
In this article, two MARKAL models of Québec and Ontario are used to simulate several scenarios of CO₂ emission reductions, under two alternative economic growth rates assumptions in each province. The results show that emission reductions of up to 35% in Ontario and up to 50% in Québec are possible, at costs which vary considerably with the scenario and the economic growth rate. The article includes a detailed discussion of the conservation, fuel and technological changes that are needed to respond efficiently to the CO₂ constraints. Large amounts of conservation are selected by the models, as well as a marked switch toward nuclear electricity in Ontario and toward hydro electricity in Québec. Several variant scenarios explore the feasibility and cost of a restriction of nuclear in Ontario and of hydro in Québec. Further runs of the models also reveal large benefits for the two provinces to cooperate in managing efficiently Québec's hydro electricity and emission rights.

Dans cet article, deux modèles MARKAL pour le Québec et l'Ontario sont utilisés pour simuler plusieurs scénarios de réduction des émissions de CO₂, sous deux types de croissance économique. Les résultats montrent que des réductions d'émissions allant jusqu'à 35% en Ontario et 50% au Québec sont possibles, à des coûts qui varient considérablement selon le scénario et l'hypothèse de croissance retenus. L'article comprend une analyse détaillée des mesures de conservation et des changements énergétiques et technologiques provoqués par le respect des contraintes d'émission. La conservation est largement favorisée, ainsi que l'augmentation de la ressource nucléaire en Ontario et hydro électrique au Québec. Plusieurs autres passages du modèle permettent aussi d'évaluer la possibilité de restreindre le nucléaire en Ontario et l'hydro-électricité au Québec, tout en maintenant des contraintes d'émissions. Finalement, il est établi que les deux provinces peuvent fortement bénéficier d'une coopération en ce qui concerne la gestion efficace de la ressource hydro électrique du Québec et des droits d'émission.

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CO₂ Control with Cooperation in Québec and Ontario: A MARKAL Perspective

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1. Introduction

The main objective of this research is to explore efficient ways to reduce global CO₂ emissions in the provinces of Québec and Ontario, using two MARKAL models representing the energy and industrial systems of the two provinces.

The question of climate change due to the increase of concentration of various green house gases (GHG's) in the atmosphere is a very active area of research at several levels. The first level is the emission and absorption of such gases from natural and man-made sources, among which energy systems rank as the most significant. The second level concerns the effect of atmospheric concentration of these gases on the global and regional climates of the planet. The third level is the impact of climate changes on the environment (taken in the broadest sense).

The complexity of these issues makes it imperative to study each of these three levels in a decoupled way, while keeping in mind the contingencies introduced by the other two. For

example, the study of environmental impacts is contingent upon the extent of climate changes, which in turn depends upon the emission and absorption of GHG's. For the purpose of establishing policy, the three levels must eventually be integrated, and such integration represents a fourth area of active investigation. Integrated models will therefore require results obtained from single-level models and including contingencies.

It is in this spirit that the work presented here was undertaken. Indeed, our study is driven by contingent quotas of GHG's emissions by each region, country, or other well defined entity. The efficient quotas are not yet known, and therefore will be considered as a parameter that can be varied. Once a quota level is fixed, the energy system must respect it, and therefore evolve in such a way as to restructure itself over the horizon considered, while never emitting more GHG's than the set quota, and yet still satisfy the socio-economic (useful) demands of the region studied, which are set by scenario. If we add that the system's restructuring should be done at minimum total cost, we have a concise definition of our approach. CO₂ is the main gas explicitly considered as a GHG whose control is within the reach of human intervention, although methane emissions from hydroelectric reservoirs are also accounted for. The warming effect of other emissions such as methane from pipelines, CO, CFC's, and nitrous oxide are omitted from our current analysis, either because they are less important in the regions considered, or because they are not directly related to the energy system. Future work will examine this issue in more detail.

In previous works (Berger *et al.*, 1990 and 1991), we discussed in some detail the impacts of restricting emissions of sulphur and nitrogen oxides on these systems, and we presented complete trade-off curves relating the emission level to the system cost in the case of SO₂ emissions in Québec (while keeping NO_x emissions constant). In this study, we present similar results in the case of CO₂ emissions, while assuming that SO₂ and NO_x emissions are also constrained at prespecified levels. In order to

effect the simulations, the Québec and Ontario models have been significantly modified and augmented. In particular, CO₂ emission coefficients have been included in all relevant technologies, numerous options have been added in the Ontario electricity generation subsystem, conservation options and efficient technologies have been added in all sectors, and the economic demand scenarios have been entirely reworked. In view of their importance, the two electricity sectors are modelled in very much detail.

This research was effected as part of an ongoing research effort at GERAD, aimed at assessing the Canadian energy system via the development and use of the MARKAL methodology, and the partial sponsorship of Environment Canada and of FCAR Québec is gracefully acknowledged.

The model used for this project is a much improved Canadian version of the generic MARKAL linear programming model, which computes a competitive equilibrium in an energy market subject to many constraints such as: resource scarcity, availability of certain technologies, and upper bounds on pollutant emissions. MARKAL configures an optimal mix of technologies so as to satisfy exogenous socio-economic demands at minimum total discounted system cost. Therefore, by making several runs of the model with various CO₂ emission levels, it is possible to compute the net cost of emission reductions incurred by an optimized system. Of course, MARKAL results include much more than just the optimal system cost, and provide a detailed view of the technological evolution of the energy system over the chosen horizon. The Canadian version of MARKAL includes several modifications made in order to make it more flexible; they are described in Berger *et al.* (1992). The runs were made using the PC version of MARKAL, and the MUSS interface developed at Brookhaven National Laboratory (Goldstein, 1991). MARKAL uses the Assembler OMNI matrix and report generators, and the XPRESS optimizer. Standard equipment is a personal computer with a 33 MHz 80486 central processor unit and 16 MB of RAM.

Both MARKAL models have 9 periods of 5 years each, centred in 1985,..., 2025, in the Ontario model, and in 1980,..., 2020, in the Québec model. All improvements and additions made to the two models over the last few years, and reported in Berger *et al.* (1990, 1991, 1992) are also included in the present versions, bringing more realism and accuracy to the representation of the two energy systems, but at the same time entailing non negligible increases in the sizes of the data bases and of the resulting linear programming matrices. The Québec model has 8894 rows and the Ontario model 9320 rows.

This research throws light upon the following questions, although discussion of some of these issues will not be included in the article, for the sake of conciseness.

1) Is it feasible, and if so at what cost, to curb CO₂ emissions in each province by specified quantities in 2005 and thereafter? In particular, average and marginal cost per tonne of CO₂ will be computed for each scenario.

2) What are the energy supply consequences of imposing CO₂ emission constraints?

3) What are the main end-use substitutions proposed by MARKAL in response to CO₂ limits? In particular, the penetration of conservation and of efficient end-use devices and processes in each sector is examined.

4) What are the main differences in the responses of the two provinces to CO₂ emission constraints, and what are the main synergies that should be exploited for an efficient emission management in the two provinces working in cooperation?

5) What is the impact of several policy scenarios on the feasibility and cost of the CO₂ reductions? We shall for example examine such policy scenarios as a restriction on nuclear capacity in Ontario, and a moratorium on large hydro electric projects in Québec.

In section 2, the economic and emission scenarios are explained. In section 3, the main results of the Québec runs are presented and commented on, followed by a similar discussion for Ontario in section 4. Section 5 discusses the benefits of exploiting cooperation between the two provinces, in the form of

energy and emissions trading, and section 6 concludes.

2. Scenarios and Model Assumptions

2.1 Economic scenarios

In both models, a 6.5% real discount rate is used to compute the objective function, which is the discounted net present value of total system cost. Discounting is done to the beginning of 1990. All monetary units are in 1990 Canadian dollars, unless specified otherwise.

For each province, we have retained two alternate demand scenarios, corresponding to High and Low economic growths respectively. Tables 1 and 2 below show the average yearly growths of the sectoral demands for each scenario and each province. As can be seen from these two tables, the growths are fairly contrasted in the industrial sector, and less so in the residential and the transportation sectors. This is so because the latter two sectors, being in a larger part determined by demography, are much less subject to variations than industrial activity.

Underlying the High (Low) scenario, is the assumption that after an initial period, Québec's GDP will grow at an annual rate 2.1% (1.35%) in the 1990 to 2020 periods, whereas the Ontario GDP will grow annually at a rate of 2.5% (1.8%) from 1995 to 2025. It can be seen that the Ontario growth rates are more volatile than the Québec ones, a fact which is well established in the economic history of the two provinces.

In addition to economic demand growth rates, the models require a set of prices for imported energy forms. These are summarized in tables 3 and 4 for the two provinces. Moderate oil and gas price increases, and constant coal prices from 1990 on, are assumed. Reference world oil prices never exceed \$30 (US 1990) per barrel, in the long run. The slight price differences shown in table 3 and table 4 are due to delivery costs and to some differences in the nature of the product in the case of oil and coal. Differences in growth rates are mainly due to the two models having different

Table 1: Demand yearly growth assumptions (%) (Québec 1980-2020)

	Scenario	
	High	Low
Aluminum	2.72	2.18
Pulp & Paper	1.76	0.84
Other industries	3.08	2.52
Residential	1.25	1.13
Commercial	1.69	1.11
Transportation		
passengers	2.12	1.61
freight	2.39	1.84

Table 2: Demand yearly growth assumptions (%) (Ontario 1985-2025)

	Scenario	
	High	Low
Petrochemistry	3.25	2.41
Other industries	1.91	1.25
Residential	1.59	1.50
Commercial	1.34	0.99
Transport		
passengers	2.46	1.82
freight	2.64	1.95

horizons.

