Sustainable Greenhouse Gas Abatement: The Case of Québec

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The technology-based MARKALED model is used to simulate several greenhouse gas (GHG) abatement scenarios for the Province of Québec, under a common set of economic assumptions. The six scenarios are selected in order either to investigate much publicized reduction targets, or to explore GHG taxes proposed by other researchers working with global models. The results of the analyses are discussed in some detail, and the role of supply options such as biofuels, hydro, and wind electricity is compared with the role of end-use conservation and technological change, such as electric or hybrid automobiles, biofuel conversion of vehicles, and modification of the fuel mix for heating.

Le modèle fondé sur la technologie MARKALED sert à simuler des scénarios de fortes réductions des émissions de gaz à effet de serre, destinés à la province du Québec, dans le cadre d'un ensemble commun de suppositions économiques. Le choix des six scénarios a pour objectif soit d'examiner des cibles de réduction qui ont fait l'objet d'une forte publicité, soit d'analyser les taxes imposées sur les gaz à effet de serre qu'ont proposées d'autres chercheurs qui travaillent sur des modèles mondiaux. Les résultats des différentes analyses font l'objet d'une discussion détaillée et le rôle des options d'approvisionnement, comme par exemple les carburants biologiques ou l'électricité hydraulique ou éolienne, est comparé au rôle des économies réalisées dans l'utilisation finale ainsi qu'au rôle des changements technologiques impliqués, tels que les automobiles électriques ou hybrides, la conversion des automobiles aux biocarburants et la modification du mélange de carburants pour le chauffage.

1. Introduction

Since the Rio de Janeiro Conference of 1992, Canada, along with many other countries, has been engaged in a course to curb greenhouse gas (GHG) emissions, where specific target emission reductions have been set for the early years of the 21st century. Inside Canada, a tacit policy of similarly curbing GHG emissions within each province seems to be in place. In this research, we examine local abatement targets within the global context of worldwide GHG control, with the objective of establishing the feasibility, cost, and technological implications of various possible abatement objectives for the Province of Québec. Because the greenhouse effect is a global phenomenon, it is essential for any country, state or province, to adopt abatement targets which are at least approximately in harmony with an efficient worldwide effort to provide a globally desirable response to climate change, at the level of the planet. If this were not the case, local abatement policies would be inefficient (*i.e.*, either insufficient or too stringent), and thus wasteful. Although our results are obtained for Québec, we believe that they are representative of results that would be obtained in similarly endowed developed regions of the world. At any rate, it is our belief that each country must "do its homework" of computing its own efficient responses to alternative abatement targets, before an overall clear picture will emerge for the whole world. Before describing our modelling approach and results, we provide an initial justification of the abatement scenarios which will be adopted, by relating the Québec scenarios to the global question of worldwide GHG reduction.

1.1 The Global Greenhouse Problem

Conceptually, the greenhouse effect must be examined through its two types of impact: the impacts of global warming, and the impacts of preventing such warming from taking place (*i.e.*, the impacts of GHG mitigation). The two sets of impacts differ greatly by their nature, as well as by the time and places at which they are likely to occur, thus making global analysis that much more difficult. To illustrate this, consider that GHG emissions are currently much more abundant in developed countries, and therefore their reduction should, at least in a first phase, be concentrated in these countries. On the other hand, much evidence points out that future damages due to global warming would be more severe in developing countries (if only because their economies are much more dependent on agriculture, and a larger fraction of sea-level lands are heavily populated, making them vulnerable to flooding). The picture is made even more complex by the fact that many developing countries have high rates of economic growth, which will soon put them in the club of large GHG producers, if no abatement policies are implemented there. We have here all the elements of a difficult economic and political international problem, which involves efficiency as well as equity issues.

Regarding efficiency, one may ask: (i) what is the socially optimal degree of control of GHG emissions for the planet?; and (ii) given the answer to the first question, what abatement measures should be implemented (as well as when and where), so as to achieve the desirable global target at least cost?

Regarding equity, it is essential to realize that even if a globally efficient mitigation plan is established, it will involve widely disparate abatement measures as well as climate change impacts in different regions of the world. The equity question then amounts to arriving at a fair sharing of the total costs between nations of the world.

Hence, before setting meaningful targets for Canada and Québec, one must know the level of an efficient worldwide target. Since 1991, several studies have attempted to quantify the need for global GHG abatement, taking into account both the cost of abatement and the cost of damages, and attempting to strike an optimal compromise between the two, at the world level. Nordhaus (1991, 1993, 1994) was the first to propose a quantitative model, later known as DICE, which included the complete chain of subsystems from emissions to concentration change, to climate change, to damages. Although simplified, his model was a first step in the direction of quantifying tradeoffs between the two main economic aspects of global warming, namely the abatement and the damage sides of the phenomenon. Manne and Richels (1992) proposed the multi-region GLOBAL 2100 model of the same kind, which explicitly recognized the differences between developed and less developed nations, and introduced additional modelling detail in the energy part of the system. Manne, Mendelssohn, and Richels (1995) refined and extended the approach by extending the horizon to 2200 and introducing uncertainty, leading to the MERGE 2 multi-regional GHG model of the world. Along similar philosophical lines, Peck and Teisberg (1992, 1995) first developed the CETA model, and later the CETA-R model, which includes uncertainty. Edmonds *et al.*'s model (1994) divides the world into 20 regions, and includes more detail on the feedback from climate change onto land use and agriculture.

Most of these models can be used in several different ways: for instance, one may impose specific *concentration targets* for GHGs at various dates, and force the model to adapt to these. In this way, two targets have become somewhat famous: global stabilization of concentration at the pre-industrial level of 275 parts per million (ppm) (sometimes called the

1X target); and global stabilization at twice the pre-industrial concentration level (550 ppm, or the *2X target*). Current CO_2 concentration is about 370 ppm. Also in the same vein, one may impose *global stabilization of emissions* at certain specified levels, for instance at 1990 level, or at 80% of that level, *etc.*

Contrary to concentration targets, which are only meaningful at the global level, emission targets may be imposed globally, or regionally (for countries, states, or provinces). We will call the above class of approaches, the *constraint* or *threshold* approach. Another, more ambitious way to use these global models is to explicitly include in them a damage cost function, and to then minimize the overall societal cost (abatement plus damage costs), thus obtaining a theoretically optimal tradeoff between the two types of cost. This latter approach is often called the *cost-benefit* method, and is accepted by many researchers, but rejected, sometimes vehemently, by others (*e.g.*, Meyer and Cooper, 1995) who argue that much of the damage cost is too intangible and uncertain to be quantified, and that, consequently, stringent concentration targets should be set and respected, so as to avoid the risk of unforeseen future catastrophic events related to climate change. This second group of authors invokes the *precautionary principle* included in section 3.3 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) to support their approach. The current state of the debate within the Intergovernmental Panel on Climate Change (IPCC) Workgroup III reflects these two different views, and their reports (IPCC, 1996) present a comprehensive review of work in this domain. Whether one subscribes to the constraint or to the cost-benefit view of the world, it is essential to recognize that costs vary widely across countries and regions of the world, and therefore that a globally efficient abatement strategy will in all likelihood be *geographically differentiated*.

Such efficiency considerations should not be confused with equity issues, whereby some kind of fair sharing of the climate change burden must be arrived at. In other words, it may well be that certain abatement actions should happen in a group A of countries (for efficiency reasons), but that their cost should be borne, at least in some proportion, by a group B of countries (for equity reasons). The separation of efficiency and equity issues is essentially correct (Manne and Richels, 1995), and simplifies the analysis of the overall GHG problem, but this is not to say that it would be easily implementable in the real world. However, the confusion of these two issues will inevitably lead to grave misunderstandings, and to inefficient national and international policies. In this research, equity issues are not really discussed, and therefore, any recommendations regarding the amount of abatement to be implemented in any particular country or province, do not imply that their cost should or should not be borne by the same entity.

In this article, we aim at exploring various GHG abatement policies for the Province of Québec, while keeping them in perspective with the global climate change question. To do so, we will simulate a number of policies, some of which are based on global analyses similar to those in the preceding discussion, while others are based on more arbitrary, but nevertheless much debated considerations. Section 2 describes our methodology, including the model used and the abatement scenarios considered, while section 3 presents numerical results and analysis, and section 4 concludes the article.

