This paper reports on the use of an advanced multi-region, bottom-up model (Extended MARKAL) for an in-depth investigation of the responses by the Québec-Ontario energy system to a series of increasingly severe greenhouse gas (GHG) emissions reduction targets. For each target, the responses are analyzed under four policies resulting from the adoption (or not) of a joint emissions target and of electricity exchanges. Results indicate significant cost savings and a reduction in the need for nuclear energy in Ontario, which suggests that cooperative responses to GHG emissions caps should be seriously considered by the two provinces.

Cet article utilise le modèle multi-régional Extended MARKAL pour explorer en détail la réponse de la région Québec-Ontario à l'imposition de contraintes plus ou moins sévères sur l'émission de gaz à effet de serre (GES) par cette région. Pour chaque cible de réduction, la réponse est analysée sous quatre politiques contrastées, chacune incluant ou excluant l'échange d'électricité et l'échange de permis d'émission entre les deux provinces. Les résultats indiquent des économies substantielles sur le coût total des réductions de GES, lorsque les deux provinces coopèrent. De plus, la coopération diminue fortement le besoin pour l'Ontario de développer sa capacité nucléaire, lorsqu'une cible de réduction est imposée. Ces résultats soulignent l'importance de la coopération interprovinciale future si des quotas d'émission de GES étaient imposés.

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GHG Abatement in Central Canada with Interprovincial Cooperation

RICHARD LOULOU, AMIT KANUDIA and DENIS LAVIGNE

1. Introduction

Canada is a signatory to the UNFCCC (United Nations Framework Convention on Climate Change 1992), and has been an active player in the subsequent meetings of the Conference of Parties (COP), a political-level group of national delegates from all major United Nations countries charged with devising global policies on the climate change issue. As an active member of the COP, Canada has put greenhouse gas (GHG) emissions targets on its own political agenda, consisting of a return to the 1990 level of emissions by year 2000, and a subsequent 20% reduction of Canadian GHG emissions by 2010. Whereas it appears that the 2000 Canadian emissions stabilization will not materialize, other studies like those by the Intergovernmental Panel on Climate Change (IPCC 1995 a, b, c) are indicating a high degree of uncertainty in the setting of globally desirable (optimal) reduction levels by OECD countries. The range of possible targets is quite wide, leaving each country in a quandary as to the setting of national policies. Faced with uncertainty, Canada would benefit from a thorough investigation of contingent plans to meet a wide range of targets.

In this study, we focus on the analysis of a coordinated response to alternative GHG reduction targets by Central Canada (*i.e.*, the two populous Canadian provinces, Québec and Ontario). Thus defined, Central Canada comprises slightly more than 60% of the Canadian population and GDP. Although this study does not claim to be directly applicable to Canada as a whole, it provides a useful analysis of a significant fraction of the country, and furthermore, serves as an illustration of the potential benefits of interprovincial cooperation in dealing with GHG abatement. Since Québec enjoys a substantial hydroelectric potential, it is of interest to examine how this could be used efficiently to reduce GHG emissions in Central Canada as a whole.

In order to reflect the high degree of uncertainty regarding the amount and the timing of future GHG abatement, we chose to examine five alternative targets, *viz.* 0%, 10%, 20%, 30%, and 40% cumulative emissions reductions compared to the 1990 level. In addition, a base-case scenario with no emissions cap is also included in the analysis. Each reduction scenario is run four times, with each run assuming a combination of the following choices: with/without electricity exchanges between the two provinces, and with/without emissions trading between the two provinces. In this way, we can identify the potential benefits from cooperation along the two dimensions of electricity trading and of emissions trading.

In section 2, the methodology is outlined, and in section 3, some key results and analyses are developed. In section 4, we conclude this paper and indicate further avenues for research and development.