2.2 Hydro Moratorium and Restricted Nuclear scenarios

In addition, we tested the impact of a total moratorium on all large future hydro-electric projects in the province of Québec (together with the High economic growth assumption). This will be called the Moratorium scenario for that province. In Ontario, we tested the impact of limiting future investments in nuclear plants; a total nuclear moratorium proved to be incompatible with CO₂ reduction constraints, so that we limited our study to a permanent nuclear capacity restriction of 40 GW at any time (the 40GW figure is a little higher than the strict minimum nuclear capacity below which the constant CO₂ scenario is infeasible). The Restricted nuclear scenario is tested only in the case of constant CO₂ (see below).

These two variant scenarios were suggested by the examination of the models results in

Table 3: Prices of imported energy forms in Québec

	1990 price	Yearly growth (%)	
	(\$/GJ)	High	Low
Coal	3.73	0	0
Natural Gas	3.38	1.97	0
Oil-Arabian Light	3.73	0.92	0
-TiaJuana Med.	3.26	0.92	0
-Canadian	4.10	0.92	0

Table 4: Prices of imported energy forms in Ontario

	1990 price	Yearly growth (%)	
	(\$/GJ)	High	Low
Western coal, lignite	3.40	0	0
US coal	2.00	0	0
Metallurgical coal	2.47	0	0
Natural Gas	3.14	1.43	0
Crude Oil	3.99	0.80	0

both provinces, and by the current debates in these two provinces regarding the future development of electricity generation. They are also attempts at answering criticisms sometimes addressed to the other scenarios, i.e., that the accounting of negative side-effects (nuclear risk in the case of nuclear sources, territorial damages in the case of hydro dams) are ignored in the modelling of CO₂ emissions.

2.3 Emission scenarios

For each economic scenario, and for the Québec Moratorium scenario, we define several alternate CO₂ emission scenarios. In all emission scenarios, it is assumed that acid gas emissions are constrained in the same following manner: the emissions of NO_x are unconstrained up to 1990 and limited to their 1985 level in 1995 and thereafter. The emissions of SO₂ are unconstrained up to 1990, and limited to 50% of their observed 1980 level in 1995 and thereafter.

In contrast, CO₂ emission levels are varied across scenarios, as follows: the Free CO₂ scenario imposes no constraint on CO₂, whereas each Constrained CO₂ scenario imposes a CO₂ limit starting in 2000 and becoming progressively tighter until the end of the horizon. The

Free scenario is denoted C-50-F, where the first symbol refers to NO_x , the second to SO_2 , and the third to CO_2 . The Constrained scenarios are denoted C-50-x, where x is the imposed reduction of CO_2 emissions in 2030, computed as a percentage of the 1990 emission level. All constrained scenarios assume that emissions in 2000 are equal to the 1990 level (zero growth), and decline linearly to the specified level in 2030. In Québec, the following percentage reductions (in 2030) are used: 0, 10, 20, 35, and 50. In Ontario, the 50% reduction is not reported, since the model is unable to satisfy such a constraint at a reasonable cost. To summarize, the following emission scenarios are run and analyzed in this report: C-50-F, C-50-0, C-50-10, C-50-20, C-50-35, and C-50-50 (Québec only). Figures Q1 and O1 in sections 3 and 4 show the actual emission profiles corresponding to these scenarios.

2.4 Inter Provincial Cooperation

We also tested the effect of inter-provincial electricity trading on the cost of CO_2 reduction in both provinces. To do so, we assumed that Y megawatts of Québec's future hydro capacity was taken away from Québec's potential, and added to Ontario's (the investment cost of this capacity was also adjusted to reflect the additional transportation cost — via high voltage lines — from the Québec site to Ontario). For several values of Y, the C-50-0 scenario was run in each province, in order to compute the benefit of cooperation.

3. Results for Quebec

3.1 Emissions

Figure Q1 indicates the evolution of CO_2 emissions through time. In a completely unconstrained scenario (F-F-F, not discussed in this report), CO_2 emissions increase by some 75% from 1990 to 2020 in the High case, and by 36% in the Low case. These increases occur even though many end-use energy savings are adopted by the model (even in the absence of air emission constraints).

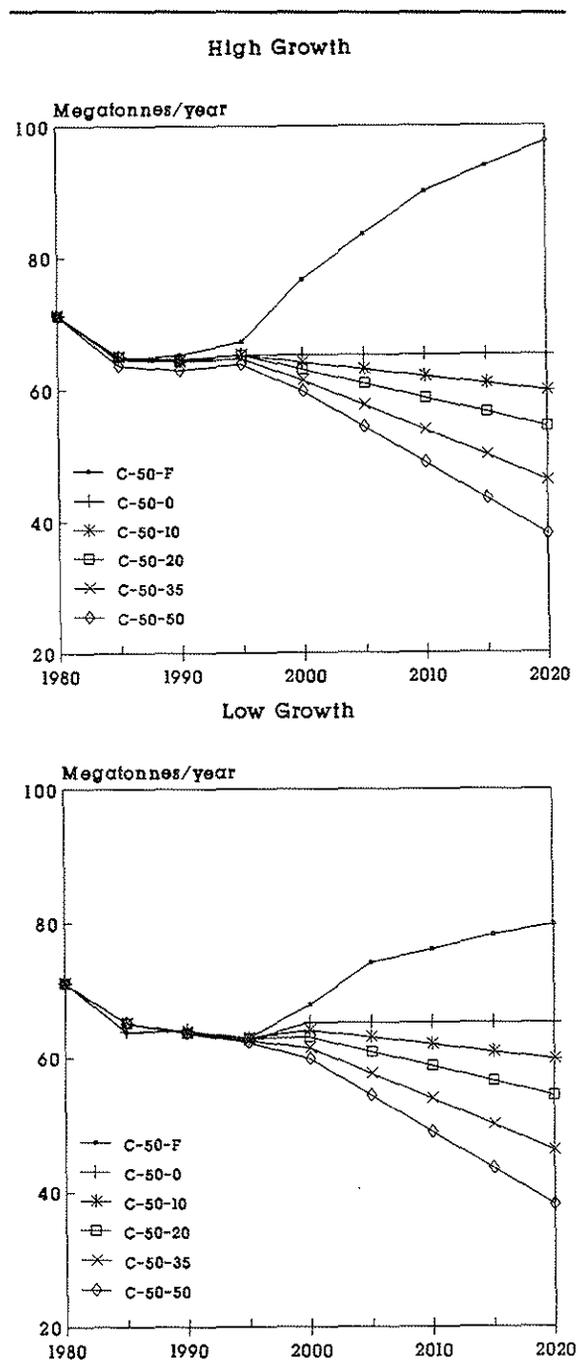


Figure Q1: CO_2 Emissions

The imposition of the acid gas emission constraint (scenario C-50-F) induces a significant reduction of CO_2 emissions, but CO_2 emis-

sions still grow by 50% from 1990 to 2020 in the High case, and by 25% in the Low case. Of course, many options used for NO_x reduction also act to decrease CO₂. Roughly speaking, both gases are linked to combustion, although CO₂ is linked more specifically to combustion of fossil fuel, whereas NO_x is produced by any combustion.

The principal observation from figure Q1 is that the C-50-0 scenario represents an enormous CO₂ reduction when compared to the base case C-50-F scenario. As a global indicator for the High case, more than 31% of the CO₂ is avoided in 2020, and this figure is 22% in the Low case. In comparison, the more severe CO₂ constraints in C-50-10, ..., C-50-50, represent relatively mild additional restrictions compared to the initial constraint of C-50-0.

Results not shown here indicate that the emissions of NO_x fall below their own constraint when CO₂ is constrained. This phenomenon is by no means surprising, as was noted above.

3.2 The cost of CO₂ reductions

A) COST/EMISSIONS TRADE-OFFS

Figure Q2 and table 5 show in a synthetic fashion the total discounted net system cost as a function of total avoided CO₂. The origin of the fig. Q2 graphs represents the C-50-F scenario, which serves as reference; therefore, all costs are computed relative to that of C-50-F, and avoided emissions are also computed relative to those of C-50-F. As expected, the slope of a trade-off curve is steeper when higher reductions are sought.

