GHG Abatement in Central Canada with Inter-provincial Cooperation[*]

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Abstract

This paper reports the use of an advanced Multi-region Bottom-up model, the Extended MARKAL, for an in-depth investigation of the responses by the Québec-Ontario energy system to a series of increasingly severe Greenhouse gas emission reduction targets. For each target, the responses are analyzed under four policies resulting from the adoption or not of a joint emission 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 emission caps should be seriously considered by the two provinces. The explanation of complex systemic responses underscores the advantages of using detailed bottom-up models. Results are highly credible and of immediate relevance to the policy makers. The present analysis can be readily extended to at least four Canadian provinces for which separate MARKAL models already exist (i.e. Alberta and Saskatchewan, in addition to Québec and Ontario).

Résumé

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 inter-provinciale future si des quotas d’émission de GES étaient imposés. L’utilisation d’un modèle avancé de modélisation permet aussi l’analyse fine des interactions systémiques complexes résultant des contraintes de GES. Les résultats en acquièrent une plus grande fiabilité, ainsi qu’une plus grande pertinence pour les décideurs. Cette analyse pourrait être directement généralisée à quatre provinces canadiennes pour lesquelles des modèles MARKAL existent déjà (Alberta et Saskatchewan, en plus des deux provinces faisant l’objet de cette étude).

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 GHG emission targets on its own political agenda, consisting of a return to 1990 emission levels by year 2000, and a subsequent 20% reduction of Canadian GHG emissions by 2010. Whereas it appears that the 2000 Canadian emission 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 largest 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 inter-provincial 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 emission 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 5 alternative targets, viz. 0%, 10%, 20%, 30%, and 40% cumulative emission reduction compared to the 1990 level. In addition, a base case scenario with no emission cap is also included in the analysis. Each reduction scenario is run four times, each run assuming a combination of the following choices: with/without electricity exchanges between the two provinces, and with/without emission 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 emission 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 utilized

We have developed over the years, two MARKAL activity analysis models of the energy/industrial systems of the Québec and Ontario provinces. The most recent versions of these models possess 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 production, conversion, distribution, and end-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 time period. The model covers 9 periods of 5 years each, and hence a 45 year horizon. The nine periods are centered at years 1995 to 2035, so that the actual horizon covered is from 1993 to 2037, inclusive.

The model's *engine* is Linear Programming, which, by minimizing total discounted system cost, in effect computes a partial equilibrium on energy markets. The demands for a large number of sectors and sub-sectors are specified by scenario in the base case. MARKAL determines the values of all future investments and operations levels of the technologies at each time period, while respecting demands, emission caps, and a very detailed set of technical and logical constraints. In addition to technological and energy substitutions, MARKAL may also choose to adjust demand levels endogenously, thanks to a set of own price elasticities. For example, when emission 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 to reduce some demand levels according to the demand curve. 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.

The two models' databases have undergone in-depth revisions during the last two years. In the process, the set of greenhouse gases modeled 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 modeled. The technology sets are carefully designed to include all major existing and new technologies, with a 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 of the two models, we give in **Table 1** below 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 indicate 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 individual houses). A detailed listing of technology and energy carrier names would be too space consuming for inclusion here; however a copy of the data base is available upon request.

Table 1 Energy carriers, technologies, and demand segments in MARKAL models

			MARKAL-Québec	MARKAL-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
	Total		**517**	**590**
END-USE DEMAND SEGMENTS				
		Residential	13	13
		Commercial	14	11
		Transportation	12	12
		Industry	26	7
		Non-energy uses	4	6
		Total	**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 afterwards. The economic growth assumptions are close to those assumed in Natural Resources Canada (1992), 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 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 endogenously determined and are equal to the shadow prices of these energy forms in the model. Finally, the real discount rate used in the model is 5% per year. All cost figures discussed in this article are expressed in constant 1990 Canadian dollars.

As already mentioned, we adopted six alternative emission 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, as follows:

NC	No Cooperation, i.e., no electricity trading, no GHG permit trading
EE	Electricity exchanges are allowed, but not GHG permit trading
JE	GHG permit trading is allowed, but not electricity exchanges
JEEE	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 are merged into a larger size model. The number of models is limited only by the solver capacity. Special variables are defined to represent the amounts of investments in electricity transport lines, and the amounts of electricity traded at each period between each pair of models. The model size increases to about 23,000 rows and 40,000 columns, but 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 run listed above: in the No exchange run, each province has its own GHG emission constraint, and all electricity exchange variables are set to zero. In a EE or JEEE run, the electricity trading variables are left free for the model to determine. In a JE or JEEE run, there is a single GHG emission 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 permit of one tonne).