2. Methodology

2.1 The Model

Over the years, we have developed two MARKAL activity analysis models of the energy/industrial systems of the Québec and Ontario provinces. The most recent versions of these models include descriptions of very diversified energy sources (extraction, imports), of energy transformation and distribution, and of end-use processes and devices in all economic sectors, including a set of technological and energy conservation options in each province. These elements of the energy system are referred to as technologies in the MARKAL jargon. Each provincial model has in excess of 500 technologies (Loulou and Waaub 1992). MARKAL (Fishbone *et al.* 1981, 1983) is a demand-driven model based on the minimization of the long-term discounted cost of a complete energy system, including the production, conversion, distribution, and final use of energy forms. In MARKAL, each element of the energy system (such as a technology, a fuel, or a conservation measure) is explicitly represented by a set of model variables, indexed by a time period. The model covers nine periods of five years each — a 45-year horizon. The nine periods are centered on years 1995 to 2035, so that the actual horizon covered is from 1993 to 2037, inclusively.

The model's *engine* is linear programming, which, by minimizing total discounted system cost, in effect computes a partial equilibrium solution for energy markets. The base demands for a large number of sectors and subsectors are specified exogenously for each scenario. MARKAL determines the values of all future investments and operations levels of the technologies at each time period, while respecting emissions caps and a very detailed set of technical and logical constraints. In addition to technological and energy substitutions, MARKAL may also choose to adjust base demand levels endogenously, thanks to a set of own-price elasticities. For example, when emissions caps are imposed, the implicit prices of some energy forms, and ultimately those of some economic goods and services, increase: MARKAL then has the option of reducing some demand levels according to the specified demand curves. While the main outputs from MARKAL are the values of the investments and capacities of the various technologies at all time periods, additional output consists of the set of implicit prices of each energy form and of each demand category.

Each model's database has undergone in-depth revisions during the last two years. In the process, the set of GHGs modelled was increased to include carbon dioxide (CO_2), methane (CH_4), and polychlorofluorides (C_xF). In addition, emissions of acid gases (SO_2 and NO_x) are also modelled. The technology sets are carefully designed to include all major existing and new technologies, with special emphasis on options with low or null GHG emissions, such as renewables. Following the current thinking on nuclear power, it has been assumed that there will be a *de facto* moratorium on any decision to invest in new nuclear power plants for another decade. Further, nuclear plants take about 10 years to build. Thus, the earliest that the models can set up new nuclear capacity is in 2018.

As an indication of the level of detail in the two models, Table 1 provides a count of the different energy carriers in the models, of the technologies present in each of the main sectors of the energy system, as well as the number of separate demand segments in each end-use sector. Thus, MARKAL-Quebec has 184 energy carriers, including imported energy, locally produced primary energy forms, and all secondary energy forms. The second part of Table 1 indicates the richness of technological detail in each MARKAL model. As an example, the transportation sector has a total of 69 technologies (*i.e.*, types of vehicles). Since the model is "drawn" by demands for economic goods and services, the third part of Table 1 indicates the degree of disaggregation of each broad demand sector. For instance, there are 13 demand segments in the residential sector, each capturing one homogeneous demand for an energy service (*e.g.*, space heating for pre-1991 single-family dwellings). A detailed listing of technology and energy-carrier names would be too space consuming for inclusion here; however, a copy of the database is available upon request.

Table 1: Energy Carriers, Technologies, and Demand Segments in MARKAL Models

		MARKAL	
		Québec	Ontario
Energy Carriers		184	189
Technologies			
Supply	Sources of Energy	16	17
	Power Generation	36	36
	Oil Refining	23	23
	Other Energy Processing	62	89
End-use	Residential	106	104
	Commercial	77	67
	Transportation	69	68
	Industry	124	180
	Non-energy Uses	4	6
		517	590
End-Use Demand Segments			
	Residential	13	13
	Commercial	14	11
	Transportation	12	12
	Industry	26	7
	Non-energy Uses	4	6
		69	49