For the High growth scenario, the upper curve is for the Moratorium scenario, and the additional cost of the Moratorium is equal to the vertical difference between the two curves. In the absence of any CO₂ constraint (C-50-F), the moratorium costs very little more than the High growth case (the two points are almost undistinguishable on the figure, but their costs actually differ by 110 million dollars, see Table 5). However, the additional cost of the Moratorium increases significantly when CO₂ is con-

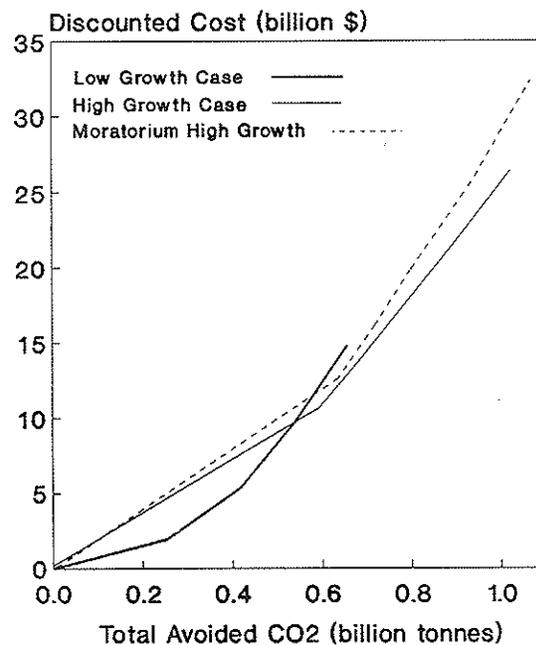


Figure Q2: Cost/Emission Tradeoffs

Table 5: Total discounted system cost of CO₂ emission reductions (10⁶ Cdn \$1990, discounted to 1990)

Scenario	High Growth	Moratorium	Low Growth
C-50-F	0	110	0
C-50-0	10520 (.36%)	12452 (.43%)	1783 (.07%)
C-50-10	13276 (.46%)	15952 (.55%)	3162 (.12%)
C-50-20	16226 (.56%)	19672 (.68%)	5220 (.20%)
C-50-35	20975 (.72%)	25659 (.88%)	9482 (.35%)
C-50-50	26183 (.90%)	32204 (1.1%)	14574 (.55%)

strained, reaching six billion dollars for C-50-50. Another obvious conclusion is that the Low growth scenario carries CO₂ reduction costs much lower than the High growth scenario.

In addition, table 5 shows in parentheses the discounted cost as a percentage of the discounted GDP. These percentages remain lower than 1% in all but one case (the C-50-50, moratorium case), but even a 0.5% cost is quite significant for any economy. A simplistic analysis ignoring all secondary effects on the economy would tell that a cost of x% amounts roughly to a permanent slow-down of the economy by the same percentage, but in reality, the actual impact on GDP cannot be pre-

cisely evaluated by our model since it does not represent the economy at large, but only the energy sector. A linkage of MARKAL with an economic model has been performed by Manne and Wene (1991).

Finally, with a current population of 6.7 million, Québec would incur a discounted reduction cost varying from \$1500 to \$4000 per capita, depending on the severity of CO₂ reductions.

B) AVERAGE REDUCTION COSTS

Table 6 shows the average cost per tonne of CO₂ (sometimes called the levelized cost) of achieving specified reductions. The calculation follows the formula below, with AC denoting the average cost:

$$AC = \frac{\text{Discounted cost of reduction}}{\sum_t (1.065)^{-t} \times \text{Emission reduction at period } t}$$

where the denominator is simply the discounted emission reductions. The reduction and the cost are computed comparatively to the C-50-F scenario, so as to reflect only the effect of the CO₂ constraint. The average cost can be defined as the value that, if applied to each tonne of CO₂ emitted, would exactly compensate for the total discounted cost of imposing the reductions.

Note the marked increase in average reduction costs when the hydro moratorium is imposed. Note also that although the Low growth case generally carries much lower average costs, this is not true in the extreme C-50-50 case: this observation will be commented on when discussing marginal reduction costs.

C) MARGINAL REDUCTION COSTS, AND THE CONCEPT OF EFFICIENT CO₂ EMISSION TAXES

Thanks to linear programming, a marginal cost of CO₂ reduction is available at each period for each scenario. It is equal to the shadow price of the CO₂ constraint for that period. The marginal CO₂ cost at period *t* is thus simply the cost of not emitting the last tonne of CO₂ at period *t*. Figure Q3 presents the time paths of the marginal reduction costs for both economic cases

Table 6: Average CO₂ reduction costs (Cdn \$1990 / tonne)

Scenario	High Growth	Moratorium	Low Growth
C-50-0	62.7	70.9	27.8
C-50-10	72.1	81.7	41.6
C-50-20	79.1	90.8	53.2
C-50-35	87.6	96.5	72.6
C-50-50	90.4	106.7	89.9

and all emission scenarios. As expected, marginal costs exceed the average costs computed above. The marginal costs are important because they constitute an efficient CO₂ tax, in the following sense: if an emission tax equal to the marginal cost is imposed on each tonne of CO₂, and if all economic agents are economically rational and have the same information that is contained in the model, then there exists a set of decisions that are optimal for the agents, and which also respect the CO₂ limits of the MARKAL model. Loosely speaking, the CO₂ limits imposed upon the model can theoretically be eliminated if emission taxes equal to the shadow prices are levied. Although theoretical, this result is of considerable interest, since it establishes a rigorous link between a prospective model like MARKAL, and a way to implement policies on the market.

Figure Q3 shows that the marginal costs evolve through time, with almost no exception, in a smooth fashion. It may appear paradoxical that shadow prices in the Low growth case are sometimes higher than their counterpart in the High growth one. "Common sense" would seem to imply the reverse. The paradox disappears when one reasons that a growing economy is in fact more resilient than a stagnating one, and thus better equipped to respond to an additional marginal CO₂ restriction. In a stagnating economy, a CO₂ restriction at period *t* may require investments that would otherwise never have been made (neither at period *t* nor later), whereas in a fast growing economy, the investments required by the CO₂ restriction will eventually be used by the economy itself as it continues to grow. Such interesting systemic effects are only detected by systems analysis, such as is accomplished via MARKAL or other globally coherent models.

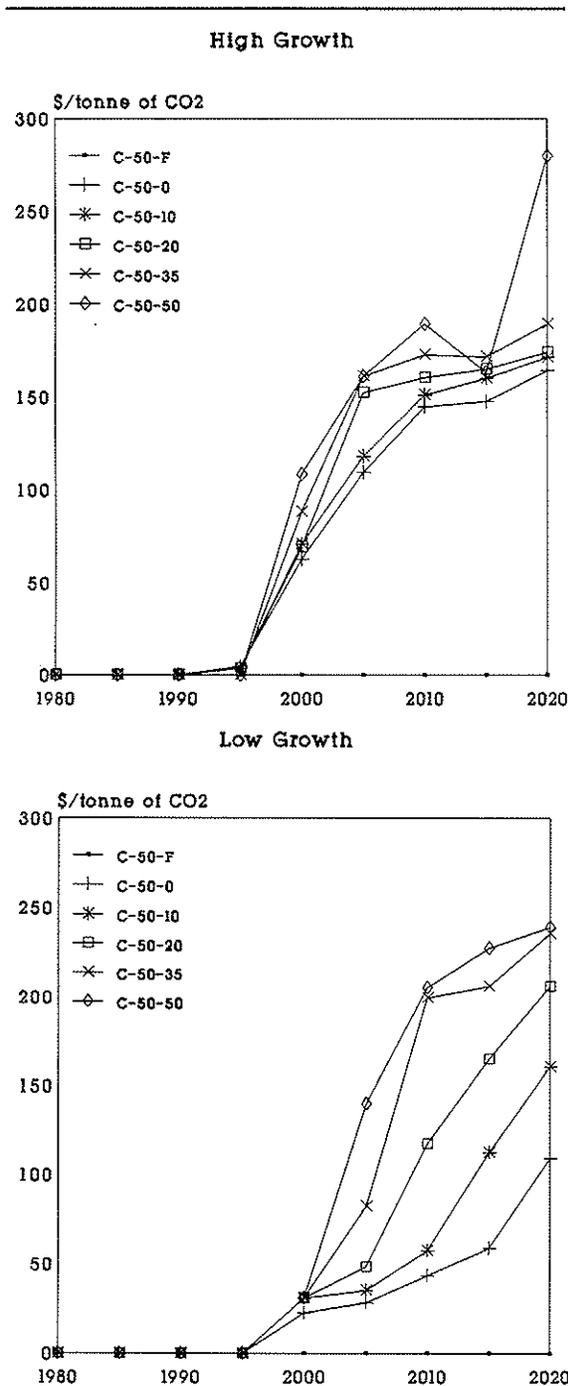


Figure Q3: Marginal Cost of CO₂ Reduction

3.3 The energy supply

A) TOTAL PRIMARY ENERGY

The imposition of CO₂ constraints does not induce dramatic changes in total primary energy requirements, and the examination of fig. Q4 shows that the shift is toward a slight increase in primary energy when CO₂ constraints are made more severe. This effect is mainly due to the way primary energy is computed, since hydroelectricity is first converted to "fossil equivalent" via multiplication by the conventional factor 2.5974. Since CO₂ constraints tend to increase hydro capacity, the result is an increase in primary energy. A better indicator of energy consumed will be given in subsection 3.4, where final energy is discussed.

Table 7 shows that the energy intensity decreases as time goes on, for all scenarios. Québec's energy intensity in 1990 is equal to 15.5 (PJ/10⁹\$), and the percentages in table 8 are the average yearly changes of the intensity over the period 1990 to 2020.

B) ENERGY SHARES

The impact of CO₂ reductions on the mix of primary energy forms is profound. We shall briefly examine the main energy forms: oil, gas, and renewable electricity. Coal, wood and nuclear energy sources play a minor role. Figure Q5 shows the shares in 2020 of the primary energy forms for each emission scenario.

