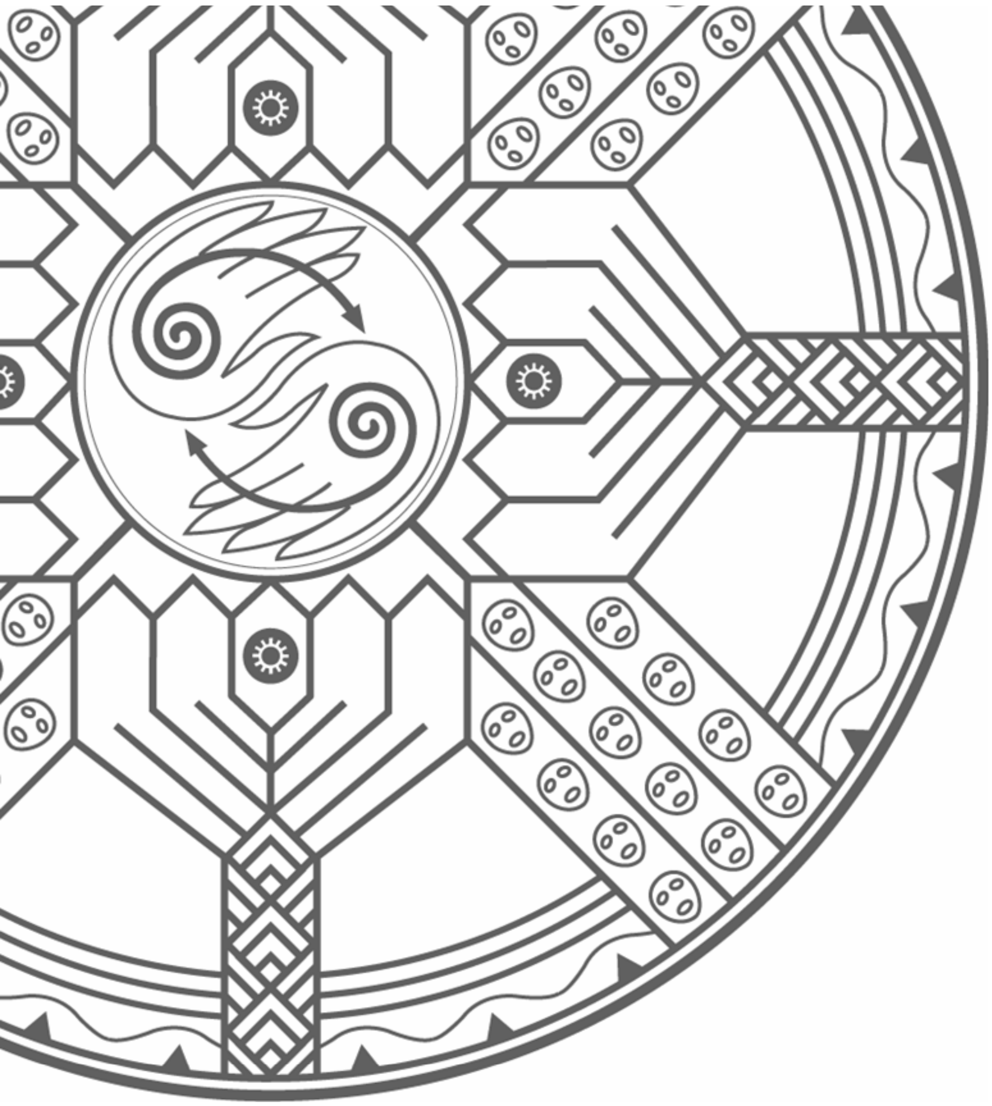

Towards Assessing the Distributional Impacts of Meeting Kyoto Targets in Canada

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Published by the International Institute for Sustainable Development

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Summary

Lower-income groups spend a bigger share of their budgets on energy expenses than higher-income groups do and are therefore more responsive to changes in energy prices. As a result, lower-income groups are more likely to bear a greater impact of increased energy prices, such as the ones resulting from meeting targets of the Kyoto Protocol. However, such assessment has not yet been performed within an energy modelling framework. MARKAL-Equity was developed to achieve this. When trying to meet Kyoto targets, Canadian data show that all income groups will see a reduction in demand for energy services. However, the reduction of energy consumption is not straightforward. Some groups, specifically the middle-income group, will choose less efficient technologies, such as wood stoves, over time. Results show that the low-income group, although it reacts to the new emission constraints by demanding less energy service, does not fundamentally change its technology, and thus its fuel consumption pattern, as do other income groups. This tends to show that the low-income group does not have the ability to cope as well as other income groups. Transitional policies should therefore be aimed at the low-income households to help them cope with energy policies that will curb emissions to reach the Kyoto targets. Although this first model of MARKAL-Equity could still be enhanced, this study shows the importance of taking into account specific income group behaviours and responses to energy policies.

1 Introduction

The Kyoto Protocol makes provision for greenhouse gas (GHG) emission reduction targets for Annex I countries. The Protocol will be effective when at least 55 per cent of the signatory countries representing at least 55 per cent of the GHG emissions ratify the Protocol. Canada signed the Protocol and ratified in December 2002. Canadian emissions account for 2.2 per cent of the world's emissions (Canada, 2001).

The reduction target for Canada is six per cent below the 1990 emissions level, on average, over the 2008–2012 period. The 1990 emissions level is estimated at 607 Mt, commanding a Kyoto target of 571 Mt, and the 1999 emissions level is estimated at 699 Mt, well above the target by 128 Mt or 22 per cent (Canada, 2001). Emissions are likely to continue rising and in 2010, it is projected that emissions will reach 705 Mt or 770 Mt if the 2000 Action Plan is excluded (Canada, 2001). Emissions will then need to be reduced by 134 Mt or 19 per cent to comply with the Kyoto Protocol (or by 199 Mt, or 26 per cent if the 2000 Action Plan is excluded).

Compliance with Kyoto targets in countries where emissions are already above the targets will result in an increase of energy prices.

In industrialized countries, lower-income households spend a larger share of their budgets on energy expenditures and are more sensitive to changes in energy prices. In Canada, low-income households spend a percentage of total expenditure on energy four times greater than the percentage spent by high-income households, as shown in Table 1. Furthermore, the same low-income households are twice as responsive to price changes that affect space heating than the high income households, as shown in Table 2. In Canada, space heating accounts for some 55 per cent of household energy needs (Guertin et al., 2002).

Table 1: Energy Expenditures of Three Canadian Terciles in 2000 (expressed in CDA $)

Income group	Income range	Electricity expenditures	Fuel expenditures	Total expenditures	Ratio of total energy expenditures to total expenditures
Low	< $30,180	900	851	21,564	8%
Medium	$31,181–61,848	964	1,089	47,166	4%
High	> $61,849	1,061	1,301	95,753	2%

Source: Statistics Canada (2001, 2002)

Table 2: Price Elasticities of Energy Services for the Three Canadian Terciles

Income group	Income range	Space heating	Water heating	Appliances and lighting
Low	< $30,180	-0.43	-0.38	-0.49
Medium	$31,181–61,848	-0.33	-0.36	-0.39
High	> $61,849	-0.25	-0.34	-0.32

Source: Guertin et al. (2002)

As a result, different income groups will behave differently when facing an increase in energy prices. The impacts of an energy price increase will depend on the structure of the demand and the presence of compensation mechanisms (Hope and Singh, 1995). For any given energy price increase, in the absence of compensation mechanisms, low-income households in Canada will be the hardest hit. This can be deduced from the energy demand structure where the low-income group spends a greater share of its budget on energy expenditures and is more sensitive to price changes.

Our objective is to demonstrate the potential hardship that will be borne by the lower- income groups in the absence of mitigation policies to help them cope with price increases. Our goal here is to raise awareness to this issue in the context of the Kyoto Protocol. Our work will be based on the Canadian MARKAL model, one of the three models used in Canada to assess economic costs of meeting the Kyoto Protocol. (Note: The other two models are CIMS and ENERGY 2020, whose descriptions are not found in the public economic literature). We will hence ensure that our work is anchored in the current stream of work in Canada.

This paper focuses on the distributional impacts of meeting the Kyoto Protocol in Canada. Results show that low-income households are the hardest hit. Compensation mechanisms are investigated elsewhere (Duraiappah et al., 2002).

2 A Brief Literature Review

Distributional impacts of energy prices increase at the household level have seldom been investigated in the context of climate change. All of the studies we reviewed assessed the efficiency impacts of an energy or carbon tax. Energy or carbon taxation reduces the demand for energy goods and thus decreases greenhouse gas emissions (GHG).

Energy taxation is most often investigated using an I/O model coupled with a demand model. The I/O model relates energy usage and CO_2 emissions for industries and final consumers, and thus determines the increase in prices due to the carbon or energy tax. The basic assumption of I/O models is that all price increases are pushed forward to the final consumer. Furthermore, it does not allow for general equilibrium effects such as changes in market shares of commodities or changes in input levels of production functions. New price levels for goods are the entry point of demand models that determine the distributional impacts of these on household categories. These demand models can simply describe expenditure shares across commodities or they can also include households' behavioural changes to changes in the prices of goods. Energy taxation was studied for Australia (Cornwell and Creedy, 1997); Canada (Hamilton and Cameron, 1994); Norway (Aasness et al., 1996); Spain (Labandeira and Labeaga, 1999); the State of New York (Dumagan and Mount, 1982); the U.K. (Symons et al., 1994); Taiwan (Yang, 2001); and the U.S. (Casler and Rafiqui, 1993; Herendeen and Fazel, 1984).

The level of taxation used in these studies is exogenous. It is taken either from elsewhere (Cornwell and Creedy, 1997; Labandeira and Labeaga, 1999), fixed at some level (Casler and Rafiqui, 1993;

Herendeen and Fazel 1984), or computed as to reach a given level of CO_2 emissions (Hamilton and Cameron, 1994; Symons et al., 1994). In the latter case, the level was obtained using a computable general equilibrium, or the I/O model coupled with the demand model, respectively.