2.2 The Scenarios

A single economic scenario is used throughout this study, which corresponds to moderate economic growth until year 2020, slowing down thereafter. The economic growth assumptions are close to those assumed in Natural Resources Canada (1994), with an average yearly GDP real growth of 2.1 % per year in Québec and 2.4% in Ontario, until 2020. These growth rates are reduced by 0.4% per year (again in real terms) after 2020. The prices of imported oil and natural gas grow by an average of 1% (in real terms) per year until 2011, and then stagnate at their 2011 levels. Gas prices converge to oil prices by year 2005, and the two remain equal thereafter. Because MARKAL is an integrated energy model that models the energy supply, the prices of domestic energy forms such as electricity, biomass, and refined petroleum products are determined endogenously and are equal to the shadow prices of these energy forms in the model. Finally, the real discount rate used is 5% per year. All cost figures discussed in this article are expressed in constant 1990 Canadian dollars.

As mentioned earlier, we adopted six alternative emissions caps: the base case and five levels of cumulative GHG reductions equal to 0%, 10%, 20%, 30%, and 40% of 1990 GHG emissions. For each reduction level, four runs were performed, corresponding to the following cooperation policies:

- NC–No cooperation (*i.e.*, no electricity trading, no GHG permit trading);
- EE–Electricity exchanges are allowed, but GHG permit trading are not;
- JE–Joint emissions target (*i.e.*, GHG permit trading is allowed, but electricity exchanges are not); and
- JEEE–Joint emissions target with electricity exchanges (*i.e.*, electricity trading and emission permit trading are both allowed).

To model Central Canada as one unit, we used the recent multi-regional feature of the Canadian MARKAL model (Kanudia and Loulou, 1997), where any number of MARKAL models can be merged into a single larger-size model. The number of models is limited only by the capacity of the numerical solver. Special variables are defined to represent the amounts of investment in electricity transport lines, and the amounts of electricity traded at each period between each pair of models. The size of the merged model reaches about 23,000 rows and 40,000 columns, but the model remains quite tractable computationally as long as the number of regions remains reasonably small (two in our case).

The Central Canada model may now be used in various ways to simulate the four types of runs listed above: in the NC run, each province has its own GHG emissions constraint, and all electricity exchange variables are set to zero. In EE or JEEE runs, the electricity trading variables are left free for the model to determine. In JE or JEEE runs, there is a single GHG emissions constraint, which the model is free to allocate optimally to each province, thus in effect simulating a permit exchange system (the model also produces the marginal cost of the last tonne of GHG abatement, which is also the economic value of the one-tonne permit).

Since sales of electricity from Québec or Ontario to other regions (*e.g.*, New York state) are set exogenously, these remain unaffected whenever the model endogenously determines electricity exchanges between these two provinces. Therefore, there is no hidden cost of lost sales attached to increased interprovincial exchanges.

3. The Impact of Cooperation on GHG Abatement

We shall examine in turn the cost aspects (and in particular the savings induced by trading electricity and/or permits), and the impacts on energy supply and demand in each province.

3.1 The Dividends of Interprovincial Cooperation

What are the advantages of a joint emissions target and electricity trading on the cost of abatement in Québec and Ontario (as compared to autarchy)?

The model described above was used to perform four sets (one for each cooperation policy outlined above) of six runs each (*i.e.*, one unconstrained-emissions run, and five with cumulative GHG emissions reductions of 0%, 10%, 20%, 30%, and 40%, respectively, when measured with respect to the 1990 level of emissions). These results were used to construct the tradeoff curves shown in Figure 1, where, for each policy, the system's discounted cost is plotted against cumulative GHG reductions. In Figure 1, the vertical axis represents the added cost of each scenario, over and above that of the base case (the NC scenario without any emissions control and without cooperation). The first observation is that, under no obligation to reduce emissions, the four policies have almost identical system costs, as witnessed by the fact that each of the four tradeoff curves starts with a zero ordinate. However, the EE and JEEE policies benefit from slight emissions reductions. When reductions are imposed, system cost increases at an increasing rate, as shown by the convexity of each tradeoff curve. For all reductions targets, there is evidently significant cost savings when electricity exchanges are allowed. However, joint emissions targets have only a marginal impact on abatement costs. Electricity trading is shown to result in total discounted savings ranging from \$7 billion in the constant-emissions case to \$10 billion in the 40% reduction case, whereas in the unconstrained-emissions scenario, the savings amount to only \$0.48 bil-