The CO₂ reductions provoke a shift from oil and gas towards hydro-electricity. The latter reaches an impressive 74.4% market share in the C-50-50, High growth scenario (versus 50.1% in C-50-F), whereas that share is 65.5% in C-50-50, Low growth scenario (versus 49.8% in C-50-F). Note that nuclear does not penetrate in any scenario.

Conversely, oil imports drop significantly in the constrained scenarios. For the CO₂ constrained cases, the oil share in 2020 stays in the 10 to 15% range with High growth, and in the 11 to 18% range with Low growth.

Finally, gas exhibits an interesting behaviour: in the High growth case, its long term

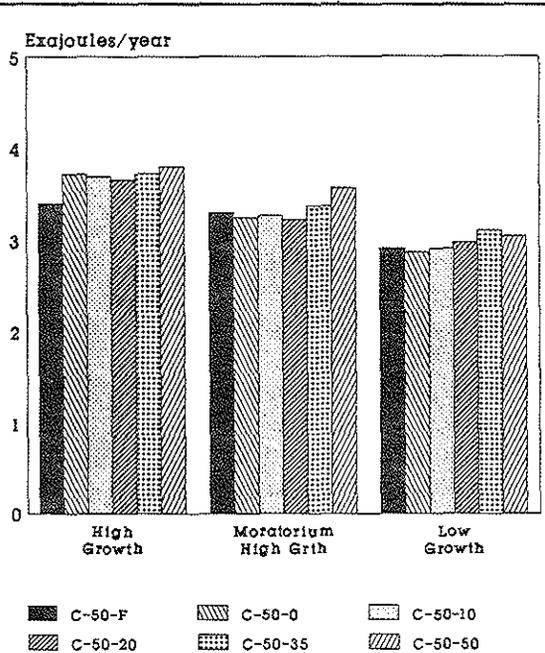


Figure Q4: Total Primary Energy in 2020

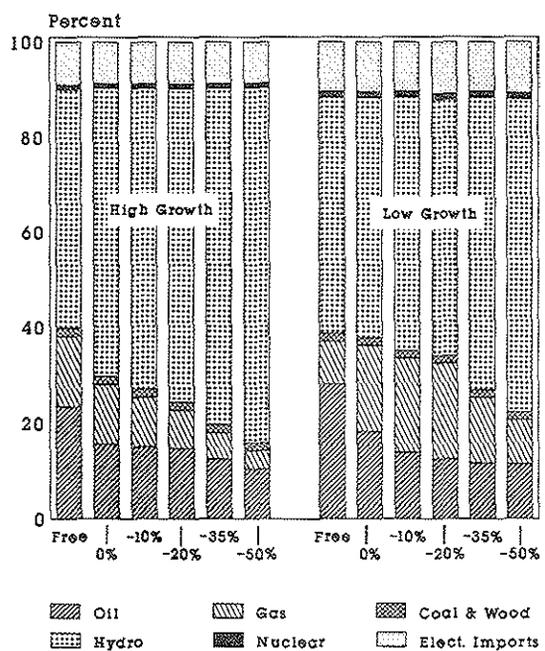


Figure Q5: Primary Energy Shares in 2020

market share increases markedly from F-F-F (not shown) to C-50-F, as a means to reduce acid gas emissions. It then gradually decreases

Table 7: Average annual changes in primary energy intensity — 1990-2020 (%)

	High	Low
C-50-F	-0.92	-0.73
C-50-0	-0.62	-0.77
C-50-10	-0.64	-0.74
C-50-20	-0.67	-0.65
C-50-35	-0.62	-0.51
C-50-50	-0.55	-0.59

when CO₂ constraints are applied, retaining a modest 4 to 12% market share depending on the severity of the CO₂ constraint. In the Low growth case, the behaviour is different, and gas keeps a higher market share of 9.3% even in the C-50-50 scenario. The implication is that gas is a cost-effective CO₂ control when moderate reductions are sought, but is insufficient in the face of large CO₂ emissions coming from a strong economic growth.

C) ELECTRICITY GENERATION

It is remarkable that, from the strict viewpoint of this study, Québec can rely on its hydroelectric power to satisfy the much increased electricity demand, without recourse to nuclear, even in the High growth case. Of course, there may well be other considerations which may alter this state of affairs, among them the current controversy around the flooding of large areas in the Québec North, with its effects on humans, flora, and fauna. It is therefore useful to examine more closely the specific hydro projects which are recommended by the model. Figure Q6 shows the installed electricity generation capacity in 2020 for all combinations of economic scenarios and CO₂ constraints. Except for the Moratorium case, hydro capacity increases as the CO₂ constraint becomes more severe, approaching 60 GW in the C-50-50, high growth combination. This is close to the complete economic potential of Québec hydro. The existing nuclear plant is kept in operation, but no additional nuclear or fossil fuel fired plant is added by the model, with the exception of a very modest capacity in gas turbines which are in fact not operated, but used only as peak reserve by the model.

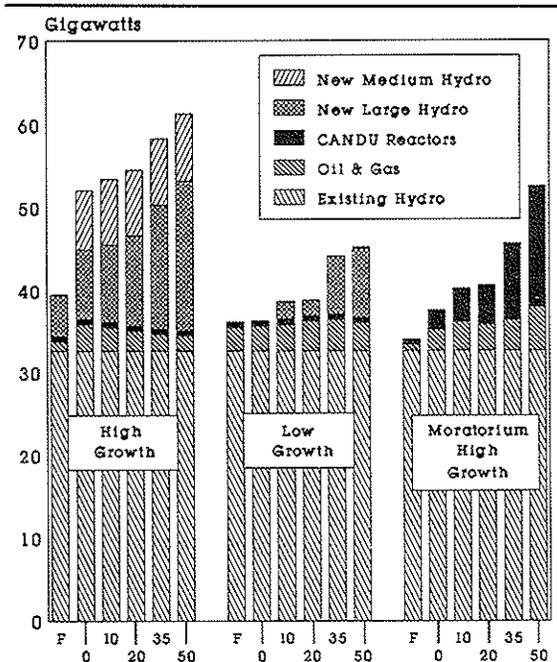


Figure Q6: Electric Capacity in 2020

The situation is of course different in the moratorium case, where the model reacts to emission restrictions by a) adopting some nuclear capacity, and b) reducing the total installed electricity generation capacity (the reduction in capacity reaches 20% in the most constrained case, compared to high growth). Naturally, the decrease in electric capacity must be compensated elsewhere, namely through additional conservation (see fig. Q9).

3.4 Final energy demand and savings

A) FINAL ENERGY

Figure Q7 shows the final energy consumption for each scenario in 2020; the imposition of CO₂ constraints entails significant decreases in energy consumption, especially in the High growth cases.

The shares of the different energy forms in total final energy are shown in figure Q8 for year 2020. The share of oil decreases steadily in both scenarios, whereas that of gas first increases and then decreases in the Low scenario only. Electricity takes an important market

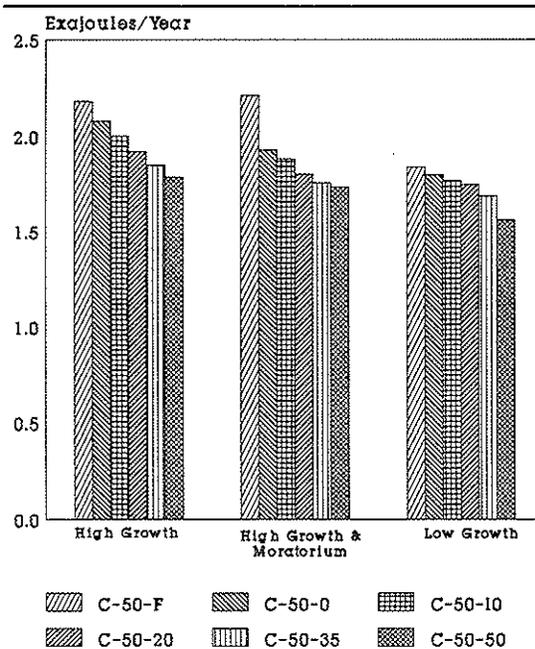


Figure Q7: Total Final Energy in 2020

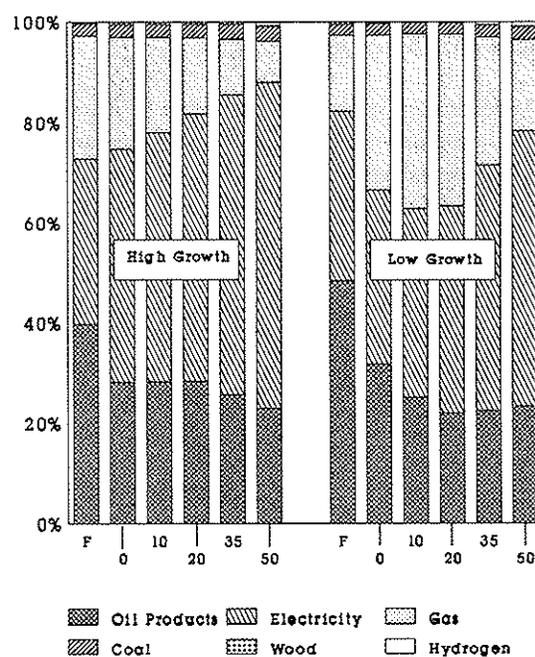


Figure Q8: Final Energy Shares in 2020

share in both scenarios, reaching 65% (55%) in the C-50-50 High (Low) case. Hydrogen makes a shy appearance in the most constrained runs.

