Exploring Acid Gas Emission Reductions in the Province of Québec via MARKAL-Québec

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The MARKAL-Québec multi-period process model is used to simulate the reaction of the Québec energy and industrial sectors to the imposition of upper limits on the global emissions of NO_X and SO_2 acid gases into the atmosphere. Two economic scenarios are used respectively for high and low demands for goods and services, with moderate prices of imported energy forms. Several emissions reduction constraints are tested. The main results are: important reductions are achieved in the copper smelting industry, a switch from heavy fuel oil to natural gas and a switch toward diesel vehicles impacting the refining of oil products and the transportation sector.

Le modèle dynamique d'analyse d'activités, MARKAL-Québec, est utilisé pour simuler la réaction des systèmes énergétique et industriel québécois à l'imposition de limites supérieures d'émissions atmosphériques des gaz acides NO_X et SO_2. Le modèle est dirigé par deux scénarios économiques contrastés, représentant respectivement des demandes fortes et faibles de biens et services, associés à des prix modérés des formes d'énergie importées. Des contraintes sur les émissions atmosphériques sont testées. Les principaux résultats sont les suivants: réalisation de réductions importantes dans l'industrie de la fonte du cuivre, un passage du mazout lourd au gaz naturel et un passage aux voitures fonctionnant au diesel, ayant des impacts se répercutant sur le raffinage des produits pétroliers et le secteur des transports.

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1. Introduction

The general objective of this research is the computation of efficient responses by the Québec energy system to the imposition of global limits on emissions of acid gas. Emission reductions can be achieved through: (i) increased energy efficiency (including end-use conservation); (ii) fuel switching (including cleaner fuels); (iii) abatement technologies; (iv) changing industrial processes; and (v) reducing end-use demands for goods and services. The model used here takes into account the first four means of reducing emissions. The fifth method is handled by running two contrasted economic scenarios and comparing the responses of the model.

In Québec SO_2 is emitted mainly by the copper smelting and refining industry (57%) and by burning coal and oil fuels in industrial boilers and furnaces (26%), whereas NO_X is emitted mainly by the transportation sector (71%) and industrial combustion (14%) (Environment Canada, 1986). Our model accounts for emissions from the complete energy and industrial system, and focuses on the above three sectors to achieve desired reductions in emissions.

The simulations were run with MARKAL, a large-scale, multi-period, linear programming, process model. The advantage of using a de-

Table 1: Prices of Imported Fuels ($CDN 1980/GJ)

	1980	1985	1990	1995	2000	2005	2010	2015
Crude Oils								
Arabian Light	2.87	4.12	2.90	3.10	3.30	3.40	3.50	3.60
Tiajuana Medium	2.62	3.77	2.62	2.81	3.00	3.09	3.19	3.28
Canadian Light	2.99	4.29	3.02	3.23	3.44	3.54	3.65	3.75
Canadian Natural Gas	2.31	2.71	2.61	3.10	3.30	3.40	3.50	3.60
Coal	2.11	2.28	2.46	2.74	3.01	3.39	3.77	4.25

tailed process model lies in the enormous flexibility to add the requisite level of detail for the subsectors that contribute most to emissions and/or to energy supply and consumption, while keeping an adequate representation of the less energy-intensive subsectors. Another flexibility of process models is that the technological consequences of various scenarios are directly and explicitly available. As discussed in Fishbone and Abilock (1981) and Fishbone *et al.* (1983), MARKAL was used for this study, with significant modifications made by our team (Berger, 1987; Berger, 1988), to facilitate detailed modelling of the industrial sector (in particular, explicit representation of material flows, in addition to the energy flows allowed by MARKAL).

In the simulation of a MARKAL model, energy is extracted from primary sources, then transformed by supply technologies into a variety of energy carriers including fuels, and electricity. These energy carriers are finally used by a vast array of end-use technologies to satisfy various socio-economic needs (useful demands), such as space heating, car travel, and steel production, without imposing the energy forms or the technologies that will satisfy these needs. The useful energy demands are provided by the user, for each period.

The technologies related to extraction, transformation, transportation and end use of energy forms constitute the Reference Energy System (RES) of the country or region being studied. The RES also specifies the various energy carriers that link together the technologies.

MARKAL simulates the competition among the available technologies via linear programming, which selects the activities that are cost-effective from the perspective of the whole system. As an example of the benefits of the system approach, Wene *et al.* (1988) show that the global cost of achieving SO_2 and NO_X emission limits is considerably reduced if the optimization takes both constraints into account simultaneously, rather than sequentially. In fact, this procedure is very close to the real life economic computations done by the agents involved in the choices; the only difference comes from the fact that the choices are computed under an assumption of perfect foresight which permits decision makers to anticipate benefits and costs far in the future.

Two contrasted *economic scenarios* are used; for each economic scenario, several levels of reduction of SO_2 emissions are tested. Each scenario assumes a series of annual limits on emissions of SO_2, one for each of the last five of the eight five-year periods from 1980 to 2015. Three alternate levels of reduction on emissions of NO_X are assumed, and are combined with the constraints on SO_2 to form the *environmental scenarios*.

In both economic scenarios, the same moderate prices for the five imported fossil energy forms are assumed, as shown in Table 1.

The "high" and "low" economic scenarios correspond respectively to high and low demands for goods and services and moderate oil and gas prices. For the "high" ("low") scenarios, the annual growth rates in the main sectors are as follows:

Table 2: Environmental Scenarios

Scenario	NO_X Limit (1995 and later)	SO_2 Limit (1995 and later)
F-F	None	None
C-F	1985 level	None
C-50	1985 level	1980 level minus 50%
C-60	1985 level	1980 level minus 60%
C-70	1985 level	1980 level minus 70%
C-80	1985 level	1980 level minus 80%
10-50	1985 level minus 10%	1980 level minus 50%

- 3.12% (0.30%) in the industrial sector as a whole (growth rates in individual industries are given in Baillard *et al.* (1987));
- 1.52% (1.00%) in the residential and commercial sectors; and,
- 2.40% (1.84%) in the transportation sector.

The environmental scenarios are described in Table 2 above. Scenario F-F imposes no restriction on either type of emission. In scenario C-F, NO_X emissions must not exceed the 1985 level, from 1995 on, while no restriction is imposed on emissions of SO_2. The next four scenarios assume that emissions of NO_X are limited to their 1985 level, but that the reductions in SO_2 are increasingly severe. In preliminary runs, intermediate levels of 0, 20, and 33% reductions in SO_2 were tried, showing that there were no *qualitative* differences between these runs and the C-50 scenario; therefore, we eliminated these intermediate runs from this presentation. The 10-50 scenario tests a plausible combination of reductions of NO_X and SO_2 emissions. All reductions are imposed starting in 1995, and the levels prior to 1995 are left free.

In the "low" case, an 80% SO_2 reduction scenario (C-80) is feasible, but not so in the "high" case. In the latter case, a C-60 scenario was run instead.

The 1980 and 1985 levels of reference used in the model are those of a MARKAL-Québec run with no constraint on emissions of SO_2 and NO_X. They are 1,045,689 tonnes of SO_2 in 1980, and 252,877 tonnes of NO_X in 1985, respectively. Both of these values are within 5% of those provided by official sources (Environment Canada, 1986; Québec Environment, 1989).

For each chosen reduction level, the model finds a minimum-cost system configuration. This information is a useful input to the selection and testing of policy alternatives in comprehensive energy/environment management. The global net cost of achieving a certain reduction of emissions is easily found as the difference between the cost of the corresponding scenario and the "do-nothing" (F-F) scenario. In addition to total system cost, the model provides a detailed account of the changes in fuel use, technologies, and energy conservation levels, thus allowing a thorough energy/technology analysis of each scenario.

The remainder of this report is organized as follows: Section 2 describes those parts of the MARKAL model that have been added or modified for an adequate representation of SO_2; Section 3 does the same for NO_X; Section 4 comments on the results of the corresponding runs of the model; Section 5 presents conclusions.