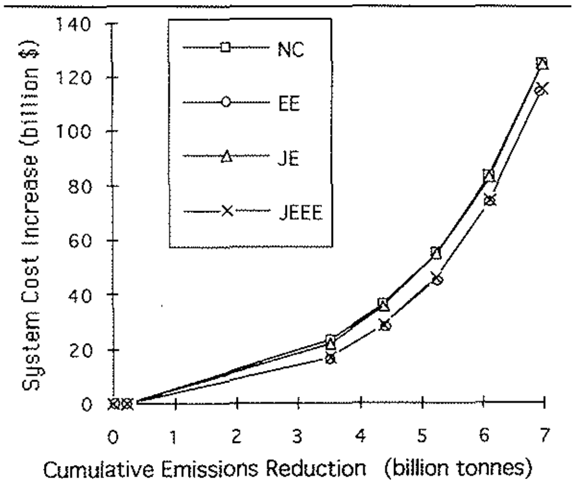

Figure 1: Cost/Emissions Reduction Tradeoff Curves

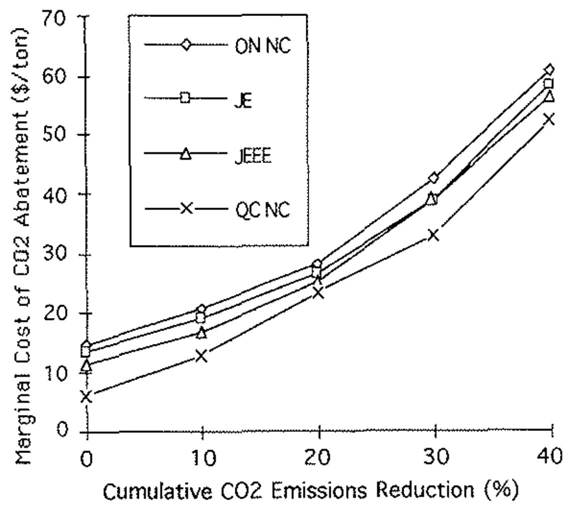

Figure 2: Marginal Cost of CO_2 Abatement

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A more subtle analysis of emissions and electricity trading is made possible by examining the behaviour of electricity exchanges on one hand, and of emissions trading on the other, across all reduction scenarios. Figure 2 shows the marginal cost of CO_2 abatement (which is the dual value of the cumulative emissions constraint) under different cooperation scenarios, and Table 2 shows the cumulative amounts (in million tonnes) of GHG permits transferred from Québec to Ontario, over the model's 45-year horizon, in scenarios JE and JEEE. From Table 2, one observes that Ontario sells permits to Québec in the JEEE scenario, whereas it buys permits from Québec under JE (in other words, Ontario either buys permits or electricity from Québec). Note that even though there is a significant difference in the marginal abatement costs in the two provinces (Figure 2), equilibrium is attained with a relatively small volume of emissions trading (Table 2). Economic theory implies that, under an efficient permit exchange system, the price of a one-tonne GHG permit should be equal to the marginal cost of abatement shown in Figure 2 (note that this article is not concerned with the question of who pays for the exchange of permits, since this is highly dependent upon the initial endowments in pollution rights of the two provinces — an ethical/political issue not modelled here).