2. Methodology

2.1 Modelling Framework

In this research, the Québec energy system is modelled by MARKALED-Québec (Loulou and Lavigne, 1996), a recent modification of the MARKAL model (Fishbone and Abilock, 1981; Berger *et al.*, 1992). MARKAL (the name stands for *mark*et *al*location) is a large-scale technology-oriented activity analysis model, integrating the supply and end-use sectors of an economy, with emphasis on the description of energy-related subsectors. The model has nine time periods of five years each, covering the 45-year span from 1993 to 2037, and defines three variables for each technology represented (*i.e.*, investment, capacity, and level of activity), at each time period (at period 1, the actual installed capacities of all technologies are imposed, thus calibrating MARKAL to the real system being modelled). MARKAL computes a dynamic, partial equilibrium on energy markets by minimizing a single objective function, which is the total system's discounted cost (the equilibrium is partial rather than general, since MARKAL does not include links with other macroeconomic variables, such as national savings, consumption, *etc.*). The system's representation of costs includes investment and fixed annual costs for all technologies, plus procurement costs for all imported fuels, minus the revenue from exported fuels, minus the salvage value of all residual technologies at the end of the horizon. The model satisfies all important constraints of an energy system, such as flow conservations, satisfaction of demands, conservation of investments, peak-electricity constraints, capacity limits, and many others. In addition, MARKAL allows the optional accounting and/or constraining of emissions of pollutants from all technologies present in the model, by means of emission coefficients and of special constraints (alternatively, one may impose emission taxes rather than constraints). In order to respect all of these constraints simultaneously and to minimize system cost, MARKAL uses optimization, namely linear programming.

MARKALED (the ED suffix stands for *e*lastic *d*emands) differs from MARKAL in the specification of demands: whereas MARKAL is driven by exogenous demands for energy services, MARKALED allows the specification of own-price elasticities for all energy services, and therefore will adjust demands in response to particular scenarios. MARKALED minimizes total welfare losses, consisting of: (i) system cost; plus (ii) the loss of welfare associated with decreased demand levels (see Loulou and Lavigne (1996) and Loulou *et al.* (1997) for additional discussion on the economic interpretation of the model). MARKAL–ED is thus a *bona fide* partial equilibrium model, whose response to GHG restrictions includes both technological adaptation and endogenous demand adjustments. It has been experimentally verified that such an approach captures almost entirely the feedback effects of general equilibrium models such as ETA-MACRO or MARKAL-MACRO (see Loulou and Lavigne, 1996).

The data base for the model includes more than 500 technologies, approximately 70 energy forms (fuels + heat + electricity), and 69 categories of energy services, with particular detail in the energy-intensive sectors. For instance, electricity generation has more than 30 distinct technologies, oil refining includes some two dozen processes and 13 final products. On the demand side, there are 13 residential demand categories, serviced by about 100 technologies; there are 14 commercial and institutional demand segments, also serviced by some 100 technologies; 30 industrial demand segments, with more than 100 technologies; and in transport, there are 12 segments, and about 70 technologies (vehicles). In most demand segments, special technologies are representing specific energy conservation measures, such as efficient devices, insulations, *etc*. Full details on the model and data base are available upon demand. Several previous applications of the MARKAL model in Québec and Ontario appear in previous publications (Berger *et al.*, 1990, 1991, 1993, 1994; Loulou and Waaub, 1992), which stress specific model features and results.

MARKAL is particularly well adapted to compute the responses of energy systems to constraints on emissions (or to emission taxes). This is so because the linear programming nature of the model allows the easy inclusion of any number of additional constraints, including emission caps. This is a real advantage of this class of models, which is not emulated by simulation or econometric models. Furthermore, the cost-minimizing feature of MARKAL ensures that the system response to emission caps or taxes is optimally allocated to the globally efficient abatement measures.

2.2 Abatement Scenarios for Québec

We will explore six abatement scenarios in this research, one of which is a base scenario with no planned abatement, three of which rely on specific emission targets, and the remaining two are based on taxation of GHG emissions.

We first describe the scenarios based on emission caps: since the objectives of stabilized GHG emissions at 1990 level and of a 20% reduction by 2010 have both been much publicized, we will include them in our analysis. In addition, we examine a variation of the 20% reduction.

- *Base Scenario*: no imposed reduction on GHG emissions;
- *Stable Emissions Scenario*: GHG emissions remain constant at their 1990 level, starting in 2000;
- 20% Reduction Scenario: GHG emissions are reduced by 10% in 2000 and by 20% in 2005 and later; and
- *Cumulative 20% Reduction Scenario*: total GHG emissions (over the entire period 1993 to 2037) are the same as in the previous scenario, but they may be allocated freely to various years.

We now turn to the tax-based scenarios. The discussion of Section 1 emphatically pleads for policies which attain some degree of global efficiency, and this objective is best achieved via GHG taxes that are the same throughout the world. Hence, two of our abatement scenarios rely on taxes. The problem with emission targets set at the national (or provincial) level is the absence of studies establishing the adequacy of these targets, making it unclear whether they are set at the right (efficient) level. A correct approach would first to establish a globally desirable world target, and then to allocate the GHG reductions to each region, country, *etc.* for instance by means of an efficient tax on GHG emissions (*i.e.*, the theoretical tax that, if imposed on the global model, would induce the latter to meet the target). The great advantage of computing such a tax is that it allows each local model to operate independently[1] from the global model: it suffices to impose the same (efficient) tax per tonne of GHG emission to any local model in order to ensure that it will implement only the amount of abatement that is globally efficient. Currently, different authors propose very different "efficient" tax levels, due to model differences, and to variations in model parameters such as discount rate, and cost of damages. As examples of recently proposed efficient tax levels, let us mention the following (all taxes are in 1995 Canadian dollars per tonne of CO_2-equivalent)[2]: Nordhaus (1991, 1994) arrives at an optimal shadow price of emissions varying from \$2/tonne of CO_2 in 1995, to about \$7/tonne in 2100. Fankhauser (1994) computes a flatter trajectory for the shadow prices from \$6 to \$9/tonne of CO_2 at the same dates. Much higher tax levels are required to implement the 1X target, but are not published, since there is no uniformly accepted date at which to return to the 275 ppm concentration. In Edmonds (1993) the per-tonne tax needed to respect the 2X target is computed at about \$3.5 in 1995, rising to \$47 by year 2035. Still higher is the tax proposed by Cline (1992) who used a zero discount rate for the utility. Cline's tax starts at \$13/tonne of CO_2 in 2000, growing to \$90 in 2100. Other authors object to the 2X target, which is judged too optimistic in view of the magnitude of damages, see for instance Meyer and Cooper (1995). More recent, unpublished results seem to require higher tax rates to achieve similar targets.

We adopt two alternative tax levels in this study:

- *Reference Tax Scenario*: the tax starts at \$25/tonne CO_2-equivalent in 2000, and grows to \$157 in 2035. It is therefore comparable to Cline's tax, although rising faster at the end of the horizon.
- *Global Tax Scenario*: We also try a much higher tax equal to four times the reference tax, representing a very high degree of abatement. We call it the Global Tax, and its

1/ Actually, local models are never quite independent, due to the existence of trading between countries/regions. What is meant is that the local models are decoupled with respect to the GHG emission controls.

2/ Some authors use tonnes of carbon rather than tonnes of CO_2. The conversion is made as follows: 1 tonne of carbon = 3.67 tonnes of CO_2. Therefore, a tax of \$x per tonne of CO_2 is equivalent to a tax 3.67 times higher when expressed in \$ per tonne of carbon.

role is to test the ability of the Québec energy system to "accept" such a high GHG reduction effort.

Table 1 summarizes the six emission scenarios (note that the actual emissions in the base scenario are not known *a priori*, and will be computed by the model). Note also that the base scenario is not a business-as-usual one, since the model optimizes the energy system, even in the absence of any GHG restrictions. The base scenario thus includes many so-called "no regret" abatement decisions.

In all runs, we have also assumed fixed reduction targets for other atmospheric emissions: NO_X is limited to its 1985 emissions level, and SO_2 is limited to 50% of its 1985 emissions level. These limits fairly well represent the objectives set by Canadian governments, and actually quite well followed up to now.

