

MEETING NATIONAL TARGETS:  
Carbon Dioxide and the Future Development of  
the Canadian Energy System

by

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## ABSTRACT

Canada, as part of its Green Plan, has committed to stabilizing emissions of greenhouse gases at 1990 levels by the year 2000. This thesis examines the costs and benefits of meeting a key component of this commitment: carbon dioxide (CO<sub>2</sub>) emissions from the energy system.

The methodology is based on “bottom-up,” techno-economic modeling of the Canadian energy system, from resource extraction through to the delivery of energy services, over the period 1990–2020. Twenty-three scenarios, including a “business as usual” base case, are analyzed to investigate the effects of different forms of CO<sub>2</sub> emission limits and different levels of CO<sub>2</sub> emission taxes. Each scenario is an internally consistent set of assumptions on the future development of the energy system. These assumptions include the growth in energy service demands, the cost and performance trajectories of technologies, and socio-political constraints (e.g, on the development of nuclear energy).

Subject to these assumptions, the key conclusions of this work are:


- CO<sub>2</sub> emission stabilization can be achieved by 2000, and can be maintained through to 2020.
- The total cost of achieving the commitment can be as low as \$26 billion (this being the sum of all discounted costs over the period 1991–2020, in 1990 Canadian dollars). This represents about \$23/tonne CO<sub>2</sub> abated, which is equivalent to a levy of
  - \$1.2/GJ natural gas,
  - \$0.06/litre gasoline, or
  - \$55/tonne hard coal.
- The cost of meeting the commitment is minimized when the energy system is allowed maximum flexibility in doing so. Emission stabilization for the energy system as a


whole (via a national system of tradable emission permits) costs \$41 billion less than the same emission limit applied individually to each sector of the energy system.


- The commitment can also be met via a CO<sub>2</sub> emissions tax of about \$60/tonne CO<sub>2</sub> emitted, i.e., a carbon tax. While the total cost now rises to \$277 billion, about \$253 of this is tax revenue.
- In this analysis the increase in costs due to CO<sub>2</sub> emission reduction is offset by a reduction in the damage costs for other emissions, particularly SO<sub>2</sub>.
- The greatest impacts of CO<sub>2</sub> emission reduction are on coal use, and especially on coal-sourced electricity generation: only 1.4% of electricity is coal-sourced in 2020 under the emission stabilization target, compared to more than 17% today.


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## Nomenclature

AIEC	Automotive Industry in Expanding Countries
ARB	(California) Air Resources Board
AWEA	American Wind Energy Association
BAT	“best available technology”
BAU	“business as usual”
BP	British Petroleum
CAA	Canadian Automobile Association
CAFE	Corporate Average Fuel Economy
CARB	California Air Resources Board
$\text{CCl}_4$	carbon tetrachloride
CERI	Canadian Energy Research Institute
CFC	chlorofluorocarbon
$\text{CH}_4$	methane
CHP	combined heat and power
$\text{CO}_2$	carbon dioxide
CO	carbon monoxide
CO2DB	CO <sub>2</sub> Database
DAU	“dynamics as usual”
ECMT	European Conference of Ministers of Transport
EJ	exajoule, 10 <sup>18</sup> Joules
EMF	Energy Modeling Forum
EMR	Energy, Mines and Resources Canada
ETSAP	Energy Technology System Analysis Project
GDP	gross domestic product
GERAD	Groupe d'études et de recherche en analyse des décisions
GHG	greenhouse gas
GJ	gigajoule, 10 <sup>9</sup> Joules
GNP	gross national product
GW	gigawatt, 10 <sup>9</sup> Watts
GWy	gigawatt-year, 10 <sup>9</sup> Watt-years
Gp-km	gigapassenger-km, 10 <sup>9</sup> passenger-kilometres
Gt	gigatonne, 10 <sup>9</sup> tonnes
Gt-km	gigatonne-km, 10 <sup>9</sup> tonne-kilometres
IEA	International Energy Agency
IFSD	Interfuel Substitution and Demand Model

IGCC	integrated gasification, combined-cycle
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
ISTUM	Intra-Sectoral Technology Use Model
LH <sub>2</sub>	liquid hydrogen
LNG	liquid natural gas
LP	linear programming
MARKAL	MARKet ALlocation model
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental impact
NEB	National Energy Board
NGL	natural gas liquid
NO <sub>x</sub>	nitrogen oxides
NPV	net present value
N <sub>2</sub> O	nitrous oxide
OECD	Organization for Economic Cooperation and Development
OECD-NEA	OECD Nuclear Energy Agency
ONCI	Ontario Nuclear Cost Inquiry
OTEC	ocean thermal energy conversion
O <sub>3</sub>	ozone
O&M	operating and maintenance
PJ	petajoule, 10 <sup>15</sup> Joules
ROI	return on investment
SAE	Society of Automotive Engineers
SCE	House of Commons Standing Committee on the Environment
SERI	Solar Energy Research Institute
SFU	Simon Fraser University
SMR	steam-methane reforming
SOCC	social opportunity cost of capital
SO <sub>2</sub>	sulphur dioxide
STP	social time preference
TED-EMR	Transportation Energy Division, Energy, Mines and Resources Canada
UNCED	United Nations Conference on Environment and Development
USDOE	U.S. Department of Energy
USOTA	U.S. Office of Technology Assessment
VOC	volatile organic compounds
WMO	World Meteorological Organization

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## Chapter 1

# Introduction

Canada has committed to stabilizing emissions of carbon dioxide and other greenhouse gases at 1990 levels by the year 2000 (Government of Canada 1990). This thesis describes the formulation of a techno-economic model of the Canadian energy system, and its use to examine the feasibility, potential costs, and potential benefits of Canada meeting its commitment. More specifically, this work investigates reduction of the most important subset of greenhouse gas emissions: carbon dioxide from the energy system.

### 1.1 Motivation: Greenhouse Gas Emission Reductions

The term *greenhouse effect*<sup>1</sup> refers to the phenomenon by which radiatively active gases or greenhouse gases (GHGs) in the earth's atmosphere, primarily carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), nitrous oxide (N<sub>2</sub>O), and chlorofluorocarbons (CFCs)<sup>2</sup> maintain the temperature of the earth's surface higher than it would otherwise be. The property these gases share, in differing degree, is transparency to the shorter-wavelength radiation which the

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<sup>1</sup>As pointed out in *The State of Canada's Environment* (Government of Canada 1991b, p. 22-5), *greenhouse effect* is a misnomer. Greenhouses remain warmer than their surroundings primarily because the structure reduces convective heat losses, and only to a lesser extent because of changes in the radiative energy balance.

<sup>2</sup>The most radiatively important gas in the atmosphere is water vapour (H<sub>2</sub>O). However, H<sub>2</sub>O is generally not included among GHGs because its concentration in the atmosphere is too large to be directly affected by human activities. Here, as elsewhere, the term *greenhouse gases* implies trace gases. Other GHGs are ozone (O<sub>3</sub>) and carbon tetrachloride (CCl<sub>4</sub>) (Houghton, Callander & Varney 1992, p. 8).

earth receives from the sun, and absorptivity for the longer-wavelength radiation emitted by the earth back into space. Thus their effect is to modify the earth's energy balance.

The existence of a natural greenhouse effect is unquestioned (Houghton, Jenkins & Ephraums 1990, p. xxxvii), and it is estimated that this natural effect has raised the earth's surface temperature about 32°C. Also, there is little doubt that emissions from human activities are raising atmospheric concentrations of the primary GHGs, resulting in an enhanced greenhouse effect (Houghton et al. 1990, p. xi) — what Ramanathan (1988) refers to as “an inadvertent global experiment.” (Table 1.1 lists the relative contributions of the primary GHGs to this enhanced effect and the major sources of each gas.) Finally, while it is not universal<sup>3</sup> a scientific consensus exists that if anthropogenic emissions of GHGs are not curtailed, the result will be widespread and potentially irreversible changes to the earth's climate (Houghton et al. 1990, p. xi).

Even if one does not accept the consensus view, what cannot be disputed is that this experiment is being performed on an extraordinarily complex, non-linear system, and thus the *threat* of negative impacts on climate cannot be easily dismissed. In the face of such a threat reasonable people may disagree about how much they are willing to pay for “insurance” against it, but not whether insurance is warranted<sup>4</sup> (Rogner & Britton 1991, Manne & Richels 1991).

### 1.1.1 International Greenhouse Gas Emission Commitments

With the exception of ozone-depleting substances, most atmospheric pollutants can be addressed at a national or, at most, continental scale. However the emission of GHGs is a truly global issue. Any negative impacts these emissions may have on climate will be spread, however unequally, around the globe. Moreover, GHG emission reductions will have little impact unless carried out world-wide by a majority of emitters. Thus efforts

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<sup>3</sup>For dissenting opinions see, e.g., Marshall Institute (1989), Brookes (1989), Idso (1989), and O'Brien (1992).

<sup>4</sup>Many have offered the analogy: one does not have to be absolutely certain that the house is going to burn down for fire insurance to make sense.

Greenhouse Gas	Fraction of Total Radiative Forcing 1765–1990	Major Sources
CO <sub>2</sub>	61.2%	Fossil fuel combustion, land-use changes, cement production
CH <sub>4</sub>	22.9%	Natural wetlands, rice paddies, enteric fermentation in animals, termites, biomass, landfills, fossil fuel production
CFCs	11.7%	Aerosol propellants, refrigerants, foam-blowing agents, solvents, fire retardants
N <sub>2</sub> O	4.1%	Uncertain; soil denitrification, nitrogen fertilizer use, nylon and nitric acid production, automobile catalytic convertors, fossil fuel combustion
Total	100.0%	

**Table 1.1:** Percentage share of total estimated radiative forcing ( $2.45 \text{ W/m}^2$ ), for each of the primary GHGs, and their major sources. The contribution of methane also includes an indirect component due to stratospheric water vapour. Radiative forcing data is from Table 2.6 in Shine et al. (1990); sources are from Houghton et al. (1992, pp. 8–9) and Watson et al. (1990).

to negotiate reductions in GHG emissions have necessarily taken place at an international level.

### Toronto Conference: The Changing Atmosphere

One of the earliest international recommendations for concrete reductions in GHG emissions emerged from the conference entitled *The Changing Atmosphere: Implications for Global Security*, held in June, 1988 in Toronto, Canada. The resulting “Toronto target” is the reduction of CO<sub>2</sub> emissions (alone) to 80% of the 1988 level by the year 2005 (WMO 1989, p. 296).

### Second World Climate Conference

The Second World Climate Conference, held in Geneva, Switzerland in late 1990, resulted in a new GHG emission target. Although it expanded the focus of concern to all GHGs

not otherwise controlled by the Montreal Protocol,<sup>5</sup> it was in one sense a step backwards from the Toronto target, in proposing only the stabilization of GHG emissions at 1990 levels by the year 2000, rather than their reduction (WMO 1991, p. 535). However, this new target gained importance from the commitment of a significant number of developed countries, including the European Community and other northern European nations, Japan, Australia, New Zealand, and not least of all Canada, to take action towards meeting it. Previously, only a handful of countries had made commitments towards meeting the Toronto target (Government of Canada 1991b, p. 22·25).

### **United Nations Framework Convention on Climate Change**

The Framework Convention on Climate Change was negotiated at intergovernmental meetings leading up to the United Nations Conference on Environment and Development (UNCED), held in Rio de Janeiro, Brazil in June 1992. This convention continued the trend set by the two earlier agreements:

- broadening international support, with 154 countries signing the agreement (Climate Institute 1992);
- lessened commitment to strict emission controls—the convention contains no specific emission target.

#### **1.1.2 The Canadian Commitment**

Canada's current commitment for GHG emission reductions remains the Second World Climate Conference target of stabilization of CO<sub>2</sub> and other GHGs not covered by the Montreal Protocol<sup>6</sup> at 1990 levels by the year 2000. The government states that this target is only a first step, with expectations that further reductions up to and beyond the Toronto target will likely be required (Government of Canada 1990, p. 101).

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<sup>5</sup>The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (Government of Canada 1991b, p. 23·20). Many ozone-depleting substances, particularly CFCs, are also very effective GHGs (Shine et al. 1990).

<sup>6</sup>Canada has committed to eliminating CFC production and consumption by 1997 (three years earlier than required by international agreements), with emissions expected to fall below the current level by 2000 (Government of Canada 1990, p. 108).

Many groups have called on the government to commit to greater emission reductions. Within the government itself, the House of Commons Standing Committee on Environment recommended that the Toronto target be accepted as a minimum short term reduction goal, and that by 2020 CO<sub>2</sub> emissions be cut by 50% over 1988 levels (SCE 1991, p. 48).

To put these emission reduction targets in context, the Intergovernmental Panel on Climate Change (IPCC) estimated in 1990 that emissions of CO<sub>2</sub>, N<sub>2</sub>O, and CFCs would have to be cut immediately by approximately 60% simply to stabilize their atmospheric concentrations at current levels<sup>7</sup> (Houghton et al. 1990, p. xviii).

## 1.2 Objective: On Meeting the Canadian Commitment

The commitment to any GHG emission reduction target leads directly to the questions:

- How can the target be reached?
- What are the costs and benefits of doing so?