Only two studies assessed the distributional impacts of a carbon tax on different household categories using an integrated general equilibrium framework. Aasness et al. (1996) used an integrated energy-environment model (empirical general equilibrium model) to assess distributional impacts following the introduction of a carbon tax in Norway, while Yang (2001) used a computable general equilibrium framework for Taiwanese households.

Finally, only one study used a partial equilibrium approach to assess distributional impacts of a carbon tax. Dumagan and Mount (1982) investigated welfare impacts on households in the State of New York using hypothetical representative households for each of the three income groups.

All studies except one show that low-income groups are more likely to feel the adverse impacts of energy taxes than high-income groups. This is not the case for Norwegian households. Because of positive trade effects, households' utilities increase but not as much for lower-income households (Aasness et al., 1996). Results for Spain show an ambiguous distributional variation in welfare losses (Labandeira and Labeaga, 1999). According to Hope and Sing (1995), the distributional impacts of an increase in energy prices depend on the structure of the energy demand coupled with the mitigation assistance programs introduced, if any.

3 MARKAL

MARKAL (for MARKet ALlocation) was developed in the late 1970s by member countries of the OECD under the guidance of the International Energy Agency (IEA) (Berger et al., 1992; Condevaux-Lanloy and Fragnière, 2000; Fishbone and Abilock, 1981), and is therefore a mature tool. It is now in use in more than 35 countries (Condevaux-Lanloy and Fragnière, 2000).

MARKAL is a dynamic optimization model that tracks energy flows from production sources to end-use energy. In that sense it is an energy-process model or a bottom-up model. MARKAL is a partial equilibrium model as the equilibrium is only met on the energy market. Feedback on macro-economic parameters such as employment rates, consumption and interest rates are not considered. However, some of the MARKAL models can handle feedback on energy prices, including the Canadian MARKAL-ED model (Loulou and Lavigne, 1995).

MARKAL is driven by the demand for energy services and this is the subject of Section 3.1. Section 3.2 presents the Canadian residential sector model. Descriptions of MARKAL and MARKAL-ED are given in Appendix I.

3.1 The MARKAL Driver: The Demand for Energy Services

The MARKAL model is driven by the demand for energy services. The objective of MARKAL is to determine the mix of fuel and technologies to meet the demand with the least cost. Figure 1 presents the residential sector model.

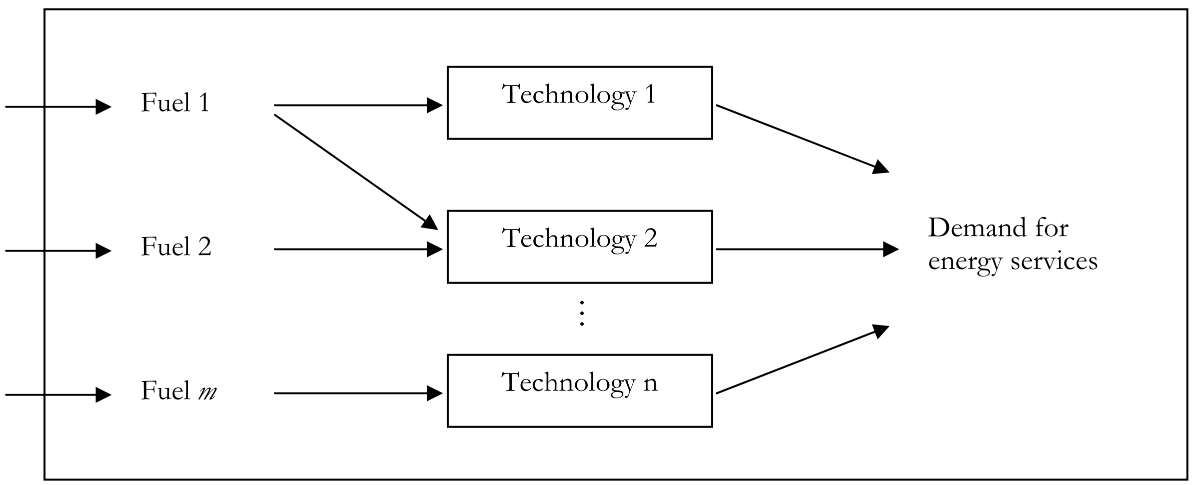

Figure 1: Generic Model of the Residential Sector.

In general, there are more technologies than fuel types, therefore *n>m*. Demands for energy services are given in Joules (J) or in a number of houses while fuels can be given in kilowatt-hours (kWh), litres (l) or cubic meters (m^3).

It can be seen from Figure 1 that the demand for energy services and the mediating technologies determine the demand for fuels in the residential sector. Any climate change mitigation policy will be directed at curbing the use of carbon-intensive fuels. Therefore, in order to understand the impacts of a climate change mitigation policy on the low-income group, an analysis that tracks the relationship between fuels, technologies, and energy services will be required.

3.2 The Canadian Residential Sector Model

The Canadian residential sector is "driven" by the vector of demands for energy services (space heat, water heat, lighting, appliances) from 1995 to 2020. Furthermore, the sector is divided into three categories of dwellings: detached houses, attached houses and apartments. Each type is further split into existing and new dwellings. The demands for energy services are themselves elastic to their own prices. For each *demand segment* (e.g., space heating in existing detached houses), MARKAL's database includes a number of competing *technologies* (each representing a heating device, in the case of space heating). The rest of this section describes each of these elements of the residential sector.

3.2.1 Demand for Energy Services

Energy services in the residential sector consist of space heating, water heating, lighting and appliances. The demands for energy services are given in Joules (J) in the case of lighting and appliances. In MARKAL, the demand for space heating and water heating is expressed in number of dwellings and is disaggregated by dwelling type (apartments, detached houses including mobile homes, and attached houses) and, in the case of space heating, is further disaggregated by time of construction (existing and new). Thus, there are six dwelling types for space heating: existing and new attached houses; existing and new detached houses; and existing and new apartments. Therefore, the residential sector as modelled in MARKAL has nine demands for energy services as presented in Table 3.

Dwellings are converted into Joules using the specific energy consumption of the dwelling for that demand segment (space or water heating), i.e., the energy input to satisfy one unit of the demand. This specific energy consumption, of course, varies across provinces. As a result, the specific energy consumption of space heating for apartments will vary across provinces and will be different from that of a detached house and an attached house.

Table 3: Types of Residential Demands for Energy Services

Energy Service	Unit
Lighting	Joule
Appliances	Joule
Space heating – existing apartments	10,000 dwellings
Space heating – existing detached houses	10,000 dwellings
Space heating – existing attached houses	10,000 dwellings
Space heating – new apartments	10,000 dwellings
Space heating – new detached houses	10,000 dwellings
Space heating – new attached houses	10,000 dwellings
Water heating	10,000 dwellings

The discrimination between old and new dwellings is based on the assumption of a 0.5 per cent annual demolition rate of old dwellings. As 1995 is chosen as the base year, all 1995 dwellings are considered "old." Beyond 1995, the old stock of dwelling is determined by applying the annual demolition rate to the previous stock of dwelling. New dwellings are given by the total estimated stock of dwellings minus the current stock of (old) dwellings.

The demand for appliances is determined by the demand in 1995 and the growth rate. In the Eastern Canadian provinces, the growth rate is set to zero while in Western Canada, the growth rate varies according to the province. The 1995 demand is given as a percentage of total residential energy consumption obtained by the Canadian Energy Outlook (CEO, 1996) and is shown in Table 4. The same approach is used for the demand for lighting and its characteristics are presented in Table 5.

Table 4: Demand for Appliances Given as a Fraction of Total Demand for Energy

Province/Region	Share in 1995	Growth Rate
Atlantic Provinces	13.5%	0%
Quebec	15.0%	0%
Ontario	13.0%	0%
Manitoba	7.6%	0%
Saskatchewan	11.0%	0.25%
Alberta	11.0%	0.25%
British Columbia	16.0%	0.2%

Table 5: Demand for Lighting Given as a Fraction of Total Demand for Energy

Province/Region	Share in 1995	Growth Rate
Atlantic Provinces	4.5%	0.8%
Quebec	5.0%	0.6%
Ontario	4.0%	1.0%
Manitoba	2.0%	0.7%
Saskatchewan	3.0%	1.4%
Alberta	3.0%	1.0%
British Columbia	5.0%	1.1%

3.2.2 Price Elasticities

In MARKAL-ED, price-elasticities of residential energy services in Canada were based on price-elasticities of residential utility consumption determined for Quebec and adapted to the MARKAL model using expert judgment (Kanudia and Loulou, 1999). Long-term price elasticities are given in Table 6. Short-term own price elasticities are set to half of the value of the long-term.

Table 6: Price Elasticities Used in MARKAL-ED

	Price Elasticity
Space heating	-0.100
Water heating	-0.300
Appliances	-0.055
Lighting	-0.184

3.2.3 Fuel Shares

Fuels consist of, among others, electricity, natural gas, oil, wood and liquid petroleum gas (LPG). The corresponding units are kilowatt-hours (kWh), litres (l) or cubic metres (m^3). In some cases, a technology requires two types of fuel. For example, a dual energy furnace requires electricity and heating oil. This is illustrated in Figure 1 under technology 2.

Demand for space heating and water heating can be satisfied by the use of electricity, natural gas, oil, LPG, coal and wood. Fuel shares for space heating of detached houses are determined for 1995, the base year, and are chosen such that overall consumption of the different fuels is calibrated to the 1996 Canada's Energy Outlook (CEO, 1996). Tables 7 and 8 give fuel shares for space heating of detached houses. Coal is not modelled in MARKAL-ED.