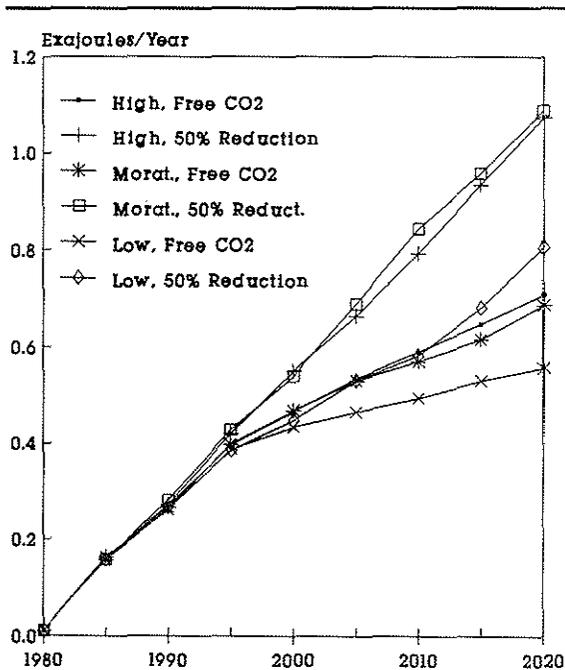


Figure Q9: System Energy Savings

B) ENERGY SAVINGS

Accounting for energy savings is not an easy task because, for some technologies, some savings are implicitly obtained via efficiency specifications throughout the horizon, whereas others result from model optimization. In this article, energy savings are defined at time t for each demand segment, as the energy needed to satisfy that demand at period 1 minus the energy needed to satisfy the same demand at time t . Savings thus come from fuel and technology substitutions, and from retrofits chosen by the model, as well as from built-in efficiency gains in the demand devices, such as progressively more efficient vehicles, better insulated new houses, etc.

Figure Q9 shows total energy savings for all scenarios. MARKAL implements important savings even in the C-50-F case, while optimizing the energy system. The CO₂ constraints induce even more savings, and this is more pronounced for the Moratorium scenario. In 2020, High case, savings increase from 24% (of final energy) in C-50-F to 36.5% in C-50-50,

while with the Moratorium, savings are 24% of final energy for C-50-F, and almost 39% in C-50-50. The Low growth case commands slightly smaller savings (23% for C-50-F and 34% for C-50-50).

4. Results for Ontario

We adopt for this section the same plan as for section 3 treating the Québec results, but we emphasize the differences between the two provinces rather than elaborate on the similarities. The Restricted scenario (with nuclear capacity limited to 40 GW) results are presented only for the constant CO₂ case.

4.1 Emissions

Figure O1 exhibits the time paths of CO₂ emissions. In the F-F-F scenario (not shown), CO₂ emissions triple from 1990 to 2025 in the High case, and more than double in the Low case. These large increases occur in spite of significant energy savings which the model adopts even in the F-F-F scenario (energy savings will be discussed in subsection 4.4). The imposition of the acid gas emission constraint (scenario C-50-F) induces a minor relative reduction of CO₂ emissions, but the latter are still multiplied by 2.89 from 1990 to 2025 in the High case, and by 2.22 in the Low case. Therefore, just as in the Québec situation, the C-50-0 scenario represents very large decreases of CO₂ emissions when compared to C-50-F: indeed, in the High case, 65% of the CO₂ is not emitted in 2025, and this figure is 53% in the Low case. In comparison, the additional reductions imposed by C-50-10, C-50-20, and C-50-35, induce relatively smaller reductions, compared to the initial constraint of C-50-0. This effect is much more pronounced than in Québec, because Ontario uses more coal, a large emitter of CO₂, and because Ontario's economy is assumed to grow more rapidly than the Québec economy (also because the horizon extends farther, to 2025, in the Ontario model).

Finally, the CO₂ constraints have the same effect of inducing large reductions in NO_x emissions, as was observed in the Québec case.

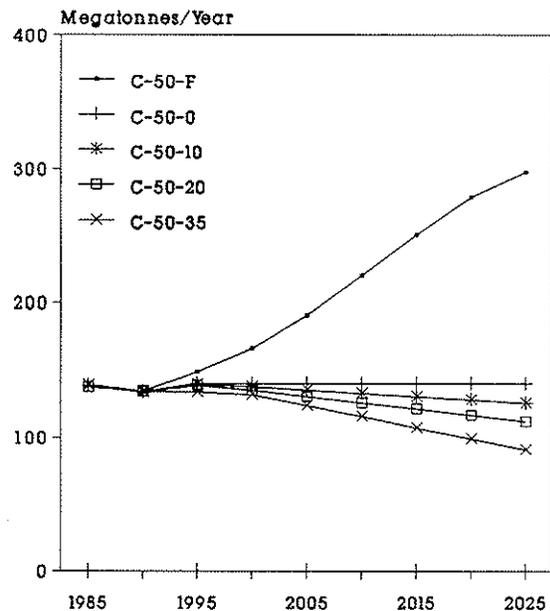
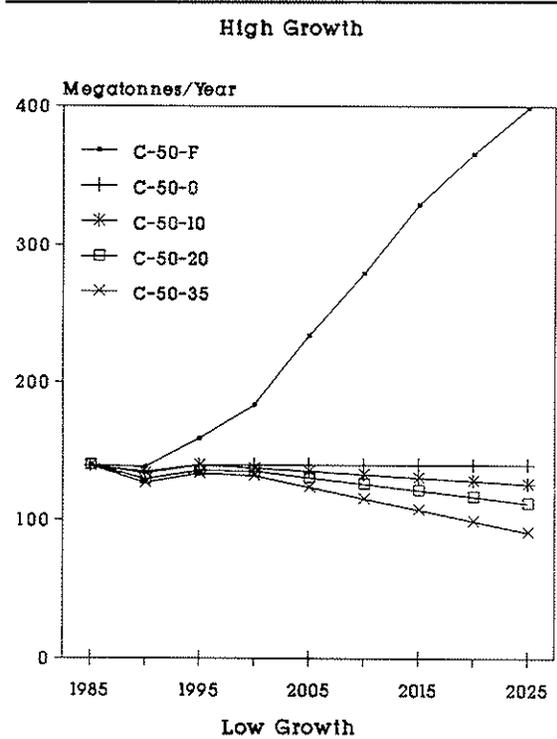


Figure O1: Total CO₂ Emissions

The Restricted scenario also entails much lower levels of NO_x than the regular C-50-0.

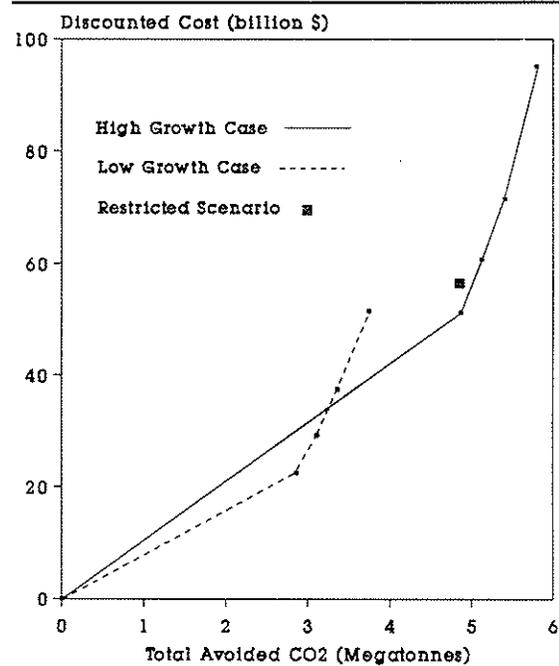


Figure O2: Discounted Cost of Reductions

4.2 The cost of CO₂ reductions

A) TOTAL COST AND COST/EMISSIONS TRADE-OFFS

Figure O2 shows in a synthetic way total system cost versus total CO₂ emissions, for each scenario. As in the Québec case, all values in this figure are relative to the C-50-F case represented by the origin. Again here, the slope of the trade-off curve is steeper when higher reductions are sought. Table 8 gives the cost figures used in figure O2, expressed both in absolute terms and as a percentage of the Ontario discounted GDP. Compared to those of Québec, total reduction costs represent a higher fraction of GDP in Ontario, in spite of the fact that the average costs per tonne of CO₂ reduction are actually lower in Ontario than in Québec (see table 9 below). This is due to the sheer magnitude of the total avoided CO₂ in Ontario. The isolated point in figure O2 represents the Restricted scenario, whose total cost exceeds that of C-50-0 by 2.95 billion dollars. This figure is thus the net cost of restricting nuclear capacity to 40 GW, while enforcing a constant CO₂ policy.