2. Modelling SO_2

The accounting of SO_2 emissions, energy conservation measures, fuel switching, and more efficient processes are modelled in each sector (residential, commercial, industrial and transportation). The copper industry and the boilers and furnaces, identified as key sectors regarding

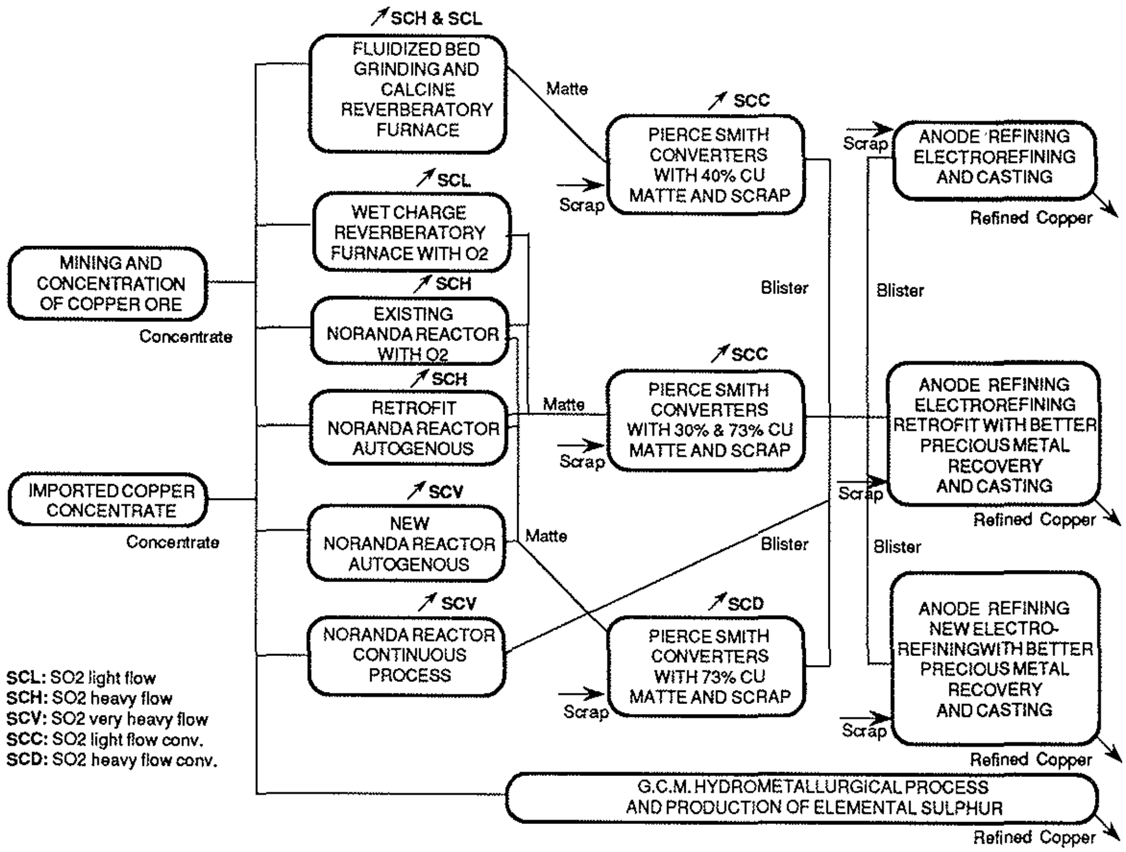

Figure 1: Copper Module

their contributions to global SO_2 emissions (see Section 1), are presented in detail below, since they required substantial modelling improvements for the representation of SO_2 emissions and abatement measures.

2.1 The Copper Industry

The primary copper industry in Québec uses a sulfide ore which is currently processed by pyrometallurgy. The modelling effort for the copper sector focuses on the different processes that can be used to produce refined copper through the current pyrometallurgy process. Processes are modeled with sufficient detail to allow a good representation of emissions of SO_2 from burning sulfur in the materials involved. Furthermore, an alternate hydrometallurgy process is modeled as an alternative to the current pyrometallurgy path. Figure 1 illustrates the copper module of MARKAL-Québec. As pictured, the pyrometallurgy of copper is divided into four parts: (1) mining and concentration; (2) smelting of copper concentrate; (3) converting of different matte grades, and (4) refining of blister copper. The Noranda Gaspé operations (hot calcine reverberatory smelting) are represented by the boxes in the top row. The Noranda Horne operations (wet charge reverberatory and Noranda reactor under different operation modes) are represented in rows below. Use of oxygen in the Noranda reactor is emphasized as a way to improve energy efficiency and to reduce operating costs. Different operation modes of Pierce-Smith

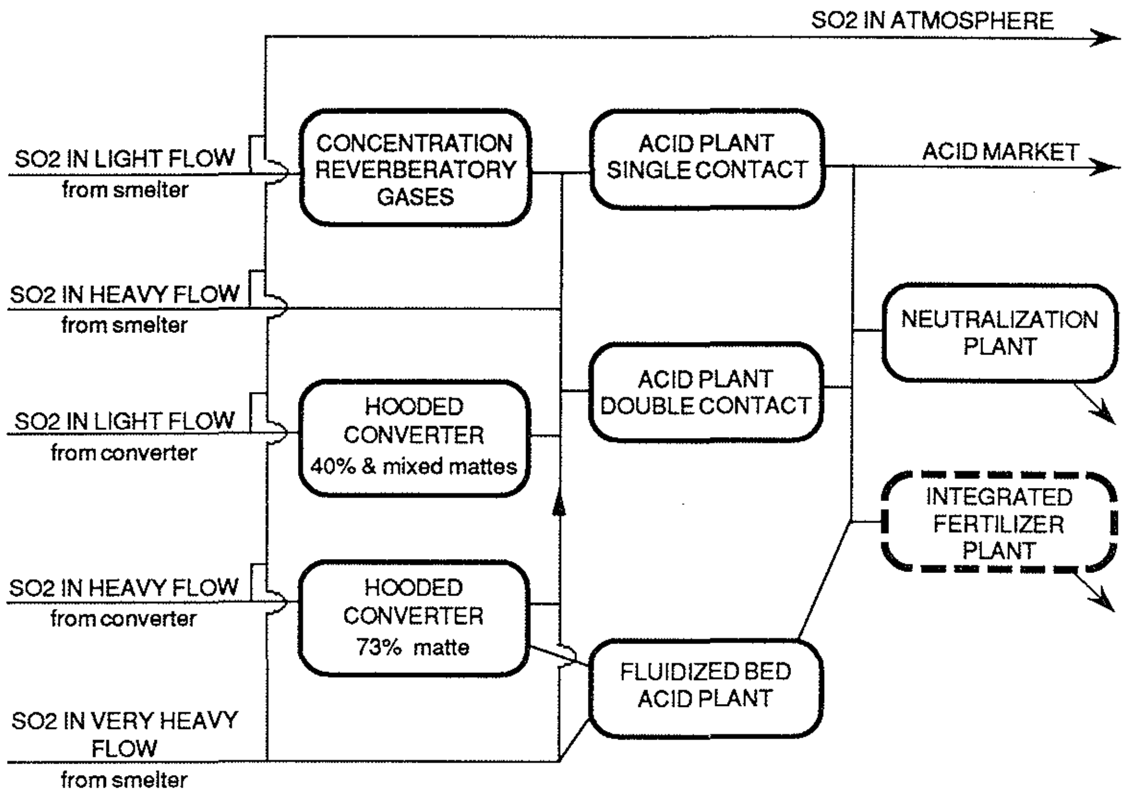

Figure 2: SO_2 Module

converters referring to the matte grades are considered to reflect the necessary flexibility in the treatment of "dirty" concentrates.

The continuous operation mode of the Noranda reactor is represented in the model. Use of scrap is allowed, both at the converting (second quality scrap) and at the refining (first quality scrap) stages, to decrease the growing dependence upon imported concentrates, and to reduce emissions of SO_2. Better precious metal recovery is also modeled (existing, retrofitted and new capacities). The hydrometallurgy of copper is modeled as small integrated plants, and is represented in the last row. The Great Central Mines Ltd (GCM) hydrometallurgical process produces elemental sulfur which is less costly to produce and to market than sulfuric acid.

Emissions of SO_2 from each source are computed according to the concentration of the gas flow. Figure 2 shows that SO_2 can be emitted directly to the atmosphere or transferred to acid plants (single contact, double contact and fluidized bed options). In addition, hooding of converters and concentration of reverberatory gases are also available. In the model, acid is neutralized, even though it can be sold on a local market; this modelling choice thus represents a "worst case" situation. It might also be interesting to add the promising potential of using the acid in a phosphate fertilizer plant (dotted line box) whose market is growing, as opposed to the traditional market for acid.

2.2 Boilers and Furnaces

The SO_2 emitted is directly proportional to the sulfur content of the following fuels: coal, light fuel oil (No. 2), and heavy fuel oil (No. 6). Coal is a marginal fuel in Québec and is modeled as a single quality coal. In MARKAL, fuel oils are produced endogenously by the petroleum refining module; this permits modelling of emission reductions by making available a series of different sulfur contents in fuels at the supply point (the refinery). The model can respond to a demand for low sulfur fuels by additional investments in desulfurization units, etc., or by purchasing crudes which are lighter and sweeter (i.e. with less sulfur), at a higher price. To insure adequate flexibility, we have modeled four different levels of sulfur content in heavy fuel oil (HFO) — 0.5, 1, 1.5, and 2.5%. The 2.5% level is the maximum currently allowed in most of Québec. Each category of boiler and furnace is allowed to switch between the different HFO qualities.

