e. the gap between technologies actually chosen by consumers and the best (cost-minimizing) technologies available on the market (Krause, 1996). Improved and hybrid models are now available, which attempt to merge top-down and bottom-up characteristics. As a result, cost differences between models are more and more related to data and scenario assumptions rather than due to structural paradigms. Thanks to its elastic end-use demands, bottom-up MARKAL model is now closer to general equilibrium models.

[3] While the total energy cost of the system is linear, the net social surplus, which includes the loss of welfare due to demand reduction, is nonlinear and is linearized by piecewise linear functions (Kanudia and Loulou, 1997).

agents of all sectors are assumed to act as perfectly rational (cost minimizing rationality) and with perfect information and foresight to costs of technologies, prices of fuels and other factors that affect energy choices. In the "real world", these conditions are satisfied in varying ways and to varying degrees in different sectors. Therefore the optimal response in the model may not actually occur, and MARKAL does produce prospective analysis of least-cost solutions but does not produce forecasts, or predictions. The transition to competitive energy markets under way in North America and other regions of the world, is an additional reason to use competitive equilibrium models such as MARKAL (Loulou *et al.*, 2000).

The strengths of MARKAL are: spatial integration (multi-regions model allows fully endogenized energy trades between countries or regions), economic integration (economic demands are allowed to react to their own prices, via own-price elasticities supplied by the user) but also its large, detailed and regularly updated technological database. For example, the Canadian database (covering 7 regional sub-models) include more than 4000 technologies, describing in detail the existing and future technologies in end-use sectors (residential, commercial, transport, industrial) and supply-side sectors (primary energy extraction and processing, electricity production, secondary energy production). Figure 2 presents typical technology structure included in MARKAL database.

Figure 2: Typical MARKAL database



In the context of climate change, MARKAL can be used to identify or compare both sectoral and multi-sectoral techno-economic options in terms of efficiency and environmental effectiveness. The model currently includes five of the six GHG gases listed in the Kyoto Protocol: carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O, sulphur hexafluoride SF_6, and perfluorocarbons CF_4 and C_2F_6. Hydrofluorocarbons HFC is treated separately, due to the specific dynamics of its emissions/abatement. Methane from natural sources or agriculture and

CO_2 emission/sequestration from forests and soils are not directly modeled but their contributions are included by sensitivity analysis. NO_x and SO_2 are also included.

3 Case Study: analysis of the Canadian climate change strategy

In 1998, immediately following the negotiations concerning the Kyoto Protocol, a Canadian process was established to engage governments and stakeholders in examining the impacts, costs and benefits of implementing the Protocol and the various implementation options open to Canada. In order to elaborate the Canadian Climate Change Strategy, sixteen issue tables/working groups independently analyzed more than 100 GHG abatement option packages for each of their areas of concern, each option covering sometimes several measures. Two energy-technology models – MARKAL and CIMS (Canadian Integrated Modeling System developed by the Energy Research Group from Simon Fraser University) – were selected to evaluate the direct impacts in terms of required investment, changes in energy flows and GHG emissions reductions associated with path-scenario combinations, under the deliberately imposed assumption that economic activity remain unchanged (as discussed later). While MARKAL is an optimization model and therefore assesses options on the basis of their economic cost, CIMS is a behavioral model and therefore incorporates information concerning consumer preferences (i.e. less tangible non-financial considerations, such as quality or the type of technology)[4].

A presentation of the analysis[5] will help to understand how MARKAL can be used as a decision-aid tool to evaluate energy and GHG policies and which critical assumptions may influence results.