We first analyze the JEEE case, where both

Table 2: Emissions Trading from Ontario to Québec (million tonnes, cumulative)

	Reduction				
	40	30	20	10	0%
JEEE	32.8	82.9	170.0	121.5	4.0
JE	-68.8	-107.7	-98.3	-138.5	-277.1

1/ Constant emissions

sales of GHG permits by Ontario *and* Québec's electricity sales peak for the 20% reduction target. The reason is as follows: for moderate reductions, Québec can afford to let its consumption sectors use more natural gas, thus freeing some of its hydroelectricity, which is most useful in Ontario (where the main GHG-free alternative to Québec's hydro is nuclear power, an expensive energy source with long lead times). The penetration of natural gas in Québec's residential sector explains the higher GHG emissions in that province, and hence the purchase of permits from Ontario. However, when the reduction target is more stringent (30% or 40%), Québec and Ontario *both need GHG-free electricity*, and it becomes more advantageous to use that resource close to its production site so as to avoid transmission losses and investments in transmission lines.

Turning now to the JE case, Ontario buys emissions permits from Québec so that it can shift some of its (expensive) nuclear power generation to gas-based plants. Québec implements higher GHG emissions reductions by substituting alcohol for oil in the transport sector. This explains the negative signs on the second row of Table 2.

3.2 The Impact of Cooperation on Nuclear Capacity

Ontario's nuclear power capacity increases continuously as the emissions reduction grows more and more stringent. In later periods, the installed capacity varies from 3.5 gigawatt (GW) in the unconstrained-emissions scenario, to more than 30 GW in the 40% reduction scenario. Figure 3 shows nuclear power capacity under the 40% reduction targets with the four different cooperation scenarios. It is evident that interprovincial cooperation, besides reducing the joint cost of meeting reduction targets, has the supplementary advantage of reducing the need for additional nuclear power in Ontario. Given the immediacy of the debate on this issue, we conducted 10 additional runs to answer the following questions: *how much more does it cost to implement emissions reductions without investing in nuclear power?; and what is the role of electricity trading in such a scenario?*

The results are plotted as cost/emissions reduction tradeoff curves in Figure 4. Each curve has six points (the base case plus the five reduction targets). The new results concern two new policies: a 'No New Investment in Nuclear' constraint under no cooperation (No Nuc NC); and a 'No New Nuclear' under joint emissions and electricity exchanges (No Nuc JEEE). Results for the NC and JEEE scenarios have been included for purposes of comparison.

The main observation is that a nuclear freeze under NC more than doubles the cost of meeting the 40% reduction target (a $170 billion increase over NC, in net discounted cost terms). Whereas, under JEEE, the freeze costs just about $20 billion more. Even for the more moderate reduction targets, the advantage of cooperation is very large, as shown by the distance between the No Nuc NC and the No Nuc JEEE curves in Figure 4. In these cases, the bulk of the electricity used in the two provinces is generated by hydro plants in Québec, as indicated by Figure 5. This is a

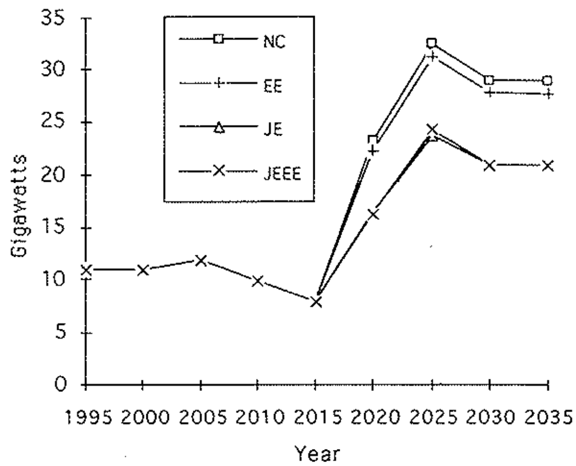

Figure 3: Nuclear Power Generation Capacity in Ontario with 40% Emissions Reduction