This thesis addresses these questions for the most important component of the government's current commitment: reduction of CO<sub>2</sub> emissions from Canada's energy system. The reasoning behind the selection of this subset of GHG emissions is:

1. Historically, CO<sub>2</sub> has been responsible for a majority of radiative forcing—about 56% over the period 1980–1990 (Shine et al. 1990, p. 55). The future importance of CO<sub>2</sub> is even greater if one accepts that CFC emissions, having the second-largest historical contribution to radiative forcing (24% over 1980–1990), are being addressed by current policies (Government of Canada 1991b, p. 23·21).

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<sup>7</sup>Stabilization of atmospheric concentrations requires such deep emissions cuts because of the long residence time, or lifetime of many GHGs in the atmosphere. The lifetime of CO<sub>2</sub> is estimated at 120 years, while the lifetime of some CFCs is greater than 500 years (Isaksen, Ramaswamy, Rodhe & Wigley 1992).

2. Accepting the uncertainties and difficulties in comparing the future impacts of emissions of different GHGs,<sup>8</sup> CO<sub>2</sub> represents about 70% of Canada's GHG emissions on a CO<sub>2</sub>-equivalent basis (Jaques 1992, p. 4).
3. Canada's energy system, from the initial extraction or harnessing of energy sources<sup>9</sup> to the final utilization of energy services,<sup>10</sup> accounts for approximately 95% of Canada's CO<sub>2</sub> emissions, 35% of CH<sub>4</sub> emissions, and 50% of N<sub>2</sub>O emissions. Understanding the role of the energy system in GHG, and particularly CO<sub>2</sub>, emissions is key to their reduction.
4. CO<sub>2</sub> emissions are the most easily quantified of the GHGs, due to a nearly one-to-one relationship between the carbon in an energy currency and the CO<sub>2</sub> emission from its combustion.<sup>11</sup>

This is not to argue that the other GHGs can or should be ignored, but rather that analysis of CO<sub>2</sub> emissions from the energy system is a necessary first step.

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<sup>8</sup>A comparison of the impact of different GHGs on the greenhouse effect, or their relative radiative forcing, becomes more complicated when considering the future effects of the emission of one additional unit of a particular gas. Such a comparison must take into account:

- the absorption properties of a single molecule of the gas;
- the average residence time, or lifetime, of the gas in the atmosphere;
- the indirect effects of the gas on radiative forcing, through transformation by chemical reaction to other compounds (Houghton et al. 1992, p. 14).

<sup>9</sup>Energy sources, or resources, are the physical stocks (e.g., of natural gas, uranium, or crude oil) or flows (e.g., of a river, or of solar radiation) from which all human utilization of energy is derived. It is important to distinguish between energy *sources*, and energy *currencies* or *carriers* (see footnote 13).

<sup>10</sup>Energy services are what people desire from the utilization of energy. People don't want energy per se, they want illumination, or a comfortable dwelling, or transportation (Häfele 1981, p. 693; Brookes, Robinson & Torrie 1983). The distinction is essential, since a given energy service may be provided in different ways, with differing energy requirements.

<sup>11</sup>Some fraction of carbon may survive unoxidized (e.g., remain as unburned coal, or emitted as unburned CH<sub>4</sub>), some fraction may be only partially oxidized to CO (although this will eventually be oxidized to CO<sub>2</sub> in the atmosphere), and some may be transformed into other hydrocarbons.

## 1.3 Approach

### 1.3.1 The Need for Models

Any investigation of something as large, complex and diffuse as a national energy system must be based on a simplifying framework or description—in other words, a model. Thus, in energy systems analysis, the first question is not whether a model should be used, but what kind of model and to what end.

#### The Role of Modeling

If one asks the question “Why model?” the answer is likely to be a variation on “To predict something” with the implication that what is to be predicted is the time path of one or more variables. Yet such prediction is only one of a number of possible overlapping motives for undertaking a modeling task (Williams 1985, Simon 1988):

1. As a different form of prediction, one may wish to determine the stability or instability of a system, without concern for the time paths of its variables.
2. One may use a model to perform experiments on systems for which actual physical experiment is awkward, dangerous, or impossible.
3. In normative (Beaujean, Charpentier & Nakićenović 1977) or prescriptive (Simon 1988) modeling the goal for the system is known and the question then becomes how to reach that goal. This is the usual case in policy analysis, where the process is often referred to as scenario-building (Häfele & Rogner 1984).

Finally, and not least of all, the knowledge and clarification of thought gained from the modeling process itself may be, if not a direct goal then at least an important outcome of that process (Häfele & Rogner 1984, Williams 1985).

### 1.3.2 Energy System Modeling

The key issue is creating a model appropriate to the questions being asked. The term *energy model* encompasses a broad range of analytic approaches, with different authors using a variety of scales by which to compare them including:<sup>12</sup>

- **Purpose** - Is the model intended to be descriptive, normative, or predictive?
- **Energy Scope** - Does the model address one energy currency<sup>13</sup> or many?
- **Temporal Scope** - Is it a static model (i.e., analyzing a single point in time) or a dynamic model (analyzing an evolution over time)? If dynamic, what time frame is considered? Is it measured in months, years, or decades?
- **Geographic Scope** - Is the model focussed at a regional, national, or global level?
- **Economic Scope** - Are economic issues dealt with at a microeconomic (single institution or single market), macroeconomic (in the sense of many interacting markets at a national level), or global level?
- **Methodology** - What methodology underlies the model: Econometrics?<sup>14</sup> Optimization? Determination of economic equilibrium? What analytic technique is used to implement the methodology: Regression analysis? Mathematical programming? Input/output analysis?
- **Model Outputs** - What are inputs to the model, and what are outputs? In particular, are energy service demands exogenous, i.e., specified as inputs, or endogenous, i.e., determined internally (Hoffman & Wood 1976, Beaver & Huntington 1992)?

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<sup>12</sup>An early but comprehensive review of approaches to energy modeling is Hoffman & Wood (1976). The Energy Modeling Forum at Stanford University (EMF) has an ongoing process of energy model comparison, with 12 such studies completed to date (Beaver & Huntington 1992, Beaver 1993).

<sup>13</sup>The phrase *energy currency* is used throughout this thesis in place of the traditional word *fuel* and the more recent phrase *energy carrier*. The purpose of the substitution is not to confuse, but rather to make clear, by analogy with a monetary currency, that currencies are not *sources* of energy but are media of storage, transport, and particularly exchange. The choice of energy currency determines the energy transactions which can take place (Scott & Häfele 1990).

<sup>14</sup>Econometrics has been defined as the “empirical representation and validation of economic theories and laws” (Hoffman & Wood 1976).

However, for modeling at a national scale the key issue is whether the energy system is to be treated from an economic or engineering perspective— what many have described as the “top-down” vs. “bottom-up” dichotomy (Grubb et al. 1991, p. 145; Wene 1993, Wilson & Swisher 1993).

### **Top-down Energy System Models**

Top-down models are based in economic theory, and deal with flows of a monetary currency. They encompass both macroeconomic and econometric modeling approaches.

The name *top-down* derives from the starting point of this modeling process: the highly aggregated monetary flows and macroeconomic properties of the energy-related sectors of the economy (or of all sectors of the economy, in an energy-economy model), where top-down refers to the degree of aggregation. Other key characteristics of a top-down energy system model are:

- The demands for energy services and currencies are determined internally, as a function of other economic activities, and normally reflect historical relationships.
- The decision criterion used to solve the model depends upon its type. For macroeconomic models it is a determination of market equilibrium—the prices and flows for which all demands and supplies are balanced. The solution of econometric models involves the solution of regression equations relating prices, outputs, etc.

The economic basis of top-down models is the source of both their strengths and their weaknesses. On one hand, the use of a monetary currency to represent model flows permits the analysis of interactions between the energy system and other sectors of the economy, e.g., feedback loops between the cost of energy services and the demand for them. However, the data required to model such interactions is largely historical, leading to a tendency to “project the past” (Grubb et al. 1991, p. 147). Also, the high degree of aggregation in top-down models limits, by necessity, the technological detail which can be included. Together these attributes have led to claims that top-down models “describe, by design, a behaviorally, institutionally and technologically fixed world” (Wilson & Swisher 1993).

### **Bottom-up Energy System Models**

The bottom-up energy models are commonly referred to as engineering, process, techno-economic, or end-use models. As suggested by the word *bottom*, these models start at the other end of the energy system hierarchy, with a consideration of the demand for specific energy services. This then determines possible technologies for satisfying the demands, which in turn leads to energy currency requirements, and so on, up the many “chains” of technologies to the required energy resources. Compared to top-down models, the key characteristics of bottom-up models are:

- They are based in physical, rather than economic theory (primarily the conservation of energy). Model flows are in energy, not monetary, currencies.
- The demands for energy services must be specified exogenously. Within the model these demands are satisfied through competition between technologies.
- The decision criterion used to solve the model is the cost (or perhaps some other) optimization of the overall energy system.

As with top-down models, the strength of bottom-up models is also the source of their limitations. The explicit technological modeling allows detailed examination of the effects of technological and structural change, which is essential for scenarios extending more than a few years into the future. However, the focus on technology, and in particular on physical flows, precludes the modeling of interactions with the larger economy. End-use demands which would ideally be determined by the model become inputs to it, dependent upon subjective judgement.

Another significant hurdle to bottom-up models is the difficulty of acquiring the necessary data to support the detailed technology focus. For each technology it is necessary to specify time-dependent values for cost (both investment, and operating and maintenance), lifetime, efficiency, emissions, availability, etc.

### **Top-down vs. Bottom-up Approaches**

There has been much debate over which of these two approaches, the top-down economic one or the bottom-up engineering one, is best suited for the analysis of the potential for, and costs of, GHG emission reductions (Grubb et al. 1991, p. 145; Wilson & Swisher 1993). It is an important issue, since the two approaches have historically produced very different answers to apparently similar questions. (Compare, for example, Manne & Richels (1990) and Williams (1990).) To the extent that any firm answer can be given to this question, it is:

- The top-down models are more appropriate for the very short term (where the “projection of the past” may be appropriate) and for the very long term (where high degrees of uncertainty can justify only broad-stroke scenarios) (Lave 1990).
- The bottom-up models are best for modeling the medium term (five years to a few decades), during which structural and technological change can be reasonably forecast and are important processes.

This complementarity suggests combining the two approaches. However, while such combining has theoretical attractiveness, it yields a large increase in complexity and data requirements (Grubb et al. 1991, p. 151). Even recent attempts at linkage (Wene 1993) appear to have fallen prey to conceptual difficulties in the reconciliation of the two approaches (Wilson & Swisher 1993).

### **Choice of Approach**

Two factors strongly recommending a bottom-up, techno-economic approach to the investigation of the feasibility of meeting Canada’s GHG emission target:

1. the time frame under consideration, i.e., GHG emissions over the next two to three decades;
2. the importance of available technology alternatives in determining the amount one should be willing to pay for “insurance” against negative climate change (Ayres 1993).

## 1.4 Related Work

### 1.4.1 Terminology

For important reasons this thesis generally uses the terms *energy sources*, *energy currencies* and *energy services*, rather than the more common but less precise terms resources, fuels, end-use demands, etc. (Scott & Häfele 1990). However, when discussing modeling results, both of this work and of work done by others, the following recognized terms are used:

- **Energy Production** - The total quantity of energy sources extracted or harnessed.
- **Primary Energy** - Energy production, plus imported energy sources, less exported energy sources. The hydroelectric component of primary energy is *not* converted to a thermal equivalent using some assumed efficiency.<sup>15</sup>
- **Secondary Energy** - The total of all energy currencies, following conversion from primary energy sources, but before distribution to final consumers.<sup>16</sup> The majority of secondary energy in Canada consists of refined petroleum products, natural gas, and electricity.
- **Final Energy** The total of all energy currencies, at the point following any transmission, transportation and distribution to final consumers.
- **Useful Energy** - Rarely tabulated, this is the total output of all final-to-useful energy conversion technologies. It is what others often refer to as *end-use* energy.

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<sup>15</sup>This conversion was an international convention for hydroelectric energy until recently, and remains in use for nuclear and geothermal-generated electricity (IEA 1991a).

<sup>16</sup>Final consumers are those who utilize energy to provide energy services, including the production of non-energy products like petrochemicals, rather than converting the energy into a different energy currency. Natural gas combusted to heat a building is included in final energy; natural gas combusted to generate electricity is not. Unfortunately this is not a rigorous definition, since, e.g., coal is a form of both primary energy and secondary energy, depending on its use.

### More on Energy Services

A proper understanding of the energy system requires that final energy, useful energy and energy services be clearly distinguished, especially since the differences between them are not always obvious.

- **Energy services** are people's energy-based needs and wants. In their most general form energy services include warmth, heat for cooking, illumination, transportation, etc.
- **Useful energy** satisfies energy service needs and wants. Useful energy corresponding to the energy service examples just given could include hot air from a furnace, heat rising from the flame of a gas stove, light from an incandescent bulb, and the kinetic energy of a moving car.

Useful energy is not so much converted to an energy service, as it provides the service subject to the mediating influence of technologies and the surrounding environment. For example, the ability of hot air from a furnace to satisfy a person's desire for warmth depends on:

- the nature of the outside environment: how cold, or windy, or sunny it is.
  - the nature of the building envelope: its insulation, windows, degree of air infiltration, etc.
  - the nature of the building interior: the ceiling height, floor and wall coverings, location of the hot air delivery (near the floor or near the ceiling), etc.
  - The person being warmed: their preferences, their dress, etc.
- **Final energy** is what people buy or collect to “feed” the technologies which, in turn, provide useful energy. Final energy is the oil for a residential furnace, the natural gas for a stove, the electricity for a light bulb, and the gasoline for a car. Final energy represents what has been traditionally been considered “energy demand.”