Table 7: Fuel Shares of Space Heating of Detached Houses in 1995: Eastern Canada

Fuel	**Province**				
	Quebec	**New Brunswick**	**Nova Scotia**	**Prince Edward Island**	**Newfoundland**
Electricity	58.2%	41.3%	18.1%	1.6%	39.8%
Natural gas	9.3%	0%	0%	0%	0%
Oil	18.8%	35.0%	60.8%	70.0%	40.0%
Coal	0%	0%	2.0%	0%	0%
LPG	0.7%	2.7%	1.1%	1.6%	1.2%
Wood	13.0%	21.0%	18.0%	26.9%	19.0%

Table 8: Fuel Shares of Space Heating of Detached Houses in 1995: Western Canada

Fuel	Province				
	British Columbia	Alberta	Saskatchewan	Manitoba	Ontario
Electricity	29.5%	5.0%	14.2%	46.9%	21.3%
Natural gas	60.0%	92.3%	80.5%	45.0%	66.2%
Oil	5.0%	0.6%	2.0%	1.6%	7.5%
Coal	0%	0.6%	0%	0%	0%
LPG	1.5%	1.1%	1.5%	3.1%	1.2%
Wood	4.0%	0.4%	1.8%	3.5%	3.8%

Fuel shares of other energy services, space heating of attached houses and apartments and water heating, are set to the ones of space heating of detached houses. There are two exceptions. In the case for apartments, the fuel share of wood is set to zero and the balance is added to the fuel share of electricity for space heating and water heating.

Demand for lighting and appliances are wholly satisfied by the use of electricity. Some appliances use natural gas, but at the aggregate level, this is marginal, and is not modelled.

3.2.4 Technologies

Competing technologies are defined for each energy services demand. They are described by their type (space heaters, water heaters, light bulbs and appliances); their efficiency; their technical life; and by their specific costs (capital cost, and fixed and variable annual costs). For a given technology (e.g., natural gas furnace), the combination of its age and cost define its efficiency. An older gas furnace is less efficient than a newer one, and the same applies to the cost. Some technologies have an efficiency rating of one. This is the case for all technologies that run with electricity: space heaters, water heaters, light bulbs and appliances.

4 Developing MARKAL-Equity

MARKAL-Equity was built from an existing Canadian MARKAL model—the Extended MARKAL-ED used for the Canadian National Climate Change Implementation Process. The foundation model is similar to the one described in Haloa Inc. (2000).

MARKAL-Equity extends MARKAL-ED by explicitly differentiating the residential sector into three main income groups with each group having its own price elasticity for the demand of the various energy services. Rather than changing the structural equations of MARKAL-ED, we disaggregated the residential sector database to capture the three income groups with the respective price elasticities. This approach helped us preserve the structure of the existing MARKAL model and made the solution process much easier and more efficient.

We changed the characteristics of the residential sector, defined by the provincial demand for energy services, price elasticities and the available technologies. Besides the modelling of income groups, there are two differences between the model for this study and the one for the Canadian National Climate Change Implementation Process. First, Issue Table's options, expressed by actions aimed at influencing technological choices (Haloa Inc., 2000), were turned off because of the complexity involved in determining which income group is impacted by those actions and at what level. Second, in the 2000 model, there were then only seven regions where the Atlantic provinces were combined into a single region. In the version we used, Atlantic provinces are individually modelled.

In turn, we will look at the selected income groups (Section 4.1), the price elasticities for energy services by income groups (Section 4.2), and the forecasted demand for energy services by income groups (Section 4.3).

4.1 Remarks on the Datasets Used

Three datasets are used to determine income groups, price elasticities for energy services by income groups and the forecasted demand for energy services by income groups. These are: household expenditures in 2000; household equipment in 2000; and a subset of the 1993 Survey of Household Energy Use (SHEU). The first two datasets are processed from the same survey, the 2000 household spending survey (Statistics Canada 2001).

The income groups were determined using the household expenditures in 2000, the distribution of dwelling types across income groups, used to specify space heating, was determined using the household equipment in 2000, and appliance consumption across income groups was based on the subset of the 1993 SHEU. The mandatory use of different databases to extract the needed data gave rise to some discrepancies. A brief description of these discrepancies follows. Results are judged representative.

There is a fundamental difference between households and dwellings: there can be more than one household in a single dwelling. The data we used were solely based on household information.

The income groups were determined using the 2000 household spending survey (Statistics Canada, 2001). This survey is processed in two separate datasets, one on household expenditures and the other on equipment. Statistics Canada (2001) performed the categorization of income groups based on the household equipment dataset whose reference period is December 31, 2000 while the household expenditures reference period is January 1 to December 31, 2000. It results in a slightly different number of reporting households, but the difference is considered marginal. For quintiles, Statistics Canada (2002) reported differences in income ranges less than $1,500.

Although each income group does not have the same number of households in the subset of the 1993 SHEU, tercile shares are computed as if they were, coherently with the way income groups were determined. That the number of households is different across income groups in the subset of the 1993 SHEU database is due to two factors (Guertin et al., 2002). First, income groups were determined on another database (household equipment in 2000, see above). Second, this subset is not fully representative of the residential sector because it only comprises detached and attached houses and only households that agreed to report their energy bill.

4.2 The Three Income Groups

The households are split into three income groups—lower-, middle- and higher- income households. The range in income that defines each group is presented in Table 1 and was defined using household equipment data in 2000 (see Section 4.1). We use "terciles," where all income groups contain the same number of households at the Canadian level within the household equipment dataset in 2000. The number of estimated Canadian households in each group is 3,899,787. This equal number of households did not translate into an equal number of dwellings (see Section 4.4.2).

4.3 Determining Price Elasticities for Energy Services

In this study, price-elasticities of residential energy services for the three income groups were determined using an econometric approach (Guertin, 2002). The estimated values are given in Table 9 and are compared to the elasticities previously used in the MARKAL-ED and determined using expert judgment (Kanudia and Loulou, 1999).

Table 9: Comparison of Price Elasticities of Energy Services Used in MARKAL-ED and MARKAL-Equity

<table>
<tr><th rowspan="2">Income Group</th><th colspan="2">Space Heating</th><th colspan="2">Water Heating</th><th colspan="3">Appliances and Lighting</th></tr>
<tr><th>MARKAL-Equity</th><th>MARKAL-ED</th><th>MARKAL-Equity</th><th>MARKAL-ED</th><th>MARKAL-Equity</th><th>Appliances MARKAL-ED</th><th>Lighting MARKAL-ED</th></tr>
<tr><td>Low</td><td>-0.43</td><td rowspan="4">-0.100</td><td>-0.38</td><td rowspan="4">-0.300</td><td>-0.49</td><td rowspan="4">-0.055</td><td rowspan="4">-0.184</td></tr>
<tr><td>Medium</td><td>-0.33</td><td>-0.36</td><td>-0.39</td></tr>
<tr><td>High</td><td>-0.25</td><td>-0.34</td><td>-0.32</td></tr>
<tr><td>Average</td><td>-0.34</td><td>-0.36</td><td>-0.40</td></tr>
</table>

4.4 Allocating Energy Services to Each Tercile

For each province, we split all of the energy services demands, except one, into the three income groups. Lighting was not disaggregated because it is a marginal energy service with respect to its share of total energy requirements. Each of the disaggregated energy services is discussed in turn.

4.4.1 Appliances

The share of appliances for each tercile is determined using data from Guertin et al. (2002). The database used by the authors is a subset of the 1993 Survey of Household Energy Use (SHEU) where energy consumption has been explicitly disaggregated into three end uses, appliances and lighting; water heating; and space heating. We assume that the share of appliance usage is similar to that of appliance and lighting as a single end use.

Table 10: Share of Appliance Usage by Terciles

(Guertin et al. 2002)

Income Group	Appliance Usage	Share
Low	24 GJ	26%
Medium	31 GJ	34%
High	37 GJ	40%
Total	92 GJ	100%

4.4.2 Space Heating

Space heating is given in units of 10,000 dwellings. Six types of dwellings are explicitly modelled: detached houses, attached houses and apartments, and two dwelling ages (existing and new) for each, for a total of six space heating demands. We then split each space heating demand into the three income groups using the 2000 Survey of Household Spending (Statistics Canada, 2002). Tables 11 to 16 present the distribution of dwelling types across income groups.

Table 11: Distribution of Dwellings According to Income Groups: Canada

Income Group	Income Group			Total
	Low	Medium	High	
Detached	22.9%	33.8%	43.3%	100%
Attached	32.7%	34.8%	32.5%	100%
Apartments	56.8%	31.4%	11.8%	100%

Source: Statistics Canada (2002)

Table 12: Distribution of Dwellings According to Income Groups: Atlantic Provinces

Income Group	Income Group			Total
	Low	Medium	High	
Detached	32.8%	38.4%	28.8%	100%
Attached	45.9%	34.6%	19.5%	100%
Apartments	66.4%	26.9%	6.7%	100%

Source: Statistics Canada (2002)

Table 13: Distribution of Dwellings According to Income Groups: Quebec

Income Group	Income Group			Total
	Low	Medium	High	
Detached	23.8%	36.6%	39.6%	100%
Attached	41.6%	33.4%	25.0%	100%
Apartments	61.0%	28.5%	10.5%	100%

Source: Statistics Canada (2002)

Table 14: Distribution of Dwellings According to Income Groups: Ontario

Income Group	Income Group			Total
	Low	Medium	High	
Detached	19.7%	29.9%	50.4%	100%
Attached	23.8%	34.0%	42.2%	100%
Apartments	49.7%	36.3%	14.0%	100%

Source: Statistics Canada (2002)

Table 15: Distribution of Dwellings According to Income Groups: Prairies

Income Group	Income Group			Total
	Low	Medium	High	
Detached	22.9%	35.6%	41.5%	100%
Attached	35.0%	39.5%	25.5%	100%
Apartments	62.2%	29.6%	8.2%	100%

Source: Statistics Canada (2002)

Table 16: Distribution of Dwellings According to Income Groups: British Columbia

Income Group	Income Group			Total
	Low	Medium	High	
Detached	22.9%	33.8%	43.3%	100%
Attached	33.6%	35.8%	30.6%	100%
Apartments	58.4%	28.5%	13.1%	100%

Source: Statistics Canada (2002)

The sample sizes for the Atlantic and Prairie provinces were not sufficient to provide for specific data on the distribution of dwelling types across income groups at the provincial level. To circumvent this, we then grouped some provinces together.