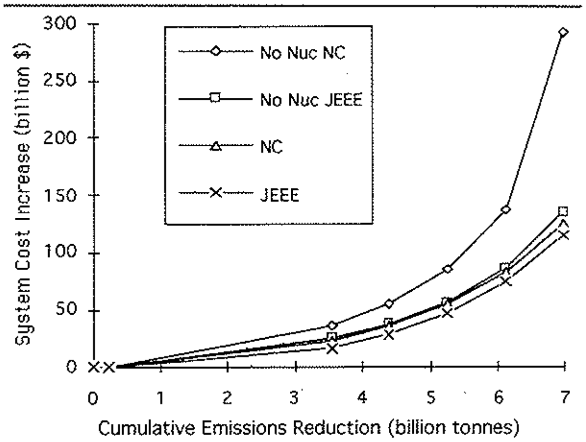

Figure 4: Cost/Emissions Reduction Tradeoff Curves (Nuclear-free Cases)

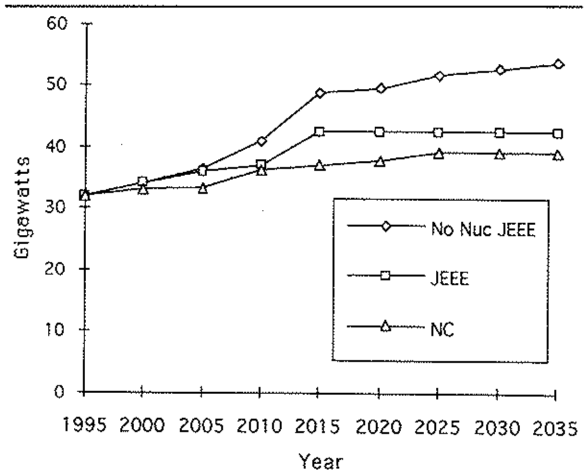

Figure 5: Hydro Capacity in Québec with 40% Emissions Reduction

major finding, since it provides an attractive alternative to nuclear in the event of the adoption of a GHG emissions target.

3.3 Other Energy/Technology Implications

Let us now focus on the energy substitutions responsible for all the results documented in the previous subsection. Broadly speaking, alcohol replaces oil in the transport sector in all reduction scenarios. Natural gas emerges as a very competitive option under mild reduction scenarios in both provinces. Under severe reductions, there is a heavy penetration of electricity in the residential and commercial heating demand segments.

Both emissions and electricity trading tend to reduce the need for expensive nuclear power in Ontario, as pointed out earlier. Emissions trading (JE) is used to increase emissions in Ontario so that some of the nuclear power can be replaced by gas-based power. Electricity exchanges (EE) directly displace generation from nuclear plants. In the JEEE scenario, on top of the additional generation in Québec, more electricity is released for export from Québec's residential and commercial sectors through gas substitution. Higher emissions reductions are implemented in Ontario by delaying gas-based electricity generation and by the increased use of renewable energy. This is why electricity and emissions exports from Québec to Ontario peak in the same scenario (*i.e.*, the one with a 20% emissions reduction).

We now turn to a more detailed analysis of the NC scenario for the two provinces, and then highlight the important impacts of the three exchange policy scenarios, namely joint emissions target (JE), electricity exchanges (EE), and joint emissions target with electricity exchanges (JEEE).

THE NO COOPERATION SCENARIO (NC)

Under NC, the two provinces implement their reduction targets in very different ways. Québec mainly uses substitutions in demand sectors, whereas in Ontario the supply sector also undergoes significant changes.

Alcohol replaces oil in the Québec transport sector and comprises over one-half of the sectoral energy consumption in later periods, under 40% emissions reduction. There is a 10-15% increase in aggregate electricity consumption on account of residential and commercial end-use demands. In commercial heating, oil is displaced by gas in the mild mitigation scenarios, and by electricity in the severe ones. Natural gas is replaced by electricity for residential heating in all reduction scenarios.