2.3 Economic Assumptions

The economic demand profiles used assume low growth from heavy industries, and medium growth in light industries, transportation, residential, and commercial sectors. Demands in heavy industries such as aluminum or steel production grow on average by less than 0.5% per year (all demand growth rates discussed here are in the physical units appropriate to each segment, and *not* in monetary units), and some others such as copper production stagnate over the horizon. Demand from the cement industry maintains an average yearly growth of 0.7%. Light industrial demands grow on average at an annual rate of 1.7%. Commercial sector demands grow on average at the same rate of 1.7% per year, whereas residential space heating demand has a growth rate of 0.6% per year, reflecting average-to-low population growth. In the transportation sector, demand for air travel purposes grows at an average rate of 0.9% per year, whereas demands in road transport grow at only 0.7%. All demands grow faster during the initial 20 years, and then slow down markedly. The assumed average GDP growth rate is 2% yearly from 1993 to 2012, and about 1% per year thereafter (both rates in real terms).

The own-price elasticities of demands were estimated using results of a study for Central and Eastern Canada (Bernard and Genest-Laplante, 1995), adjusted to reflect the elasticities of energy services, rather than those of final energy consumptions. Long-term price elasticities were used from period 2 to 9, whereas half of these long-term elasticities were used for period 1. For most of the 69 demand segments, the long-term price elasticities of demands were thus taken to be -0.30 (and -0.15 for period 1), with several exceptions: residential and commercial demands for freezers, refrigerators, ventilation, and motors were assumed to have zero elasticity, as well as ship transportation demand.

Regarding costs, prices and taxes, the model uses only constant, 1995 Canadian dollars, and otherwise ignores inflation. Imported energy prices are assumed to grow moderately from 1993 to 2012, and then to stagnate for the remaining 25 years of the horizon. The average rates of price increases from 1993 to 2012 are: 2.8% for crude oil, 3.3% for natural gas (from Western Canada), and 0.2% for coal (from the United States), all in real terms. Finally, the model uses a 6.5% real discount rate.

3. Results

3.1 Cost and Emission Levels

Table 2 indicates in compact form the total cumulative emissions and the total discounted costs of the six scenarios. The costs are expressed in 1995 Canadian dollars, and are reported relative to that of the base scenario: in the first column are the technology and fuel costs; in the second column, the welfare loss due to demand reductions; and in the third, the sum of these two (*i.e.*, the *total* loss of welfare). All costs exclude the related tax proceeds, if any. The detailed emission trajectories are shown in Figure 1.

The base scenario represents a fairly moderate 14% increase of cumulative emissions relative to the 1990 level (*i.e.*, relative to the stable scenario), whereas the next three scenarios have virtually the same cumulative emissions. For example, the reference tax achieves

Table 1: Four GHG Emission Targets and Two GHG Tax Scenarios for Québec (targets are in million tonnes CO_2-equivalent per year; taxes are in 1995 $Cdn/tonne of CO_2-equivalent)

	2000	2005	2010	2015	2020	2025	2030	2035
Target-based Scenarios								
Stable Emissions	61.73	61.73	61.73	61.73	61.73	61.73	61.73	61.73
20% Reduction	55.56	49.38	49.38	49.38	49.38	49.38	49.38	49.38
Cum. 20% Reduction				See Note				
Tax-based Scenarios								
Reference Tax	25.20	37.80	56.25	74.25	93.15	112.95	132.75	157.50
Global Tax	100.80	151.20	285.00	297.00	372.60	451.80	531.00	630.00

Note: The cumulative 20% reduction scenario assumes the same total emissions as the 20% scenario, but leaves the model free to allocate the reductions to various periods.

Table 2: Cumulative Emissions and Total Costs

Scenario	Cumulative Emissions (10^9 tonnes)	System Discounted Cost (billions of 1995 dollars)		
		Technology Cost	Loss of Demand	Total Welfare Loss
Base	3.16	0	0	0
Stable Emissions	2.78	0.04	0.66	0.70
20% Reduction	2.31	-2.30	7.09	4.79
Cumulative 20% Reduction	2.31	-1.18	5.08	3.90
Reference Tax	2.32	-2.19	6.06	3.87
Global Tax	1.60	23.62	13.76	37.38

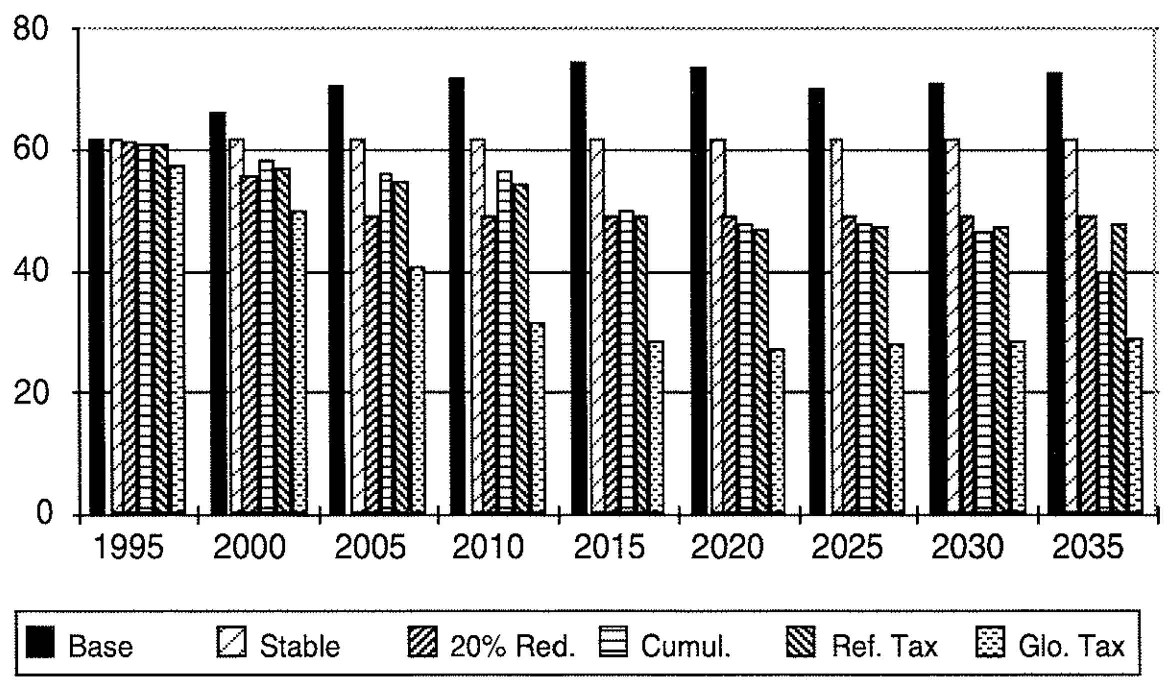

Figure 1: GHG Emissions Trajectories

very nearly the same result as a cumulative 20% reduction strategy. The global tax scenario is by far the more drastic one, achieving a 49.3% reduction relative to base, and a 42.5% reduction relative to 1990 emissions (the stable scenario).

The total costs of implementing these reductions (last column of Table 2) follow the same pattern: the stable scenario exhibits a very moderate cost of $700 million (*i.e.*, 0.005% of discounted GDP over the same period), whereas the next three scenarios exhibit costs in the vicinity of $4 billion each, or 0.03% of GDP (however, the 20% reduction scenario is 23% costlier than the cumulative 20% reduction scenario, even though both achieve the same overall reductions). Note also that the reference tax achieves very much the same cost and emissions as the cumulative 20% reduction, although the means to achieve them are different in the two scenarios. The global tax scenario is very costly, at about ten times the cost of the middle scenarios: 0.95% of GDP, a very significant cost indeed!

We complete this discussion of costs and emissions by observing the marginal cost of emission abatement, equal to the shadow price of the emission constraint, if any. These values indicate the additional costs of the next tonne of GHG reduction. For the tax scenarios, the tax plays the same role as the marginal cost. All these marginal costs are shown in Figure 2. The cumulative 20% reduction scenario has a single shadow price for the cumulative constraint, from which a per period marginal cost is derived, and also shown in Figure 2. As may be seen from that figure, the stable scenario has marginal costs which never exceed $40/tonne CO_2-equivalent, whereas the period-by-period 20% reduction carries much higher marginal costs of up to $130/tonne, and their profile is much more "bumpy" than those of the cumulative scenario.