Actions, paths, scenarios and target

Figure 3 illustrates some of the actions, which were modeled in each of the activity sectors. *Five paths* were defined as various combinations of specific measures, targets (sectoral or economy-wide targets) and emission trading assumptions (none, electricity sector only, large final emitters only – 35% of emitters - or broadest practicable – 80% of emitters). Only two of them (Paths 2 - Economy-wide target, permit trading for Large final emitters - and Path 4 - Economy-wide target, permit trading Broadest practicable) are illustrated, as they are the most representative of possible and realistic policies. *Three international scenarios* were also defined to reflect the range of international flexible responses to GHG policies: “Canada alone” considers that no other country implements any emission reduction initiatives and 100% of the Canadian target is reached by domestic actions (it shows the impact of Canadian GHG policy in isolation); “Kyoto-tight” is based on a not well developed international permit trading system

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[4] Because of their different pricing philosophies and because of some different assumptions, CIMS’costs are generally higher than those computed by MARKAL. We won’t insist on the differences between CIMS and MARKAL, as such an analysis would require a dedicated article.

[5] Full report (Analysis and Modeling Group, 2000) available at: http://www.nccp.ca/NCCP/pdf/AMG_finalreport_eng.pdf

and high transaction costs (International permit price = 58$/t in 2010); "Kyoto-loose" is based on a well established international permit trading system and low transaction costs (international permit price = 24$/t in 2010). The *Kyoto emission target* (emission of 565 Mt/year must be reached between 2008 and 2012) is arbitrary held constant after 2012.

Some other imposed and restrictive constraints must also be noted: non-energy sector output and energy exports volumes and prices are kept constant at reference case levels (except in the transportation sector, where road travel demand is allowed to change), because the modeling working group wanted to capture macro-economic effects separately and control the assumptions for US actions and their implications for Canada.

Figure 3: Example of options packages

Sector	**Ex. of Option Package / Measures**
Building (commercial, residential, institutional) *(90 options)*	Building retrofit program Low income housing program National standards Program for Equipment and Appliances
Primary energy process (petroleum, gas, oil sands) *(64 options)*	Cogeneration Fuel switching Flare gas recovery Leak detection and repair (gas plants, transmission) Flatting of vented gas
Refinery *(13 options)*	Liquid fuel replacement Cogeneration Increase surface area for heat exchange etc.
Other industries *(35 options)*	PFC reduction (aluminum) Cogeneration (pulp and paper) Conversion to elc (mining)
Electricity *(2 options)*	Sector-wide cap (endogeneous technology selection) Subsidy to Low Emitting Emerging Technologies (wind, biomass, small hydro, micro-turbine)
Transport *(113 actions)*	Transit pricing Alternative fuel infrastructure Improved efficiency Truck driver training
Municipality *(7 options)*	Incentives for the capture and flaring of landfill gas Support to Community Energy Systems (cogeneration)
Forest / Agriculture *(1 option)*	Sequestration in the forest sector is assumed at 10 Mt CO2 in 2010 and later. Kyoto Canadian target has been adjusted to 4.33%

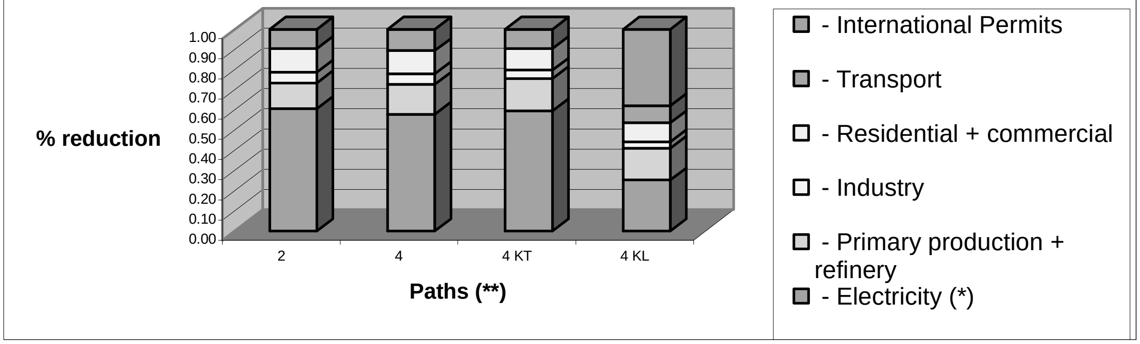
MARKAL outputs

Table 1 presents the different kind of typical outputs obtained from MARKAL modeling and some illustrative results in the context of the Canadian Climate Change Strategy.