When applying the distribution of income groups to each space heating demand (e.g., detached houses in British Columbia), we do not obtain anequal number of dwellings across income groups in Canada. The low-income groups contain the highest number of dwellings and the high-income group the lowest. There are two reasons for this. First, the distribution of dwellings at the provincial level in MARKAL-ED is different from the one from which the distribution of income groups was determined. Second, MARKAL is based on dwellings while the income groups were determined using household data. A single dwelling can sometimes house two or more households. Despite this discrepancy, results obtained are expected to be representative. All results are normalized to 1995 value to simplify our analysis and reporting.

4.4.3 Water Heating

Water heating is given in units of 10,000 dwellings without regard to the dwelling type. There is no need to explicitly split the water heating demand into three income groups as it is automatically derived from the space heating fuel shares as explained in Section 3.2.3.

4.4.4 Available Technologies

Technologies are defined for each energy services demand (Section 3.2). For a given energy services demand, the same set of technologies is available to all income groups.

5 Distributional Impacts of Meeting the Kyoto Target for Canada

Three simulations were run to analyze the distributional impacts of the Kyoto Protocol being implemented in Canada. The first simulation—the base case is the business as usual (BAU) scenario. It acts as a reference against which comparison can be performed. As its name indicates, no carbon constraint policy is considered. In the BAU, demands for energy services are inelastic and the residential sector is considered as one large homogenous group.

In the second simulation, a Kyoto target for Canada—six per cent reduction of GHG emissions below the 1990 level (Section 1)—is put into effect starting in 2010. It is important to note that the target is applied to Canada as a whole, and not to individual sectors of the economy (residential, commercial, transport, industrial). In this scenario, we still assume that the residential sector is a homogenous group but is modelled as a group with specific price elasticity. The price elasticity used for the group as a whole is taken as the average of the elasticities of the three income groups. We call this simulation Kyoto.

In the third simulation, we model the residential sector as a heterogeneous group made up of three different income groups, each with their own price elasticity for energy services. This simulation is called KyotoE. Comparison between simulations 2 and 3 will allow us to study if income differentiation is an important variable to consider when policy-makers decided to implement a Kyoto protocol. It will also give us some clue to policy interventions that may be used to reduce the burden on certain income groups if the need arises. This is a critical dimension that has often been overlooked by the aggregative models that are used to evaluate the welfare impacts of the Kyoto Protocol.

5.1 Emissions Profile

Figure 2 shows total emissions by the Canadian residential sector from 1995 to 2020. These include emissions from space heating, water heating and appliances. We observe that even under BAU, GHG emissions can be expected to decrease over time and tend to plateau out around 2010. This can be explained by the renewal of dwellings factor, whereby five per cent of old dwellings are replaced by new ones with improved insulation and furnace efficiency.

Once the Kyoto target comes into action in 2010, we observe a sharp decrease in emissions by the residential sector. By 2020, emissions have been reduced by 28 Mt or 77 per cent.

Results also show that, at the aggregate level total emissions reduction levels are almost identical in Kyoto and KyotoE. Differentiating income groups with specific elasticities does not add more information at the aggregate level as we observe a difference in emissions of about one per cent between Kyoto and KyotoE.[1] Emissions are a function of energy consumed and technology choices, which in turn depend on income (via the price elasticity). The relative size of each group does not play a major role because they are the same in the BAU case. Results suggest that factors determining emissions cancel out in KyotoE with respect to Kyoto through the aggregation process, and that income group modelling does not add new information. However, results show otherwise when looking at technology choices, fuel patterns and energy consumption: income groups will go through different paths. This is the focus of the next section.

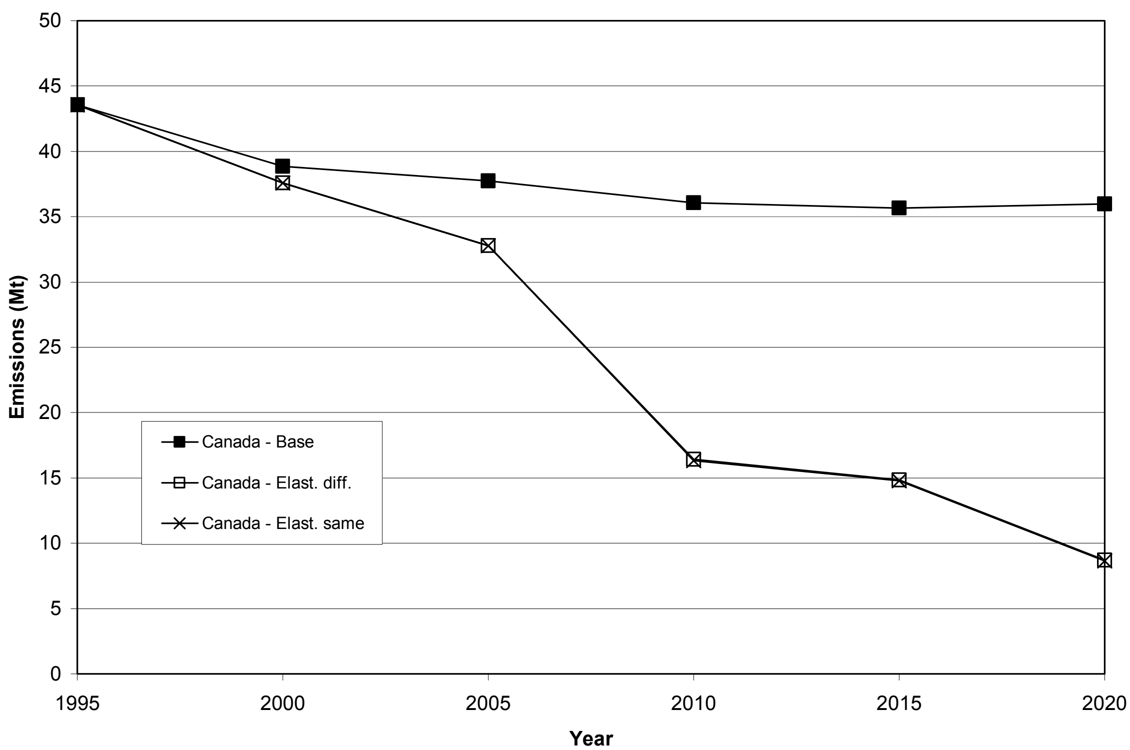

Figure 2: Emissions in the Canadian Residential Sector from 1995 to 2020

[1] The current MARKAL model does not allow disaggregating emissions into the three income groups.

5.2 Demand for Energy Services

Demand for energy services is either expressed in Joules (appliance usage and lighting) or in number of dwellings (space and water heating) as shown in Table 3. Figure 3 shows the loss in demand for energy services—in particular space heating for old apartments in British Columbia—under Kyoto and KyotoE. Under Kyoto, the loss in demand for space heating is approximately 14 per cent. Under KyotoE, we observe that the low-income group actually experiences a greater demand loss of up to 16 per cent by 2020, while the high-income group suffers a smaller drop of up to 10 per cent by 2020. This is consistent with the relative price elasticities of energy services of the respective income groups (see Table 2). This additional information can prove to be important for equity and distributive justice issues when policy-makers are designing the instruments to implement the Kyoto accord.

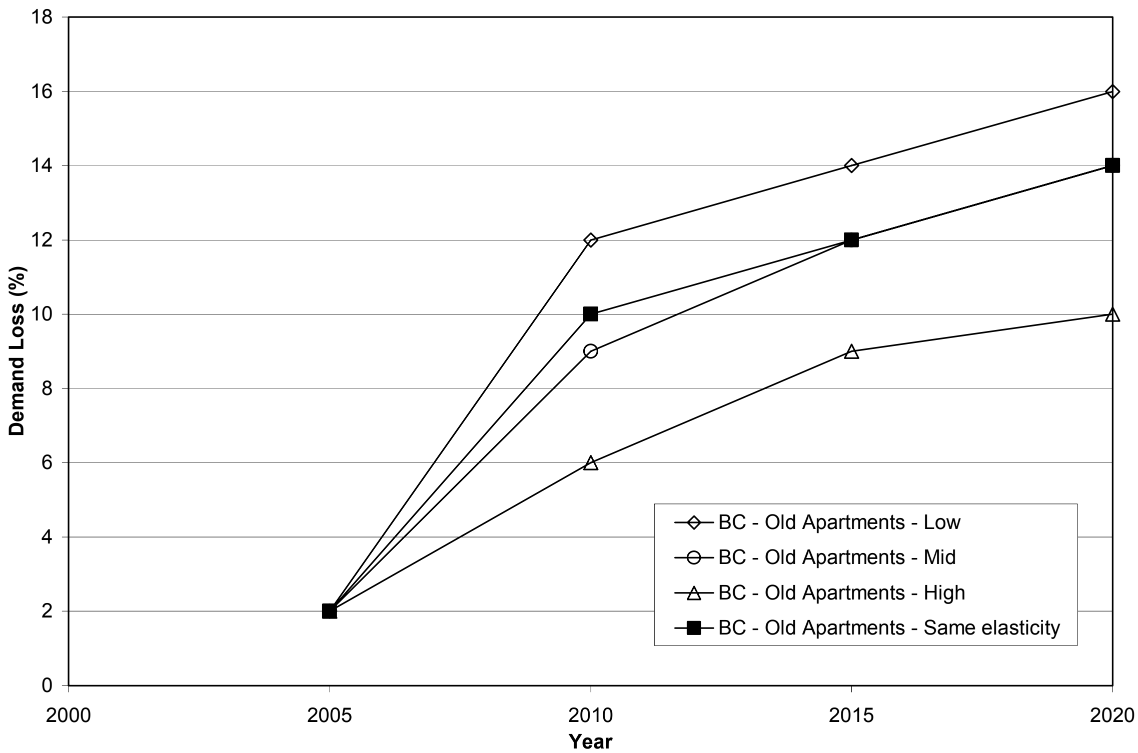

Figure 3: Energy Services Demand Loss for Space Heating Load in Existing Apartments in British Columbia

5.3 Technological Choices, Fuel Patterns and Energy Consumption

Fuel consumption is directly linked to technological choices. A given technology will use one or two fuels at most (e.g., dual-fuel furnace such as electric-oil furnace) to provide an energy service. The level of fuel consumption depends on the efficiency of the technology in converting fuel into energy service.