### 1.4.2 Energy Modeling in Canada: Application to CO<sub>2</sub> Emission Reduction

Traditionally energy system models in Canada (both top-down and bottom-up) have been used for utility, particularly electric utility, planning<sup>17</sup> or for national energy policy planning. However, to date there has been only limited use of energy system models to investigate GHG reduction potentials in Canada.

#### An Econometric Approach

In 1990 Haites reported on the use of an econometric model developed by Energy, Mines and Resources Canada, the Interfuel Substitution and Demand Model (IFSD), to investigate the potential for energy-related CO<sub>2</sub> emission reductions in Canada. To summarize this study:

- The key inputs to IFSD were forecasts for population, gross national product (GNP), and the world price of oil. The model outputs were the sectoral demands for primary, secondary and final energy.
- The CO<sub>2</sub> emission goal was the Toronto target.
- Approximately 140 unspecified emission abatement measures were applied to the residential, commercial, industrial, transportation sectors, at three levels of market penetration: technical, economic and market.
- The cost for the abatement measures, in 1988 \$US, ranged from approximately minus \$510 to plus \$1300 per tonne of CO<sub>2</sub> abated, with nearly all costing less than \$150/tCO<sub>2</sub>.<sup>18</sup>
- The key results of the study were:

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<sup>17</sup>In 1981 the Canadian Energy Research Institute surveyed some 70 energy models from around the world for their suitability to long-term Canadian electric utility planning (Foat, Protti & Douglas 1981).

<sup>18</sup>In the Haites study, a negative abatement cost arises when the cost of the incremental energy savings associated with the adoption of a measure is greater than the required incremental investment.

- The Toronto emission reduction target could be achieved by using essentially all technically available abatement measures identified in the model, of which about two-thirds involved demand reduction. The conclusion was that the Toronto target is “very ambitious.”
  - Improved energy efficiency was the most cost effective means of reducing CO<sub>2</sub> emissions, although it was insufficient alone to reach the Toronto target.
  - Achieving the Toronto target would require replacing almost all existing fossil-fueled generation capacity with non-fossil (presumably hydroelectric and/or nuclear) capacity.
- Haites concludes with a discussion of relevant issues surrounding implementation of emissions constraints, including:
    - sectoral and regional equity,
    - resistance to structural change in the energy sector,
    - the need for significant energy taxes, and
    - the role for emission trading or marketable permit systems.

**Comments:** This study is of special interest because it is the only published work found which addresses CO<sub>2</sub> emission reduction for Canada as a whole. Moreover, the discussion of implementation issues makes some interesting points. Unfortunately, the conclusions regarding the measures needed to reach the Toronto target are, in this author’s opinion, of limited value because:

- The emission abatement measures are not identified except by general class, making informed judgement of the work impossible.
- No explanation is given of how a such a rich menu of abatement technologies was integrated into an econometric framework, again precluding validation of the work.

- The base case scenario, upon which the results and conclusions are necessarily based, assumes rates of growth in energy demand which are quite high.<sup>19</sup> Without knowing more detail on the reduction measures, it is impossible to judge the degree to which the pessimistic demand is balanced by optimistic estimates of opportunities for abatement.

### **MARKAL in Canada**

The MARKET ALlocation model (MARKAL) is a dynamic (multi-time period) techno-economic energy system model based on a linear programming framework. MARKAL is in use in many countries around the world, in part because it was selected by the Energy Technology System Analysis Project (ETSAP) of the IEA as a common modeling framework for the investigation by 11 countries of technical options for GHG emission reduction (Hollins et al. 1992). The group representing Canada within ETSAP is based within the Groupe d'études et de recherche en analyse des décisions (GERAD), where they have created an enhanced Canadian version of MARKAL (Berger et al. 1992b).

Recently GERAD published a report on the use of MARKAL to examine potentials for CO<sub>2</sub> emission control in Ontario and Quebec (Berger et al. 1992a). This is of special interest given the decision to use a techno-economic approach for the work presented in this thesis. The key features of the GERAD study are:

- Quebec and Ontario are modeled separately. Inputs to the model include assumptions on sectoral economic growth, prices for the different forms of imported energy, and techno-economic data on more than 500 technologies. A discount rate of 7% was chosen.
- The base set of scenarios cover high and low economic growth, with and without limits on SO<sub>2</sub> and nitrogen oxides (NO<sub>x</sub>), and with CO<sub>2</sub> constrained at 0%, 10%, and 20% below the 1985 level in the year 2005 (giving a total of eight base scenarios).

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<sup>19</sup>For example, only one year later the NEB (1991, p. 351) published a forecast of total primary energy for 2005 which was nearly 30% lower than the value used in the Haites study.

Special scenarios deal with, e.g., a moratorium on future hydroelectric projects, a partial moratorium on the construction of future nuclear generation capacity, and either an advancement or a postponement of the date at which the CO<sub>2</sub> limit takes force. All special scenarios are variations on the high economic growth, constrained SO<sub>2</sub> and NO<sub>x</sub>, base scenario.

- The level of technological detail is high, with key industries modeled individually.
- Biomass-sourced energy is *not* considered to be CO<sub>2</sub>-neutral—CO<sub>2</sub> emissions from biomass carry the same weight as from any other energy currency.<sup>20</sup>
- The key results of the Quebec portion of the study are:
  - Quebec begins with relatively low CO<sub>2</sub> emissions, since about 39% of their primary energy comes from hydroelectricity.
  - CO<sub>2</sub> emission reductions are accomplished largely by increases in hydroelectric generation capacity, aided by fuel switching to natural gas.
  - The average unit cost of CO<sub>2</sub> reduction ranges from \$43 to \$121 per tonne (all costs in 1990 \$Cdn), depending upon the level of economic growth and the level of reduction.
- The key results for Ontario are:
  - Ontario's annual CO<sub>2</sub> emissions begin at nearly twice the level of Quebec's, and grow more quickly. The higher growth rate requires greater absolute abatement, thus increasing costs and difficulty. An exception is at the early stages of the higher-growth scenarios, where Ontario can, with relative ease, switch from more- to less-CO<sub>2</sub> intensive energy sources.
  - CO<sub>2</sub> emission reductions are accomplished via the elimination of coal use, and the increasing use of natural gas and nuclear-generated electricity.

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<sup>20</sup>As discussed in Section 2.2.1, one can argue that CO<sub>2</sub> from biomass utilization, to the extent that the original biomass is regenerated, is not a net emission of CO<sub>2</sub>.

- The cost of CO<sub>2</sub> abatement is increased by a constraint prohibiting new nuclear generating capacity before 2010. For Ontario, the cost of meeting the CO<sub>2</sub> limit depends in large part upon the timing between the imposition of the limit, and availability of new nuclear generation capacity.
- The average unit cost of abatement ranges from \$61 to \$136/tCO<sub>2</sub>. The total cost is much higher than in Quebec, reflecting the greater emission reduction required.
- Interestingly, total costs (sum of those for Quebec and Ontario) were reduced considerably when Ontario was allowed to import the electricity from 3 GW of hydroelectric capacity in Quebec.
- The report concludes that CO<sub>2</sub> emission reductions of up to 20% from the 1985 level in the year 2005 are technically feasible, for the base case scenarios. Adding hydroelectric and nuclear moratoria greatly increases the costs, but with one exception, does not lead to infeasibility.

**Comments:** The GERAD report is important, both because it is a comprehensive techno-economic look at the problem of CO<sub>2</sub> emission reductions in a significant fraction of Canada, and because it represents the Canadian contribution to an international effort addressing this issue.

However, one criticism can be made: as with the Haites study, the report presents essentially no data for the technological alternatives used in the model. Since the model outputs lead directly from these inputs, it is impossible to judge the validity of the report's conclusions without this data.

Finally, two interesting issues arise from this report:

- In the one scenario addressing the concept, considerable benefits result from inter-provincial cooperation. This highlights the need to approach the problem of GHG emission reductions within a national framework. An overall Canadian model is clearly needed.

- The question of regional equity, while not addressed directly in the report, is obvious: Should Quebec, with relatively low current CO<sub>2</sub> emissions, have to make the same cut in emissions as other more carbon-intensive provinces?

### **Industrial End-Use Modeling: ISTUM**

Margolick et al. (1992) recently reported on a study of the potential response of energy-intensive Canadian industries to various levels of a combined CO<sub>2</sub> and CH<sub>4</sub> tax. The methodology was process-oriented, end-use modeling using ISTUM (Intra-Sectoral Technology Use Model). The essential aspects of the study are:

- Five industrial sectors were examined: pulp and paper, iron and steel, aluminum smelting, cement manufacture, and oil refining. Each sector appears to have been modeled in considerable detail, e.g., to the level of electrode type for aluminum smelting.
- Biomass energy was taxed at various fractions of its full CO<sub>2</sub> potential. CH<sub>4</sub> was taxed at 21 times (on a weight basis) the rate of CO<sub>2</sub>.
- The key overall results of this study were:
  - The response of industries to the taxes varied immensely, from almost no response in aluminum smelting, to considerable response in cement manufacture, to an indeterminate response in pulp and paper.
  - Product quality and feedstock availability are far more important issues in industrial decision-making than energy costs, but are difficult to incorporate into a modeling framework.

**Comments:** This study presents some very interesting conclusions on the potential for CO<sub>2</sub> and CH<sub>4</sub> emission reductions from the industrial sector. However, it cannot (and does not attempt) to say anything about the other sectors of the Canadian economy.

### 1.4.3 Conclusion

Prior studies have examined two aspects of Canadian CO<sub>2</sub> emission reductions:

- national reductions, using an economic approach, and
- provincial and sectoral reductions, using a techno-economic approach.

However, a techno-economic modeling framework has yet to be applied to the issue of CO<sub>2</sub> emission reductions for Canada as a whole.

## 1.5 Scope of This Work

This study investigates the feasibility, costs and benefits of Canada meeting its commitment on GHG emission reductions for a key subset of those emissions: CO<sub>2</sub> from the energy system. The target, as agreed upon at the Second World Energy Conference, is stabilization of emissions at the 1990 level by the year 2000; it is assumed that this level will be maintained into the future.

While stabilization is the primary target, the feasibility of further energy-related CO<sub>2</sub> emission reductions is also briefly addressed. In particular, the Toronto Target, requiring a 20% reduction from the 1988 level by the year 2005, is considered. (1988 emissions have been estimated from 1990 data.)

### Methodology

A bottom-up, techno-economic approach has been selected as being most appropriate both for this time horizon, and for an examination of technological alternatives. A dynamic linear programming methodology is employed, based on the use of the MESSAGE (a Model for Energy Supply Strategy Alternatives and their General Environmental impact) modeling system (Messner 1984a, Messner 1984b, Strubegger 1984). This system grew out of early work with the Energy Systems Group at the International Institute for Applied Systems Analysis, in Laxenburg, Austria (Häfele 1981). It has since been used for a number of regional, national and international energy studies (Rogner & Britton 1991, EcoPlan 1990, Rogner 1989).

MESSAGE has been used extensively since its early development at IIASA, yet until now it has not been applied to any aspect of the Canadian energy system. Thus a significant portion of this work necessarily focusses on the representation of the Canadian energy system using a MESSAGE framework.

### **Assumptions**

The following assumptions outline the boundaries of this work:

- The time frame considered is 1990 to 2020, to allow for the investigation of the sustainability of the emission targets, i.e., whether emission reductions can be maintained beyond the initial target year,
- The base case scenario represents “business-as-usual” (BAU). This certainly does not imply a static projection of today’s conditions into the future, but instead represents informed judgement as to where current trends are leading. A more descriptive, if less common phrase than BAU is “dynamics-as-usual” (DAU).
- The model is constrained so as to represent the many socio-political factors which affect the development of the energy system, but which are difficult to value. An example is society’s reluctance to invest in large scale expansion of hydroelectric or nuclear generating capacity.

### **Issues Addressed**

The core results of this work address:

- Can the emission stabilization target be reached?
- If it can be reached, what are the costs? What are the collateral benefits? What structural changes are brought about?
- How do these issues change as emission reductions are increased? In particular, what are the implications of aiming for the Toronto Target?

- How does the energy system respond to either an absolute limit on emissions, or an increasing emissions tax?

In addition, results for several alternative scenarios are presented, all having the Canadian commitment (stabilization) as an emission target, but with:

- reduced constraints on new hydroelectric generating capacity;
- reduced constraints on new nuclear generating capacity;
- reduced constraints on, and costs for, energy service demand reduction measures;
- each sector of the economy (industry, commerce, transport, etc.) required to individually meet the emission stabilization target.

## Chapter 2

# Approaches to CO<sub>2</sub> Emission Reduction

Several studies have extensively investigated possible responses to the threat of GHG-induced climate change; it is not within the scope of this work to repeat their results here (see, e.g., IPCC 1991, Carlsmith, Chandler, McMahon & Santini 1990, Grubb et al. 1991, Nakićenović et al. 1993). Nonetheless, a brief outline of possible actions, particularly the available paths to CO<sub>2</sub> emission reduction, will provide some background for later discussions of methodology and results.