Table 8: Total discounted system cost of CO₂ emission reductions (10⁶ Cdn \$1990, discounted to 1990)

	High growth	Low growth
C-50-F	--	--
C-50-0	51208 (0.88%)	22410 (0.42%)
C-50-10	60760 (1.04%)	29172 (0.55%)
C-50-20	71420 (1.23%)	37394 (0.71%)
C-50-35	95112 (1.63%)	51480 (0.97%)
Restricted	54158 (0.93%)	

Table 9: Average reduction costs (Cdn 1990 \$ / tonne)

	High case	Low case
C-50-0	46.5	36.0
C-50-10	52.4	43.3
C-50-20	57.4	50.8
C-50-35	70.7	62.7
Restricted	49.2	

B) AVERAGE REDUCTION COSTS

Using formula (1) of section 3, the average costs of CO₂ reduction are computed and shown in table 9. They are significantly lower than the Québec costs. Note also that the Low scenario has average costs moderately smaller than the High one, a fact which was analyzed in the Québec section. The Restricted scenario has slightly higher average cost than its regular counterpart C-50-0.

C) MARGINAL REDUCTION COSTS

Figure O3 and table 10 present the time paths of the marginal CO₂ reduction costs in Ontario, for both economic cases. A first observation is the high value in 2005 of the shadow prices, for all scenarios, but especially for the C-50-35 scenario in the High case, where the shadow price reaches \$650 per tonne. Such high marginal costs are due to the scarcity of non fossil electricity sources in that period: new nuclear plants (beyond those already planned) can be put in service only starting in 2010, and no important new hydro sites are available in Ontario. Therefore, as will be seen in the following subsections, the system resorts to gas in a massive way in 2005; but this recourse is

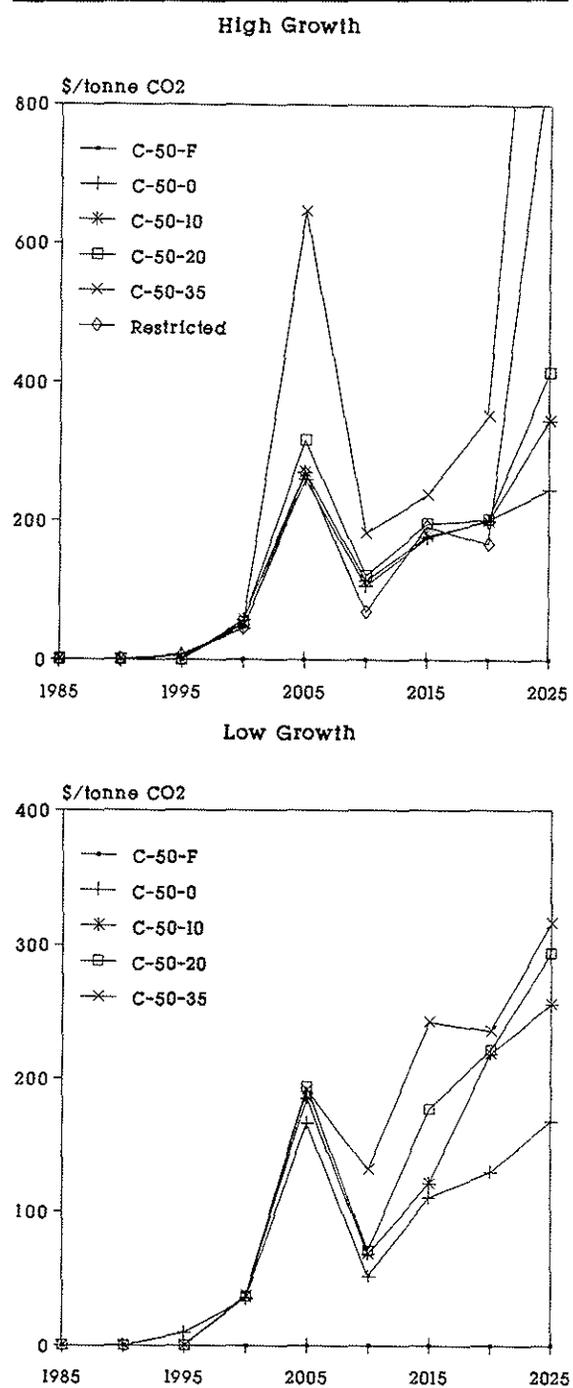


Figure O3: Marginal Reduction Costs

short lived, since the abundance of nuclear power in 2010 and later makes some gas fired technologies (acquired in 2005) economically

Table 10: Average annual changes in primary energy intensity — 1990-2025 (%)

	High	Low
C-50-F	-0.49	-0.46
C-50-0	-0.48	-0.79
C-50-10	-0.32	-0.72
C-50-20	-0.14	-0.55
C-50-35	+0.14	-0.25
Restricted	-0.29	

obsolete before the end of their physical life. Therefore, the cost of these short-lived investments is borne mostly by the 2005 period, which explains why CO₂ shadow prices are high in 2005 and normal later.

Another very high shadow price is observable in 2025 in the High growth scenario, due to the continued economic growth, the progressive tightening of the CO₂ constraint, and the lack of good CO₂ reduction options. It can be said that the 35% reduction scenario is near the limit of what Ontario can effectively achieve at "reasonable" cost. Such a situation constitutes a real problem for Ontario, and one that could be resolved by importing more renewable electricity from elsewhere, perhaps Québec. Section 5 will discuss this issue in more detail. For the Restricted scenario, the situation is somewhat similar to that of C-50-35, with a very high shadow price in 2025, due to a lack of good options.

It is interesting to note that average CO₂ reduction costs in Ontario are lower than in Québec, but that Ontario's marginal costs are comparable to or higher than Québec's. This simply translates the fact that Ontario has an initial potential of cheap reductions of carbon dioxide, but that at the levels required by the scenarios, this potential has already been used, and marginal reductions are now expensive.

4.3 The energy supply

A) TOTAL PRIMARY ENERGY

Figure O4 shows the primary energy requirements (TPER) in 2025, for all scenarios. More detailed period by period results show that

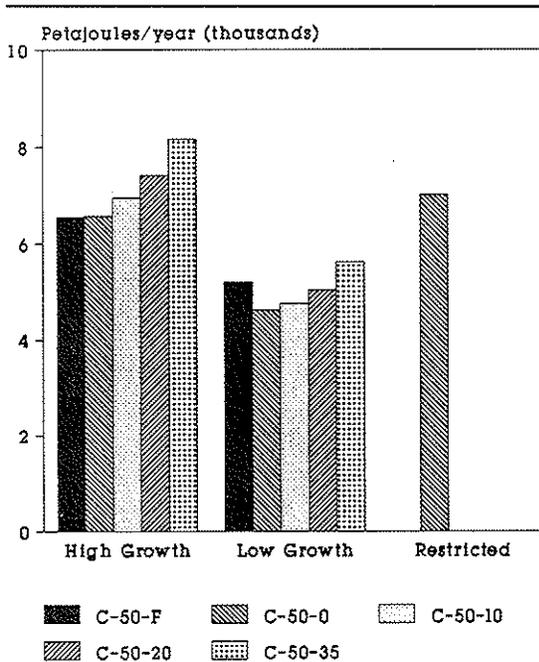


Figure O4: Total Primary Energy in 2025

when CO₂ reductions are imposed, the system first tends to reduce its TPER compared to C-50-F (roughly, up to 2015), but later increases it, and ends in 2025 with a TPER higher than in C-50-F. In great part, this is due to the accounting of TPER for nuclear energy, as discussed in the Québec section.

The percentages in table 10 are the rates of growth of primary energy intensity (i.e., TPER divided by GDP) over the horizon 1990-2025. In 1990, Ontario's intensity is 11.47 PJ/10⁹\$ (lower than Québec's). The intensities tend to decrease at a lower rate in Ontario than in Québec, over the 35 year horizon. In one case (C-50-35, High growth), the intensity even increases by an annual average of 0.14%, which confirms the difficulty posed by that scenario combination, as noted earlier.

B) COMPOSITION OF PRIMARY ENERGY

The impact of CO₂ reductions on the mix of primary energy forms is profound. We shall briefly examine the four main energy forms: oil, coal, gas, and nuclear electricity.

Figure O5 shows two interesting facts con-

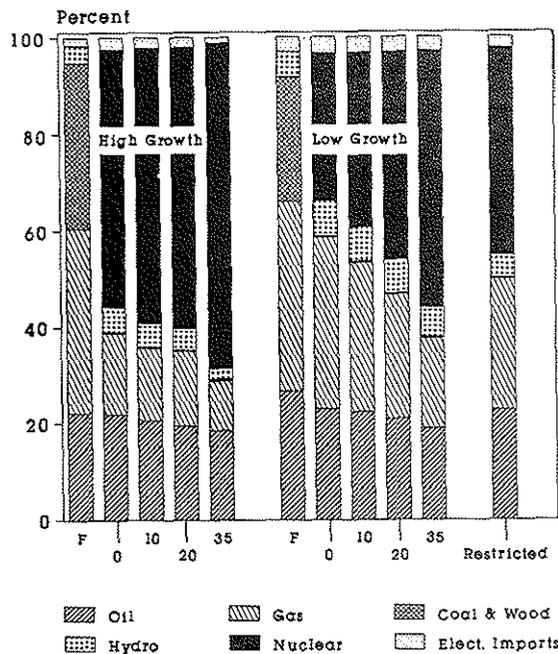


Figure O5: Primary Energy Shares in 2025

cerning the mix of energy forms: first, the optimal response to C-50-F is via a mix of gas and coal, the first being SO₂ free and fairly low NO_x, whereas the second, although less clean, is cheap. When CO₂ is constrained, that combination is no longer effective, and nuclear electricity becomes an important fraction of the energy supply, reaching almost 70% of TPER in 2025 for the C-50-35, High case, and totally eliminating coal. Gas retains an appreciable market share in all scenarios, ranging from about 40% in C-50-F cases to 10% in C-50-35, High growth. In all scenarios, oil is confined to a modest role (between 18% and 23% of TPER in 2025, depending on the severity of the CO₂ constraint). However, the shares of oil and gas in the Restricted case are both increased in order to compensate for the limited nuclear availability.