3.2 Aggregate Primary and Final Energy Profiles

PRIMARY ENERGY

Figures 3 to 6 exhibit the evolutions of the main four primary energy forms for all scenarios, respectively: oil, natural gas, biomass, and electricity. Oil usage varies inversely with the amount of GHG abatement (Figure 3), whereas electricity production (which is composed of more than 98% hydro) increases with GHG abatement effort (Figure 6). Natural gas has a more complex sensitivity to GHG abatement: as Figure 4 shows, for low to moderate abatement levels, there is little correlation between GHG level and gas usage, but for drastic GHG abatement (the global tax scenario, for example), gas is no longer the solution, and electricity is a vastly preferred option. Similarly, biomass production (Figure 5) increases moderately in the moderate GHG abatement scenarios, but jumps to very high levels in the global tax one, reaching almost 500 petajoules (PJ), or 18% of total primary energy use. Biomass is assumed to be renewable, and therefore there is no GHG emission attached to the resource (although there are some emissions related to the extraction and transformation processes). Biomass includes wood, mainly used in pulp and paper, and alcohols used as transportation fuels.

Electricity production (Figure 6) increases as the GHG constraints become more severe. In the base scenario, its growth over the horizon is from 613 to 683 PJ per year (a very low annual growth rate of 0.3%). The growth rate is more substantial in the cumulative 20% reduction scenario (0.8% per year), and even more so in the global tax scenario (0.9% per year). In all scenarios, hydro has the lion's share of electricity production, namely 100% in the base scenario, and more than 98% in the cumulative 20% reduction and global tax scenarios. In the base scenario, hydro capacity reaches 36.2 gigawatt (GW) in 2035, a 4 GW increase over 1995 capacity. In the cumulative 20% reduction scenario, hydro reaches almost 42 GW in 2035, and wind makes an appearance in the last period, with 2 GW of installed capacity. In the global tax scenario, hydro peaks at 42.6 GW in 2035, wind appears in 2010, and then stabilizes at 4 GW in 2025. In all scenarios, some small thermal capacity remains in all periods, in the form of gas tur

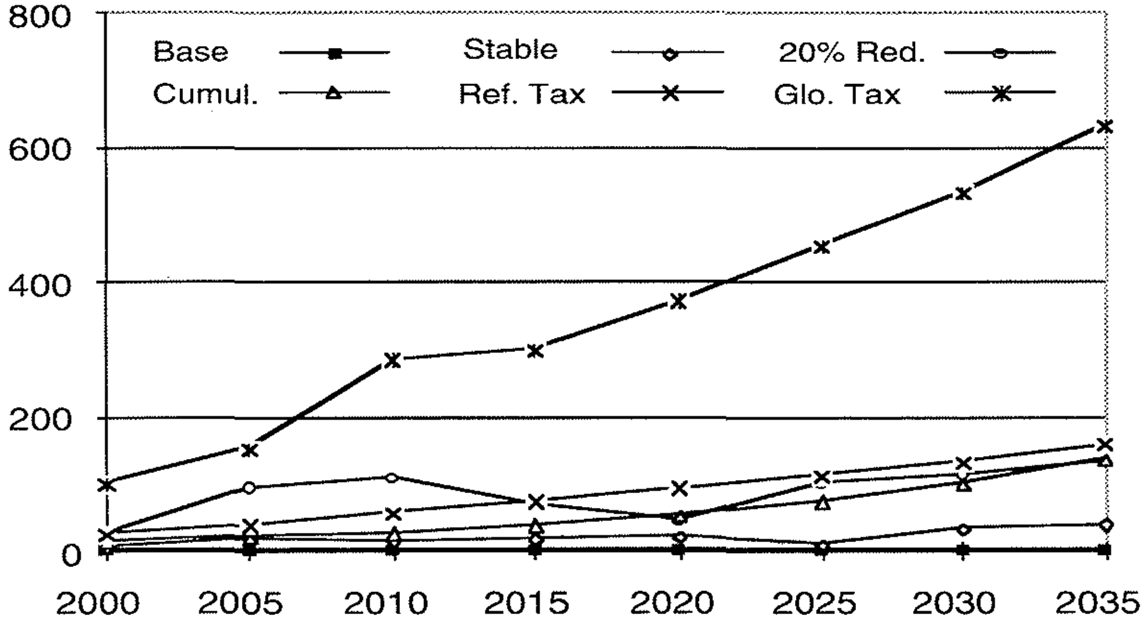

Figure 2: Marginal Cost of GHG Reductions (1995 $Cdn/tonne of CO_2-equivalent)

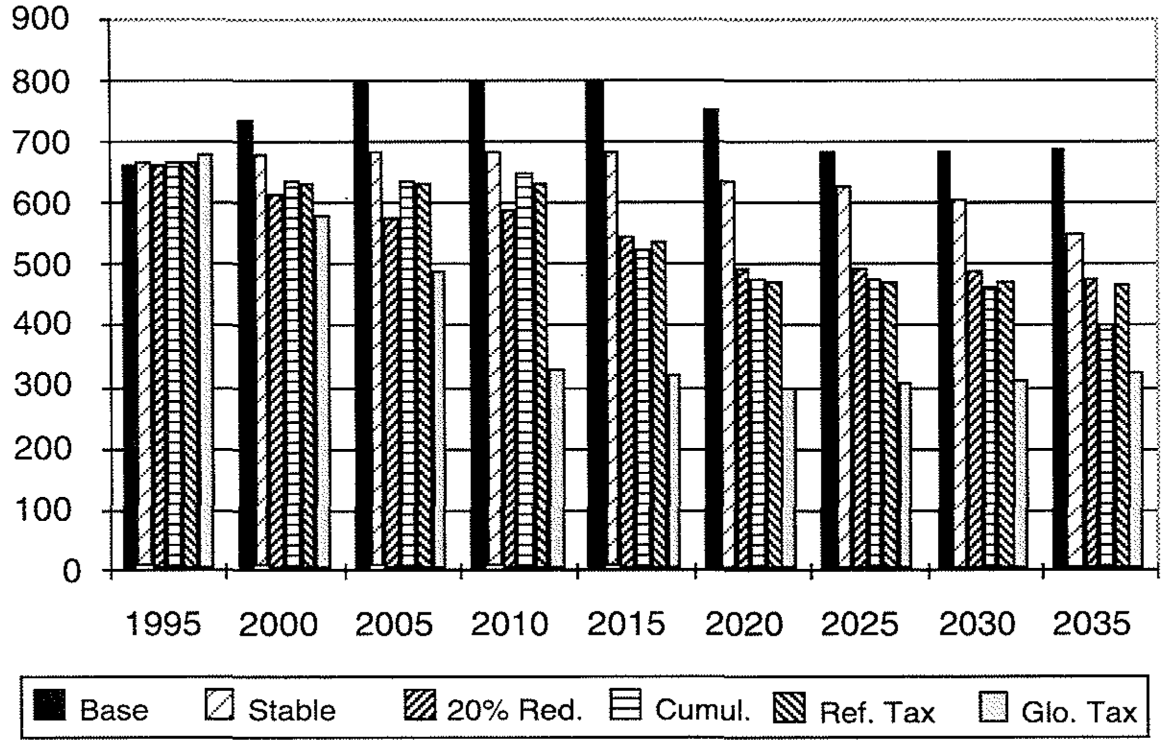

Figure 3: Crude Oil Consumption (PJ per year)