In Québec, light fuel oil was used mainly for residential heating during the seventies, but was rapidly replaced by electric heaters, so that only one level of sulfur content is retained in the model; this level is 0.5%, which already satisfies Québec regulations.

3. Modelling NO_X

As with SO_2, the accounting of NO_X emissions, energy conservation measures, fuel switching, and more efficient processes are modelled in each sector, with particular care in the industrial heat and transportation sectors.

The transportation sector is modeled with the vehicle classes used by the United States Environmental Protection Agency (1985) and adapted to Canadian conditions (Environment Canada, 1988). Emissions of NO_X and SO_2 from all types of vehicles are accounted for in the model. The main concern of the modelling is to allow a sufficient capability for reducing emissions of NO_X. This is achieved in three ways: (1) better efficiency of the vehicles; (2) gradual implementation of abatement technologies (different types of catalytic converters); and (3) fuel and technology switching (e.g., gasoline, compressed natural gas (CNG), propane, diesel). Electric cars are not considered in this discussion.

4. Scenario Analysis

In this section, we discuss the MARKAL-Québec runs for the two contrasted economic scenarios and the set of emission level scenarios of Table 2. The analysis starts with an overview of the main results, including the cost/emission trade-off curves and other general observations. This is followed by a sectoral analysis of the technological changes in the "high" and "low" cases. Throughout this section, the analysis emphasizes the copper sector, the oil refining sector and the transportation sector. In all figures, results for the first and second periods (1980 and 1985, respectively) are historical, whereas results for periods three to eight (1990 to 2015) are obtained from the model runs.

4.1 Overview of Results

COST/EMISSION TRADE-OFFS

Figures 3A and 3B summarize in graphical form the total costs incurred in the system to achieve specific reductions in emissions. The costs are expressed in 1989 Canadian dollars discounted at 7% to 1989; the abscissa indicates the reduction of SO_2 emissions in 2015 as a percentage of 1985 emission levels. In both cases, the cost curve is remarkably linear between the C-F scenario and the C-50 scenario (this was verified by running several intermediate cases that are not presented here), meaning that, when the limit on emissions of NO_X is held constant, reducing emissions of SO_2 has a fairly constant unit cost up to a 50% reduction (and probably up to almost 60%). Further reduction of SO_2 emissions is much more costly to achieve: the slopes are much steeper from 50 to 70% or more. Detailed analyses of the two cases support this observation.

In order to put the costs of figures 3A and 3B in perspective, we computed, for each scenario, the discounted net present value (DNPV) of the future stream of Québec annual gross domestic product (GDP) over the post 1989 horizon, and we then established the value of discounted reduction costs as a percentage of the DNPV of the GDP stream. For example, in the "high" case, the largest (discounted) reduction cost of $4.6 billion

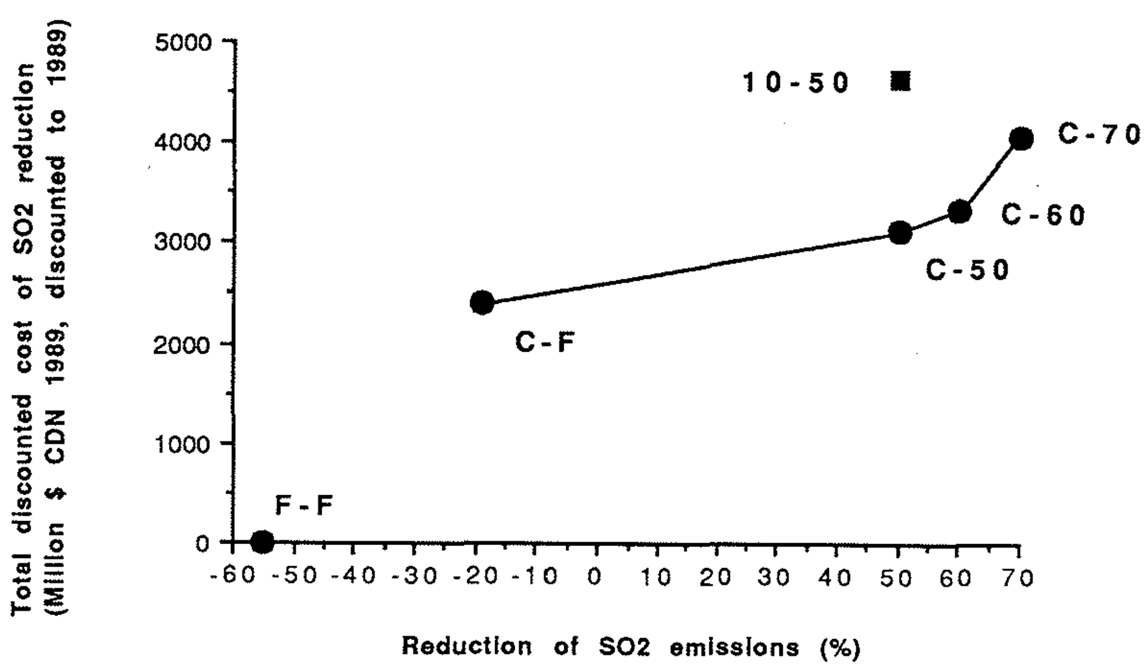

Figure 3a: Cost/Emission Trade-Off Curve — "High"

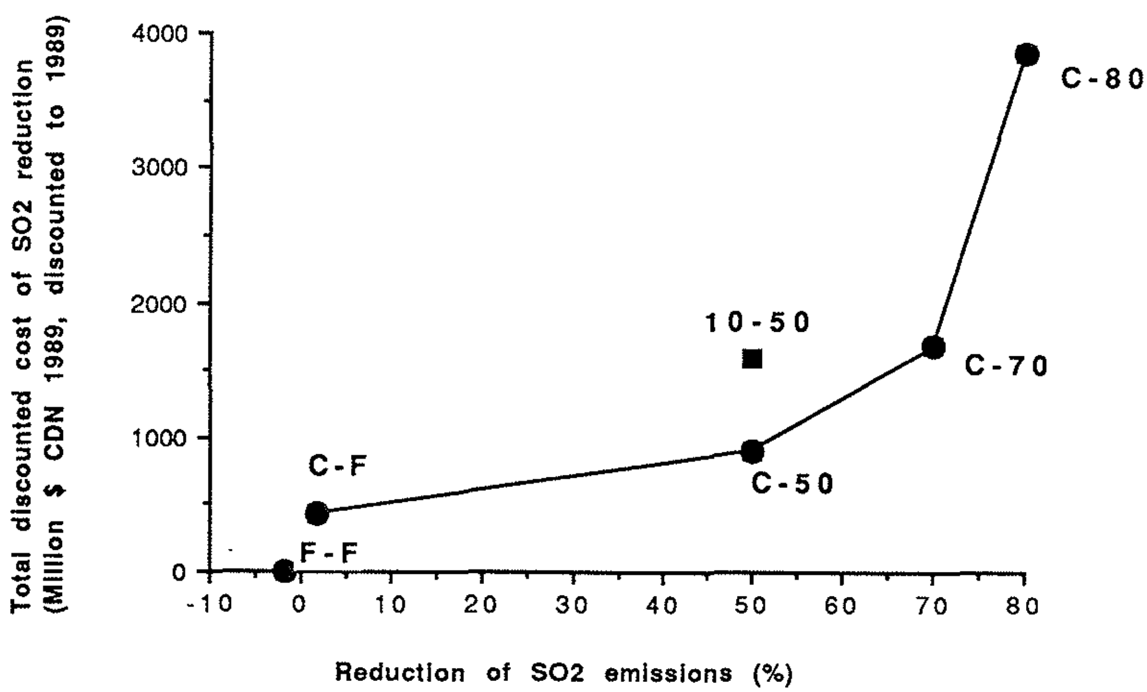

Figure 3b: Cost/Emission Trade-Off Curve — "Low"

(scenario 10-50) represents 0.23% of the discounted GDP, whereas in the "low" case, the largest cost of $3.8 billion (scenario C-80) amounts to 0.20% of discounted GDP. These are relatively very small costs indeed.

Another interesting point is that in the absence of constraints on NO_X or SO_2 (scenario F-F), the quantity of SO_2 emitted in 2015, for the "high" case, exceeds by 55% the 1980 level, whereas when only NO_X is constrained (scenario C-F), the quantity of SO_2 emitted in 2015 exceeds the 1980 level by only 19%. This clearly illustrates that when demands are high, the initial reduction of NO_X induces an important reduction of SO_2 as well. This beneficial side-effect disappears when a stricter constraint is imposed on emissions of NO_X, as may be seen by comparing scenarios C-50 and 10-50.