## 2.1 Responding to the Threat of Climate Change

### 2.1.1 Impact of Uncertainty

The key difficulty in providing a rational response to the threat of GHG-induced climate change is uncertainty. As the Response Strategies Working Group of the IPCC has noted, there is simply insufficient information to make sound, rational policy decisions, with information gaps in (IPCC 1991, p. xxxiv):

- the magnitude, timing, rate, and regional impacts of climate change;
- the effectiveness of particular response strategies in reducing the threat of climate change;
- the economic, social and other costs of potential response strategies.

Yet as Grubb (1993) notes, uncertainty alone is rarely a justification for inaction.

### 2.1.2 Possible Responses

In the face of this uncertainty, three general responses are possible:

1. **Wait and see.** Wait until further research has resolved some of the more important uncertainties, and then act appropriately.
2. **Limit.** Move to stabilize atmospheric concentrations of GHGs, particularly by curbing emissions.
3. **Mitigate and Adapt.** Act to minimize the impacts of climate change as they arise, and adapt to those which remain.

Given the nature of Canada's commitment, the focus of this work is necessarily limitation. Nonetheless, the other responses require brief comment:

- The wait-and-see approach was appealing when three to five years was the estimated time required to resolve the key uncertainties (Marshall Institute 1989). However, since then the IPCC has estimated that 10–15 years will be required just to resolve some of the key climate modeling issues (Houghton et al. 1990, p. xxxiii).
- The need to pursue the mitigation and adaptation route is, to some degree, inevitable—the world is unlikely to cut CO<sub>2</sub> emissions by the 60% required to simply stabilize atmospheric CO<sub>2</sub> at current levels (and this ignores the question of whether such stabilization would eliminate all threats of climate change). The choice of response, then, is not a case of limitation *or* adaption, but rather a matter of emphasis. Yet the appropriate emphasis remains clouded in uncertainty.

## 2.2 Limitation Options

CO<sub>2</sub> limitation approaches can be grouped according to the time frame for action. In the short term (less than 25 years) most approaches are focussed at directly reducing CO<sub>2</sub> emissions, by:

- switching to energy sources and currencies containing less carbon per unit energy;

- improving the efficiency of energy utilization, i.e., reducing the final energy required for a given energy service; and
- reducing the demand for energy services.

The time scale of this thesis, as well as its techno-economic approach, necessarily focusses attention on this group of limitation options. Nonetheless, over a longer time frame other options are available :

- Separation of CO<sub>2</sub> from flue gases, followed by disposal, storage, or utilization (broadly referred to as CO<sub>2</sub> sequestering).
- “Eco-engineering,” the enhancement of natural CO<sub>2</sub> sinks to remove CO<sub>2</sub> from the atmosphere once it has been emitted. Reforestation is the most frequently discussed alternative, although other schemes have been proposed, including fertilizing the Southern ocean with iron (Roberts 1991).
- “Geo-engineering,” the use of technological means to counteract the radiative forcing of atmospheric CO<sub>2</sub>. One example is the delivery of dust or sulphuric acid aerosols into the stratosphere to shade a small fraction of incoming solar radiation<sup>1</sup> (Nakićenović et al. 1993).

### 2.2.1 Low-carbon and Carbon-free Energy

#### Low Carbon Sources and Currencies

One obvious path to reduced CO<sub>2</sub> emissions is to use energy currencies and sources with less carbon per unit energy. Table 2.1 lists the CO<sub>2</sub> emitted per unit energy for common currencies. Since this data ignores systemic effects (i.e., emissions of CO<sub>2</sub> and other GHGs from the production, processing and transmission of the currencies), it should be used cautiously. Yet there is clearly a potential for considerable CO<sub>2</sub> emission reductions by switching from high-carbon to low-carbon currencies.

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<sup>1</sup>Although one could argue that this falls into the category of mitigation responses.

Energy Currency	CO <sub>2</sub> Emitted (tonne/GJ)
Natural gas	49.7
Gasoline	68.0
Methanol	69.2
Diesel fuel	70.7
Aviation turbo fuel	70.8
Light fuel oil	73.1
Heavy/Residual fuel oil	74.0
Hard coal	87.0
Soft coal	94.2

**Table 2.1:** CO<sub>2</sub> emissions (at the point of use) from complete combustion of one GJ of various energy currencies, from Jaques (1992).

### Carbon-free Energy

The limiting case of a low-carbon source is a carbon-free source, a category including both nuclear energy and what are termed *renewables*.<sup>2</sup> Sources falling into the renewable category include:

- bioenergy, or biomass-derived energy; this is organic material which is either combusted to produce heat (or, indirectly, electricity), or is converted through physical and chemical processes into other liquid or gaseous currencies;
- hydropower, from falling water;
- geothermal power, harnessing the internal heat of the earth;
- wind power;
- solar power, converted either directly to electricity using photovoltaics, or collected as heat which is then used directly or converted into electricity;
- tidal and wave power, which harness the kinetic energy of the oceans;
- ocean thermal conversion (OTEC), harnessing the thermal gradients in the ocean (other conceptual systems harness saline gradients).

<sup>2</sup>The use of the word “renewable” implies that there is something which must be replaced; of all the sources which typically fall under this heading, only biomass must actually be renewed.

Providing energy services without the emission of CO<sub>2</sub> requires not only carbon-free sources but also carbon-free energy currencies. Presently electricity is the only widely-used carbon-free currency, although a potential complement to electricity, especially where storage is a concern, is hydrogen.

### **Biomass and CO<sub>2</sub>**

A key issue in accounting for CO<sub>2</sub> emissions from the energy system is the CO<sub>2</sub>-neutrality of biomass: should a kg of CO<sub>2</sub> emitted from the combustion of biomass be considered equivalent to a kg of CO<sub>2</sub> from a fossil source? Unfortunately, there is no simple answer to this question.

Some argue that because biomass is “renewable on human time-scales,” (Jaques 1992) it should be treated separately from fossil carbon energy sources. Doing so, and basing his conclusions on results of national biomass models, Jaques reported that even at current rates of total biomass use (i.e., not limiting consideration to bioenergy utilization), the uptake of atmospheric CO<sub>2</sub> in Canada by newly growing biomass results in a net CO<sub>2</sub> sink.

Others are less certain of the sustainability of current biomass production (Margolick et al. 1992), and argue that as a minimum, biomass should be modeled with a range of CO<sub>2</sub> emission factors.

#### **2.2.2 Improved Efficiency**

While conversion efficiencies can be improved at all steps in the energy system, from resources through to services, the greatest potential is associated with final-to-useful and useful-to-service conversions. Overall primary-to-final efficiency<sup>3</sup> in industrialized countries has been estimated at about 70%, with an average final-to-useful efficiency of about

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<sup>3</sup>Efficiency values in this work are, unless noted otherwise, thermal, or *first-law* efficiencies, i.e., based on the first law of thermodynamics. Efficiencies can also be calculated based on the second law of thermodynamics, using ratios of *available work* or *exergy*; such ratios are referred to as *second-law* or *exergy* efficiencies, and unlike first-law efficiencies, truly reflect a fraction of the maximum theoretical work which is possible.

50% (Nakićenović et al. 1993). However, here the more illuminating measure is second-law, or exergy efficiency: while average second-law primary-to-final efficiency remains about 70%, second-law final-to-useful efficiency is only about 25%, and lower still, final-to-service efficiency is only 10%.

### Technical Efficiency Improvements

These second-law efficiencies values indicate a maximum theoretical potential. The technical potential, taking into account what can be manufactured using current technology, is necessarily less than this, while an economic potential, representing cost-effective options (i.e., those which cost less than the money they save), is lower still. Nonetheless many cost-effective technologies for efficiency improvements, either available or in commercial development, have been identified (see, e.g., Lovins & Lovins 1991, Carlsmith et al. 1990, US-OTA 1991). Areas having particular potential include:

- use of natural gas-fired combined-cycle<sup>4</sup> turbines for electricity generation;
- use of district heating<sup>5</sup> for both residential and commercial buildings;
- expanded use of industrial cogeneration;<sup>6</sup>
- reduced weight, better electronic control, and improved aerodynamics for automobiles;
- improved heating and air conditioning in commercial buildings;
- replacement of industrial electric drive motors with high-efficiency adjustable speed drives;
- improvements to commercial fluorescent lighting;
- improved building envelope insulation for residential dwellings;

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<sup>4</sup>In a combined cycle system, the energy in a combustion turbine's exhaust gases is used to raise steam, which then drives a steam turbine.

<sup>5</sup>The name commonly given to centrally-generated steam or hot water distributed via underground pipes to individual buildings. District heat is often linked via cogeneration to electricity production.

<sup>6</sup>Cogeneration is the production of both useful heat and work from a single system. See, e.g., Horlock (1987).

Efficiency improvement is an ongoing process. Ten years will bring improvements in all of the above areas, as well as additions to the list.

### **Improving Service Efficiency**

Service efficiency, as used by Nakićenović et al. (1993), represents the amount of useful energy required to satisfy a given energy service demand. Electric and natural gas utilities often refer to improvements in service efficiency as demand-side or energy management, although the concept can be more widely applied.

To the extent that service efficiency is governed by strictly technological factors, such as insulation levels in dwellings, improvements are addressed in the previous section. Here the focus is on behavioral change, with the goal being to reduce “wasted” energy: that which does not contribute to providing an energy service. Examples of improved service efficiency are often very simple things like turning off unnecessary lights, not leaving vehicles idling unnecessarily for extended periods of time, and ensuring in freight transport that return trips aren’t made empty.

### **2.2.3 Reduced Energy Service Demand**

An underlying assumption in the preceding section is that the energy service remains constant. The distinction between measures representing improved service efficiency and those representing reduced service demand depend on how broadly each energy service is defined. For example, whether taking a bus is an improvement in passenger transport service efficiency compared to driving a car depends on whether these modes of travel are assumed to satisfy the same service.

In this thesis a narrower definition of energy service is used, where aspects such as privacy, flexibility, etc. are only indirectly considered (e.g., through constraints on growth rates of technologies). This, in turn, leads to a narrower definition of demand reduction, essentially limited to behavioral changes which actually reduce the demand for services. One example of such a change is the choice to live in a smaller dwelling having lower energy requirements.

If particular changes in social, commercial, or industrial practice become ingrained, they may come to reflect an underlying *structural change*, which can affect long-term trends in energy utilization. Examples include:

- a trend towards smaller dwellings, as the population as a whole ages, and as families become smaller;
- a trend away from production of primary commodities and towards manufactured goods, or from manufacturing to service industries;
- lower rates of economic growth (a factor to the extent that energy utilization is linked to such growth).

## 2.3 Implementation Issues

The extent to which potential CO<sub>2</sub> reductions are realized is constrained by many factors, encompassing technological, social, and policy-related issues.

### 2.3.1 Technology Dynamics

Technologies can be viewed as having a *life cycle* or a series of stages of development. Nakićenović et al. (1993) present one view of the technological life cycle, having the following stages:

- invention;
- innovation, leading to commercialization;
- diffusion, the spread of the technology through the market, in competition with other technologies;
- saturation, as limits to the application of the technology are reached;

This view of technological development is important in that it offers cautions against optimistic expectations of newly developed technologies (CO<sub>2</sub> limitation technologies, in this case) becoming instantly and widely available. While technological development can perhaps be encouraged, particular stages of development cannot be “leap-frogged.”

Other work has looked at the rate of technological development, e.g., the observation that 100 years is required for a new energy source to gain a dominant (50%) share of the world market (Marchetti & Nakićenović 1979). One useful observation of this work is that larger systems evolve, and are replaced, more slowly than smaller systems, and those nearer to the final consumer (Nakićenović et al. 1993).

### 2.3.2 Social and Institutional Limits

Many paths to greater energy efficiency have been identified which have a negative cost, i.e., they cost less to purchase, install and maintain than does the energy which they displace. Yet such measures are not widely adopted.

Some of the reasons are, no doubt, related to the issues of technology development outlined in the previous section. However, there has also been much research into the social, behavioral and institutional obstacles to improved energy utilization, which include (Grubb 1990, Jochem & Gruber 1990, Levine et al. 1992):

- lack of knowledge on the part of consumers of available options, as well as a lack of the specialized knowledge required to evaluate them, e.g., of life cycle costs;
- limited access to capital for small consumers, and high costs of capital, i.e., interest rates;
- split incentives between the purchaser of a piece of equipment (e.g., a landlord) and the person who must pay for its operation and maintenance (e.g., a tenant);
- risk aversion, leading to insistence on very short payback periods for investments in efficiency improvement;
- indifference to peripheral operating costs, which may be a small part of total expenditures;
- energy tariffs for which unit costs decrease as consumption increases; also, tariffs which are based on the average cost of the currency provided, rather than the marginal cost required to provide the next unit;

- legal and administrative hurdles, such as rent controls which don't take account of the reduced operation costs of more efficient dwellings.

### 2.3.3 Policy Instruments

The connection between potential measures to reduce emissions and actual emission reductions is the choice of policy instruments, i.e., the “means government uses to require or encourage a desired technical or behavioral response” (US-OTA 1991). There are two broad policy approaches available for CO<sub>2</sub>emission reduction:

- regulation, or “command and control,” and
- market-based or economic incentives.

In terms of emission reductions, the command and control approach leads to emission limits, either direct or indirect, while the market-based approach can be implemented either as emission charges or as systems of tradeable emission permits.