Table 1: Typical MARKAL outputs

MARKAL outputs	**Some illustrative results (Canadian Climate Change Strategy)**
Sectoral emissions (or GHG reduction efforts)	See figure 4. In economy-wide target paths, the electricity sector effects large reductions and it plays a pivotal role in GHG abatement. For example, coal based electricity production disappears in Ontario and is considerably reduced in the Atlantic Provinces, replaced by hydro-electricity imports from Quebec, Manitoba, and Labrador.
Provincial emissions (or GHG reduction efforts)	See figure 5. A few provinces (Saskatchewan, Quebec and Ontario) effect more than proportional emission reductions. This can be explained from the energy endowments of the provinces, mainly the electricity trade (helps to reduce emissions) and the upstream emissions (important and relatively inelastic source of emissions).
Marginal cost	Broader permit trading produces of course smaller marginal cost (48.7 $\$_{98}$ /t CO_2-eq in Path 4 against 56.5 $\$_{98}$ /t CO_2-eq in Path 2) . International GHG permits at $58/tonne (Kyoto tight) don’t really modify domestic GHG strategies, as marginal costs of domestic actions are lower than GHG permit price. On the contrary, domestic reductions drop dramatically under permits priced at $24/tonne, especially in the electricity sector.
Total cost (compared to reference case) (divided into investment, operation costs, fuel costs, loss of welfare)	International GHG permits at $58/tonne (Kyoto tight) system increases the value of Canadian gas and electricity exports so that the overall cost for Canada is much lower in the Kyoto tight scenario than in the Canada Alone scenario and even in the Kyoto loose scenario. Under permits priced at $24/tonne, purchase of cheap permits replace costly actions.
Sectoral costs	The sectoral distribution of costs depends very greatly on the form and design of instrument chosen – taxes, tradable permits (and their initial allocations)
Technology choices and energy impacts	Not detailed here. Depends on paths and sectors.
Fuel prices	Not detailed here. Depends on paths and sectors.

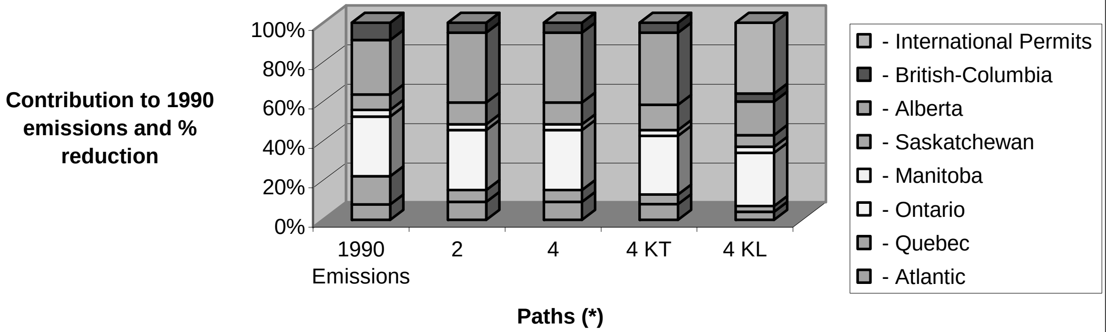
Figure 4 : Sectoral contribution to abatement (2010)



(*) Electricity sector also includes the capture and the sinking of CO_2 into deep saline aquifers of Western Canada.

(**) Path 2: Economy-wide target, permit trading for Large final emitters). Path 4: Economy-wide target, permit trading Broadest practicable. KT = Kyoto tight, KL = Kyoto loose.

Figure 5 : Provincial contribution to abatement (2010)



(*) Path 2: Economy-wide target, permit trading for Large final emitters). Path 4: Economy-wide target, permit trading Broadest practicable. KT = Kyoto tight, KL = Kyoto loose.