A similar analysis in the "low" case shows that reducing emissions of NO_X does not significantly affect emissions of SO_2, which in scenarios F-F and C-F, remain close to constant at their 1985 level; this is caused by the modest increase in demands in the low economic scenario, which makes it possible to achieve sufficient reductions in emissions of NO_X within the transportation sector alone.

The above remarks help explain why the cost of maintaining emissions of NO_X at the 1985 level while leaving emissions of SO_2 free (obtained by comparing scenarios F-F and C-F) is much higher in the "high" case than in the "low" case ($2.4 billion and $0.42 billion respectively). Similarly, the additional cost of cutting emissions of NO_X by 10% and SO_2 by 50%, versus constant emissions of NO_X and a 50% cut in emissions of SO_2 (by comparison of C-50 and 10-50), is roughly 2.5 times larger in the "high" than in the "low" case.

REDUCTION STRATEGIES

This section describes in broad terms, the means used by the model to achieve the emission constraints imposed in both economic cases. Comparing scenarios F-F and C-F, the means to achieve NO_X reductions in both economic cases, are mainly:

- an important switch from oil products (especially heavy fuel oil) to natural gas as shown in Figure 4, which presents for each scenario the amounts of natural gas imported into Québec. There are of course corresponding decreases in the amounts of crude oil imported into Québec; and,
- an important switch toward diesel vehicles as shown in Figure 5, which presents the share of diesel by transportation vehicles.

Figure 6 shows that the changes are accompanied by an increased share of imported, lighter and "sweeter" crude oil (a "sweet" crude is one with a low sulfur content, as opposed to a "sour" crude which has a high sulfur content). These switches are more pronounced and occur earlier in the "high" than in the "low" cases. Detailed analysis shows that the impact of scenario C-F on the refining supply and structure is much larger in the "high" case, which explains the high cost differential between F-F and C-F. The copper sector is not affected by this scenario.

Reductions in emissions of SO_2 from C-F to C-50 are achieved mostly in the copper industry (Figure 7), as well as from small additional gas imports. In the C-50 scenario, the copper industry emits almost no SO_2. Note that this occurs even though the acid produced in this sector must be neutralized in our model (we assume no significant market for acid).

With the 70% reduction constraint, the abatement potential in the copper industry is already exhausted, and the model achieves the desired emission level by a large switch to light and sweet crude oil, which more than doubles its share of the total imports of crude oil in 2015 (Figure 6). This provokes important changes in the structure of the refining industry, which are discussed in more detail below. These changes in oil refining account for the high additional cost of scenario C-70.

In the "low" case, reducing further the emissions of SO_2 from 70 to 80% costs more than the cumulative cost of previous reductions of SO_2 and NO_X. This shows clearly that the C-80 scenario challenges the ability of the model (and indeed of the energy system), which responds by an almost total conversion of boilers and furnaces to natural gas and other "clean" fuels, and

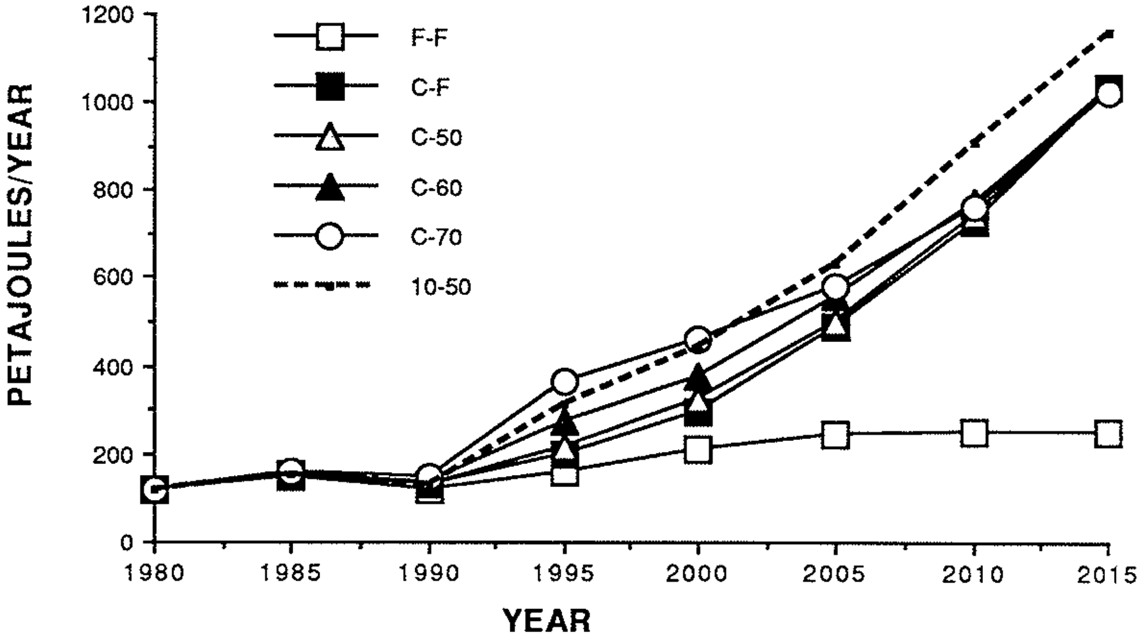

Figure 4a: Importation of Natural Gas — "High"

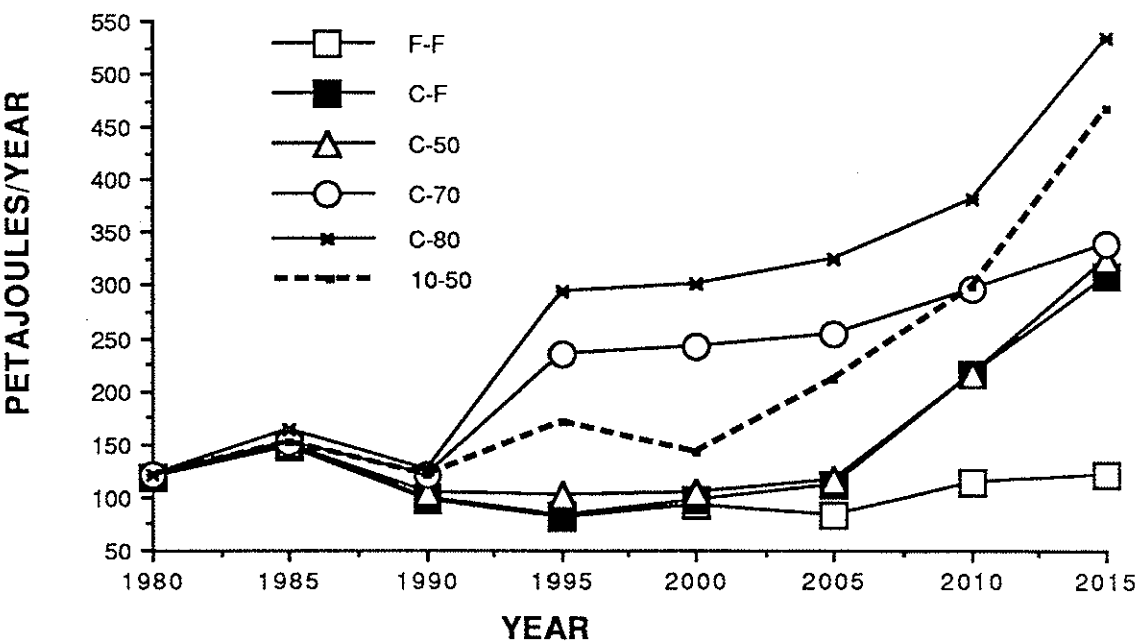

Figure 4b: Importation of Natural Gas — "Low"