#### Emission Limits

Some technologies or systems are amenable to direct limits, e.g., emission limits for motor vehicles. Where a limit as such cannot be easily enforced, regulation is typically framed in terms of requirements to utilize specified “best available technologies” (BAT), or in terms of required practice, as in national building codes.

Emission limits have the advantage that, to the extent that they successfully implemented, the total level of emissions is known in advance. Also, in practical terms limits are easily enacted, if not enforced. However, the regulation approach has drawbacks. First, it applies the same limits to all emitters, regardless of the individual cost of emission reduction, leading to the criticism that the regulatory or command and control approach is not cost-effective. A second drawback is that limits discourage innovation, in that they provide no further incentive to reduce emissions once they are reached.

### **Emission Charges**

Another approach to CO<sub>2</sub> emission reduction is to impose a charge, or tax, on each currency in proportion to its carbon-content, thus penalizing each according to its CO<sub>2</sub> emission potential.

Here, in contrast to the emission limit approach, the cost of reduction is the same for all emitters, and the total cost is capped. What is uncertain, however, is the degree of reduction which will result from a given level of tax. This is the major drawback of the tax approach: it requires an iterative process to determine the rate which will result in a desired emission reduction.

As an alternative to taxing the carbon content of a currency, and thus motivating switching to low-carbon currencies, some countries are considering a general energy tax (IPCC 1991). This would act indirectly, by encouraging overall energy efficiency improvements.

### **Emission Trading**

In an emission trading, or marketable permit system, allowances or permits for fixed emissions levels are allocated to current emitters (on some basis having at least some claim to equity), and a market for permits is then created. (Generally only large emitters in industry and electricity generation would fall under such a scheme.) In theory, those who can reduce their emissions at low cost now have an incentive to do, since they can then sell some of their emission permits to others for whom emission reduction is more expensive.

A permit trading system can potentially address the problems associated with both limits and taxes:

- The total emissions and the total cost can be determined in advance.
- Subject to a well-functioning permit trading market, the cost of emission reduction is equalized across all emitters.
- There is a continuous incentive for an individual emitter to reduce emissions, as long as permits can be sold.

The disadvantages of emission-trading systems are related to the administrative overhead, as well as the socio-political resistance to creating a “right to pollute.”

Grubb’s summary of reviews of US permit trading systems judges them “qualified successes,” although he goes on to conclude that they have a very limited role to play in the control of CO<sub>2</sub> at a national level, except with certain large users (Grubb 1990, p. 103).

### **Other Policy Instruments**

The US-OTA (1991) has identified other policy instruments which, while not primary paths to emission reduction, address some of the limitations and obstacles to potential reduction:

- **Financial incentives** - These could take the form of tax incentives, low cost loans, or direct payments. Regardless, they serve to overcome the high initial cost of many efficiency improvement measures.
- **Research and development** - This could be focussed on the development of improved low-carbon and carbon-free energy technologies.
- **Information** - Information programs could be aimed at overcoming some of the barriers to efficient energy utilization outlined in Section 2.3.2

#### **2.3.4 Summary**

The message of the preceding sections can be summarized in three points:

1. There are many options available to reduce emissions of CO<sub>2</sub>.
2. There are many barriers, technological, institutional, and social, which prevent these measures from being fully adopted.
3. Answers to this dilemma must be found in the policy arena.

## Chapter 3

# Methodology: A Canadian Energy System Model

### 3.1 A Conceptual Model

In most modeling exercises there are two models:

1. A *conceptual* model of the entities and their relationships within the problem under study.
2. An *analytical* model, determined by the approach chosen to analyze the problem (be it a simple equation on a piece of paper or a sophisticated computer-based system).<sup>1</sup>

While the starting point is a conceptual model, this then evolves into the analytical model according to the requirements of the available analytical techniques.<sup>2</sup> The presentation below reflects this process.

#### 3.1.1 Techno-economic Representation

Bottom-up, techno-economic modeling requires a finely-divided representation of the energy system to allow meaningful competition between technologies. At a national or

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<sup>1</sup>The exception is a *Gedankenexperiment*, or thought experiment, which by definition involves only a conceptual model.

<sup>2</sup>As suggested by the adage "When your only tool is a hammer, everything begins to look like a nail."

international level this is naturally accomplished by dividing the real-world energy system along the following three dimensions.

### **System Levels**

The highest division splits the energy system into seven energy *levels* along the axis connecting energy resources to energy services. Based on the terminology of Section 1.4.1, these levels are:

- resources,
- primary energy,
- secondary energy, at the point of conversion,
- secondary energy, after any long-distance transmission/transportation, but before local distribution,
- final energy,
- useful energy, and
- energy services.

### **Energy Resources, Sources, Currencies, and Services**

The second division in this conceptual model splits the total energy flow at each of the six levels:

- The resources level is split into particular resources: deposits of coal and crude oil, potential flows of biomass and hydropower, etc.
- The primary energy level is split into the corresponding similar energy sources: coal, crude oil, biomass, etc.
- The secondary and final energy levels are split into energy currencies; coal and natural gas are carried across from the primary level, but crude oil is replaced by, e.g., gasoline and fuel oil, and other sources are replaced by, typically, electricity.

- At the levels of useful energy and energy services the division differs slightly. Here the total energy service demand is split into categories defined by:
  - related energy service technologies, e.g., residential furnaces defining the category *residential space heat*;
  - similar expectations for future changes in demand, e.g., separating growing and dying industries;
  - the degree of substitutability between the currencies supplying the service, e.g., for the case of electricity, separating thermal services provided by electricity (which other currencies can, in principle, supply equally well) from the services which can *only* reasonably be provided by electricity.

### Energy Conversion Technologies

The last division splits the two-dimensional matrix defined by *levels*  $\times$  {*resources*, *currencies*, and *demands*} into a three-dimensional network in which the various resources, sources, currencies and service demands are linked by energy conversion technologies. These technologies are classified according to the particular levels linked, and thus the conversions provided:

- **Extraction** technologies convert resources to primary energy sources; they include coal and uranium mining, crude oil and gas production, and biomass harvesting.
- **Primary conversion** technologies convert primary energy sources to secondary energy currencies; they include natural gas processing, crude oil refining, and fossil-fuel electricity generation.
- **Transportation and transmission** technologies connect the production of energy currencies to the point of large-scale utilization, and include long-distance gas and electricity transmission. Some of these technologies may also be linked to large-scale energy service demands, such as energy-intensive industries.
- **Distribution** technologies connect the large-scale transmission or transportation of secondary energy currencies to the final energy currencies required by smaller-scale

users; they include urban gas pipelines, urban electricity distribution, and local distribution of liquid fuels.

- **End-use** technologies convert final energy currencies into the energy services which consumers demand.

## 3.2 Modeling With MESSAGE

Structure is one aspect of a model, and may be shared across a broad range of analytic approaches. Data, on the other hand, tends to be approach-specific. The parameters, or data, which characterize a MESSAGE model fall into five categories:

- global values applicable to the model as a whole,
- resource availabilities and costs,
- energy service demands,
- techno-economic parameters for each technology, and
- miscellaneous optional parameters.

### 3.2.1 Global Parameters

Two parameters determine the overall scope of the model:

#### Time Periods

The model's time frame must be subdivided if the time-evolution of the energy system is to be investigated. MESSAGE permits the specification of unequal length time periods, thus enabling

- shorter periods at the beginning of the time frame, where, presumably, there is less uncertainty in parameters, and thus where short term dynamics are of interest;
- longer periods towards the end of the time frame, where uncertainties in the data may only support the identification of broad trends.

## Discount Rate

All parameters in the model are specified and reported in constant dollars, i.e., net of any inflation. However, even in the absence of inflation there is a *time value of money*: a dollar received today is worth more than a dollar received in a year's time. This difference in worth is quantified in terms of the interest which must be added to next year's dollar to give a total value equal to that of a dollar today.

Because of the time value of money, two sums at different times cannot be directly compared. Both must first be *discounted* to a common point in time using an appropriate interest or discount rate. High discount rates reduce the value today of expenditures and incomes made in the future, thus biasing against future income and biasing in favour of future expenditures. Low discount rates create an opposite bias against future expenditures and in favour of future income.

In selecting a discount rate the key issue is whose time values, or preferences, the rate should reflect. For projects having a national scope the principle is that the rate should reflect the time values of society as a whole, not the private preferences of any particular group of individuals. This leads to the term *social discount rate*.

MESSAGE, in common with all dynamic (i.e., multi-time period) models, accounts for intertemporal monetary flows by discounting all such flows to the beginning of the first model period. To do this it must be supplied with an appropriate discount rate.

### 3.2.2 Energy Service Demands

Energy service demands are the driving force within a techno-economic model, and thus are key parameters. Because of the difficulties in modeling the transformation of useful energy into energy services (see Section 1.4.1), MESSAGE combines these two levels. Thus, depending on the type of service, demands may be specified in the natural units of an energy service, e.g., tonne-km of freight transported, or in terms of useful energy.

Demands must be specified for each period of the model, and can be given either as absolute values, or as a base value and a series of relative changes.

## Load Curves

MESSAGE allows energy demands (and thus the sources and currencies which serve the demands) to be optionally subdivided one level further, by time, to specify *load curves*. In the real energy system the demand for an energy currency varies over time, and on multiple time scales. Electricity utilization has daily peaks in the morning and in the early evening, and has seasonal peaks in the summer and winter corresponding to high demands for air conditioning and for space heating, respectively. Natural gas demand also fluctuates, with a significant winter peak due to space heating requirements.

For energy currencies which are difficult or expensive to store it may be important to represent these variations in flow, since the system must then have sufficient capacity installed (and paid for) to satisfy the peak, rather than the average, flow.

### 3.2.3 Energy Resources

Each of the resources in the model must be characterized by

- a total quantity available, in energy units, and
- a unit cost.

Resources also can be optionally subdivided into *grades*, with each grade having a different quantity and unit cost.

Solar and hydropower resources are not represented explicitly. Their availability is determined only by the technological capacity which exists to harness them at any point in time. (This capacity is, in turn, determined by the cost and other techno-economic parameters describing the harnessing technologies.)

### Resource Classifications

Estimates of available resources are often expressed in terms of *reserves*, *discovered resources*, and *undiscovered resources*, or similar classifications. These are distinguished by their relative position on two scales: one scale representing decreasing degree of economic viability, i.e., increasing cost of extraction, and the other scale representing the decreasing

degree of geological certainty.<sup>3</sup> Reserves are those resources which are both well-defined geologically, and economically recoverable under current conditions. Discovered resources are those which are known to exist, but which cannot be extracted economically under existing conditions. Undiscovered resources are those which have not yet been identified, but are surmised to exist on the basis of geological evidence.

Note that in this classification, essentially all resources are accounted for (barring truly surprise discoveries). Resources become less expensive to extract, and move from one category to another, but there is no need to account for new “discoveries.”

### 3.2.4 Energy Conversion Technologies

While energy service demands are the driving force within the model, how they are satisfied is determined by the techno-economic parameters assigned to the technologies which service the demands, both directly and indirectly. Each technology is characterized by the following parameters.

- **Inputs:** the quantity of each energy resource, source or currency which is an input to the technology;
- **Outputs:** the corresponding quantity of each energy source, currency or service demand which is an output from the technology (thus specifying implicitly the efficiency of the conversion);
- **Emissions:** the quantities of any emissions from the technology;
- **First year available:** the first year in which the technology is available, for technologies without significant historical capacity;
- **Historical activity and capacity:** the historical activity of the technology, and any existing capacity at the start of the model;

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<sup>3</sup>These two scales can be presented as perpendicular axes on a single graph to produce what is referred to as a McKelvey diagram (see, e.g., Häfele 1981, p. 18).

- **Availability:** the plant factor, or availability of the technology, i.e., the fraction of the year that the technology is available;<sup>4</sup>
- **Lifetime:** the lifetime of the technology, in years;
- **Investment cost:** the investment cost of the technology, per unit of output capacity;
- **Fixed o&m cost:** the fixed operating and maintenance (o&m) cost associated with the technology, i.e., the sum of all costs which are a function only of the installed capacity, independent of the activity in any time period;
- **Variable o&m cost:** the variable o&m cost associated with the technology, i.e., the total of those costs which vary directly with the activity of the technology in a particular time period.

Most of these values may be specified separately for each time period in the model, and as either absolute values or as relative changes from a base value.

### 3.2.5 Imposed Constraints

In modeling, any question concerning feasibility only makes sense in terms of the imposed constraints—without constraints anything is possible. Thus the constraints imposed on the model are a key determinant of the results which will be obtained.

#### Inherent Constraints

Many of the constraints in a MESSAGE model are implicit in the structure and parameters described above:

- Every energy service demand must be satisfied.

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<sup>4</sup>The plant factor is interpreted within the model as the fraction of excess capacity which must be installed, but which is not available for use, e.g., a plant factor of 80% means that for a given capacity requirement,  $1/0.80 = 1.25$  times this capacity must be installed and paid for.

- The quantity extracted from a resource cannot exceed the quantity available.
- Each technology must be supplied with all of the inputs required to satisfy the outputs demanded of it. This is equivalent to saying that the total quantity of each energy source or currency produced must equal the total quantity demanded.
- Each technology must have sufficient installed capacity to satisfy the outputs demanded of it.