Energy consumption is usually not equivalent to energy services demand. Energy consumption refers to utilities that are then transformed into energy services using a conversion technology, such as light bulbs, furnaces, water heaters, etc. (see Figure 1). In MARKAL, demand for energy services is expressed in Joules (appliances and lighting) but also in number of dwellings (space and water heating). In the later case, these demands are converted in units of Joules using the specific energy consumption, which varies from one dwelling type to the other and also across provinces (see Section 3.2.1).

Energy consumption is equivalent to demand for energy services in the case of appliance usage and lighting. It is equivalent in MARKAL because the efficiency of the conversion technologies is 100 per cent.

As a result, the level of energy consumption directly depends on technological choices made.

5.3.1 Technology choices and Fuel Patterns by End Use and Income Groups

5.3.1.1 Appliance Usage

In the Canadian MARKAL model, appliance usage is modelled as a single fuel and technology: a 100 per cent electricity-based conversion technology. There is thus no technological choice with respect to appliance usage.

The energy consumption for appliances slightly increases over time in the absence of carbon constraint. But with a Kyoto target, the energy consumption sharply decreases beyond 2005 for the three end uses (see Figure 4). We observe that the high-income group sees the least reduction of its appliance consumption with the low-income group the highest reduction. In the presence of a single technology using a single fuel, these results are not surprising; they are consistent with the relative price elasticities of the income groups (see Table 2).

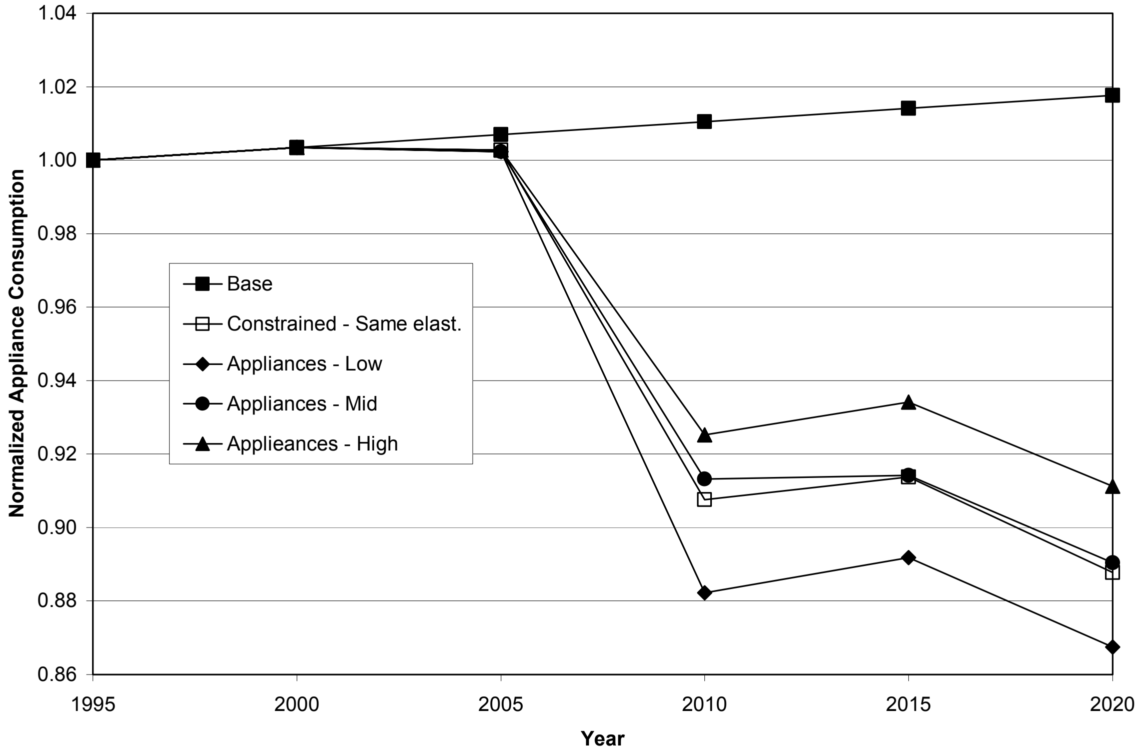

Figure 4: Normalized Appliance Consumption

5.3.1.2 Space Heating

Space heating is the single biggest end use and its share remains stable over time in the base and constrained cases. It accounts for 66 per cent of energy consumption in 1995 and 68 per cent in the base case, Kyoto, and KyotoE in 2020.

Technological choices in MARKAL are based on the lowest economic costs and, in presence of an emissions constraint, the choice is made on the lowest economic costs to meet the constraint. Fuel prices, investment costs of technology, lifetime, efficiency and emissions are the main variables that determine final costs and therefore the final choice of the technologies by the respective income groups. Technological choice is thus a complex process, and in a non-linear optimization framework, such as MARKAL-ED, many choices are equivalent with respect to the objective sought, i.e., lowest costs to meet the emissions constraint. Furthermore, technological choices in MARKAL are not given in terms of numbers of devices but in energy consumption (Joules). As a result, comparing technological choices from one group to another is not always straightforward.

Results show a transfer of technologies from natural gas heating and oil furnaces to the benefit of electric space heating (see Figures 5 and 6). The introduction of an emissions constraint results in the disappearance of natural gas furnaces and oil furnaces in old dwellings by 2010, and the increase in popularity of electric space heating. Furthermore, new dwellings' use of oil furnaces was only marginal. Overall, propane-based technologies are marginal (see Table 17) and are thus not shown in Figures 5 and 6.

Historically, hydro-generated electricity is favoured in Canada representing about 62 per cent of total electricity production in 1997 (NCCP, 1999). Two provinces account for 40 per cent of total electricity production using hydro. Coal-fired plants are the second largest electricity producers and account for 17 per cent of total production in 1997 (NCCP, 1999). In the presence of a carbon constraint, non-fossil-fuel generation for electricity is enhanced. We observe a shift from coal-fired plants to hydro, natural gas and wind, all of which emit fewer GHGs or none at all (Haloa, 2000).

Table 17: Fuel Consumption in Space Heating (PJ)

Fuel-based Technology	BAU		KyotoE	
	1995	2020	1995	2020
Electricity	192	258	192	371
Natural gas	477	431	477	111
Wood	90	332	90	334
Oil	115	43	115	2
Propane	12	0.1	12	9.5

Income groups present distinctive behaviours. While the high-income group clearly favours electric space heating, the middle-income groups favours wood stoves (see Figures 5 and 6). Electric space heating is more expensive to install than wood stoves and is also more costly to use. Results show that the high-income group is less responsive to energy price changes than the middle-income group in terms of reducing its demand for energy services, as shown by its price elasticity (see Table 2 and Figure 3), but is quite responsive in changing the technologies, and thus its fuels, to adapt to the introduction of a carbon constraint. The low-income group, highly sensitive to price changes, greatly reduces its demand for energy services and thus its fuel consumption. Fuel switching is less prominent within the low-income group than other income groups.

The low-income group, although it adapts to new constraints by reducing its demand in energy services, does not fundamentally change its fuel consumption pattern as do other groups. This tends to show that the low-income group is not able to cope as easily to new constraints as other income groups.