It should be added here that whenever the model endogenously determines electricity exchanges between the two provinces, this does not affect the sales of electricity from Quebec or Ontario to other regions (e.g. New-York State), which remain at the exogenously set level. 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 Inter-Provincial Cooperation

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

The model described above was used to perform four sets of runs, each comprising 6 runs, i.e. one free emission run, and five with cumulative GHG emission reductions of 0%, 10%, 20%, 30%, and 40%, respectively, with respect to the 1990 emission levels. The four sets were: no cooperation (NC), joint emission target (JE), electricity exchanges (EE), and joint emission target with electricity exchange (JEEE). These results were used to construct the trade-off curves shown in **Figure 1**, where, for each policy, the system's discounted cost is plotted against cumulative GHG reduction. In figure 1, the vertical axis represents the added cost of each scenario, over and above that of the base case (i.e. the NC scenario without any emission control, and without cooperation). The first observation is that, under no obligation to reduce emissions, the four policies have 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 emission reductions. When reductions are imposed, system cost increases with increasing slope, as shown by the convexity of each trade-off curve. For all reduction targets, there is evidently significant cost savings when electricity exchanges are allowed. However, joint emission targets have only a marginal impact on the abatement costs. Electricity trading is shown to result in total discounted savings ranging from $7 billion in the constant emission case to $10 billion in the 40% reduction case, whereas under the free carbon scenario, the savings amount to only $0.48 billion.

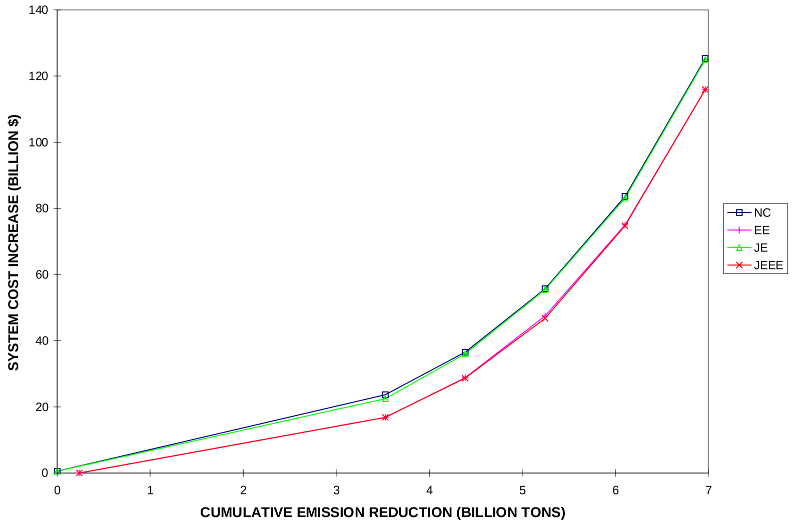

Figure 1 Cost-Emission Reduction Trade-off Curves

A more subtle analysis of emission and electricity trading is made possible by examining the behaviour of electricity exchanges on one hand, and of emission trading on the other hand, across all reduction scenarios. **Figure 2** shows the marginal cost of CO_2 abatement (which is the dual value of the cumulative emission constraint), under different policy scenarios, and **Table 2** shows the cumulative amounts (in million tonnes) of GHG permits transferred from Quebec to Ontario over the 45 year horizon, in scenarios JE and JEEE. From table 2, one observes that Ontario sells permits to Quebec under the JEEE scenario whereas it buys permits from Quebec under JE (in other words, Ontario either buys permits or electricity from Quebec). Note that although there is a significant difference in the marginal abatement costs in the two provinces (figure 2), equilibrium is attained with a relatively small trading of emissions (table 2. Economic theory implies that, under an efficient permit exchange system, the price of one tonne of GHG permit should be equal to the marginal cost of abatement shown in figure 2 (however, 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 the sales of GHG permits by Ontario to Québec *and* Québec's electricity sales peak for the 20% 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 source with long lead time). The penetration of natural gas in Québec's residential sector explains the higher GHG emissions in that province and hence the purchasing 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 emission permits from Québec so that it can shift some of the (expensive) nuclear power generation to gas based plants. Québec implements higher reductions by substituting oil with alcohol in the transport sector. This explains the negative signs on the second row of **Table 2**.