### **Optional Constraints**

In addition to the physically-based constraints listed above, MESSAGE allows the specification of many other types of constraints:

- The rate of extraction of each resource can be limited.
- Separate upper and lower limits can be applied, separately, to the activity and the newly-installed capacity of each technology. As well, for each end-use technology these limits can be specified in terms of market shares of the demand(s) which the technology serves, i.e., a technology can be restricted to supplying no more than some percentage of a particular energy service demand.
- Within each period of the model, the activity and newly-installed capacity of a technology can be constrained, separately, in terms of the activity or capacity added in the period before. This allows control of the rate of growth of a technology, and thus the rate at which it penetrates a particular “market” within the model.
- The activity and/or capacity of any group of technologies can be linked such that they must satisfy some constraint jointly. For example, all public transit technologies in a model can be limited together to some fraction of the demand for urban transport, without constraining competition between these technologies.

These optional constraints are often useful in representing real-world phenomena such as technology life-cycles, institutional inertia, etc.

### 3.2.6 Penalties and Incentives

MESSAGE allows proportional penalties and incentives to be imposed on any activity in a model (including capacity additions). These usually take the form of monetary penalties and incentives.

Such incentives (be they positive or negative) are sometimes referred to as “soft constraints,” in comparison to the “hard” constraints discussed in the previous section. Although the former are not constraints in the strict sense of the word, the analogy is useful: incentives act to “push” or “pull” the model in the desired direction, without imposing a strict limit on its behavior.

One particularly useful application of penalties in the current model is to simulate the effect of an emissions tax: a tax on CO<sub>2</sub> emissions is easily modeled by imposing a financial penalty on each unit of emission.

### 3.2.7 Optimization: Linear Programming

The model described above has, in summary, three components:

1. a network of technologies, linked by flows of energy resources, sources, and currencies;
2. a set of parameters characterizing the technologies, including those specifying the external constraints, or the boundary conditions, on the network, i.e., the available resources and the exogenous demands; and,
3. a set of constraints.

In the MESSAGE framework this is ultimately represented as a system of equations, where:

- the unknown variables are the activity (or input flow of energy) and newly-installed capacity for each technology, and the depletion of each resource, during each time period,

- the equations represent energy and capacity balances for each technology, constraints on resource extraction, requirements that service demands be satisfied, and any other user-defined constraints, e.g., on maximum emissions;
- each equation is expressed in terms of a subset of the variables, and has coefficients calculated from the specified techno-economic resource and technology parameters;
- the constants (right-hand side) of the equations are calculated from the specified service demands, the available resources, the historical installed capacities of the technologies, and any other specified limits.

From this, it is then straightforward to formulate an equation for the total of all costs in the system (in constant, discounted dollars), or alternately, e.g., an equation specifying the total quantity of any particular emission.

### **Mathematical Programming**

This system just described is a framework referred to generally as *mathematical programming*, which is characterized by:

- An *objective function* to be optimized, i.e., either minimized or maximized. Objective functions are typically framed in terms of cost minimization, as that criterion has a clear connection to the real world. However, other objectives, such as emissions minimization, are also possible.
- A set of *constraints* specifying limits which the optimization process must respect.

*Linear programming* is a subset of mathematical programming in which the objective function and the constraints are linear functions of the variables. Techno-economic models are

typically based on a linear programming framework<sup>5</sup> because their inherent technological detail can lead to systems having many thousands of variables and constraints. Such systems can only practicably be optimized via linear programming.

### Essential Linear Programming Concepts

This work does not require a detailed understanding of linear programming theory. (See, e.g., Williams (1985) for a fuller description of linear programming and other mathematical programming frameworks.) However, the following LP concepts and issues can arise when interpreting model results:

1. **Non-binding Constraints** - In any non-trivial LP model, some of the constraints will be unnecessary, or non-binding on the solution, i.e., optimization of the system will find the same result whether or not these constraints are included. Knowing which constraints are binding may provide useful information.
2. **Shadow Prices of Binding Constraints** - For each of the remaining constraints, i.e., those which are binding on the solution, one can calculate how much the objective function would change if the constraint were either relaxed or tightened by one unit. This value, referred to as the *shadow price* of the constraint, can be interpreted as the marginal value of what is being constrained. For example, given a constraint on total CO<sub>2</sub> emissions, the associated shadow price can be interpreted as the value of emitting one additional unit of CO<sub>2</sub>. This has a clear value in relating model results back to the real-world energy system: to the extent that the model reflects the real world system, the shadow price gives the marginal cost of imposing the constraint. For the example of the constraint on CO<sub>2</sub> emissions, the shadow price is the marginal cost of abating CO<sub>2</sub> within the model.

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<sup>5</sup>However MESSAGE does allow the use of:

- *integer programming*, in which some variables can be constrained to take on only integer values, and
- the use of a non-linear objective function.
- the use of non-linear objective constraints.

3. **Global Optimization** - The single system of equations created from the model parameters and constraints represents all time periods of the model. Thus solving the system optimizes all time periods simultaneously, leading to a characteristic sometimes referred to, anthropomorphically, as “perfect foresight”: a model optimized as though by someone having perfect knowledge of the future.
4. **Sensitivity to Initial Conditions** - Optimization ensures, by definition, that the optimal approach is used to maximum advantage. This can lead to a “flip-flop” behavior if two different solutions have very similar optimal values (e.g., total costs, if cost optimization is being performed). Under such conditions very small changes in input parameters can result in a “flip” from one solution state to the other, with large changes in results.

It may be thought that linear programming imposes excessive limitations on an energy model: that real world systems are not linear, that real-world systems aren't always created with minimum cost in mind, that no one in the real world has perfect foresight, and that real-world systems don't flip-flop around but rather change slowly from one trajectory to another. However, while the observations are certainly correct, the conclusion that they invalidate a linear programming approach to energy modeling is not. The answer to this has three parts:

1. Linearity is a restriction, but problems can be minimized by careful selection of parameters or by the use of piecewise linear approximations.
2. Undesirable flip-flop behavior can be controlled through the liberal use of constraints, particularly constraints relating activities between adjacent periods. These serve to dampen, in a mechanical sense, the dynamics of the model.
3. While cost minimization and perfect foresight may be rare in the real world, their inclusion in a model leads to a solution which is, in a strict sense, *optimal*; it is not what will come to pass in the real world (except by accident) but it represents a useful target.

### 3.2.8 Using the MESSAGE System

MESSAGE is a combination matrix generator and report generator, i.e., it is not a single software program, but rather a set of programs. The following steps summarize the use of the MESSAGE system. (Refer also to Appendices A and B and to the MESSAGE manuals (Messner 1984a, Messner 1984b, Strubegger 1984) for further information.)

1. Four input files are created by the user for each set of scenarios:
  - one file containing general technology data which may be common to a number of related energy system models;
  - a second file containing the structure of a single model, and often all data for the BAU or reference case;
  - a third file for each scenario, specifying how that scenario differs from the reference case;
  - a fourth control file.
  
2. The data for the BAU case and for each additional scenario are entered into these files, following a fixed structure. The required data includes:
  - energy levels, currencies and service demand categories;
  - timesteps and the discount rate;
  - load regions, and load curves for those demand categories having them;
  - assumed future service demands;
  - available quantities of resources by grade, and their associated costs;
  - technologies and their associated techno-economic parameters;
  - the links between technologies, resources, sources, currencies, and service demands;
  - constraints, penalties, incentives, and other relations between technologies.
  
3. The program `mxg` converts the input files into an output file specifying the (sparse) matrix of coefficients corresponding to the system of linear equations referred to in Section 3.2.7. This step is referred to as *matrix generation* and `mxg` as the *matrix generator*.

4. A second program (`rlp`) invokes a commercially available linear programming solver to optimize the linear system for the specified objective function. The optimal solution (assuming one can be found) is recorded in another output file, along with shadow prices and other diagnostic information.
5. A report generator named `cap` reads the data contained in the input files and in the output solution file, producing custom output tables. An example set of output tables is included in Appendix B. The content and format of the tables is defined by the user.

The essential modeling process involves:

1. Creating the input files, based on the preliminary structure and data chosen for the model.
2. Running the MESSAGE programs described above on the input files, to produce output tables. (It is often necessary to modify the input files to produce a model specification which has a solution, i.e., which is *feasible*.)
3. Analyzing the model results for plausibility and consistency with the assumptions underlying the scenario.
4. Modifying the input files and repeating the above process until the model results are judged to be plausible.

### **3.3 Implementation: Modeling the Canadian Energy System**

The components of a MESSAGE model, and their assembly and solution as a whole have been outlined. What remains is to show how the reality of the Canadian energy system can be framed in these terms.

(References for most data sources are given in Appendix A; only directly-relevant data references are cited below. All costs quoted here, and elsewhere, are in Canadian dollars at 1990 prices and exchange rates, unless stated otherwise.)

### 3.3.1 Global Parameter Values

#### Time Periods

The model results span 1991 to 2020, for the eight periods listed in Table 3.1.<sup>6</sup> Results are reported for the years at the approximate midpoint of each period.

Starting Year:	1991	1992	1994	1996	1998	2003	2008	2013
Period Length:	1	2	2	2	5	5	5	15
Midpoint:	1991	1992	1994	1996	2000	2005	2010	2020

**Table 3.1:** Periods comprising model time frame. Throughout this work model results are reported for period midpoints.

#### Discount Rate

During the last two decades, 10% has been the mandated discount rate for the analysis of federal government projects in both Canada (Treasury Board Secretariat 1976) and the United States (Lind et al. 1982, p. 5). This value was originally derived from a perspective referred to as the social opportunity cost of capital (SOCC), which reflects primarily the pre-tax return earned by marginal capital investments. Many have criticized this 10% rate, however, arguing either (NEB 1985):

1. that the SOCC approach is correct, but a proper calculation leads to a lower value, nearer to 7% or 8%; or
2. that the SOCC approach is incorrect; an appropriate social discount rate should be based on a social time preference (STP) for current consumption, reflected primarily in the after-tax return on savings (which in the early 1970s was about 4%).

The value used here is a compromise. It is based on a SOCC approach, in particular Ontario Hydro's current estimate of their cost of capital. While it is considerably lower than the

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<sup>6</sup>The model actually has one additional period, from 2028–2043, which is not reported. This ensures that the last period which is reported doesn't suffer from the anomalous results often characterizing the final period of an LP model. For example, with no need to provide capacity beyond the end of the model time horizon, high investment, low O&M technologies may be ignored in favour of low investment, high O&M ones.

traditional rates based on a SOCC approach, it is a rate commonly used by electric utilities (OECD-NEA 1989, p. 35).

Ontario Hydro's current discount rate (in constant dollars) is approximately 5.4%, with a long term rate estimated to be closer to 4.5% (ONCI 1989). For this model a value near the the midpoint of the Ontario Hydro range — 5% — has been selected.

### Load Curves

In the current model the year is divided into fractions of 5%, 15%, 50%, and 30%, in order of highest flow or capacity requirements to lowest; they are referred to, respectively, as *peak-peak*, *peak*, *intermediate*, and *baseload* regions. An example of the use of load regions is residential space heating, whose allocation to the regions is 9%, 27%, 54%, and 10%. The relative flow is given by the ratio of the allocation to the load region fraction, e.g., the relative flow in the peak-peak load region is  $9\% \div 5\% = 1.8$  while the relative flow in the baseload region is  $10\% \div 30\% = 0.33$ . The set of relative flow values for a particular flow is referred to as its *load-curve*.

The model currently uses two load curves, one which is applied to most electricity demands, and one which is applied to space heating and cooling demands (see Table 3.2).

Service	Relative Demand for Fraction of Period			
	5%	15%	50%	30%
Electricity	1.40	1.20	1.00	0.83
Space and water heating	1.80	1.80	1.08	0.33

**Table 3.2:** Load curves for classes of energy service demands, expressed in terms of relative power required for each fraction of any time period.

## Oil Prices

In this model the cost of domestic oil is internally determined. However, the prices of imported and exported sources and currencies are tied to an assumed world oil price. This price starts rising from approximately \$3.3/GJ in 1990, and levels off at \$5.2/GJ by 2010.

### 3.3.2 System Levels

The system levels used in the current model are implemented as described in Sections 3.1.1 and 3.2.2: resources, primary energy, secondary energy before and after transmission and transportation, final energy, and useful energy/energy services. While additional levels representing, e.g., a subdivision of transportation or distribution, are also possible, none are used in the current model.

### 3.3.3 Energy Service Demands

#### Theory versus Practice

Ideally all energy services should be expressed in non-energy units representing the actual service desired by the end-user, through a four-step process:

1. identification of the desired service;
2. selection of suitable units for the expression of the service;
3. calculation of the magnitude of the historical service in the selected units;
4. determination of the relationships between final energy input, useful energy, and energy service output for the conversion technologies to be included in the model.

However, this ideal approach has two problems. First, it may be difficult to separate energy services from other services that people desire. On one hand a car seems a natural example of an end-use technology, one providing the energy service *passenger transportation*. Yet one need only look at the range of cars available to see that they provide many other services besides transportation: privacy, recreation, status, and so on. How much of the price of a car should be allocated to transportation, and how much to other services?

The second problem with the ideal approach is that it is often infeasible. Consider the data requirements implied by the list of factors in Section 1.4.1 which govern the transformation of useful thermal energy into residential space heat. Even with an estimate for the total energy service, it is infeasible to try to account for all the factors determining the relationship between this and the tabulated final energy utilization.