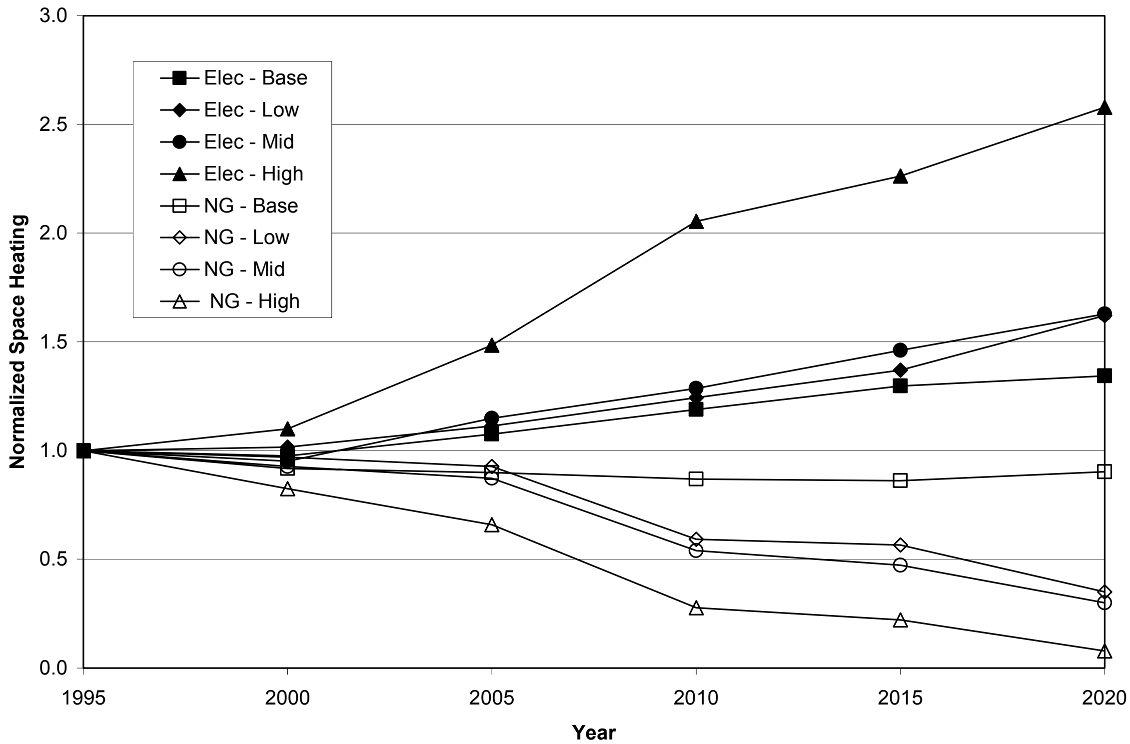

Figure 5: Normalized Space Heating Consumption: Electricity and Natural Gas

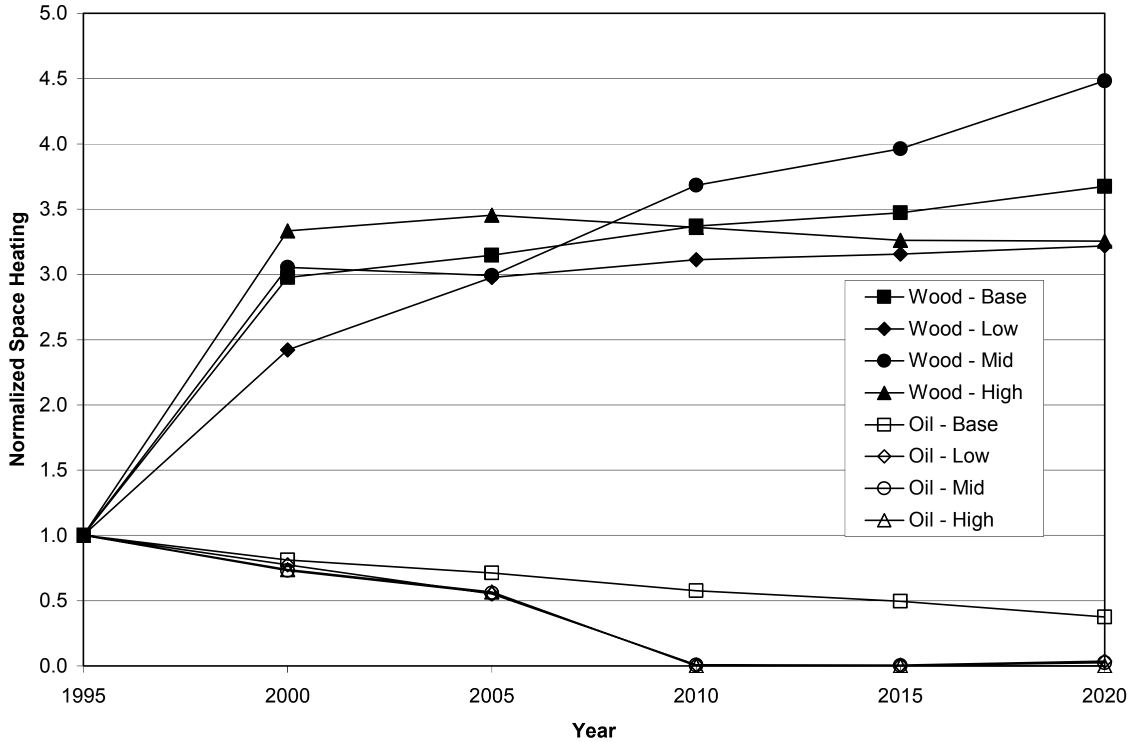

Figure 6: Normalized Space Heating Consumption: Wood and Oil

Looking at aggregate results, the presence of the emissions constraint forces the lower-income group to reduce its space heating consumption by 13 per cent by 2020 while the middle-income group experiences a small increase in space heating consumption by one per cent in 2020 (see Figure 7). The response of the high-income group is between these two extremes, with a reduction of its space heating consumption by 10 per cent in 2020. As expected, the low-income group faces the greatest reduction of its energy consumption, consistent with the fact that it has the greatest price elasticity for space heating. Although the middle-income group reduces its demand in energy services (see Figure 3), its energy consumption, about the same order of magnitude in 2020 or in 1995, raises questions. This behaviour is explained when looking at technological choices made by the middle-income group with respect to space heating. The middle-income group favours wood stoves over electric space heating in terms of energy consumption while the high-income group favours electric space heating (see Section 5.3.1.2). Knowing that wood stoves are not as efficient as electric space heaters, the level of energy consumption to meet space heating demand with wood stoves is greater than that of electric space heaters. As a result, level of energy consumption by the middle-income group is greater in 2020 than the high-income group. It is really the choice of technology (and fuel) that explains the rather surprising level of energy consumption of the middle-income group.

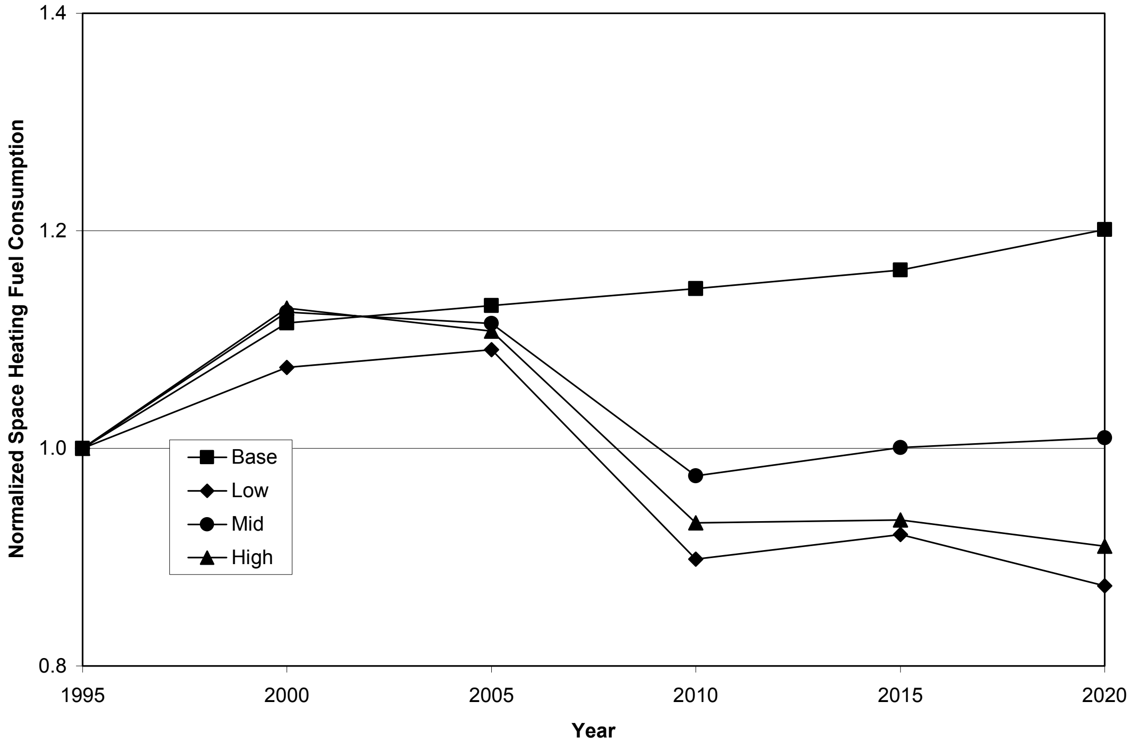

Figure 7: Normalized Space Heating

5.3.1.3 Water Heating

Water heating technologies modelled in MARKAL are all based on a single fuel: electric, natural gas, oil and propane water heaters.

The presence of an emissions constraint favours electric water heaters over natural gas water heaters, propane-based technologies and oil water heaters (see Table 18 and Figure 8). Propane-based technologies and oil water heaters are marginal and are thus not shown in Figure 8. The popularity of electric water heaters in an emissions-constrained Canada is due to the change in generation mix over time and is explained above (see Section 5.3.1.2)

Table 18: Fuel Consumption in Water Heating (PJ)

Fuel-based Technology	BAU		KyotoE	
	1995	2020	1995	2020
Electricity	72	104	72	166
Natural gas	146	160	146	38
Oil	37	25	37	0
Propane	3	20	3	11

When looking at specific income group behaviour, we once more observe that groups that are less sensitive to changes in energy prices exhibit a preference for switching fuels despite the fact that the range of price elasticities is not as broad for water heating as it is for space heating (see Table 2). The low-income group, which is more sensitive to changes in price, also switch fuels but to a lesser degree.

As in the case of space heating, results tend to show that groups that face greater reduction in their demand in energy services will not change their technology as much as higher income groups, despite the fact that the cost of investing in an electric water heater is less than the cost of a gas water heater. This is consistent with the fact that the low-income group has less buying power.

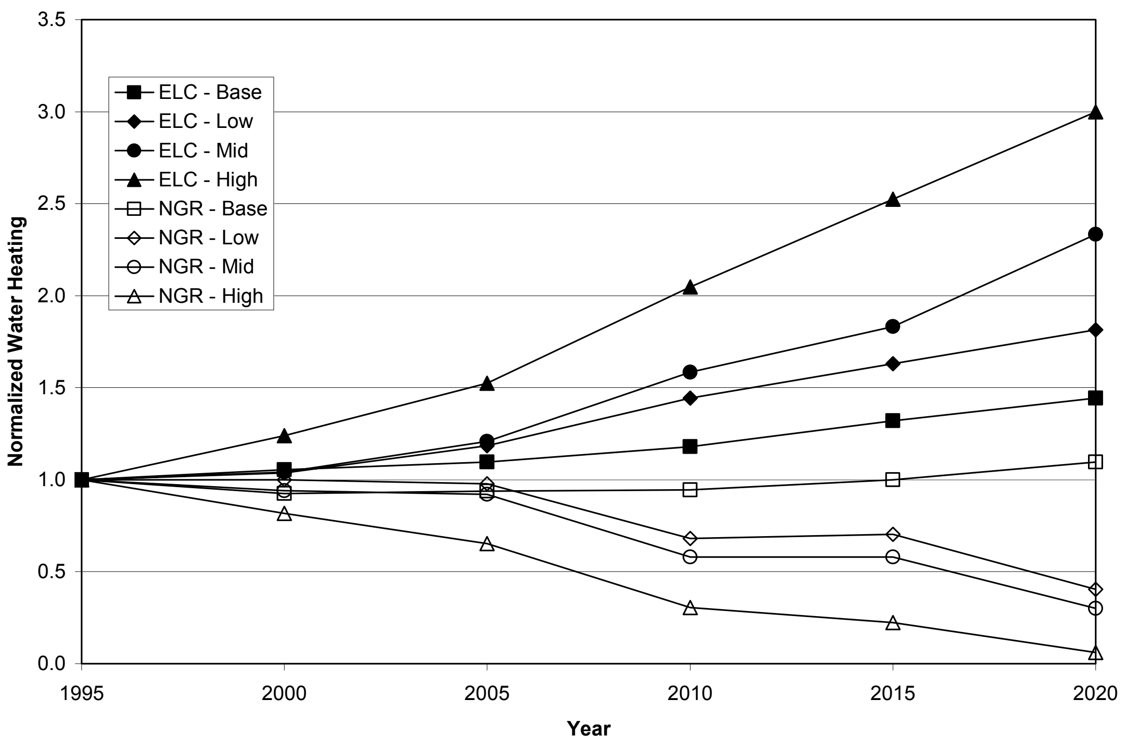

Figure 8: Normalized Water Heating Consumption: Electricity and Natural Gas

Energy consumption for hot water use, at the aggregate level, exhibits a similar pattern to that of space heating. The hot water consumption of the low-income group decreases most—down to 76 per cent by 2020—while the middle-income group shows the least reduction, down to 89 per cent (see Figure 9). The hot water consumption of the high-income group reduces over time between these two extremes. When looking at energy consumption for water heating by income group and fuel (see Figure 8), we noted that, by 2020, the pattern of energy consumption moved in opposite directions (but not necessarily symmetrically) for electricity and natural gas, the two main fuels for water heating. When adding together energy consumption for different fuels, the resulting level of energy consumption is a function of the disaggregated fuel pattern.