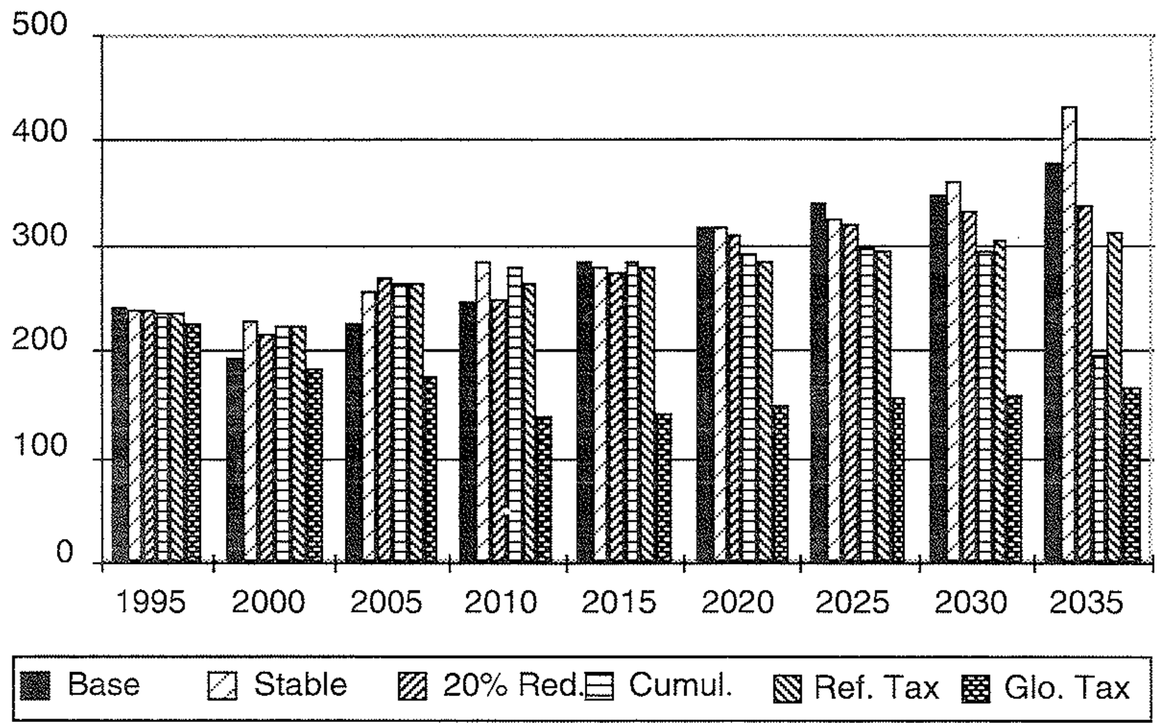

Figure 4: Natural Gas Consumption (PJ per year)

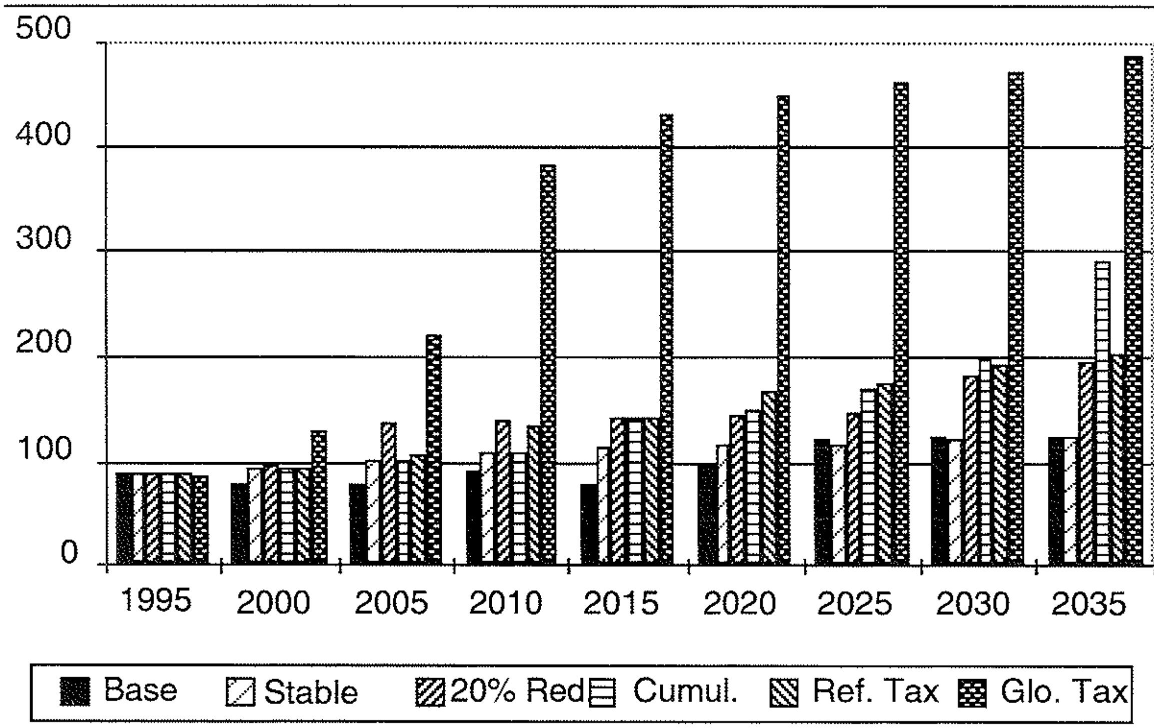

Figure 5: Renewable Biomass (PJ per year)

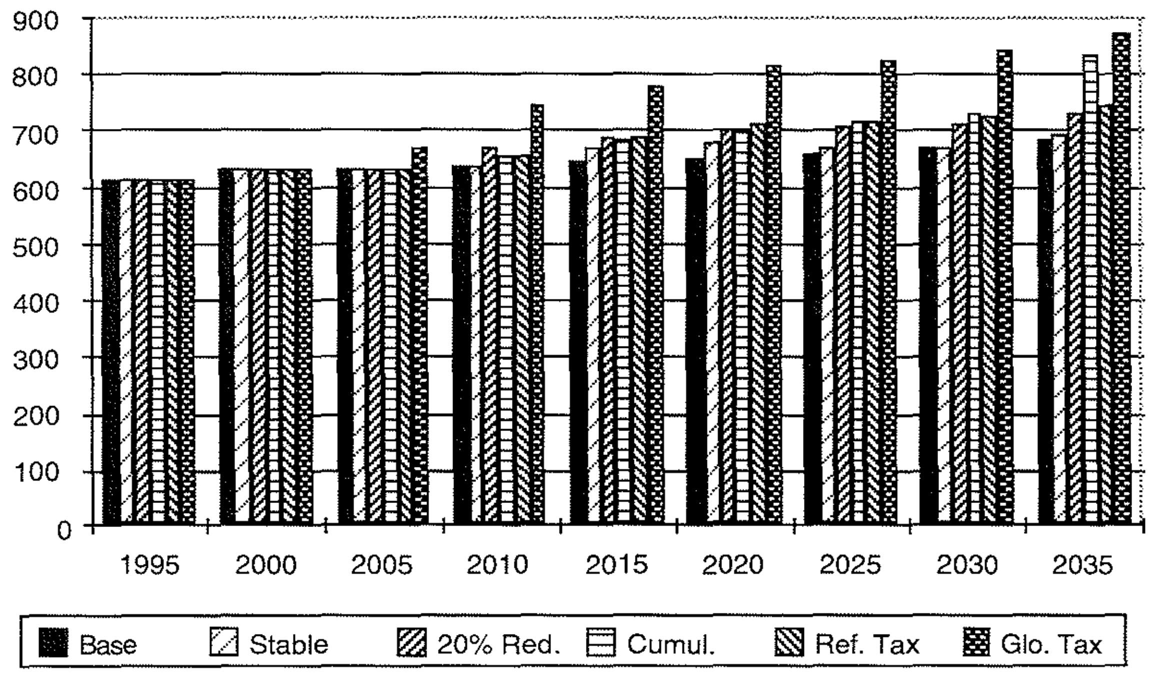

Figure 6: Electricity Production (PJ per year)

bines, which supply peak reserve capacity, *but which do not actually produce energy in a sustained manner.* Power exports are severely reduced in all scenarios, mainly because the only exports modelled are interruptible energy exports, which have a low value of 2.5¢/kWh. Therefore, power consumption, which is equal to net production minus exports, grows actually less fast than does power generation.

FINAL ENERGY PATTERNS

Total final energy (Figure 7) undergoes a slight growth in the base scenario, from 1560 PJ in 1995, to 1930 PJ in 2035, representing an annual average growth rate of only 0.5%. This is due to the moderate economic growth assumptions, and to a number of energy efficiency improvements implemented by the model. Growth is even smaller for the other scenarios, and reaches its lowest value of 0.2% per annum in the global tax scenario. One reason for such low final energy levels in the abatement scenarios is that the model progressively introduces more hydro to control GHGs, thereby also increasing end-use efficiency. The final energy trajectories are even more varied when examined sector by sector.

3.3 Sectoral Fuel and Technology Selection

We shall focus our analysis on the three sectors where the most interesting fuel and technology switches occur, namely: transportation, residential, and commercial/institutional.