In the end, the only reasonable approach for this type of energy service, at least at a national level, is to:

1. Start from the available statistics on final energy utilization in the sector of interest;
2. Assume certain techno-economic parameters for the identified technologies converting final energy into useful energy in this sector, e.g., residential furnaces, for residential space heating demands;
3. Estimate the historical total useful energy based on the technological assumptions, and use this as a proxy for the true energy service;
4. Adjust the estimated useful energy as necessary to account for structural, intensity, and other changes affecting its transformation to energy services, e.g., for residential space heating, adjust for the number and size of dwellings, per-dwelling energy requirements, etc.

The difficulties in estimating the residential space heating energy service are exacerbated when the service demands are poorly defined, or when they represent an aggregate of many different types of demands, as in:

- *non-substitutable electricity consumption*, the sum of a myriad of individually small, but cumulatively large energy service demands which can only reasonably be provided by the energy currency electricity;
- *industrial sectors*, when aggregated at a national level;

One approach in these situations is to use monetary value-added (in dollars) as a measure of energy service.<sup>7</sup> The difficulty with this approach is that the value-added dollars represent many factors beyond energy services, such as labour productivity, non-energy related process improvements, and currency exchange rates, factors which a techno-economic model should attempt to exclude.

### **Modeled Service Demands**

A different approach, and the one used here, is to use final energy as a proxy for poorly-defined energy service demands. As with other demands, adjustments to this value can then be made to account for structural changes, technological improvements, etc.

Table 3.3 lists all energy service demands in the current model, with the average annual change in demand over the period 1990–2020. As well, the complete specification of energy service demands can be found in the model description contained in Appendix A.

The starting point for these demands is the energy utilization in the base year, 1990, obtained from Statistics Canada publications (see Appendix A for complete references). From here, the approach taken in specifying future demands begins with data for:

- historical trends in total energy and electricity utilization, and the ratios of these to population, gross domestic product (GDP), and industrial production for the period 1980–1989 (IEA 1991a);
- projections of various residential and commercial energy demands for the City of Toronto (Marbek 1992a–d);
- projections of sectoral electricity growth for Ontario (Ontario Hydro 1989);
- forecasts of population growth in Canada (Perreault 1990);
- forecasts of GDP growth (NEB 1991).

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<sup>7</sup>This approach is often taken, by necessity, in studies of historical changes in energy intensity. See, for example, Meyers & Schipper (1992).

Energy Service Category Energy Service	1990 Demand	Average Annual % Change 1990-2020	Units
<b>Residential</b>			
Non-substitutable electric	303.3	2.51	PJ
Space and water heat	629.6	0.19	PJ
<b>Commercial</b>			
Non-substitutable electric	254.4	2.89	PJ
Space and water heat	383.1	2.16	PJ
Pumps and fans	71.8	2.60	PJ
Space cooling	59.5	2.60	PJ
<b>Metals Industries</b>			
Non-substitutable electric	142.2	0.29	PJ
Non-substitutable liquid fuel	1.9	0.29	PJ
Thermal	83.9	-0.21	PJ
Non-substitutable coke	98.0	-0.21	PJ
<b>Pulp, Paper and Sawmills</b>			
Non-substitutable electric	150.4	0.29	PJ
Non-substitutable liquid fuel	10.5	0.29	PJ
Thermal	270.8	-0.21	PJ
<b>Chemical Industries</b>			
Non-substitutable electric	55.5	2.36	PJ
Non-substitutable liquid fuel	0.3	2.36	PJ
Thermal	118.2	2.36	PJ
<b>Other Industry and Manufacturing</b>			
Non-substitutable electric	223.6	2.36	PJ
Non-substitutable liquid fuel	84.5	2.36	PJ
Thermal	429.8	2.36	PJ
<b>Forestry and Agriculture</b>			
Non-substitutable electric	31.2	-0.61	PJ
Non-substitutable liquid fuel	134.4	-0.61	PJ
Thermal	57.4	-0.61	PJ
<b>Transportation</b>			
Road and rail freight	418.2	0.29	Gt-km
Marine freight	373.2	0.29	Gt-km
Air freight	1.8	2.89	Gt-km
Intercity passenger transport	245.7	2.14	Gp-km
Urban passenger transport	216.6	2.64	Gp-km

**Table 3.3:** Historical energy service demands in 1990, and average forecast change in service over model time frame (Gt-km = gigatonne-km, Gp-km = gigaperson-km).

Based on this data, estimates of GDP and population growth have been made, followed by estimates of the future relationships between the different service demands and these two variables.

### 3.3.4 Energy Resources, Sources and Currencies

#### Modeled Resources

The fossil resources included in the model are listed in Table 3.4; they are:

- **Natural gas and natural gas liquids (NGLs)**,<sup>8</sup> including non-conventional gas resources;<sup>9</sup>
- **Crude oil**, including tar sands/bitumen resources;<sup>10</sup>
- **Coal**, both "hard" (bituminous) and "soft" (sub-bituminous and lignite).<sup>11</sup>

The following non-fossil resources already make significant contributions to Canada's energy requirements. However, they are treated slightly differently than fossil resources; rather than constraining extraction to some defined quantity, these resources are constrained through the technologies which harness them, as mentioned earlier and discussed in greater detail in Section 3.4 below.

- **Hydropower** - Hydropower potential is based on sites identified by provincial utilities for development between 1990 and 2010, according to the NEB (1991).

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<sup>8</sup>Natural gas liquids (NGLs) are the heavier fractions (in terms of molecular weight) of natural gas, including ethane, propane, butane, and pentane, which are liquid either at standard temperature and pressure, or at the conditions typically found in pipeline compressors. It is for the latter reason that they are extracted from natural gas before transmission. NGLs represent about 10% of the energy content of total natural gas production.

<sup>9</sup>Most natural gas has been discovered while exploring for oil, and produced from similar geological conditions. Non-conventional gas is found where oil is not, e.g., deeper offshore fields, non-porous (tight) geological formations, coal seams, gas hydrates, etc. (Rogner 1989).

<sup>10</sup>Tar sands resources are vast deposits (see Table 3.4) of very viscous crude oil, or bitumen, mixed with sand. The deposits may be located near the earth's surface, (permitting extraction using mining techniques) or they may be farther underground (in which case techniques such as steam injection must be employed). Once extracted the bitumen must be separated from the sand and then refined or upgraded into a synthetic light crude oil.

<sup>11</sup>Coals are classified by many characteristics. The most relevant measure for modeling purposes is energy content, with bituminous coal having greater than 24 kJ/kg, lignite having less than 17 kJ/kg, and sub-bituminous coal falling in between (IEA 1992b).

Resource Category	Quantity (EJ)			Cost Range (\$ per GJ)
	Reserves	Discovered Resources	Undiscovered Resources	
Natural Gas and NGLs				
Onshore	110		118	0.95 - 3.5
Offshore	13	32	290	3.2 - 5.7
Non-conventional			345	7.8 - 9.4
Crude Oil				
Onshore	24	17	38	2.6 - 7.9
Offshore	4	20	107	2.8 - 7.4
Tar Sands/Bitumen		2600		6.7
Coal				
Hard (bituminous)	103	620	1500	3.1 - 3.7
Soft (sub-bit. and lignite)	51	680	770	1.5 - 1.9

**Table 3.4:** Fossil resource categories included in model, with estimated quantities and extraction costs. Resource estimates are based on data in NEB (1991), with cost data from Rogner (1992). To put these values in context, 1990 extraction of natural gas and NGLs, crude oil and coal was 4.3, 3.7, and 1.7 EJ respectively. (sub-bit. = sub-bituminous)

- **Uranium** - As a resource, uranium is not an issue; there is considerably more uranium available in Canada than can be used here. Rather, the issue is the resistance to construction of new nuclear generating capacity which can utilize this resource.
- **Biomass** - No detailed biomass inventory has been used in this model; instead, as explained in Section 3.4, the utilization of biomass is constrained to a level which is assumed to be easily sustainable.

The following resources are currently insignificant in terms of Canada's energy flows, but are included in the model as future resource options:

- **Solar radiation,**
- **Municipal waste,**
- **Intensive bioenergy cultivation.**

## Energy Currencies

Table 3.5 lists the major energy currencies in Canada and their contribution to total final energy utilization in 1990. The table also includes currencies which have been historically less important, but which are included in the model as future alternatives. Some of the currencies deserve additional comment:

- **Coke**<sup>12</sup> is used only in the metals smelting and processing industries, and is included only so the CO<sub>2</sub> emission associated with it can be accounted for.
- While **coal** is an important energy resource and source in Canada, it has very limited use as an energy currency. Like coke, its inclusion here is mainly to ensure a full accounting of CO<sub>2</sub> emissions.
- **Hydrogen** (H<sub>2</sub>) can be produced via either electrolysis or steam-methane reforming (SMR) of natural gas. The SMR process outputs the carbon contained in the natural gas as CO<sub>2</sub>; in the model this CO<sub>2</sub> can either be emitted to the atmosphere or disposed of, within limits, via injection in Western Canadian gas fields.

Within the model H<sub>2</sub> can be utilized either as a carbon-free addition to natural gas pipelines,<sup>13</sup> or as a separate currency (in either gas or liquid form) in the transport sector.<sup>14</sup>

- **Methanol** is produced in the model from biomass (currently assumed to be CO<sub>2</sub>-neutral) for use as a motor vehicle fuel.
- **District heat** is a mature technology but one which has found limited application so far in North America. While district heat is included as a future option, the limited existing capacity is not represented in the model.

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<sup>12</sup>Coke is coal which has been *carbonized*, i.e., heated to a high temperature in the absence of air to drive off its volatile components.

<sup>13</sup>Hydrogen can be blended with natural gas at ratios of up to 10% by volume (equivalent to 3% by energy) with no negative effects on combustion properties (Steinmetz 1984).

<sup>14</sup>The model has the choice of producing this H<sub>2</sub> via electrolysis or steam-methane reforming (SMR) of natural gas, and chooses the latter. Disposal is the method chosen.

Energy Currency	1990 Utilization [PJ]
Natural gas and NGLs	1,930
Electricity	1,510
Gasoline	1,180
Diesel fuel/Light fuel oil	920
Biomass	590
Heavy/Residual fuel oil	270
Aviation turbo fuel	190
Coke	98
Hard coal	47
Hydrogen	<i>n/a</i>
Methanol	<i>n/a</i>
District heat	<i>n/a</i>

**Table 3.5:** Energy currencies included in the model, along with 1990 data on utilization in Canada. Those marked *n/a* are currently utilized to an insignificant degree, and are modeled only as future options.

### 3.3.5 Energy Conversion Technologies

The current model has a total of approximately 230 technologies, from extraction to end-use. Technology categories other than those representing end-use-to-final conversion are listed in Table 3.6. End-use technologies are discussed below. A list of all technologies and their techno-economic parameters is included in the model description contained in Appendix A.

A few technology categories from Table 3.6 require comment:

- Import and export technologies are not balanced. In some cases the flow is essentially one-way, while in other cases a single technology represents only the net flow, be it an import or export.

Technology Category	Technologies in Model
<b>Resource Extraction</b>	
Natural gas	7
Crude oil	7
Coal	2
Others	3
Import & Export of Energy Currencies	9
<b>Thermal Electricity Generation</b>	
Natural gas	4
Coal	7
Light and heavy fuel oil	2
Biomass	1
Municipal waste	1
Multifuel	3
Cogeneration (multifuel)	2
<b>Other Electricity Generation</b>	
Hydroelectric	4
Candu nuclear	1
Wind turbine	1
Solar photovoltaic	1
<b>District Heat/Steam Generation</b>	
Municipal waste combustion	1
Multifuel combustion	2
<b>Other Currency Processing/Production</b>	
Natural gas cleaning	4
Crude oil refining	5
Hydrogen	3
Others	3
<b>Transmission and Distribution</b>	
Natural gas	8
Electricity	4
Others	18
<b>Emission Reduction</b>	
SO <sub>2</sub> , NO <sub>x</sub> scrubbing	8
CO <sub>2</sub> disposal	1

**Table 3.6:** Energy conversion technologies included in model, except those providing end-use services. Techno-economic parameters are given in Appendix A.

- Electricity generation technologies include steam turbine plants, integrated gasification/combined cycle (IGCC) and fluidized bed options for coal, and both combined cycle and cogeneration<sup>15</sup> options for natural gas.
- SO<sub>2</sub> and NO<sub>x</sub> abatement technologies represent systems which can be retrofitted to those existing plants which do not yet have emission controls. The CO<sub>2</sub> technology, on the other hand, represents the disposal of CO<sub>2</sub> which has been separated elsewhere (either from reforming of natural gas into hydrogen, or from the coal-fueled IGCC plant).

### Modeling Demand Reduction

As discussed in Chapter 2, reduction in the utilization of final energy, what people often incorrectly refer to as “energy conservation,”<sup>16</sup> can be accomplished in one of three ways:

1. Improve the efficiency of final-to-useful energy conversion.
2. Improve the “efficiency” of useful energy-to-energy services processes, usually by investing capital.
3. Reduce the demand for the energy service, through changes in behavior.

In the case of residential space heating, an example of the first approach would be replacing the furnace with a more efficient model; the second approach might mean insulating the outer shell of the dwelling; the third approach could mean wearing a sweater, or turning down the thermostat at night and when no one is at home.