Table 2 Emission Trading from Ontario to Québec

Scenario	40% Red	30% Red	20% Red	10% Red	Const Em
JEEE	32.80	82.95	170.00	121.50	4.05
JE	-68.80	-107.70	-98.30	-138.55	-277.10

Cumulative Million Tons

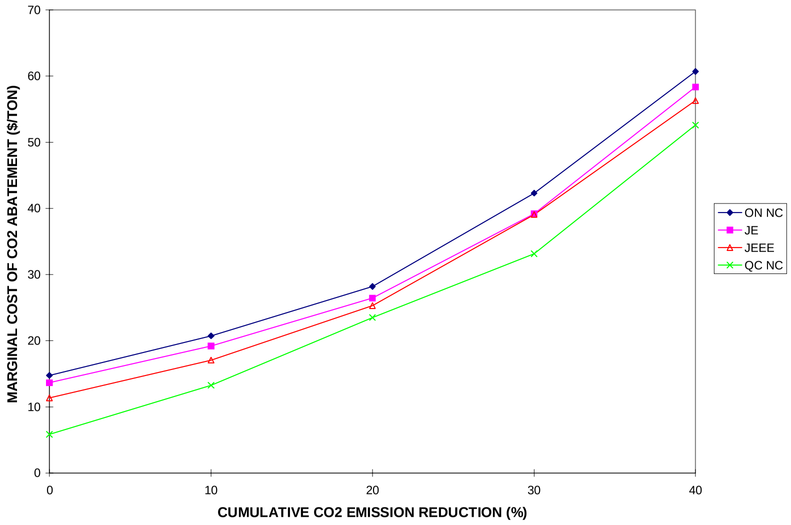

Figure 2 Marginal Cost of CO_2 Abatement

3.2. The Impact of Cooperation on Nuclear Capacity

The nuclear power capacity increases continuously in Ontario as the emission reduction grows more and more stringent. In later periods, the installed capacity varies from 3.5 GW under the free carbon scenario to more than 30 GW under the 40% reduction scenario. **Figure 3** shows the nuclear power capacity under the 40% reduction targets with the four different collaboration policy scenarios. It is evident that inter-provincial 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 currency of the debate on this issue, we conducted 10 additional runs to answer the following question: *how much more does it cost to implement emission reductions without investing in nuclear power, and what is the role of electricity trading in such a scenario?*

The results are plotted as Cost/Reduction trade-off curves in **Figure 4**. Each curve has six points (the base case plus the five reduction targets). The new results concern two new policies: 'No New Investment in Nuclear' constraint under No Cooperation (No Nuc NC); and 'No New Nuclear' under Joint Emission and Electricity Exchange policy (No Nuc JEEE). The scenarios NC and JEEE have been included for comparison.

The main observation is that a nuclear freeze under NC policy 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**. The bulk of the electricity is now generated by the hydro plants in Québec, as indicated by **Figure 5**. This is a major finding, as it provides an attractive alternative to nuclear in the event of the adoption of a GHG emission target.