In Ontario, aggregate electricity consumption remains constant, except in the last periods under the two most severe reduction levels. However, the electricity generation sector undergoes profound changes. In the unconstrained-emissions case, electricity generation is dominated by coal-based power and there is no fresh investment in nuclear power capacity. As GHG reductions are imposed, coal-based plants disappear immediately and are replaced by natural gas plants and nuclear plants in the mild reduction scenarios. The gas-based capacity peaks at 12 GW in the constant emissions case. Nuclear capacity reaches over 30 GW in the 40% reduction scenario. On the demand side, the transport sector shows the same alcohol-oil substitution as Québec, but here alcohol supplies less than one-half the total energy demand for that sector. As additional nuclear capacity is not available in the first half of the planning horizon, there is a substitution of natural gas for electricity in residential and commercial heating demands. As a result, aggregate electricity consumption drops by 10-15%. There is also a significant penetration of wood for residential heating in the later periods.

EMISSIONS TRADING (JE)

In the emissions trading (without electricity exchanges) scenario, there is a marked reduction in nuclear power generation in Ontario. To achieve this, the emissions restriction in Ontario is relaxed by implementing a higher reduction in Québec. In the constant-emissions scenario, emissions trade amounts to 9.4% of Québec's cumulative emissions over the model's planning horizon of 45 years.

Higher reductions are achieved in Québec through substitution of alcohol for oil in the transport sector. Ontario uses the relaxed emissions target to replace nuclear power by gas-based power. In the constant-emissions scenario, generation from nuclear plants almost assumes the unconstrained-emissions trajectory (*i.e.*, no fresh investment in nuclear capacity). Aggregate electricity consumption remains unaffected in both Ontario and Québec.

ELECTRICITY EXCHANGES (EE)

When we allow electricity exchanges without emissions trading, Québec sets up additional capacity and reduces consumption to export electricity to Ontario. Ontario, in turn, reduces its nuclear power generation and increases its own electricity consumption.

Electricity production in Québec increases by up to 18% in the 20% emissions reduction scenario. Further, natural gas displaces electricity for residential and commercial heating to release 15-20% of aggregate electricity production for export. Electricity exports to Ontario reach a peak of about 300 petajoules in the later periods under 20% emissions reduction, which comprises over 40% of aggregate electricity consumption in Ontario. The substitution away from electricity in Québec results in higher emissions, which are compensated by additional substitution of alcohol for oil in the transport sector. The most important change in Ontario is the reduction in nuclear power requirements. Even under 20% emissions reduction, no fresh investments in nuclear capacity are required. Electricity consumption rises in the residential and industrial sectors, increasing overall consumption by up to 10%. This naturally gives an emissions advantage, which is offset by substituting oil for some renewables in the transport sector.

EMISSIONS TRADING WITH ELECTRICITY EXCHANGES (JEEE)

In this scenario, the effects of the EE scenario and the *reverse* of the JE scenario are superimposed. Québec maintains its electricity production at the higher levels reached in the EE scenario, and reduces its consumption even further. But instead of reducing emissions elsewhere, it transfers the burden to Ontario.

There is a further substitution of natural gas for electricity in Québec's residential and commercial sectors, thus reducing aggregate electricity consumption by another 4%. Electricity exports peak in the 20% emissions reduction scenario. The new feature over the EE scenario is that, instead of adjusting emissions through the transport sector, these are increased further because of the replacement of some alcohol by oil; the increased emissions burden is then transferred to Ontario. In this case, Ontario has a clearly defined job to do: it has to bring about higher emissions reductions than in the EE scenario, and has some additional electricity with which to do this. This is achieved by substituting renewable energy and, of course, electricity for natural gas. Penetration of gas-based power plants is delayed, alcohol is substituted for oil in the transport sector, and wood is substituted for natural gas in residential heating.

The discussion of this section is summarized in Table 3 below. In the NC column, we characterize the trends of the main energy forms as a function of the severity of the reduction target. In the EE and JE columns, we compare the energy trends to those of the NC policy. Finally, in the JEEE column, the trends are compared to those of the JE policy.