In the High economic growth case and for the C-50-35 scenario, additional results not shown in figure O5 indicate that the market share of gas increases markedly in 2005, and then decreases rapidly in 2010 and thereafter to reach 10% in 2025. The sharp increase in 2005

is due to the scarcity of nuclear power sources in that period. The decrease after 2005 means that the gas fired equipment purchased in 2005 is abandoned after five or ten years (much before the end of its physical life), so that the cost of the 2005 investment in gas technologies must be borne to a large extent by that period: this explains the high CO₂ marginal cost in 2005 that was noted in subsection 4.2.

C) ELECTRIC CAPACITY

In scenario C-50-F, figure O6 shows that efficient coal fired generating plants are the preferred technology for electricity production, although some gas fired plants are also implemented in the Low growth scenario. In contrast, for all CO₂ constrained cases, coal technologies disappear and are replaced mainly by nuclear electricity and a modest number of gas plants. In fact, the model installs new nuclear plants as soon as it is allowed to do so, i.e., in 2010. Nuclear capacity reaches high levels in the CO₂ constrained scenarios, culminating at 86 GW in 2025 in the C-50-35, High case (and 45.6GW for Low growth). This is an enormous amount, which from other points of view, is probably inconsistent with current thinking and opinions in that province. Even the constant CO₂ scenario (C-50-0) requires 54GW of nuclear capacity for High growth and 21.5GW for Low growth. Note that the C-50-F nuclear capacity in 2025 is 0, which shows that nuclear electricity is not the most efficient way to reduce acid gas emissions. As for the Restricted scenario, its total electric capacity is much reduced compared to C-50-0; this is so because it is more efficient to burn directly gas and oil, rather than use them to produce electricity (and then use the latter for heating!).

4.4 Final energy and savings

A) TOTAL FINAL ENERGY

Figure O9 shows energy savings for all emission scenarios. Final energy itself is seen to decrease sharply as CO₂ limits are imposed (figure O7). There is a remarkable increase of

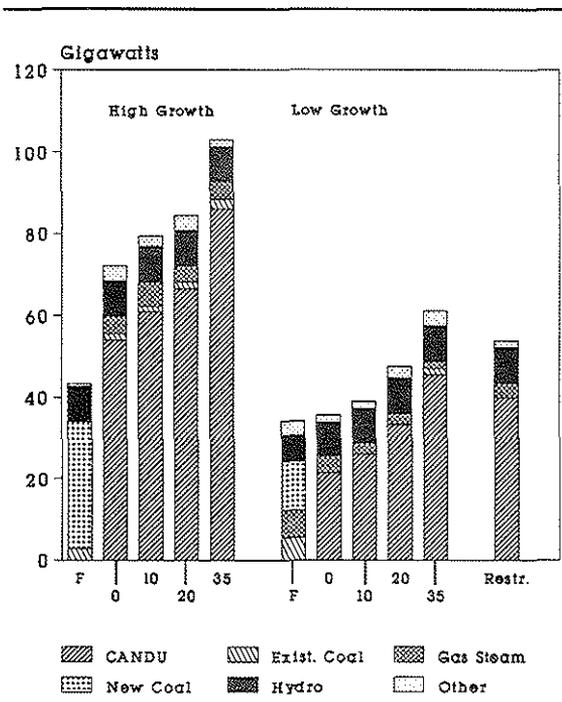


Figure O6: Electric Capacity in 2025

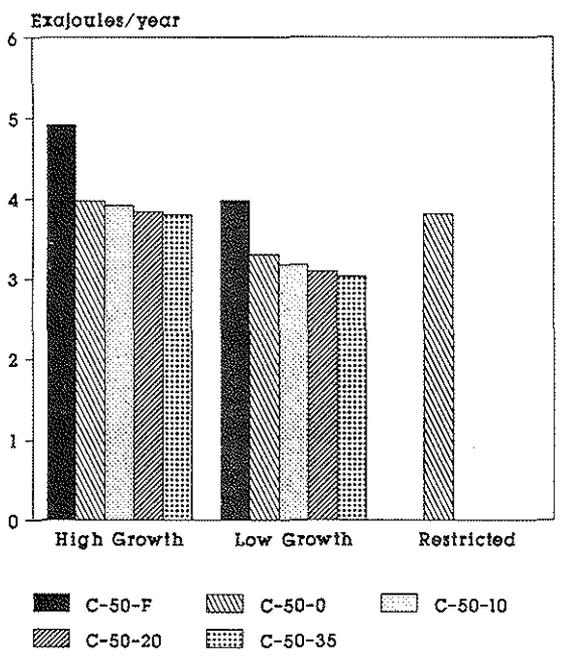


Figure O7: Total Final Energy in 2025

savings, from about 10% in 2025 in the free CO₂ case, to about 24% in 2025 in the C-50-35 scenario, for both economic growths. The reader will notice that these figures are lower than in Québec. The Restricted nuclear scenario implements energy savings close to those of C-50-35 towards the end of the horizon, confirming the similarity between these two scenarios.

B) MIX OF ENERGY FORMS IN 2025

Figure O8 confirms the market shares already discussed in the subsection on primary energy, although final energy computations do not use an artificial scaling of renewable electricity into fossil equivalent, since each petajoule of final energy represents an actual consumption. An interesting phenomenon is the modest but significant presence of hydrogen as a fuel (2.6% in both C-50-35 scenarios). Hydrogen is used as a fuel in buses and planes. The progressive decrease in gas is compensated by a commensurate increase in (nuclear) electricity, except in the Restricted case where the market share of gas is much larger than those of other CO₂ constrained scenarios, and is indeed rather similar to that of C-50-F.

5. Interprovincial cooperation

In this section, a series of coordinated runs of the Québec and Ontario models are exploited in order to analyze the benefits derived from a cooperative usage of Québec's hydro-electricity and from the trading of CO₂ emission rights.

5.1 Electricity trading

It has already been observed that the hydro moratorium in Québec had only a moderately adverse impact on the cost of CO₂ reductions. Furthermore, the rather massive recourse to nuclear electricity in Ontario's runs indicates that that province has few other options for large CO₂ reductions. In this simulation, we dedicate certain amounts of well identified Québec hydro capacity for exportation to Ontario. For each level of dedicated capacity, a modified Ontario model to which the approx-

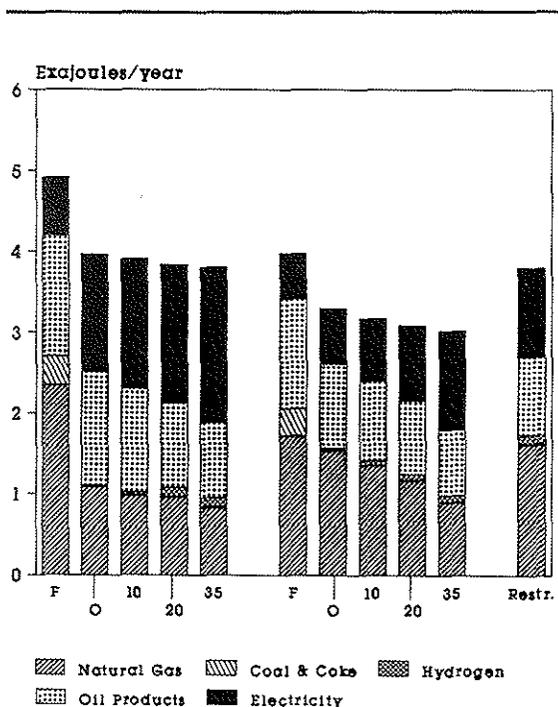


Figure 08: Final Energy Shares in 2025

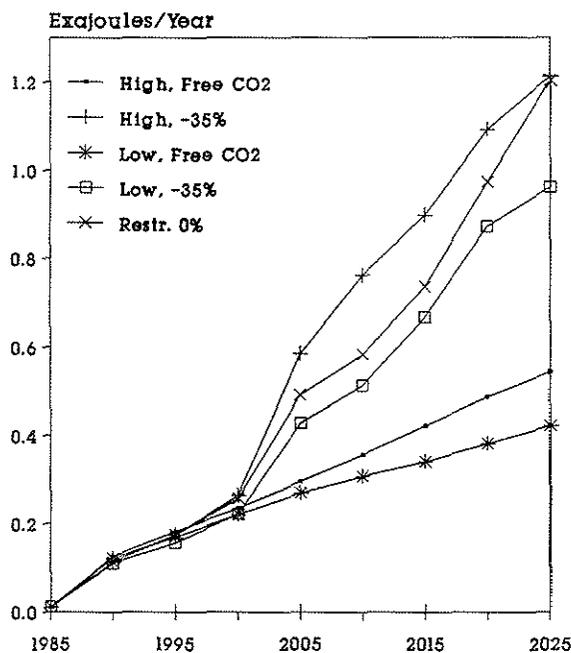


Figure 09: Final Energy Savings

appropriate hydro project(s) has been added, is run. Also, a modified Québec model from which the corresponding project(s) has been eliminated, is run. In the Ontario model, the additional cost of extended transport lines and exchange equipment is included in the investment cost of the dedicated project(s). The sum of the two models total costs indicates whether the dedicated amount of hydroelectricity is jointly profitable or not. We chose to make this experiment in the case of High growth and constant CO₂ in both provinces.