ROAD TRANSPORTATION SECTOR

The three panels of Figure 8 show the evolution of the fuel mix over the model's 45-year time horizon, for each of three selected scenarios: base, cumulative 20% reduction, and global tax. Results for the others are close enough to one of these three for the observations made here to apply to them as well. First of all, the total use of fuels for road transport in the long term experiences a 30% reduction compared to 1990, irrespective of the scenario. The only differences that can be observed appear at two levels: the fuel mix; and the date at which this 30% reduction is reached. Total fuel consumption for road transport starts at 325 PJ

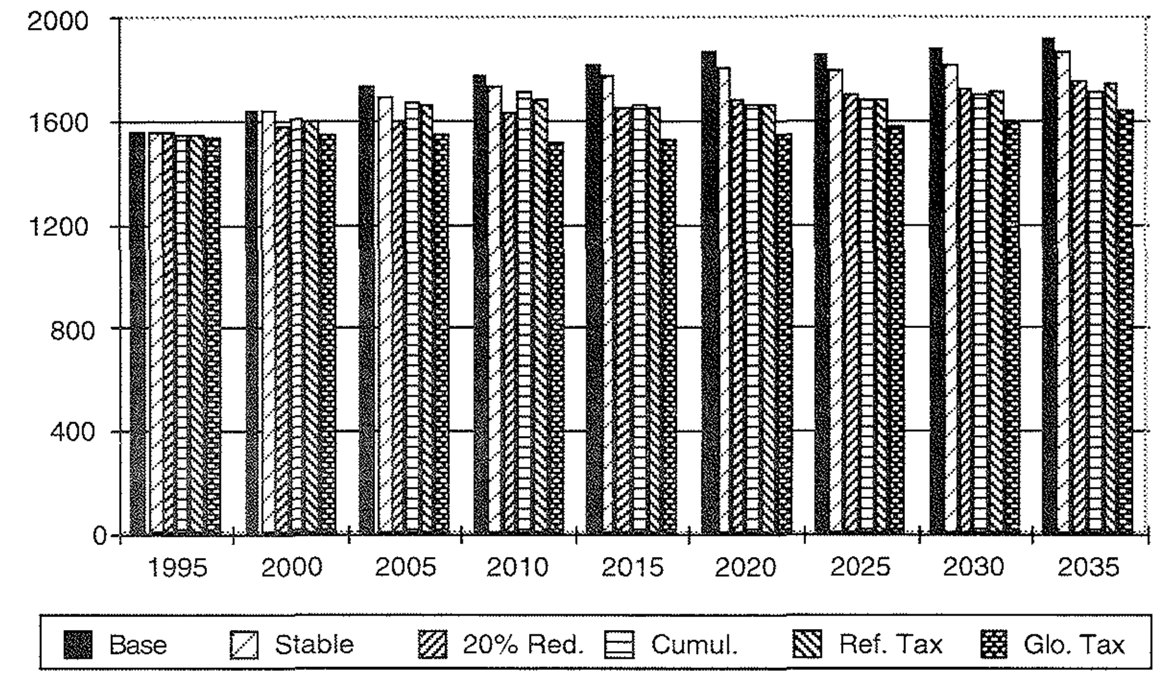

Figure 7: Total Final Energy Use (PJ per year)

per year in 1995, and peaks at 350 PJ per year around year 2005 for all scenarios except the global tax one, in which the maximum level (343 PJ per year) is reached in 2000. In the long term, the road transportation sector thus offers the largest contribution to total systemic energy savings, mainly due to the energy efficiency of electric vehicles which penetrate the market progressively, even in the base scenario. In the base scenario, total fuel consumption stays above its 1995 level until 2020 and then decreases to 230 PJ per year by 2030. This same level is attained in 2020 (cumulative 20% reduction), or in 2015 (global tax).

Concerning the fuel mix, we examine the consumption of gasoline (Table 3) and diesel (Table 4) for all six scenarios. The use of gasoline experiences at least a 60% decrease in all scenarios in the long term (2035), compared to its 1995 level. Two scenarios are even more severe: the cumulative 20% reduction one, with a 64% decrease; and the global tax one, with a spectacular near 90% decrease in gasoline use. Traditional gasoline cars are totally replaced with electric or hybrid cars (electricity + gasoline) in all scenarios. Light trucks keep running on gasoline for all scenarios but one, and ethanol reaches a 22% market share by 2035 in the cumulative 20% reduction scenario. The global tax scenario sees a complete switch to ethanol trucks, with a temporary methanol transition between 2010 and 2030. Ethanol reaches an impressive 50% of road transport final energy in the global tax scenario.

The use of diesel fuel shows a pattern similar to that of gasoline. It decreases throughout the horizon by amounts ranging from 33% in the base scenario, to 100% in the global tax scenario, as shown in Table 4. Diesel is discontinued for private cars as early as in 2005. It is used for heavy trucks and buses, where it is progressively replaced first by methanol and then by ethanol as the GHG constraint becomes more severe. Concerning medium trucks, diesel is replaced first by gasohol (for example, in the base and stable scenarios, gasohol supplies 65% of demand) and next by ethanol, as the environmental constraint becomes more stringent (*e.g.*, in the cumulative 20% reduction and global tax scenarios, ethanol satisfies respectively 58% and 100% of that demand).

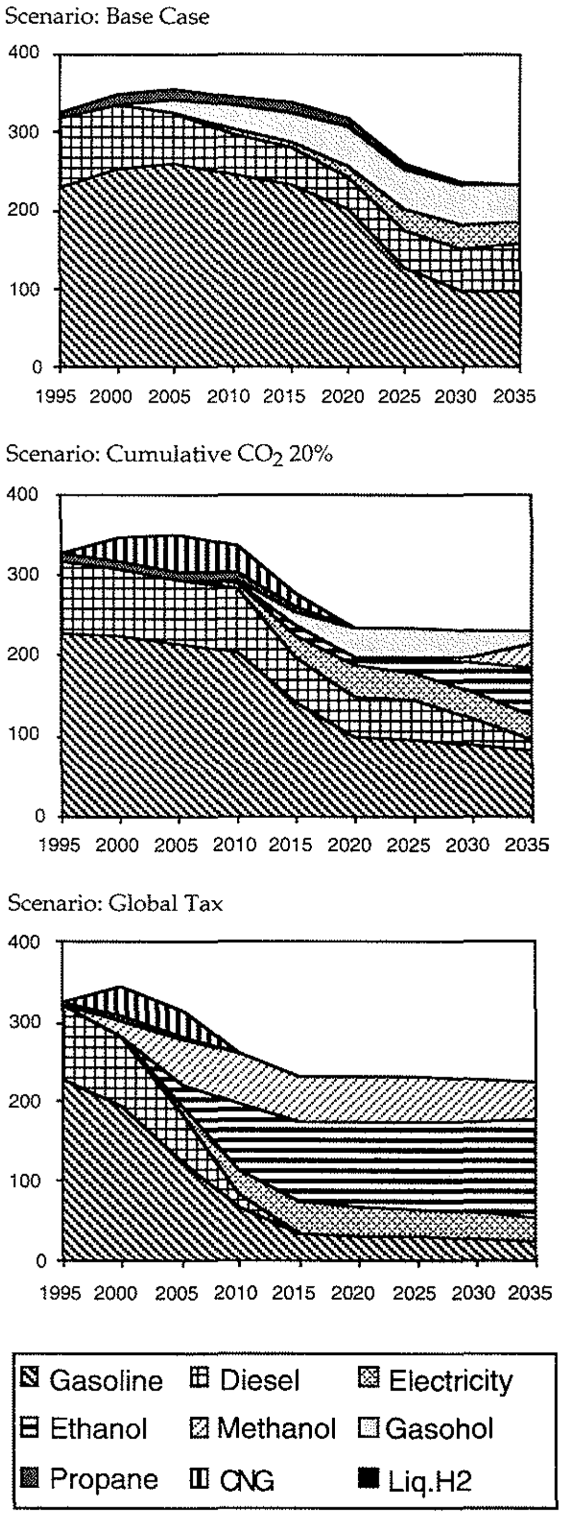

Figure 8: Fuels for Road Transport (PY per year)

Table 3: Use of Gasoline

	1995	2005	2035	Reduction in 2035
Base	230	262	97	58%
Stable Emissions	230	245	97	58%
20% Reduction	230	174	97	58%
Cumulative 20% Reduction	230	214	82	64%
Reference Tax	230	210	96	58%
Global Tax	230	126	26	89%

Table 4: Use of Diesel Fuel

	1995	2005	2035	Reduction in 2035
Base	89	63	60	33%
Stable Emissions	89	67	56	37%
20% Reduction	89	81	36	60%
Cumulative 20% Reduction	89	78	16	82%
Reference Tax	89	83	36	59%
Global Tax	89	59	0	100%

Even with no GHG constraint or tax, electricity makes a remarkable appearance, eventually capturing a 12% final-energy share in the transportation sector, principally to fuel electric cars and hybrid (electric+gasoline) cars. This means a much higher share of the transportation service expressed in km, since the electric car is much more efficient than any internal combustion technology. The energy share of electricity does not change much across scenarios, which shows that electric cars will play an important role in the future, independently of their specific contribution in achieving potential emission reductions. However, the timing differs across scenarios.