4. Conclusion

In this paper, the advanced multi-region, bottom-up model, Extended MARKAL, was used for an in-depth investigation of the responses by the Québec-Ontario energy system to a series of increasingly severe GHG reduction targets, ranging from unconstrained emissions to a cumulative 40% reduction over the next 45 years. For each target, the responses were analyzed under four cooperation policies resulting from the adoption or not of a joint emissions target and of electricity exchanges. In the full cooperation policy, the joint MARKAL model endogenizes the trading of GHG emissions permits, as well as the electricity exchanges

Table 3: Key Energy Substitutions under Different Exchange Policies

	Policy			
	No Cooperation (NC)	Joint Emissions Target (JE)	Electricity Exchanges (EE)	Joint Emissions & Electricity Exchanges (JEEE)
	behaviour when reduction target becomes more severe	*compared to NC*	*compared to NC*	*compared to JE*
Québec				
Aggregate Electricity Production	increases	no change	increases	no change
Petroleum Consumption in Transport	decreases	decreases	decreases	increases
Alcohol Consumption in Transport	increases	increases	increases	decreases
Electricity Consumption in Residential and Commercial	increases under severe reduction	no change	decreases	decreases
Natural Gas Consumption in Residential and Commercial	increases under mild reduction	no change	increases	increases
Aggregate Electricity Consumption	increases	no change	decreases	decreases
Ontario				
Generation from Nuclear Plants	increases	decreases	decreases	decreases
Generation from Gas-based Plants	increases under mild reduction	increases	decreases	decreases
Petroleum Consumption in Transport	decreases	no change	increases	decreases
Alcohol Consumption in Transport	increases	no change	decreases	increases
Electricity Consumption in Residential and Commercial	decreases in mild; increases in severe	no change	increases	increases
Natural Gas Consumption in Residential and Commercial	increases in mild; decreases in severe	no change	decreases	decreases
Wood Consumption in Residential Heating	increases	no change	decreases	increases
Aggregate Electricity Consumption	increases only under severe targets	no change	increases	increases

within the two provinces.

The most dramatic effects of cooperation were found to be: a) a marked reduction of the cost incurred to meet the desired GHG reduction; and b) a much reduced need for nuclear energy in Ontario, when a cooperative policy is adopted. Both findings suggest that cooperative responses to GHG emissions caps should be seriously considered by the two provinces. Another interesting finding is that electricity exchanges play a more important role than do permit exchanges in achieving large cost savings.

Although the paper did not discuss the precise sharing of the cooperation dividends between the two provinces, it did establish the size of the dividends to be shared. Under full cooperation, the theory of cooperative games proposes several alternative schemes for a realistic or an equitable sharing formula. One of the simplest and most appealing sharing scheme is the Shapley value (Shapley, 1953), by which, in the case of two players, the benefits of cooperation should be shared equally.

The Shapley value approach was used in similar contexts in Berger *et al.* (1990a, 1990b). Once a sharing scheme is agreed upon by the two partners, it serves as a basis for the pricing of electricity sales and of permits.

Many additional energy and technology substitutions are used by the combined Québec-Ontario system in order to achieve a least-cost solution to the imposition of GHG reduction targets. In this paper, the complex systemic responses have been explained, thanks to the detailed nature of the models used. Such system-wide effects would be impossible to capture fully via simplified aggregated modelling. In addition, the ability always to exhibit a technological rationale for the solutions arrived at by the model, constitutes a powerful additional validation of the bottom-up philosophy.

It would be quite possible to extend the present analysis to at least four Canadian provinces for which separate MARKAL models do exist (*i.e.*, Alberta and Saskatchewan, in addition to Québec and Ontario). Of course, extensions to several countries is also possible, and is indeed being undertaken by the ETSAP group of MARKAL modellers, in particular by Bahn *et al.* (1994).

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