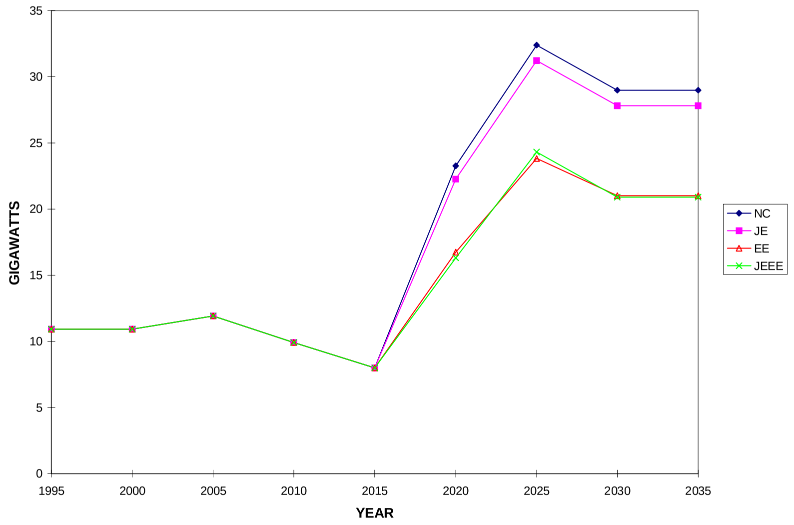

Figure 3 Nuclear Power Generation Capacity in Ontario Under 40% Reduction

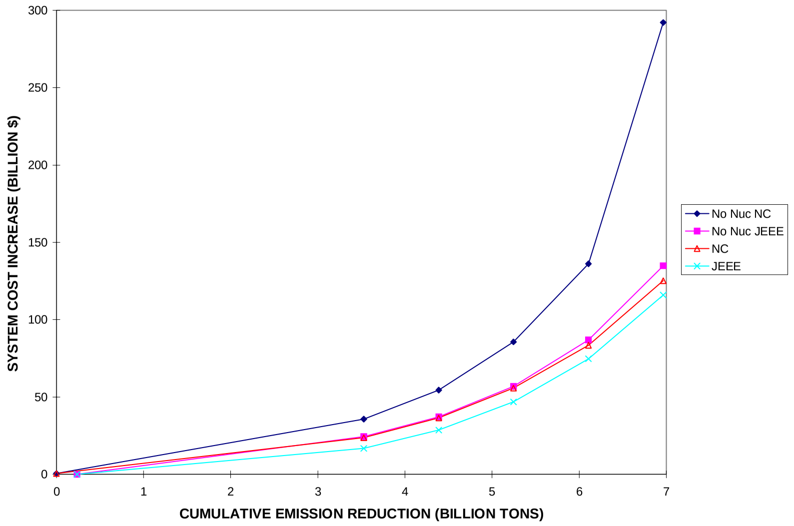

Figure 4 Cost-Emission Reduction Trade-off Curves (Nuclear-Free Case)

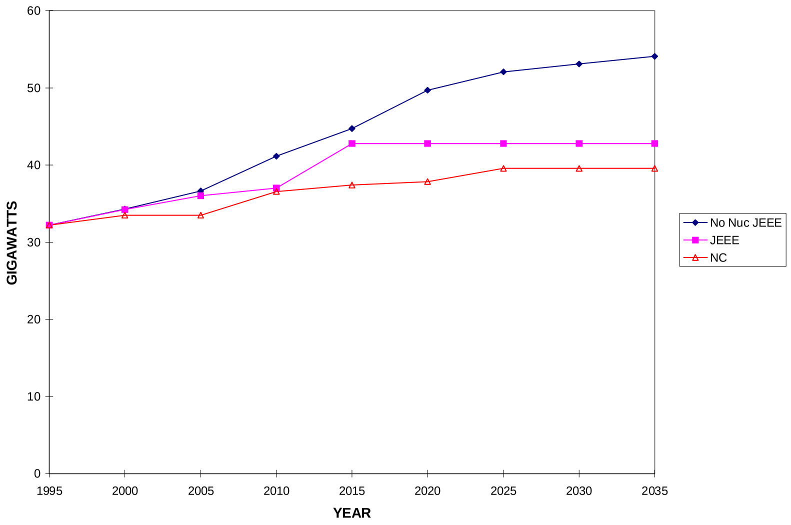

Figure 5: Hydro Capacity in Québec under 40% Reduction

3.3. Other Energy/Technology Implications

Let us now focus on the energy substitutions responsible for all that we observed in the last section. Broadly speaking, alcohol replaces oil in the transport sector under 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 emission and electricity trading tend to reduce the expensive nuclear power in Ontario, as was already discussed. Emission trading (JE) is used to increase the emission in Ontario so that some of the nuclear power can be substituted by gas based power. Electricity exchanges (EE) directly substitute the generation from nuclear plants. Under the JEEE scenario, besides the additional generation in Québec, more electricity is released for export from the Québec's residential and commercial sectors through gas substitution. Higher emission reduction is implemented in Ontario by delaying gas based electricity generation and by additional renewable energy. This is why electricity and emission exports from Québec to Ontario peak in the same scenario, i.e. the one with 20% reduction.

First we analyze the No Cooperation scenario for the two provinces, and then highlight the important impacts of the three exchange policy scenarios, namely, Joint Emission Targets, Electricity Exchange, and Electricity Exchange with Joint Emission Targets.