Urban cars switch from gasoline to electric and hybrid technologies in 2025 in the base and stable emissions scenarios, in 2015 in the cumulative 20% reduction and reference tax scenarios, and in 2005 in the 20% reduction and global tax scenarios (the model restricts electric cars to only 50% of urban car travel, since it is assumed that the other 50% occurs in mixed mode (city + intercity) and requires a hybrid technology). The switch away from gasoline and diesel occurs first to electric cars, and then to hybrid cars, at slightly different periods. Taxis switch 100% to the hybrid technology in 2005. The transition is made via compressed natural gas (CNG) vehicles (in all but the base and global tax scenarios) or via methanol (in the global tax scenario), because electric cars are not available before 2005. Intercity cars switch from gasoline to the hybrid technology after a transition period of 10 to 5 years, in 2020 for the base and stable emissions scenarios, in 2015 for the 20% reduction, cumulative 20% reduction and reference tax scenarios, and in 2010 for the global tax scenario.

It is also interesting to note that CNG is only used for a short period of time (1995-2010 to 2020) in mildly to heavily constrained scenarios (20% reduction, cumulative 20% reduction, reference tax, and global tax), to insure the transition to electricity. In the base and stable emissions scenarios, propane is the marginal fuel for several periods, but never captures a large market share. Methanol plays a similar transitional role.

Finally, environmental constraints induce significant endogenous demand reductions in most segments, in the vicinity of 5 to 10%. For example, the cumulative 20% reduction scenario entails a 10% demand reduction of intercity bus travel in the last three periods, as well as for city buses and trucks. The global tax scenario induces demand reductions for inter-urban cars, taxis, trucks, and all types of buses.

In summary, the cumulative 20% reduction and reference tax scenarios behave in very much the same way. The global tax scenario is very particular, and is characterized by a huge (76%) share for biomass fuels, a 12% share for electricity, and 12% for gasoline, the latter used mainly in hybrid cars. Demand levels are affected to various degrees by the imposition of environmental constraints.

RESIDENTIAL SECTOR

Here too, an examination of three scenarios (base, cumulative 20% reduction, and global tax) captures the essential system responses. In the base scenario, final energy in the residential sector (Figure 9) exhibits an 11% increase over the selected time horizon. Over the same period, environmental constraints induce a 2% decrease in the cumulative 20% reduction scenario and a 6% decrease in the global tax scenario. Electricity is chosen by a majority of consumers: it accounts for 65% of the sector's final energy in 1995. This market share is stable in the base scenario, and increases to 89% 2035 in constrained scenarios, mainly due to the decreased use of fossil fuels. The total use of electricity peaks in 2000 and then decreases to about the 1995 level, or thereabout, in most scenarios. This is so because electricity is basically in a surplus situation until the early years of the 21st century, so that its marginal value is quite low.

Figure 9 also reveals that natural gas captures the increase in fuel consumption for the base scenario since its market share rises from 8% to 25%. But when environmental constraints are applied, natural gas progressively disappears from the market, still playing a role in the cumulative 20% reduction scenario (until 2030), but disappearing nearly completely in 2000 in the global tax scenario. Heating oil decreases in all scenarios and stabilizes at a long-term market share of 7%. Wood remains marginal and never increases over 4% of the sector's final energy, even in the global tax scenario.

We now take a closer look at two typical and important segments of the residential market. The technological substitutions discussed below explain the patterns of fuel shares presented above.

Existing houses and apartments: These two segments behave similarly. The common features are that in all scenarios, traditional oil furnaces disappear, dual energy (electricity + oil) slightly decreases to approximately 50% of its 1995 level (40,000 houses and 38,200 apartments), and the insulation potential is fully exploited (*i.e.*, up to the equivalent of 96,300 houses or 8% of this market, and 56,600 apartments or 4% of that market). This occurs independently of the environmental constraint but the timing differs across scenarios.

The main differences between the scenarios concern the stock of existing houses and apartments heated with electricity and natural gas. Electricity starts to increase sharply from

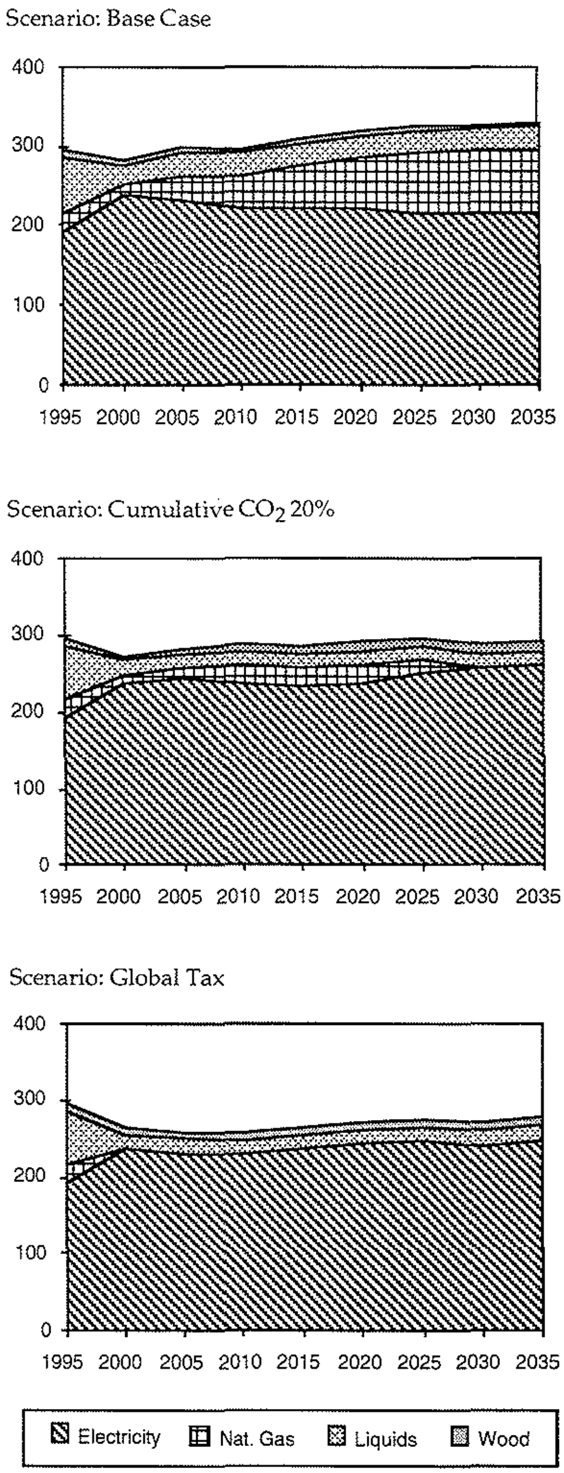

Figure 9: Fuels for the Residential Sector (PJ/year)

1995 to 2000 in all scenarios. In the base scenario, it decreases and stabilizes in 2025 at the 1995 level for houses (*i.e.*, 700,000 houses) and at a lower level for apartments (*i.e.*, 656,000 apartments), the balance of the market being captured by new gas furnaces, which replace existing oil and gas furnaces and heat as much as 500,000 houses in 2035 (38% of the market) and 525,000 apartments in 2035 (41% of the market). In the cumulative 20% reduction scenario, natural gas is swapped for electricity in houses, with the latter stabilizing in 2015 at around 1,120,000 units. In the global tax scenario, electric heating reaches the 1,050, 000 level a few years earlier, in 2010. This difference is due to a greater endogenous reduction in demand by MARKALED in the global tax scenario than in the cumulative 20% reduction scenario (10 and 5% reductions, respectively).