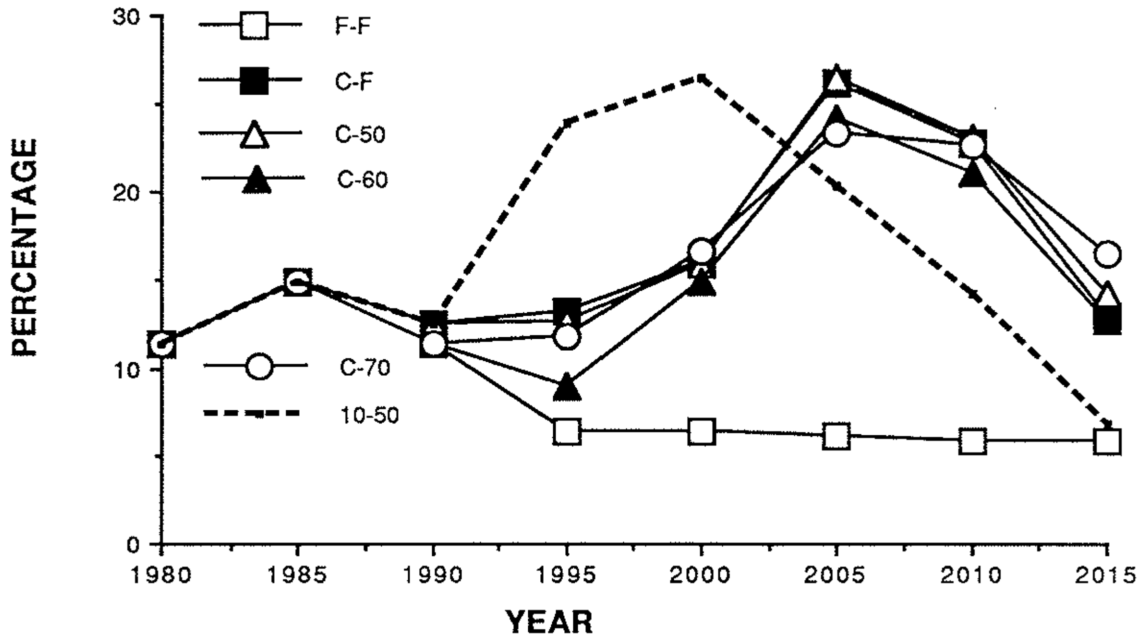

Figure 5a: Diesel Share of Road Transportation Fuels — "High"

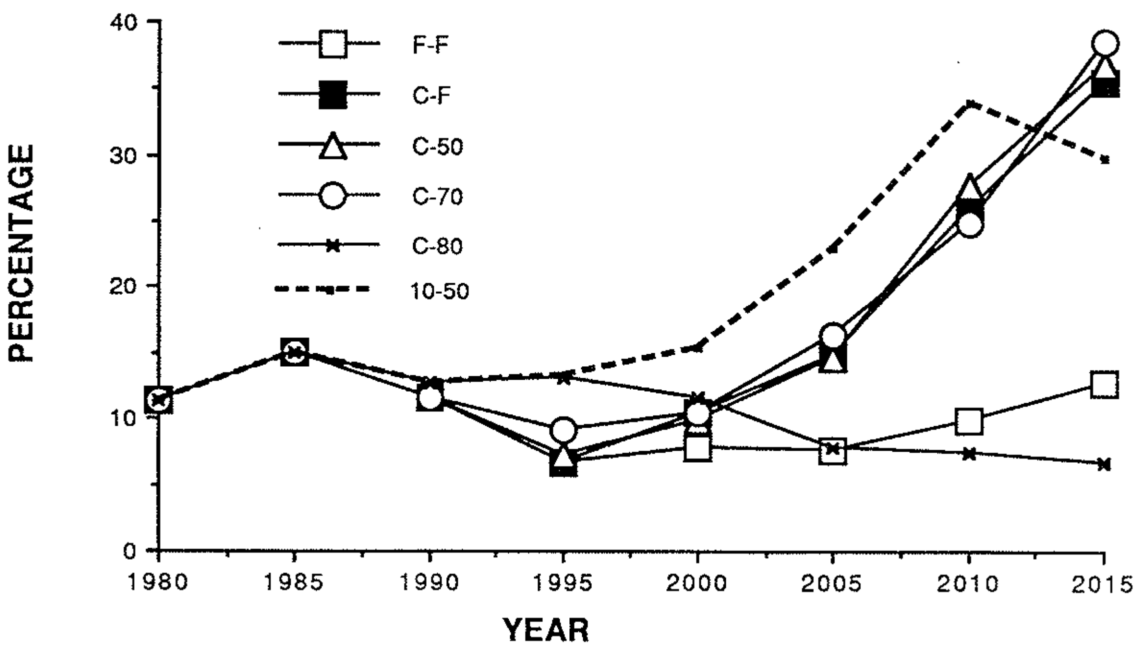

Figure 5b: Diesel Share of Road Transportation Fuels — "Low"

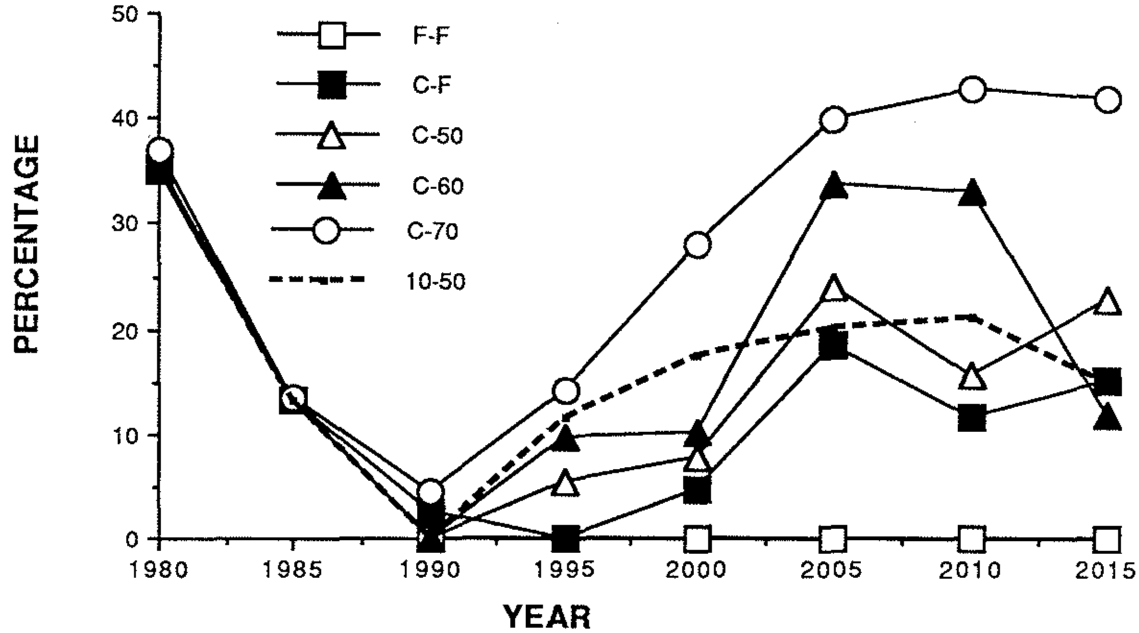

Figure 6a: Share of Light Sweet Crude Oil in Oil Supply — "High"

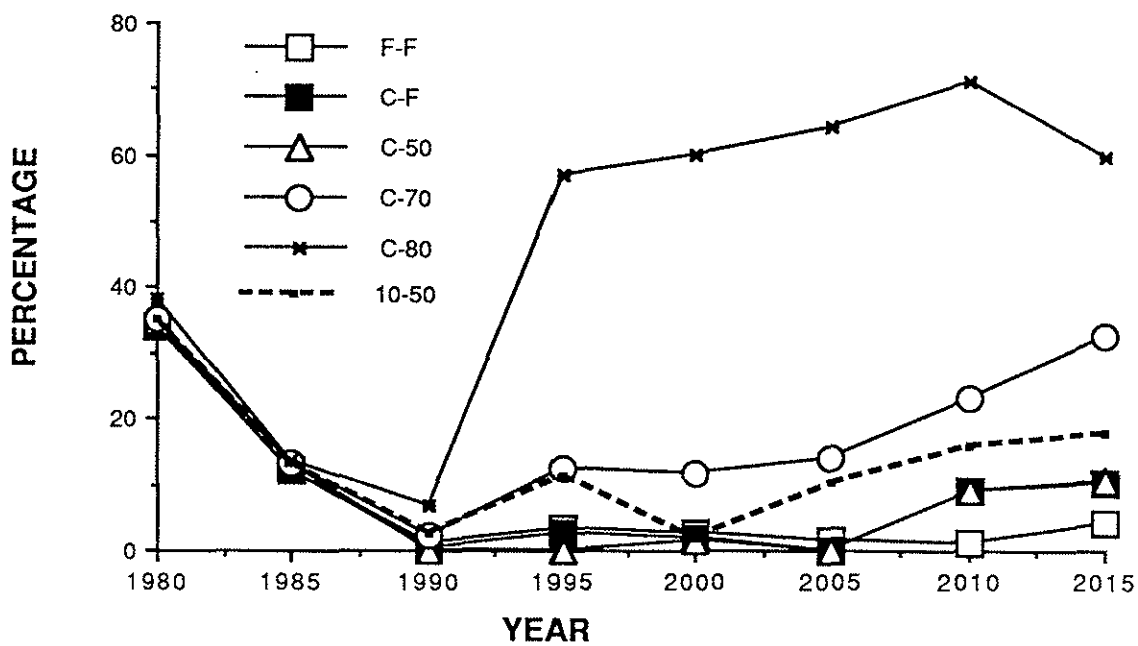

Figure 6b: Share of Light Sweet Crude Oil in Oil Supply — "Low"