Critical links between modeling and “real” GHG policies

As suggested by paths definitions and by some of the outputs, critical modeling assumptions were necessary to represent and analyze the GHG control policies. This section will remind some of them in order to explain how such assumptions, which represent basic links between the "real world" and operational research tools, are at the heart of any operational research work, and may broadly influence the results *(*more details can be found in *Loulou et al., 2000)*:

- When a perturbation (such as a measure) is introduced in some sector, the equilibrium may be affected in very complex ways, and the adjustments performed by the model may involve a number of technology and fuel adjustments in other sectors as well as in that sector itself: the so-called "system-effects". For example, increase energy efficiency of cars may reduce petroleum products demands and refinery activity. Or replacement of oil by electricity for heating purpose adds a new competitive use for electricity. In this context, the analysis consists of more than simply adding up the impacts of individual measures or options, and only whole system integrated analysis, as proposed by MARKAL model, must be used.
- Translation of measures as described by the sectoral tables into MARKAL techno-economic language was a big challenge as information was not always directly "usable" because of missing or inappropriate data.
- Given international energy flows, energy policy analysis require that options be embedded within at least a North-American economy, so that imports and exports quantities and prices, costs of technologies and other data depending on international markets are fully taken into account. This aspect was only partially investigated, as Canadian MARKAL models were decoupled from the US regional module and non-energy sector output and energy exports volumes and prices were kept constant at reference case levels (end-use elasticities were deactivated except in the transportation sector). Consequently, macro-economics impacts were analyzed separately[6], and feedbacks between macro and micro-economic impacts were not fully explored.
- The most simplifying assumption made by MARKAL is optimization: the model finds the optimal (or least-cost) response to any policy it stimulates under assumption of perfect competition, information and foresight (see section 2). For example, MARKAL does not include taxes affecting actual (opposed to optimal) investments. In that sense, the optimal response may never occur in the real energy system, and MARKAL does not produce forecasts or predictions but helps to identify policies that tend to least cost solutions.
- Because of the optimization property of MARKAL, model calibration to some forecasting system requires endogenous constraints. This process has no particular interest from the viewpoint of policy analysis, as constraints must be relaxed when policies are modeled. This is also the reason why results always refer to a reference case, which is the free optimization scenario.
- The disparity of sectoral and provincial reductions puts importance to the consideration of the equitable sharing of the cost burden (i.e. 'who pays'), a subject which should become an important focus of further analysis. MARKAL calculates the least-cost response to a policy

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[6] According to macro-economic analysis undertaken by the Informetrica model and the Canadien Sectoral General Equilibrium Model, reduction in GDP in 2010 relative to the business-a-usual GDP in the same year is less than 2% for paths 2 and 4.

but does not distribute the costs and benefits among producers, consumers, governments, provinces (see Section 2).

- Finally, sensitivity analyses have been undertaken to examine the impact of using some assumptions such as: biological carbon sinks potential (agriculture soil and forestry), geological carbon sinks (capture and storage in deep aquifers of Western Canada) and inter-provincial electricity trade.

4 World GHG Policies Modeling

Canadian GHG strategies analysis required several assumptions on the international context of GHG control, the international energy trades and also the non-energy production levels. Moreover, leakage is a concern of any emission control regime, whereby industries could shift their production to countries that do not have emission limits, or whereby emitting industries could be encouraged in those countries as a result of low energy price induced by low energy demand in industrialized countries (Bruce, Lee et Haites, 1996). In this context, the need for international integrated modeling is more and more required. TIMES (« The Integrated MARKAL-EFOM System ») is a long term (2100) and world version of MARKAL which formalizes but also extends MARKAL capabilities such as multi-regional modeling, demands elastic to their own price, emissions, material and financial flows modeling, vintaging of technologies, decoupling data from model use, variable time period lengths, more friendly modeling of flexible processes, etc. (ETSAP, 2000).