For existing apartments, new natural gas furnaces remain competitive for a longer period (until 2025) in the cumulative 20% reduction scenario, but not at all in the global tax scenario. Existing apartments also experience endogenous demand reductions of respectively 5% and 10% in the cumulative 20% reduction and global tax scenarios.

***New houses and new apartments*:** In the new house segment, electricity progresses continuously to stabilize around 483,000 units until 2020 in the base scenario, at which time new natural gas furnaces appear marginally (5%). In constrained scenarios, gas furnaces do not appear and all the new demand is captured by electricity; but increases in electricity prices induce demand reductions of 5% and 10% in the cumulative 20% reduction and global tax scenarios, respectively.

In the new apartment segment, the picture is very similar, but natural gas plays a slightly more significant role than for houses. This is due to the relatively more predominant role of capital expenditures in apartments than in houses. Electricity stagnates at 30% in the base scenario, with natural gas capturing the rest of the segment. When environmental constraints are imposed, electricity progressively captures the whole segment. Here again, environmental constraints induce endogenous demand reduc tions of 10% and 15% reductions in the cumulative 20% reduction and the global tax scenarios, respectively.

COMMERCIAL AND INSTITUTIONAL SECTOR

The final energy consumption for the commercial/institutional sector (Figure 10) experiences increases of 53%, 12%, and 1% in the base, cumulative 20% reduction, and global tax scenarios, respectively. In the base scenario, electricity stagnates on an absolute basis and decreases on a relative basis (from 57% in 1995, to 32% in 2035), because of the competitiveness of natural gas and of petroleum products. With the imposition of environmental constraints, however, electricity first replaces petroleum products and then natural gas, while reaching a dominating market share of 90% in the global tax scenario.

We now take a look at specific technological choices in some key segments of this sector.

***Existing commercial and institutional space and water heating*:** The global sizes of these markets decrease over time, from 119.13 million square metres (Mm^2) in 1995 to 27.19 Mm^2 in 2035 (a 77% decrease), but electricity decreases even faster, from 33% to 26% of the market in the base scenario. New oil furnaces dominate the market with a 53% share, and new natural gas furnaces come in third with 20%. In the cumulative 20% reduction scenario, dual energy (electricity + oil) replaces oil, and is used as a transition, peaking with a 42% market share between 2005 and 2025, and then decreasing to around its 1995 level. At the end of the horizon, the electric heat pump replaces natural gas furnaces to achieve the desired emission reductions. Demand reductions (0–5%) are observed in this scenario. In the global tax scenario, dual energy is progressively replaced by the heat pump. By 2035, heat pumps occupy 75% of the market and electric furnaces another 15%, with the remaining 10% being saved by demand reductions due to higher energy prices.

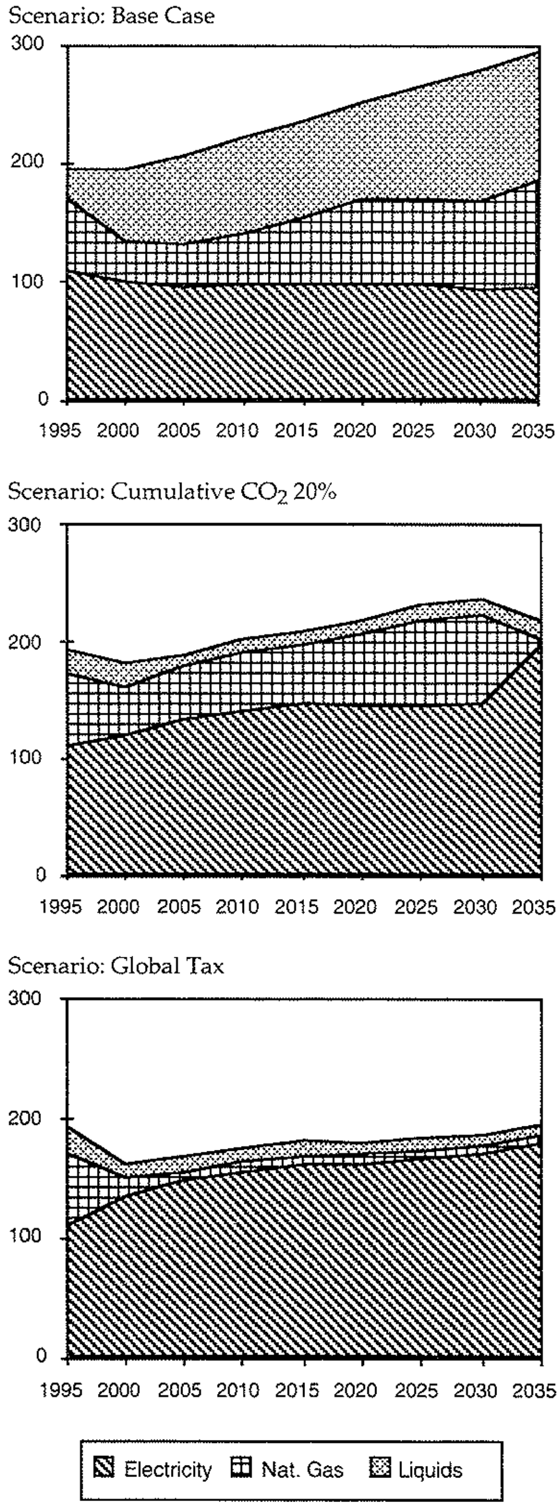

Figure 10: Fuels for the Commercial/Institutional Sector (PJ per year)

New commercial and institutional space and water heating: In the base scenario, these segments behave somewhat like new apartments: electricity experiences a stagnation, while petroleum products and natural gas penetrate the market. In the cumulative 20% reduction scenario, oil is replaced by dual energy and, at the end of the time horizon, natural gas is replaced by electricity and heat pump+oil. In the global tax scenario, all fossil fuels are replaced initially by dual energy and later by heat pump+oil or heat pump alone. Induced demand reductions are the same for the two constrained scenarios, reaching 15% in 2035.

4. Concluding Remarks

This research computes detailed system responses for the Québec energy system under a variety of GHG constraints and taxes. Out of the six scenarios, three groups emerge: first, the base scenario is not too different from the scenario in which emissions are stabilized at their 1995 levels. The second group includes three scenarios: 20% reduction (year-by-year or cumulative) and reference tax. The third group contains only the global tax scenario, which very drastically induces more than a 42% reduction in GHG emissions.

The system response consists, in each scenario, of a mix of efficiency improvements, fuel substitutions, technological switches, and demand reductions. Each sector has a particular path of responses open to it, in terms of the technologies that are available to satisfy the various segments of the sector. The transportation sector undergoes the most drastic changes, compared to the current situation. Electric cars appear fairly massively, even in the base scenario, whereas trucks and buses using alcohols as fuels appear only in the environmental scenarios. The hybrid car (electricity + gasoline) plays a large role in inter-city car travel. The residential, commercial, and institutional sectors are also significantly affected by GHG constraints or taxes, and the GHG scenarios induce an increased penetration of several electric or dual technologies in these sectors, at the expense of natural gas and oil furnaces.

Besides energy savings, one important weapon to help comply with GHG restrictions or taxes is the development of hydroelectricity production. The contrast between the base scenario and the extreme global tax scenario is significant, but not outrageous, and well within Québec's hydroelectric potential. Wind also becomes a viable alternative in the GHG-constrained scenarios. Energy crops for alcohol production are important only in the global tax scenario. However, new, improved alcohol production technologies might confer a more central role to this fuel.

One important lesson from this study is that the technological system is, in general, quite capable of responding adequately to average or even severe GHG taxes. In addition to purely technological responses, some demand reductions are implemented in a few segments, when substantial GHG constraints are imposed. Using moderate price elasticities, we have found that demand reductions of the order of 5 to 10% would occur at certain (but far from all) periods. Although the model used does not permit a precise assessment of the GDP losses induced by each scenario, the amount of demand reductions gives important clues about the likely magnitude of such losses. Qualitatively, it may be said that, except for the global tax scenario, demand reductions would not reduce GDP significantly.

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