The No Cooperation Scenario (NC)

Under the NC policy, the two provinces implement their reduction targets in very different ways. Québec uses, mainly, the 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 half the sectoral energy consumption in later periods, under 40% reduction. There is a 10-15% increase in the aggregate electricity consumption on account of the residential and commercial end-use demands. In commercial heating, oil is substituted by gas in the mild mitigation scenarios, and by electricity in the severe ones. Gas is substituted by electricity for residential heating under all reduction scenarios.

In Ontario, the 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 Ontario. In the free carbon case, it is dominated by coal based power and there is no fresh investment in nuclear power. As carbon reduction is imposed, coal based plants disappear immediately and are replaced by gas plants and nuclear plants in the mild reduction scenarios. The gas based capacity peaks at 12 GW under the Constant Emission. Nuclear capacity reaches over 30 GW under the 40% reduction scenario. On the demand side, the transport sector shows the same alcohol-oil substitution of Québec, but alcohol supplies less than half the total energy for the transport sector. As additional nuclear capacity is not available in the first half of the planning horizon, there is a substitution of electricity with natural gas in the residential and commercial heating demands. This way, the aggregate electricity consumption reduces by 10-15%. There is a significant penetration of wood for residential heating in the later periods.

Emission Trading (JE)

Under the Emission Trading scenario without electricity exchanges, there is a distinct reduction in nuclear power generation in Ontario. To achieve this, the emission restriction in Ontario is relaxed by implementing a higher reduction in Québec. Under the Constant Emission scenario, the emission trade amounts to 9.4% of Québec's cumulative emission over the planning horizon of 45 years.

Higher reduction is achieved in Québec through substitution of oil with alcohol in the transport sector. Ontario uses the relaxed emission target to substitute nuclear power with gas based power. Under the Constant Emission scenario, generation from nuclear plants almost assumes the free carbon trajectory, i.e., no fresh investment. The aggregate electricity consumption remains unaffected in both Ontario and Québec.

Electricity Exchange (EE)

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

The electricity production in Québec increases by up to 18% under the 20% reduction scenario. Further, natural gas substitutes electricity for residential and commercial heating to release 15-20% of the aggregate electricity consumption for export. Electricity export to Ontario reaches a high of about 300 petajoules in the later periods under 20% reduction, which comprises over 40% of the aggregate electricity consumption in Ontario. The electricity substitution in Québec results in higher emissions, which are compensated by additional substitution of oil with alcohol in the transport sector. Most important change in Ontario is reduction in nuclear power requirement. Even under 20% reduction, it requires no fresh investments. Electricity consumption increases in the residential and industrial sectors, increasing the overall consumption by up to 10%. This naturally gives an emission advantage, which is used by substituting some renewables with oil in the transport sector.

Emission Trading with Electricity Exchange (JEEE)

Under this scenario, the effects of the EE scenario and *reverse* of the JE scenario are superimposed. Québec maintains its electricity production at the increased level of 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 electricity with natural gas in the Québec residential and commercial sectors, reducing the aggregate electricity consumption by another 4%. The electricity exports peak under the 20% reduction scenario. The new feature over the EE scenario is that instead of adjusting the emissions through the transport sector, it increases them further by replacing some alcohol back with oil, and transfers the emission burden to Ontario. Ontario has a clearly defined job to do now: it has to bring about a higher emission reduction than that in the EE scenario, and it has some additional electricity to do this. This is achieved by substituting natural gas with renewable energy and, of course, electricity. Penetration of gas based power plants is delayed, oil is substituted with alcohol in transport sector, and gas is substituted with wood for 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 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 EE policy.

Table 3 Key Energy Substitutions Under Different Exchange Policies

IMPACTS	POLICY			
	No Cooperation *behaviour when reduction target becomes more severe*	**Joint Emission Target** *compared to NC*	**Electricity Exchange** *compared to NC*	**Joint Emission and ELC Exch.** *compared to EE*
Québec				
Aggregate Electricity Production	increases	no change	increases	no change
Petroleum oil 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 oil 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

4. Conclusion

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

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) the much reduced need for nuclear energy in Ontario, when a cooperative policy is adopted. Both findings suggest that cooperative responses to GHG emission caps should be seriously considered by the two provinces. Another interesting finding is that the electricity exchanges play a more important role than 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 alternate 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 benefit of cooperation should be shared equally. The Shapley Value approach was used in similar contexts in (Berger et al. 1990a, and 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 systems effects would be impossible to capture fully via simplified aggregated modelling. In addition, the ability to always 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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