TIMES relies on detailed database for all countries[7] covering existing energy reserves or potentials, installed capacities (including pipelines and electric grid between countries or regions), sectoral future demands (specific transportation modes, space heating, water heating, lighting, machine drive, etc.), current and future technologies (investment cost, fixed operation cost, variable operation cost, efficiency, availability factors, life, etc.), emissions factors, etc. Reference energy scenario plays a crucial role as any suggested policy is compared to this reference case. This is why it must be representative of a consensual long-term trajectory of end-use demands. Projections proposed by the International Panel on Climate Change for population, economic growth, technology availability, etc. will be used (Nakicenovic, 2000).

For the purpose of modeling, countries are grouped into regions according to political, geographical and environmental factors (countries grouped in one region are considered to cooperate). Some countries are kept alone because of their power or weight into the current and future climate change negotiations. 13 regions are proposed (number between brackets indicate the number of countries in each region): United-States (1), Canada (1), Mexico (1), Western Europe (18), Eastern Europe (13), Former Soviet Union (15), Australia, New-Zealand, Japan, South Korea (4), China (1), India (1), rest of Asia (8), Latin America (22+rest of Latin America), Africa (23+rest of Africa) and Middle East (13). Any other spatial groups of countries will be possible since databases are available on a national basis.

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[7] Data sources are International Energy Agency, Energy Information Administration (US Department of Energy), United-Nations and other industrial technology database.

TIMES will be one of the first world bottom-up optimization model with a so high level of details in end-use and supply sectors. As illustrated in section 2 with MARKAL-Canada, TIMES will be a particularly helpful tool to analyze GHG policies in integrated frameworks:

- Regional framework (e.g.: modeling of electricity trade between countries);
- Intersectoral framework (e.g.: modeling of side-effects induced by a new gas pipeline);
- World framework (e.g.: modeling of international carbon and financial flows resulting from Kyoto flexible mechanisms); more specifically, TIMES could satisfy the needs for integrated and robust methods to evaluate the real, measurable and additional properties of emissions reductions induced by Clean Development Mechanism projects and Joint Implementation projects, as required by Kyoto Protocol[8].

As with MARKAL, solution computed by TIMES is efficient. In other words, it is based on the assumption that a central planner optimizes the collective welfare of countries (the « invisible hand » of Adam Smith) while satisfying the imposed environmental constraint. But the optimal solution does not guarantee that every country is better off under this policy, in other words, that the agreement is profitable to all countries. Consequently, some countries could have an interest to deviate from the international optimum either to maximize their individual welfare or to create a new coalition which will offer them a higher welfare. Moreover, given the global nature of climate change, free-ride risks are high and make international environmental agreements unstable (Carraro, 2000). Therefore, it is important to analyze what could be the conditions for a world self-enforcement agreement on climate change. Game theory is an appropriate tool to deal with coalition formation under such assumptions and given interdependencies among countries: while each country's total environmental damage depends on global (all countries') emissions (because temperature increase depend on global emissions), marginal damage depend on the level of cooperation among countries, as the following equations explain (Folmer, Hanley and Missfeldt, 1998).

- *Business-as-usual (climate change is not considered)*: The objective function is: $\min_i (AC_i)$. The solution is characterized by: $MAC_i = 0$
- *Cooperation:* The objective function is: $\max_i \Sigma_{i=1toN}(D_i - AC_i)$. The solution is characterized by: $\Sigma_{i=1toN}MD_i = MAC_i$
- *Nash Equilibrium (non-cooperation case):* The objective function is: $\max_i (D_i - AC_i)$. The solution is characterized by: $MD_i = MAC_i$

AC = Abatement cost, MAC = Marginal abatement cost, D = Damage, MD = Marginal damage, N = number to countries (i = country).