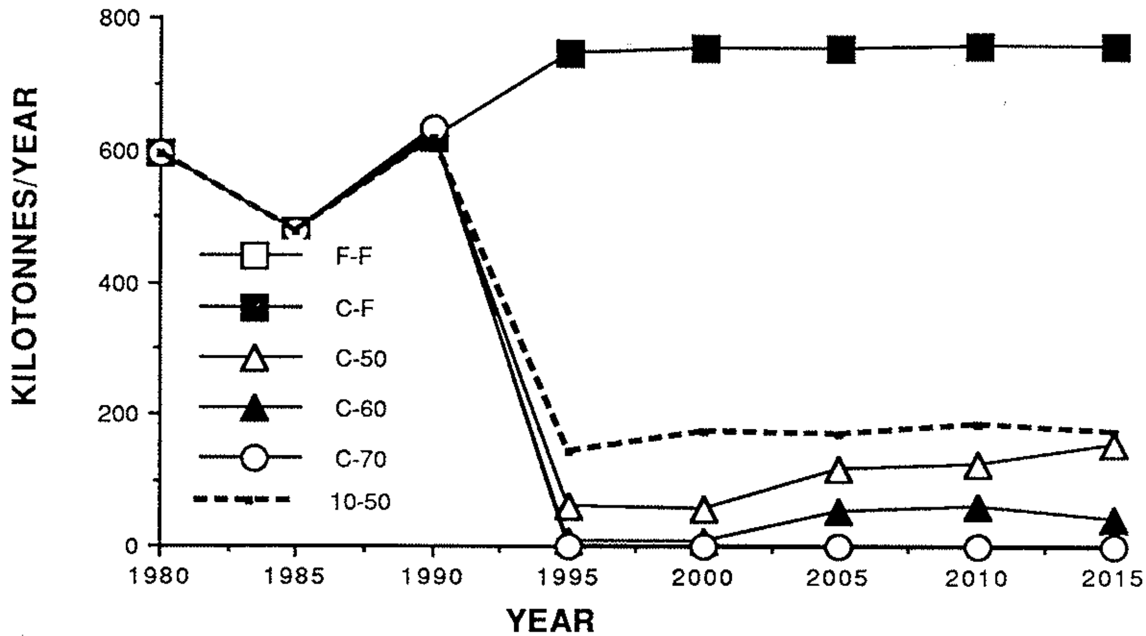

Figure 7a: SO_2 Produced by the Copper Industry — "High"

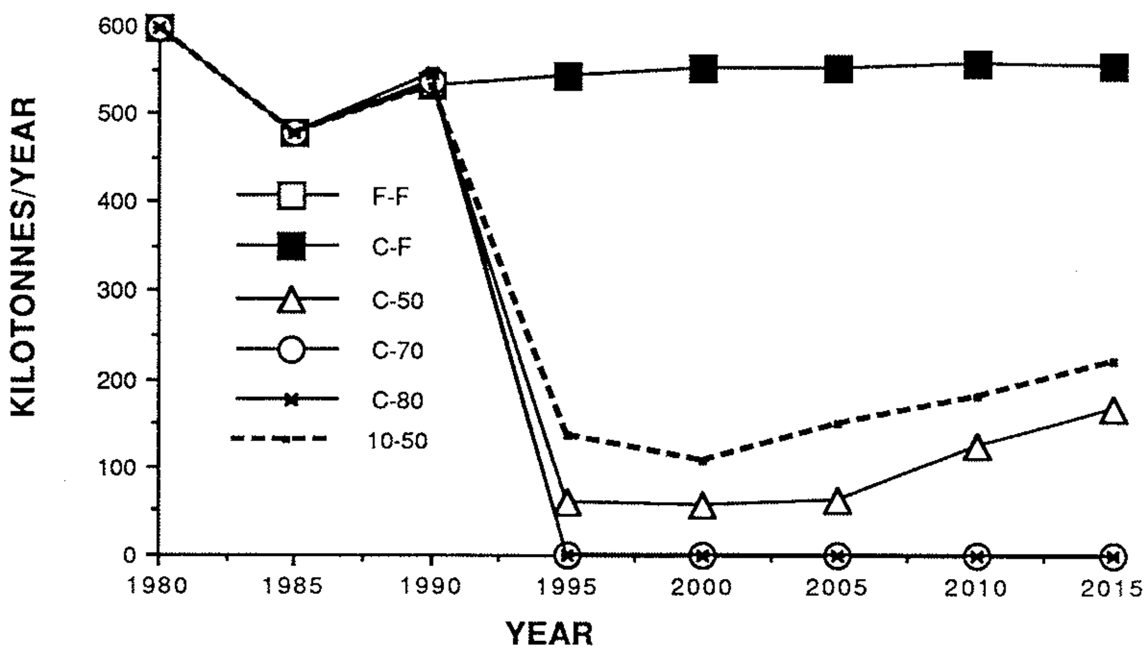

Figure 7b: SO_2 Produced by the Copper Industry — "Low"

by further structural changes in the transportation sector. To correctly analyze reductions of such severity, our model should be extended to include abatement technologies even in sectors that contribute small shares of total emissions.

Comparing scenarios C-50 and 10-50 yields interesting results. While continuing the substitution of imported crude oil or imported gas, the 10-50 scenario shows an *increase* in emissions of SO_2 by the copper sector (Figure 7) and a decrease by boilers and furnaces (Figure 8). This is so because the alternative of an early switch to gas and other fuels, although expensive, reduces emissions of SO_2 and NO_X simultaneously. Other impacts of this scenario are different in the two economic scenarios; in the "high" one, the model must act in the transportation sector (by increasing diesel and CNG cars) in spite of the high cost of doing so, whereas in the "low" case, there is still enough potential left in boilers and furnaces to achieve a good part of the desired reductions in NO_X through substitution of gas. These differences help explain the high cost differential observed.

4.2 Sectoral Analysis of the Two Economic Cases

INDUSTRIAL BOILERS AND FURNACES

Figure 8A shows a massive reduction of emissions by boilers and furnaces in the "high" case when NO_X is limited to the 1985 level, caused by replacement of heavy oil by gas, even in the C-F scenario. Further reductions (scenarios C-F to C-50) occur through minor additional penetration of gas. Another significant reduction (scenarios C-70 and 10-50) is achieved by replacing heavy fuel oil by other fuels (wood, more gas) and conservation. In the long term, all reduction scenarios use the same amount of natural gas in this sector, although scenarios C-70 and 10-50 use more gas boilers in 1995 and 2000.

As shown in figure 8B, the decrease in emissions of SO_2 by this subsector is more progressive in the "low" case, as the constraint on SO_2 is tightened. The C-80 scenario induces near-zero emissions, even as early as 1995. Another difference with the "high" case is that the long term emissions of SO_2 are different across the various constraints on SO_2, whereas they are uniformly low in the "high" case. This is because the lower industrial demands make it relatively easy to satisfy the various constraints on SO_2, except in the C-80 case.

REFINING SECTOR

The impact on refining of the fuel switching observed in the industrial boilers and furnaces is to decrease the competitiveness of heavy and sour crude in favour of light and sweet crude, with an ensuing restructuring of the refineries. The desulfurization capacity decreases up to 1995 in both "high" and "low" scenarios according the same pattern because of use of sweeter crude and the switch to natural gas. In the unconstrained F-F scenarios, the decrease is even more pronounced because of the absence of any constraint. After 1995, the requirement for constant emissions, combined with the large increase in useful demands, promotes additional investments in desulfurization units.

Scenarios C-70 and C-80 in the "high" and "low" cases, respectively, are different. The C-70 scenario induces a shift towards more diesel accompanied by a marked shift towards desulfurization, whereas the C-80 induces a shift towards more gasoline, accompanied by increased imports of sweet and light crude and less desulfurization. Cracking units exhibit a similar (although less pronounced) decrease in capacity from the C-70 to the C-80 scenarios, whereas reforming increases, so as to allow the production of extra gasoline.