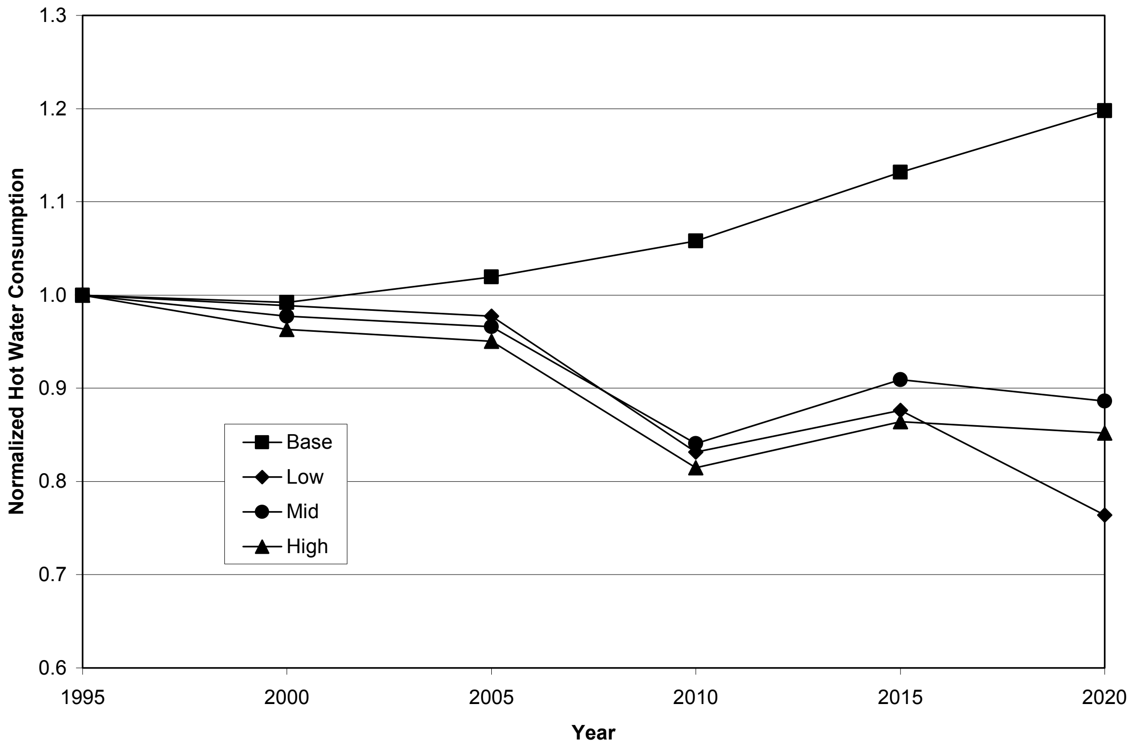

Figure 9: Normalized Hot Water Consumption

5.3.1.4 Emerging New Technology: Solar Space Heating

Solar space heating emerges when the carbon constraint is active (see Table 20). This technology is not present at any time in the base case. The emergence of this rather expensive technology in terms of investment cost (or capital cost) is rather large for the low-income group. It is ideally suited for the higher-income groups. This result therefore highlights the need to either limit the use of more expensive technologies only to higher-income groups, or to impose budget constraints across the various income groups reflecting their ability to buy.

Table 19: Solar Space Heating – Constrained Case

Income Group	1995	2020
Low	0 PJ	5.1 PJ
Middle	0 PJ	0 PJ
High	0 PJ	0 PJ

5.3.2 Energy Consumption in the Residential Sector

Space heating and hot water account for most of the increase of residential energy consumption in the base case (see Table 20). Residential energy consumption increases over time in BAU, up to 17 per cent by 2020 (see Table 20 and Figure 10). When the Kyoto target is active, energy consumption in the residential sector decreases sharply beyond 2005.

Table 20: Energy Consumption by End Use in 2020
Energy Consumption is normalized to 1 in 1995.
SH: Space heating; HW: Hot water; APP: Appliances

	Total	**SH**	**HW**	**APP**
Base Case	1.17	1.20	1.20	1.02
Constrained Case – Single Elasticity	0.91	0.93	0.83	0.89
Constrained Case – Income Groups (L+M+H)	0.91	0.93	0.83	0.89
Constrained Case – Low-Income Group	0.87	0.87	0.76	0.87
Constrained Case – Middle-Income Group	0.96	1.01	0.89	0.89
Constrained Case – High-Income Group	0.90	0.90	0.85	0.91

Results show that the low-income group experiences the greatest reduction in energy consumption, down by 13 per cent by 2020 (see Table 20 and Figure 10). It is the middle-income group that faces the smallest reduction of its residential energy consumption, with a decrease of four per cent by 2020, while the high-income group faces a 10 per cent decrease in the same period. These results are explained by looking at results disaggregated by end uses. We observed that the middle–income group exhibits the same behaviour as the one observed for that group's use of space heating. As space heating accounts for some 68 per cent of total energy consumption in any case and time, the behaviour of the middle-income group is reflected in the total energy consumption (see Table 20).

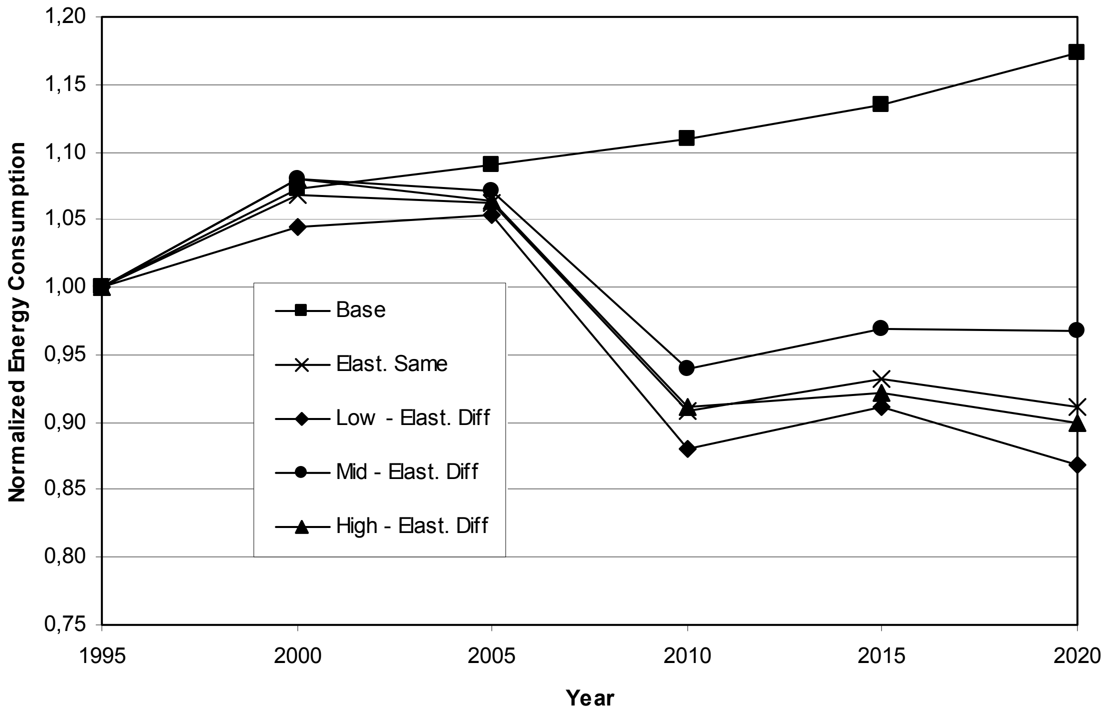

Figure 10: Normalized Energy Consumption in the Residential Sector

5.4 Policy Implications

Results show that the low-income group faces the greatest reduction in its energy consumption, due to its higher price elasticity, and is not as likely as the other groups to change its technology and thus its pattern of fuel consumption. The middle- and high-income groups are likely to present a change in technology and fuel to adapt to an emissions constrained scenario. Low-income households do not have this ability to cope.

Policies can therefore play a role in minimizing the impact of increased energy prices on low-income households in a transitional period. There are two potential kinds of policy:

Targetted at helping low-income households purchase more efficient technologies (to reduce the impact on their use of energy services). These policies could essentially be focused on space heating, which accounts for about 68 per cent of total energy consumption in provinces where space heating is not met through electric baseboards. Policies aimed at efficiency of technologies, such as space heating, have a long-lasting effect at the household level.
Reduce impacts of increased energy prices through fiscal policies.

Modelling with MARKAL-Equity does not take into account the rebound effect, where the installation of a more efficient furnace might indeed decrease the demand for energy consumption, but not as much due to the fact that the household might increase its demand for space heating by setting the house temperature slightly higher. This has been discussed in Guertin et al. (2002).