The approach we propose relies on the assumption that appropriate transfer schemes may result in a grand stable and profitable coalition for all countries by taken into account both individual and coalitional rationality as conditions for coalition stability (Eyckmans et Tulkens, 1999). It

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[8] A reduction must be additional to any that would occur in the absence of the certified project activity. Evaluation of additionality is a methodological challenge for any investor and host country who will develop CDM projects.

differs from other papers on coalition formation proposing that self-enforcing international environmental agreements usually include only a small number of countries and that when the number of signatories is large, the difference between the cooperative behavior and the non-cooperative one is small (Carraro, 2000). While the latter focus on the theory of coalition formation, the former and proposed approach supposes that the grand stable coalition exists and is based on transfers calculation and core property analysis (Tulkens, 1998). Similar work has been done by using RICE[9] model (Eyckmans et Tulkens, 1999), but not with so large detailed models such as TIMES. Basic steps will include:

- *Definition of players*: As a first approach and for methodology purposes, the number of players will be limited to three. Players will be chosen according to the very recent negotiations (the study of conditions to make the United States ratify the Kyoto Protocol, will be of particular interest).
- *Definition of climate damage functions*: The welfare function equals the difference between benefits from reducing damages and costs of abatement. Costs of abatement will be computed from TIMES model. Typical damage functions must be calculated. Their typical form $d(t) = a\left(\frac{\Delta T}{b}\right)^c$ is non-linear and will be linearized. Damage parameters (a, b, c) will be based on literature (Cline, 1992, Nordhaus et Yang, 1996).
- *Definition and calculation of non-cooperative scenario*: Open-loop Nash equilibrium will be used to describe what would happen if any international environmental agreement is reached. A Nash equilibrium maximizes every player i's welfare, given the strategies of all other players $j \neq i$. Open-loop strategies are function of time only and suppose binding pre-commitment of players to their strategies until the end of planning horizon. Even if this assumption may appear as a drawback, the interest in open-loop equilibria is based on the easier way to calculate open-loop equilibria (Fudenberg et Tirole, 1991), especially in the context of TIMES modeling. Moreover, Germain and Van Ypersele (1999) calculated that sums of transfers given or received by the different players along the planning period are of the same magnitude in the open-loop and closed-loop cases of climate change policies. This confirms that although less realistic, the open-loop solution remains appropriate.
- *Calculation of full cooperation*: TIMES optimal solution will represent such an agreement.
- *Calculation of transfers*: Several rules are proposed, such as Shapley value (its properties of unicity and equity make this rule very powerful) and the transfer mechanism proposed by Germain, Toint and Tulkens (1999), which results in an allocation in the core of the emission abatement game when damage costs are a linear function of the pollution stock (core property must be checked empirically when damage costs are not linear). While Shapley value assigns to each player a share in the benefit/cost reflecting the marginal gain added when the player i joins the coalition, the distribution rule proposed by Germain, Toint and

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[9] Regional Integrated model of Climate and the Economy (Nordhaus and Yang, 1996).

Tulkens has the property to distribute the surplus of cooperation over non-cooperation in proportion to the (marginal) climate change damage costs that countries experience (Eyckmans et Tulkens, 1999).

Results obtained with this game theory approach will be compared to results obtained from the initial allocation of GHG entitlements to players according to different equity rules as defined by the equity debate on emissions targets and efforts (Vaillancourt et Waaub, 2001).

5 Conclusion

MARKAL and its world advanced version TIMES allow detailed and integrated analysis of economic and environmental national or international energy policies such as fuel switching, technology replacement, energy efficiency, tax, permit trading, etc. The evaluation of the Canadian Climate Change Strategy illustrates the typical questions answered by such models: What are the robust and efficient technological choices? What are the resulting energy prices? What are the total costs and the marginal costs of any policy? More specifically, as a regional and sectoral integrative framework, TIMES is well adapted to satisfy the Kyoto requirements related to the international climate change framework and instruments (including permit trading) aimed at reducing GHG emissions. On-going works on burden-sharing by using some game theory principles will help to answer both efficiency and equity questions at the heart of climate change issues.

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