Finally, scenario 10-50 of the "high" case exhibits a stronger decline in desulfurization capacity. Although the use of heavy fuel oil continues to decrease, there is less need to upgrade the heavier cuts from the distillation units. Since gas powered vehicles strongly penetrate this market (because natural gas emits less NO_X than gasoline or diesel), there is less need for gasoline and diesel in the transportation sector. The strong penetration of diesel followed by a pronounced decline after 2000, is explained by the lower SO_2 emissions from gasoline and CNG cars — the increasing relative severity of the constraint forces such a switch towards these vehicles. Of

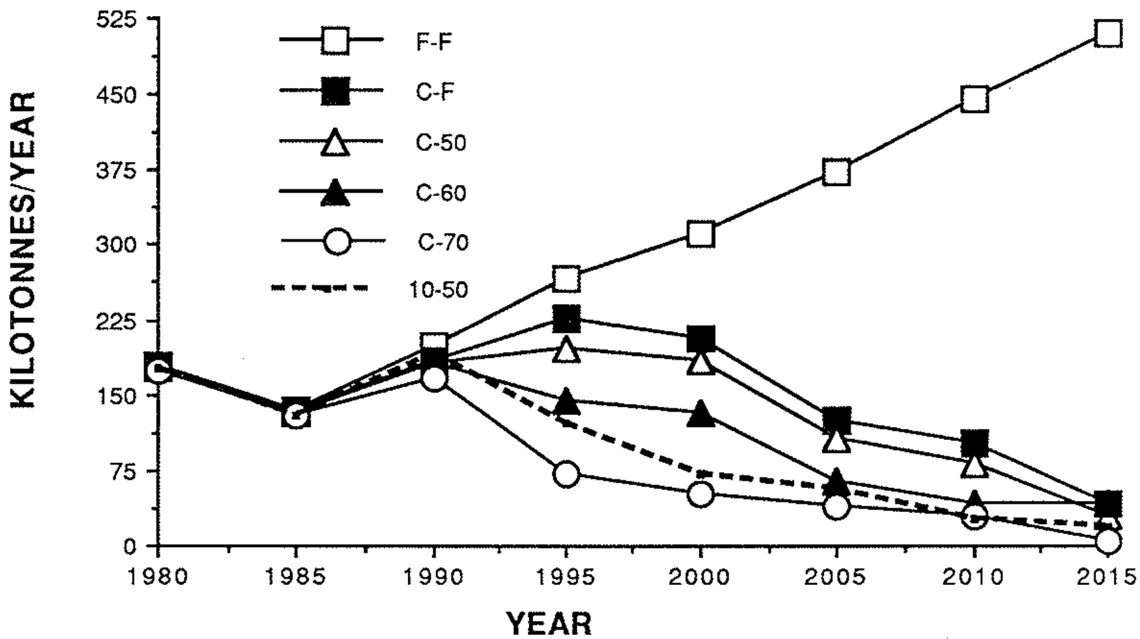

Figure 8a: SO_2 Emissions of Industrial Boilers and Furnaces — "High"

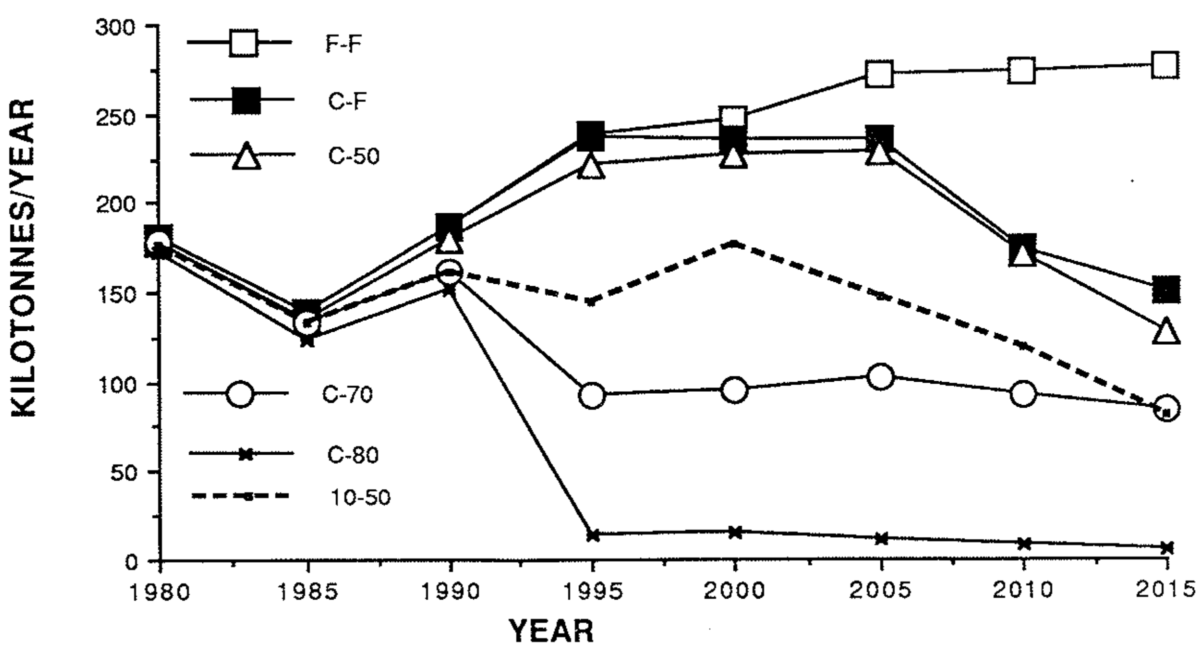

Figure 8b: SO_2 Emissions of Industrial Boilers and Furnaces — "Low"

course, the net result of this reduction in the use of oil products is a decrease in imported crude oil in favour of natural gas as shown in Figure 4A. In the "low" case, scenario 10-50 is not very much constrained because of the lower demands, and it follows the general pattern of other scenarios. Note that the above detailed analysis is made possible by the presence in MARKAL-Québec of a detailed, accurate refining module (Berger, 1985).

COPPER INDUSTRY

Major gains in emissions reductions are achieved in the copper sector as shown in Figure 7. Technological changes occur according the following sequence: in both economic cases, calcine smelting progressively disappears under scenarios with reduced emissions of SO_2, with a simultaneous increase in the use of the Noranda autogenous reactor, with which important gains in energy efficiency are achieved. In addition, concentrating the gases from a reverberatory furnace is more expensive than what is done automatically in the Noranda reactor, especially with increased use of oxygen. This constitutes an additional advantage for a Noranda reactor coupled with a fluidized-bed acid plant to treat the concentrated gases. In spite of this, the wet-charge reverberatory furnace continues to produce in all scenarios except the C-70 scenario, providing the necessary flexibility to treat dirty concentrates. It was already noted that scenario 10-50 prefers a slightly less clean copper smelting (and thus a smaller penetration of the autogenous reactor) because simultaneous reductions in emissions of SO_2 and NO_X can be achieved more cheaply through HFO replacement for boilers and furnaces.

Other observations on the copper industry are:

- the GCM hydrometallurgical process is not used (it would be competitive if fluidized bed acid plants were not permitted);
- hooding of the Pierce-Smith converters is implemented starting in 1995 for the treatment of the 73% copper matte coming from the Noranda reactor;
- use of scrap copper increases from 10% to 20% of copper contents in all scenarios;
- the maximum increase in the long term marginal production cost of refined copper (shadow price) occurs in the C-70 scenario in 1995, and is close to 6%. In all scenarios, the increase stabilizes around 4% in 2005 and later; and
- up to one million tonnes of acid are produced in the C-70 scenario, and are neutralized in our model. Acid could be considered as a useful by-product or as an environmental reject, depending on the size of the market for acid and the production of acid by other regions or countries.

TRANSPORTATION SECTOR

In both economic cases, three fuels compete in the road transportation sector: gasoline, diesel, and CNG. Methanol-fuelled vehicles are not competitive, in spite of their technical attractiveness. The high cost of methanol comes from its production process, which is based on biomass in our model. Other, possibly cheaper ways to produce methanol might change this aspect of our results but do not seem easily feasible in Québec. Electric cars have not been included in our data base.

The fraction of diesel (Figures 5A and 5B) is shown in relation to total fuel consumption in the road transportation subsector for all environmental scenarios. Diesel experiences a decrease when CNG becomes more competitive and thus takes its market share.

In the "high" case, the results are almost identical from scenarios C-F to C-70, showing that the sector is mainly sensitive to the constraint on emissions of NO_X. The transportation sector responds to the constraint on NO_X in two ways:

- Catalytic converters are used to their full potential in the C-F and all subsequent scenarios.
- Diesel vehicles partially replace the gasoline fleet, reaching around 14% of the total fleet in 2015 in all C-scenarios, and only 7% for the 10-50 scenario. Conversely, CNG vehicles appear in 2015 in all C-scenarios and much earlier (1990) in the 10-50 scenario, reaching, in 2015, a 74% market share in the 10-50 versus only about 50% in all C-scenarios. It is

thus clear that the additional constraint on emissions of NO_X induces a different strategy in this sector, with fewer diesel and more gas-powered vehicles.