6 Conclusion

This study demonstrates that the MARKAL-Equity model can assess impacts of energy policies on low-income groups, and as such is a valuable policy tool. The MARKAL-Equity model is innovative because, to our knowledge, such an assessment on low-income groups has never been done with a demand and supply energy model. Furthermore, we used specific price elasticity for each energy service and income group.

Results show that under the Kyoto target, total energy consumption in the residential sector decreases by some 10 per cent below 1995 levels while, in absence of Kyoto targets, it would increase by 17 per cent. The difference between the two scenarios is some 27 points. Space heating is the single biggest end use, accounting for some 68 per cent of total residential energy consumption. It still holds under the Kyoto target.

Aggregate results do not show specific information when comparing Kyoto and KyotoE. Looking at income groups shows otherwise. All income groups will reduce their demand for energy services but the impact on their energy consumption will vary according to the income group, showing a difference in coping mechanisms. Low-income households will unequivocally bear a greater burden of the emissions reduction constraint. They will face the greatest reduction in demand for energy services and energy consumption. Results show that the low-income group does not fundamentally replace its technology, and thus change its fuel consumption pattern. This shows that the low-income group tends not to be able to cope as easily to new constraints as other income groups. The middle-income group will also face a reduced demand for energy services but will see its overall energy consumption slightly increase. More than the other groups, the middle-income group adopts wood stoves which have a lower efficiency than other technologies. This partially explains the observable increased energy consumption while the demand for energy services decreased. Transitional policies should therefore be aimed to the low-income group to it cope with energy policies that will curb emissions to reach the Kyoto target. Policies could be designed to help low-income families purchase more efficient technologies for space heating, as it is the single biggest end use energy consumption.

This study is a first step toward MARKAL-Equity, a model focused on responses of income groups to emission constraints and other energy policies. Although the model could still be enhanced, this study showed the importance of taking into account specific income group behaviours and responses to energy policies.

This work, performed on Canadian data, can easily be extended to developing countries, especially because the MARKAL community is active in some developing countries. By developing the project within the MARKAL family, it allows the dissemination of the new approach to a large number of research groups in developed as well as developing countries.

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8 Appendix: The MARKAL Family of Models

MARKAL (for MARKet ALlocation) was developed in the late 1970s by member countries of the OECD under the guidance of the International Energy Agency (IEA) (Berger et al., 1992; Condevaux-Lanloy and Fragnière, 2000; Fishbone and Abilock, 1981), and is therefore a mature tool. It is now in use in more than 35 countries (Condevaux-Lanloy and Fragnière, 2000).

MARKAL is a dynamic optimization model that tracks energy flows from production sources to end-use energy. In that sense it is an energy-process model or a bottom-up model. It does not comprise a macro-economic module and, therefore MARKAL is a partial equilibrium model. The equilibrium is only met on the energy market. Feedback on macro-economic parameters such as employment rates, consumption and interest rates are not considered.

The standard or basic MARKAL model is first discussed in section 6.1. Then, the multi-region MARKAL is introduced in 6.2. Finally, the MARKAL-ED model is presented in section 6.3.

8.1 Standard MARKAL

MARKAL tracks energy flows from production sources to end-use energy. In that sense it is an energy-process model. It does not comprise a macro-economic module and, therefore, MARKAL is a partial equilibrium model. The equilibrium is only met on the energy markets. Feedback on macro-economic parameters such as employment rates, consumption and interest rates are not considered.

The focus of MARKAL is really on satisfying the demand for energy services with the least costs. MARKAL, in its standard form, minimizes the long-term total discounted costs subject to constraints. The discounted total costs are given by:

$$\text{Total Costs} = \text{Technology Costs} + \text{Imports} - \text{Exports} - \text{Salvage value} + \text{Emission fees} \quad (1)$$

where each component is a discounted cost. The salvage value is the "residual monetary value of all investments remaining at the end of planning period" (Loulou et al., 1997). This term avoids border effects at the end of the planning period. Without it, only investments depreciated within the time frame would be made. The constraints are: (1) electricity flow conservation; (2) electricity peak reserve constraint; (3) satisfaction of demand for energy services; (3) capacity transfer; (4) capacity utilization; (5) source capacity; (6) cap on capacity growth; and (7) emissions constraint. The problem that MARKAL solves can now be written as the following linear program:

(2)

subject to $\sum_k CAP_{k,i}(t) = DM_i(t)$ (satisfaction of energy services demand)

and the other constraints listed above.

where $CAP_{k,i}(t)$ is the capacity of end-use technologies and $DM_i(t)$ is the demand for energy service *i*. The focus is given here to the constraint that expresses the satisfaction of energy services demand. This constraint highlights the fact that it is the demand for energy services that drives the supply and not the other way around (when financial resources are not a limiting factor). The demand for energy services is exogenous to MARKAL and therefore fixed at each time period. MARKAL solves for the following five variables: (1) the investment in technology *k* at period *t*; (2) the capacity of technology *k* at period *t*; (3) the activity of technology *k* at period *t*; (4) the amount of energy form *i* imported at period *t*; and (5) the amount of energy form *i* exported at period *t*. Energy flows are expressed in terms of activity and therefore need not to be explicitly defined as a variable.

8.2 Extended MARKAL or Multi-Region MARKAL

The Extended MARKAL model, also known under Multi-Region MARKAL model, allows multiple electricity grids. This model is suitable for Canada as each province has its own electricity grid with some connections between adjoining grids. The current model for Canada represents 10 provinces or regions with the territory of Nunavut aggregated to British Columbia. The multiple grid feature is now included in MARKAL-ED.

8.3 MARKAL-ED

MARKAL, in its standard version, does not include feedback of prices on the energy services demand. Price elasticities were included in MARKAL in 1995 and this version is known as MARKAL-ED (Loulou and Lavigne, 1995). MARKAL-ED is fully implemented in most countries using MARKAL, and is invoked by specifying extra data in the input file (i.e., elasticities and ranges of variation for all elastic demands).

In MARKAL-ED, the demand for energy services varies according to the price of energy. The expression of the demand for energy services is expressed as follows:

$$DM_i(p_i, t) = K_i(t) * p_i(t)^{E_i(t)} \quad (3)$$

where:

$DM_i(t)$ is the energy services demand *i* at period *t*;

$K_i(t)$ is a constant related to energy demand *i* at period *t*, chosen so that Equation (3) is an identity in the base case run of the model;

$p_i(t)$ is the price for energy form *i* at period *t*;

$E_i(t)$ is the constant elasticity for energy services demand *i* at period *t*.

Equation (3) may also be expressed as the inverse energy services demand, i.e., the price is given as a function of the demand. It then reads:

$$p_i(DM_i, t) = \left(\frac{DM_i(t)}{K_i(t)} \right)^{1/E_i(t)} \tag{4}$$

If the point ($DM_i^0(t)$, $p_i^0(t)$), corresponding to a base case model run, is known, then the constant $K_i(t)$ can be determined and equation (4) can be rewritten as:

$$p_i(DM_i, t) = p_i^0(DM_i, t) \left(\frac{DM_i(t)}{DM_i^0(t)} \right)^{1/E_i(t)} \tag{5}$$

The problem MARKAL-ED has to solve is to find the equilibrium between the energy services demands (equations 3 or 5), and the energy supply. The equilibrium is reached when prices from both the demand and supply sides are the same. This approach ensures that the price of each energy form is the marginal value of the energy form in the Linear Program.

The equilibrium between the energy demand and the energy supply is not computed directly by using equations (2) and (5), but is computed using an equivalent equilibrium model. The equivalent equilibrium model is given by the Equivalence Theorem which states that "a supply/demand equilibrium is reached when the sum of the producers and the consumers surpluses is maximized" (Loulou and Lavigne, 1995). MARKAL-ED thus solves the following problem:

$$\text{Max} \sum_i \sum_t \left(\int_a^{DM_i(t)} p_i^0(t) \left(\frac{q}{DM_i^0(t)} \right)^{1/E_i} dq \right) - \text{total supply costs} \tag{6}$$

subject to $\sum_k CAP_{k,i}(t) - DM_i(t) = 0$

and the other constraints.

According to a classical results of mathematical economics (see Takayama and Judge, 1971; Loulou and Lavigne 1995), this equivalence is valid if the cross price elasticities of demands are symmetric. This condition is of course met when cross-elasticities are null as is the case in MARKAL-ED.

Note that the expression of the constraint for meeting the demand for energy services is now slightly different than the one found in equation (2). The new form emphasizes the fact that the demands may now vary.

When price elasticities are included, the optimization problem that has to be solved is transformed from one of minimization of total system costs to one of maximizing net social surplus, given by the difference between the integral of the inverse demand curve and the total supply costs. The net social surplus is often considered a proxi for social welfare (Loulou et al., 1996).

In practice however, the MARKAL Linear Programming code cannot directly handle the non-linearities introduced by the integral in the objective function. This difficulty is resolved by writing each demand variable as the sum of a number of increment variables, and by approximating the demand curve by a step-wise constant function (staircase shaped function). Once this is done, the objective function becomes again a linear function.

The linearization of each inverse energy demand curve is performed by subdividing it into a number of equal width intervals over a predefined range. The range of each demand for energy services must be such that any anticipated change in the demand will remain within the range. The range and the width of each interval are chosen by the modeller. The full notational details of the discretization are available in Loulou and Lavigne (1995).

The MARKAL-ED approach to computing the equilibrium leads to a two-step procedure as follows:
Preliminary Base Run – Determine the constant *K*.

> This is done by running MARKAL with fixed (exogenous) demands, $DM_i^0(t)$. This is a standard MARKAL run. The shadow prices of the demand constraints supply the prices that determine the point ($DM_i^0(t)$, $p_i^0(t)$) used to calculate the constant, using equation (4).

Run MARKAL-ED with price elasticities

> The MARKAL-ED code automatically linearizes the inverse demands for energy services according to the following input data provided by the user: elasticities; upper and lower bounds; and the number of intervals into which the demands for energy services are broken down. The output of this run may be processed so as to retrieve the two separate components of the objective function (i.e., system cost and the integral under the inverse demand curve).