In figure OQ1 and table 11, the joint total cost of both systems is plotted against the dedicated capacity (only the relative costs of both systems are reported, taking the status quo as base case). From these results it is quite clear that important benefits can be derived from cooperation between the two provinces, culminating when 14 GW of Québec hydro are dedicated to Ontario. However, the marginal benefit of each dedicated gigawatt decreases markedly when the amount increases, and a joint benefit of only 322 million dollars accrues from the last 3 GW of exchanges. The main conclusion from this analysis is that the imposition of a constant CO₂ in both provinces would create a strong incentive for large electricity transfers from Québec to Ontario. Of course, the sharing of the benefits from such transfers must also be resolved, and is not discussed in our analysis. It is however fair to say that the potential benefits are so large that there would be room for the negotiation of an agreement on electricity prices that would benefit both provinces.

5.2 Trading emission rights

All preceding discussions are based on the assumption that a CO₂ constraint is applied separately in each province. In reality, because the greenhouse effect is a global phenomenon, only the total emissions of CO₂ are relevant. Of course, pushing this argument to its logical end requires the study of the entire planet as one global system, and this indeed is the correct long term setting for this area of research. In the case of the Québec-Ontario system, we

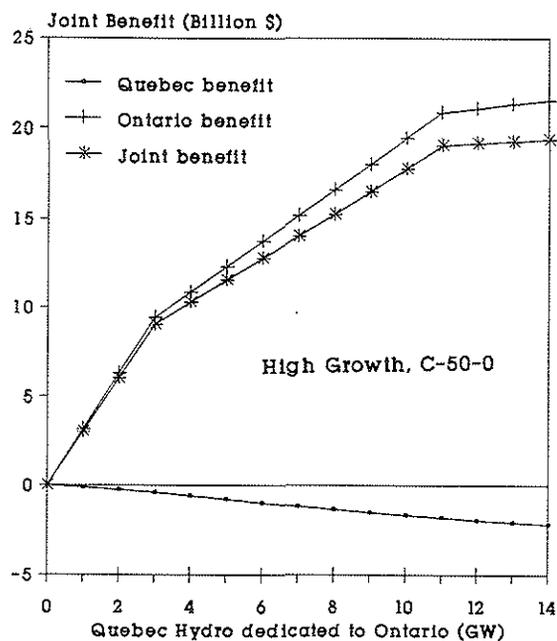


Figure OQ1: Benefit of Electricity Trade

shall be content to demonstrate that the joint satisfaction of a global CO₂ constraint may carry important benefits compared to the imposition of separate "across the board" (proportional) constraints in each province. To do so, denote by C_q(E_q) (C_o(E_o)) the total discounted cost for Québec (Ontario) of emitting E_q (E_o) tonnes of CO₂ each year on average. These two functions are the ones exhibited in figures Q2 and O2, except for a change of abscissa to convert avoided CO₂ into average yearly emissions. Supposing now that a global constraint of E (tonnes CO₂ per year) is applied to the Québec-Ontario system, the following simple mathematical program (P) can compute the optimal shares of the emissions that should be allocated to each province in order to minimize their joint total cost:

$$\begin{aligned} & \text{Min } \{ C_q(E_q) + C_o(E_o) \} \\ & E_q, E_o \\ & \text{subject to } (E_q + E_o) \leq E \end{aligned} \quad (P)$$

The above non-linear program is easily

Table 11: Total joint benefit of Québec-Ontario electricity trading (10⁶ Cdn \$1990, discounted to 1990)

Capacity (GW)	Québec benefit	Ontario benefit	Joint benefit
0	0	0	0
3	-390	9436	9046
8	-1353	16603	15250
11	-1822	20850	19028
14	-2154	21504	19350

solved, and yields the results shown in table 12. Note that for mild reduction policies (e.g., free CO₂ or an allowed increase of 20%) the savings due to inter-provincial emission trading is negligible, but that the savings rise significantly when the joint emissions are severely constrained, culminating for the 35% reduction policy. In the latter case, Ontario should buy emission rights for 4.33 million tonnes per year from Québec. The joint benefit of such trading is equal to 3.096 billion dollars, which should then be split fairly between the two provinces.

6. Conclusion

This research has presented analyses of several MARKAL runs for two fairly different provinces of Canada, with an emphasis on the cost of reducing CO₂ emissions from 2005 on.

The first conclusion is that CO₂ reductions of up to 35% by 2035 are feasible, although Ontario would find such reductions quite expensive to achieve (1.63% of GDP). In Québec, total reduction costs remain below 1% of GDP in all scenarios. Both provinces resort first to conservation when faced with CO₂ emission limits. In addition, the Québec system relies on its hydro-electric potential, whereas Ontario resorts massively to nuclear power, especially in 2010 and after.

We believe that the computation by the models of average and marginal costs of CO₂ reductions could be important contributions to the establishment of policy, perhaps in the form of a carbon tax or of quotas in the various subsectors of the economies of the two provinces.

The average cost of CO₂ reduction is on the whole higher in Québec, since CO₂ emissions

Table 12: Optimal versus across-the-board emission allocations in Québec and Ontario

	Yearly Emissions ¹						Discounted Total Costs ²						Savings
	Across-the-board allocation			Optimal allocation			Across-the-board costs			Optimal costs			
	Québec	Ontario	Total	Québec	Ontario	Total	Québec	Ontario	Total	Québec	Ontario	Total	
Free	78.85	247.27	326.12	78.85	247.27	326.12	0	0	0	0	0	0	0
20%	69.24	151.07	220.31	69.07	151.24	220.31	6732	35924	42656	6915	35739	42654	2
0%	65.69	139.19	204.88	63.82	141.06	204.88	10903	51107	62010	13455	48355	61810	200
-10%	63.96	133.60	197.56	60.98	136.59	197.57	13262	60328	73590	17834	55214	73048	542
-20%	62.14	127.31	189.45	57.55	131.90	189.45	15974	72708	88682	23859	63456	87315	1367
-35%	59.33	118.55	177.88	55.00	122.88	177.88	20626	94292	114918	28899	82923	111822	3096

¹ Yearly emissions are in million tonnes

² Costs are in million dollars (Canadian 1990) discounted to 1990

in that province are relatively low in 1990, due to the already existing electrification of the residential sector, and thus further reductions are all the more difficult to effect. However, the total burden of reductions is higher in Ontario due to a faster growing economy and to the limited options that province has besides nuclear power. For the same reasons, the Ontario system experiences larger marginal reduction costs than the Québec system.

In the case of Ontario, the marginal reduction costs exhibit a steep increase in 2005 (when a lack of non fossil electricity sources poses a special problem), and towards the end of the horizon, for the most constrained case.

In both provinces, it is observed that, for large CO₂ reductions, the marginal cost can be higher in the Low growth than in the High growth case, a fact which is explained by the greater resilience of a fast growing economy.

A total nuclear moratorium in Ontario is not compatible with even a constant CO₂ scenario in the High growth case, and even limiting nuclear capacity to 40 GW carries great costs to the province. In Québec, a total moratorium on future large hydro projects is feasible, and carries a sizable but not enormous cost, even if large CO₂ reductions are imposed.

Such "second best" solutions are important to discover and evaluate if the main sources of non-fossil electricity in the two provinces (respectively hydro and nuclear) were limited for political or other reasons.

An important part of our analysis showed

that the cooperation between the two provinces in electricity trading holds great promise, and that Québec would benefit from selling a sizable portion of its electricity to Ontario if a constant CO₂ policy were in effect in both provinces. In addition, the two provinces would also benefit from some trading of CO₂ emission rights, if a stringent CO₂ constraint were jointly imposed upon them.

References

- Berger, C., D. Fuller, A. Haurie, R. Loulou, D. Luthra, and J.-P. Waaub (1990) 'Modelling Energy Use in the Mineral Processing Industries of Ontario with MARKAL-Ontario,' *The Energy Journal*.
- Berger, C., A. Haurie, E. Lessard, R. Loulou, and J.-P. Waaub (1991) 'Exploring Acid Gas Emission Reductions in the Province of Québec via MARKAL-Québec,' *Energy Studies Review*, Vol. 3, No. 2, pp. 124-41.
- Berger, C., R. Dubois, A. Haurie, E. Lessard, R. Loulou, and J.-P. Waaub (1992) 'Canadian MARKAL: An Advanced Linear Programming System for Energy and Environmental Modelling,' *INFOR*.
- Goldstein, G. (1991) *MUSS user guide*, Brookhaven National Laboratory, May.
- Manne, A. and C.-O. Wene (1991) 'MARKAL-MACRO,' presentation at the Fall 1991 meeting of ETSAP, Brookhaven National Laboratory.