For scenarios C-F to C-50, and even 10-50, diesel has a more vigorous, steadier penetration in the "low" than in the "high" case, capturing almost 40% of the market in 2015. This happens essentially to the detriment of CNG cars, which capture less market share in the "low" case (less than 10% in 2015). This is so because the available reduction potential in the copper sector eliminates the need to reduce emissions of SO_2 by the diesel cars. In contrast, the more severe reduction in emissions of SO_2 in the C-80 scenario provokes a marked reversal of the diesel "strategy," as is explained in the preceding discussion on the structure of refining: diesel captures a 7% market share in 2015 versus 66% for gasoline cars (which emit less SO_2). In addition to the fuel switching discussed above, catalytic converters are used to their full potential in the C-F and subsequent scenarios.

4.3 Shadow Prices of Constraints on Emissions

In the "high" case, Tables 3 and 4 give the shadow prices of the constraints on emissions of SO_2 and NO_X, respectively, expressed in 1989 undiscounted Canadian dollars, and Tables 5 and 6 give them in the "low" case. The shadow price of an emission constraint is the additional cost incurred when the constraint is tightened by one unit; in other words, it is the marginal cost of emission reduction. For example, in the "high" case, it would cost $0.27 to reduce emissions of SO_2 in 1995 by one additional kilogramme per year (C-50 scenario).

In the "high" case, all shadow prices are less that $0.71 for scenarios C-F to C-60, but rise sharply to the range $1.11 to $3.50 in scenario C-70. This is in agreement with the shape of the cost/emission trade-off curve (Figure 3A). Note the drop in shadow prices in the 10-50 scenario, caused by a stronger constraint on emissions of NO_X, that has a beneficial side-effect on emissions of SO_2. The shadow prices of constraints on emissions of NO_X are generally high after 2000 in all C-scenarios, and even higher in the 10-50 scenario. This is especially true in 2005 and later. Before then, the effect of progressively stronger constraints on SO_2 is to keep the shadow prices of NO_X constraints low (often zero) until the constraint on SO_2, by itself, is no longer adequate to sufficiently reduce NO_X emissions. The most typical example is scenario C-70, where the severe constraint on SO_2 emissions is enough to keep NO_X emissions below its own limit up to the year 2000, and thus to keep its shadow price at zero. The marked increase in shadow prices observed in all scenarios after 2000 is caused by the difficulty of reducing emissions of NO_X while the fleet of vehicles is expanding. This side effect is a result of the combination of lower imports of oil (and high imports of natural gas, see Figure 4) and higher fraction of sweet crude, which characterizes the C-80 and C-70 scenarios (Figure 6).

Compared to the "high" case, the shadow prices of SO_2 constraints in the "low" case are generally smaller, but of the same order of magnitude, and they exhibit similar patterns for comparable scenarios. The difficulty of reducing emissions of SO_2 by 80% is clearly confirmed by the very high shadow prices of SO_2 in C-80, reaching $41 per kg in 2015. Except for C-80, shadow prices of constraints on emissions of NO_X are again larger than those of SO_2, just as in the "high" case. The beneficial side-effect of reducing emissions of SO_2 on the shadow prices of NO_X is even more marked here than in the "high" case. Note how progressively stiffer constraints on SO_2 delay the time at which the shadow prices of NO_X become positive; a case in point is the C-80 scenario, the shadow prices of which are all zero because of the severe reduction in emissions of SO_2.

The information provided by the shadow prices can also be used to approximate the savings in cost that would follow from postponing the imposition of the constraint on emissions of SO_2 (or NO_X) by one period. For example, in the "high" case, consider a modification of scenario C-70 which postpones the constraint on emissions of SO_2 to 2000 (instead of 1995). Call this scenario C-70-A. The theory of linear program-

Table 3: Shadow Price of SO_2 ($ CDN 1989) — "High"

Year	C-F	C-50	C-60	C-70	10-50
1995	0.00	0.27	0.49	1.11	0.17
2000	0.00	0.15	0.71	1.28	0.09
2005	0.00	0.08	0.08	1.44	0.09
2010	0.00	0.11	0.09	2.01	0.09
2015	0.00	0.11	0.12	3.50	0.11

Table 4: Shadow Price of NO_X ($ CDN 1989) — "High"

Year	C-F	C-50	C-60	C-70	10-50
1995	2.68	1.25	0.00	0.00	2.64
2000	3.28	2.01	0.11	0.00	4.88
2005	8.68	8.68	7.58	6.75	13.98
2010	12.54	11.78	11.51	10.44	13.73
2015	12.25	11.84	12.40	10.81	14.46

Table 5: Shadow Price of SO_2 ($ CDN 1989) — "Low"

Year	C-F	C-50	C-70	C-80	10-50
1995	0.00	0.33	0.76	15.12	0.12
2000	0.00	0.15	0.79	3.63	0.15
2005	0.00	0.08	1.05	25.06	0.08
2010	0.00	0.11	0.81	25.49	0.11
2015	0.00	0.11	0.24	41.34	0.09

Table 6: Shadow Price of NO_X ($ CDN 1989) — "Low"

Year	C-F	C-50	C-70	C-80	10-50
1995	0.00	0.00	0.00	0.00	2.31
2000	0.00	0.00	0.00	0.00	1.50
2005	2.13	0.78	0.00	0.00	4.79
2010	5.59	4.83	2.74	0.00	10.06
2015	10.35	10.11	9.86	0.00	10.46

ming tells us that an upper bound of the cost differential between scenarios C-70 and C-70-A can be computed by using the shadow prices in Table 3, combined with the emissions of SO_2 achieved in scenarios C-70, C-60, C-50, and C-F. This estimate is $354,147,000 (undiscounted, 1989 Canadian $). Details of the computation are omitted. Discounting to 1989 gives a sum of $230,000,000, which is a modest fraction of the reduction costs shown in Figure 3A. Therefore, there is not much point in delaying the SO_2 constraint by one period.

5. Conclusions

The preceding pages have presented an original application of the MARKAL model to the simulation of the long-term impacts of acid gases emission restrictions on the Québec energy system under two alternate economic growth scenarios. The main impacts of the emission reductions may be summarized as follows, for the high growth scenario:

a) maintaining NO_X emissions at their 1985 level (while leaving SO_2 emissions free) is costly, of the order of $3/kg NO_X in the year 2000, climbing to $12/kg in 2015. This is achieved by replacing fuel oil by natural gas in the industrial sector, by adding three-way catalytic converters on vehicles, and by partially replacing gasoline vehicles with diesel vehicles. Furthermore, the NO_X constraint induces a significant joint reduction of SO_2 emissions, mainly due to the increased use of natural gas;

b) when SO_2 constraints are added, they entail a relatively moderate additional cost, of the order of $0.27/kg SO_2 in 1995, decreasing to $0.11/kg in 2015, for a 50% reduction constraint. The cost increases markedly when the constraint reaches 70% reduction of SO_2, but is still lower than initial NO_X reduction costs. SO_2 emission reductions are first achieved in the copper sector by implementing the more efficient Noranda autogenous reactor, and condensing SO_2 in acid plants, as well as other process improvements in copper production. The higher 70% SO_2 reduction is achieved via a marked increase in imports of light, sweet crude oil and a corresponding modification of the structure of the oil refining industry, explaining the higher cost; and

c) a simultaneous reduction of NO_X by 10% and SO_2 by 50% is also very costly, mainly because of the additional NO_X constraint. In this situation, the cost per kilogramme of NO_X reduced varies from \$2.64 in 1995 to \$14.46 in 2015, very imposing figures indeed, incurred mainly in the transportation sector.

The conclusions for the low growth scenario are somewhat parallel to the above ones, with, however, much lower reduction costs in most cases, as well as occasional differences in the technological responses of the energy system.

This article demonstrates the usefulness of a detailed, multi-sectoral process model to investigate the impacts of atmospheric emission reductions. Only with such models can the systems effects be fully explored and quantified. An important discovery is that, although the two economic scenarios are quite contrasted, they elicit fairly similar qualitative responses from the energy system (fuel and process changes, energy conservation measures, abatement technologies).

Another conclusion is that SO_2 reductions beyond 60% are much more expensive than moderate reductions. This may have important implications for establishing policy in this domain. The identification of the sectors and industries where emission reductions can be achieved efficiently is also important if a regulatory approach is to be used for emission control. On the other hand, if a pollution tax approach is favoured, an understanding of the shadow prices of the various emission levels is of paramount importance in fixing the tax rate.

A few improvements of the model's data base may be suggested, such as allowing multiple sulfur contents in diesel, or modelling natural gas penetration with additional detail, or imposing upper limits on the importation of light sweet crude oil. These are minor modifications, which would be useful if more extreme emission constraints were imposed. As it stands now, the model gives a convincing picture of the socially efficient long-term response of the Québec economy to the imposition of acidic gas emissions.

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