Modeling the first approach, that of efficiency improvements, fits naturally into a technoeconomic framework; the second and third approaches are more difficult to deal with. Because demands are specified exogenously, there is no direct way to represent the real-world impact of, say, rising prices on the demand for energy services.

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<sup>15</sup>Cogeneration is the production of both useful heat and work from a single system, where *useful* means that the heat is at a sufficiently high temperature to be used, as a minimum, for space and water heating.

<sup>16</sup>Because the first law of thermodynamics tells us that energy is *always* conserved.

The approach taken in the current model is to create *demand reduction* “technologies”; these satisfy some amount of a demand for a particular useful energy or energy service, but without requiring the input of any additional final energy.

The demand reduction technologies discussed in the following sections have, of course, cost parameters, and the assignment of these can be a difficult matter. The problem is achieving the desired price-response from a small number of technologies, in an area in which a greater than usual number of non-price factors are at work. In the end, the solution generally involves starting with costs based on some representative underlying technology (say insulation of residential dwelling shells) and then adjusting these costs on a scenario-specific basis to get the model behavior which is plausible for each scenario.

### **Industrial End-use Technologies**

Each of the five industrial sectors (metals smelting and refining; pulp, paper and sawmills; chemicals; forestry & agriculture; other industry and manufacturing) has technologies representing:

- thermal services provided by selected fossil-based currencies, including natural gas and heavy fuel oil;
- thermal services provided by electricity;
- non-substitutable electricity services;
- non-substitutable liquid fuels services, to account for unidentified diesel fuel and gasoline utilization.

A small number of industry-specific technologies are also included, representing, e.g., coke in the metals industries, and thermal services from biomass in the pulp & paper and the forestry & agriculture industries.

Finally, three technologies represent increasing levels of demand-reduction. These are non-specific technologies providing services to all industrial sectors proportionately.

In all, there are 38 industrial end-use technologies.

One may wonder about the unusually high degree of aggregation applied to the industrial sector. However, as has already been mentioned in the review of Margolick et al.'s (1992) study in Chapter 1, and notwithstanding the energy intensity of Canadian industry, industrial decisions are driven primarily by product, not energy, concerns. As Margolick et al. found, the industrial sector's potential response to CO<sub>2</sub> levies varies greatly from industry to industry, and is generally determined by product, not energy, concerns.

Thus, of all sectors, industry is the one in which a detailed technological representation is least important.

### **Residential End-use Technologies**

Most of the 17 residential end-use technologies provide thermal (space and water heating) services. The most common currencies, light fuel oil and natural gas, each have three levels of increasingly efficient and costly technologies available. Technologies representing solar thermal, biomass (wood), district heat, and electric and natural gas heat pumps are also included, as are two levels of thermal demand reduction.

Non-substitutable electricity demands are serviced by one technology with two available levels of demand reduction.

### **Commercial End-use Technologies**

The commercial and public administration technologies are divided into four categories:

- Non-specific electricity service demands are supplied, as in the residential sector, by one technology and two available demand reduction options.
- Thermal services are supplied by 10 technology options similar to those in the residential sector: two levels each of natural gas and light fuel oil technologies, one residual oil technology, plus technologies representing electric and gas heat pumps, solar thermal, and district heat. There are two levels of thermal demand reduction.

- Two levels of ventilation services represent fans and pumps in larger commercial buildings. The opportunities for demand reduction are considered fewer here, and so none not included in the model.
- Cooling/air-conditioning technologies, incorporating two levels of standard vapour cycle technologies, are included, plus one district cooling option.<sup>17</sup> Two levels of cooling demand reduction are available.

### Freight Transport End-use Technologies

Freight transport is subdivided into modes between which little competition is assumed possible:

- Marine freight, handling bulk commodities where this option is available;
- Surface freight, serviced by competing road and rail technologies. Rail is assumed to carry bulk commodities where marine transport is not an option, as well as competing for some of the higher-value freight typically carried by truck;
- Air freight, for the relatively small, highest value shipments.

Two technologies compete within each of the air and marine freight service demands. Road freight is represented by five road/truck technologies, one representing a blend of the existing fleet and of “standard” new replacement trucks, and the other three representing higher efficiency trucks fueled by diesel, natural gas, and gasoline. Rail freight services are provided by two levels of standard diesel locomotives, and two advanced options: liquid natural gas (LNG) retrofitted to standard locomotives, and next-generation locomotives powered by liquid hydrogen (LH<sub>2</sub>) via fuel cells.

As with other service categories, two levels of demand reduction technologies service all freight demands. Demand reduction is *not* split proportionally; most of the reduction to satisfies road and rail services, and the remainder supplies air freight.

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<sup>17</sup>District cooling is the provision of space cooling, primarily for commercial buildings, using either

1. centralized production and storage of chilled water which is circulated through a distribution network parallel to an assumed district heating system; or,
2. absorption chillers located in each building, driven by a district heating system.

Note that both system depend on a district heating system being in place, although for different reasons.

### **Passenger Transport End-use Technologies**

Passenger transport is subdivided into two separate service demand categories: intercity, and intracity or urban. Each of these is then internally subdivided into private transport (via personal cars) and public transport (via bus, train, etc.). For each service, the split between private and public transport is allowed to change, but only within strictly set limits (see Section 3.4).

As with freight transport, the most common mode for each sub-service (cars for private, buses for public) is represented by a single existing-fleet/standard-replacement technology, with higher-efficiency, higher-cost options available which are fueled by diesel, natural gas, and, in the case of urban buses, internally-combusted LH<sub>2</sub>.

Intercity public transit has only two modes: aircraft (two levels of technology) and “surface” transport. The latter, with three technologies, represents a combination of intercity buses and trains. (The services provided by intercity buses and trains are too similar to justify a separate set of technologies for each.)

Urban and intercity car technologies share capacity; at any time a “car” can provide either service, with appropriate techno-economic parameters, while being prevented from providing both services at once. The one exception to this mode-sharing of capacity is the included battery-driven car technology, which provides only urban service.

Finally, urban and intercity services each have two levels of potential demand reduction.

#### **3.3.6 The Objective Function: Cost Minimization**

For all the scenarios considered in this work, the objective for optimization of the system is minimization of the present value (discounted) of all energy system costs. The objective function is represented as a set of coefficients for the system variables, i.e., for activities, newly-installed capacities, and resource uses in each time period (see Section 3.2.7). The objective function has the following components, summed over all technologies and all time periods:

1. variable O&M costs due to the activity of each technology;

2. fixed O&M costs due for newly-installed capacity of each technology, given its known lifetime;
3. depletion costs for each resource (in addition to any technology costs for extraction);
4. energy import costs;
5. energy export revenues;
6. capital or investment costs of newly-installed capacity for each technology;
7. penalty and incentive charges on the activity of each technology, e.g., emissions taxes;
8. penalty and incentive charges on newly-installed capacity for each technology;

Each cost component of the objective function is discounted back to the starting point of the model. Costs relating to technology activities, as well as fixed O&M costs, are discounted from the mid-point of each time period; investment costs and other charges relating to technology capacities are discounted from the start of each period.

The full form of the objective function is given in Messner (1984a), along with a full listing of the other equations (energy and capacity balances, as well as constraints) making up the linear system.

### 3.4 Scenarios

The term *scenario* has been defined by Häfele (1981, p. 423) as “a logically consistent statement or characterization of a possible future state of the world.” Replacing “the world” by the “Canadian energy system” gives the intent behind the use of the term scenario in this thesis. It is worth stressing that a scenario is not a forecast of *the* future, but rather an attempt to describe *one possible*, internally consistent, future.

In terms of energy modeling, scenario definition is the exercise of developing sets of model parameters which are internally consistent, and also, as far as possible, consistent with the real world.

Within a linear programming framework, the implementation of scenarios is primarily an exercise in specifying constraints and, to a lesser extent, penalties and incentives. Their primary role is to impose real-world behavior, although they also have other important roles (which have been described in detail above):

- to dampen the otherwise characteristic flip-flop effect in LP models;
- to reflect real-world constraints on, e.g., resource extraction and utilization.

A majority of the scenario development has necessarily focussed on the creation of a reasonable starting point, a business-as-usual (BAU) base case model. This presentation will follow the same path: a description of the key components of the BAU base case, followed by an explanation of how the other scenarios depart from BAU.

### 3.4.1 Preliminary Considerations

#### Technology Constraints

Nearly every technology in the model is bounded in one or more ways, both to dampen flip-flop behavior which may otherwise result, and to reflect characteristics of the real world. Such bounds most often take one of the following forms:

- *An absolute upper bound on activity, increasing over time.*

This bound is applied to technologies whose parameters would otherwise cause a rapid increase in activity. A bound which slowly increases over time doesn't eliminate the inherent behavior, but does dampen it. A variation on this type of bound is available for end-use technologies—since the respective energy service demand is known at the outset, one can specify an upper bound in terms of a share of that demand.

- *An absolute lower bound on activity, decreasing over time.*

An argument similar to that for the upper bound applies here, except that it is applied where the techno-economic parameters would otherwise lead to the activity of

the technology decreasing too quickly. Similarly, lower bounds for end-use technologies can be specified in terms of market share, forcing an otherwise uncompetitive technology to remain active to some degree.

- *A dynamic upper bound on the inter-period change in activity.*

Such a constraint is very useful in dampening the dynamics of a model, but is, unfortunately, limited essentially to technologies where neither the inputs nor the outputs have load curves (since each portion of a load curve has a separate activity variable).

- *A dynamic upper bound on the inter-period change in capacity additions.*

This can be adjusted to have a similar, although more indirect effect on activity as the dynamic activity bound, by constraining capacity additions. It has the advantage, however, of being applicable to all technologies, regardless of the presence of load curves (since all technologies have only one capacity addition variable).

- *A dynamic lower bound on the inter-period change in activity.*

This is often set to allow *no* decline in activity, thus forcing any increase to be permanent. This has a useful dampening function.

## **Biomass and CO<sub>2</sub>**

As discussed in Section 2.2.1, the CO<sub>2</sub> impact of biomass cannot, in general, be answered unequivocally. For the BAU base case this work follows the lead of Jaques and considers moderate biomass utilization to be CO<sub>2</sub>-neutral. However, any scenario involving a considerable expansion of biomass extraction would require reconsideration of this decision.

### **3.4.2 Business as Usual**

Everyone has a different idea of what BAU will be. Thus any scenario should be judged on criteria of internal consistency and overall reasonableness.

## Resource Constraints

In addition to the general resource extraction constraints discussed in Section 3.2.5, the BAU model incorporates a small number of more specialized constraints relating to resource availability.

- **Hydropower** - Hydroelectricity capacity additions are limited in the base case model to 50% of the projects identified by the NEB (1991) as being available for development between 1990 and 2010. This is a total of about 15 GW potential added capacity, the vast majority of which is in Quebec; it compares to a total existing capacity in Canada of approximately 57 GW.

The 50% limit has been imposed to represent the increasing public resistance to large scale hydroelectric development.

- **Uranium** - As a resource, uranium is not an issue; considerably more is available in Canada than is likely to be required domestically (ONCI 1989, p. 55). The development of nuclear generating capacity is a socio-political issue, however. In the model, social resistance to nuclear generation is represented by a constraint limiting nuclear capacity additions to the replacement of retired capacity.
- **Biomass** - While biomass provides a significant fraction of primary energy in the Canadian energy system, about 70% of this represents utilization by the forestry and pulp & paper industries of their own process by-products. Whether extensive expansion of bioenergy production in Canada is environmentally sustainable or socially acceptable are open questions. To take account of these issues, non-industrial bioenergy extraction (separate from that determined by industrial process requirements) is limited to an annual growth rate of 5%, starting from the current non-industrial extraction of about 180 PJ. Over 30 years this limit would allow non-industrial biomass to grow to about 4.3 times the current level which, while non-trivial, represents little more than a doubling of the total (including industrial) bioenergy utilization.
- **Solar** - Both solar photovoltaic and solar thermal technologies are constrained primarily by their high costs, although these do decline over time. However both also

have bounds applied to limit their rate of introduction, to reflect real-world market penetration rates.

### **Emission Constraints**

One important emission constraint is present even in the BAU model. In 1985, the seven provinces from Manitoba east to Newfoundland agreed to limits on total SO<sub>2</sub> emissions (Government of Canada 1991b, p. 12-17). As a result of these agreements, utilities such as Ontario Hydro are committed to reducing their emissions of SO<sub>2</sub> by up to 60% by 1994. To the extent that this reduction is brought about by fuel-switching away from coal, it may have important impacts on CO<sub>2</sub> emissions, which the model must account for.

### **Technology Relations**

The following are some key links between technologies in the BAU model, intended to reflect aspects of the real-world energy system.

- **Public and Private Passenger Transport** - For both intercity and intracity service demands, public and private transit are linked to reflect the general preference for private travel, in spite of its greater costs. In the base case this restricts the total share of public transport modes within each service to historical values.
- **Road and Rail Freight** - A similar process is at work in the competition between trucks and trains for freight. Rail has a definite cost advantage within the model, and must be constrained to give reasonable mode splits. As with the previous example, this is done in the BAU case on the basis of historical mode shares.
- **Natural Gas and District Heat Density Regions** - MESSAGE does not directly represent spatial dimensions. This can lead to difficulties in modelling those currencies, such as natural gas and district heat, which require an expensive and inflexible distribution infrastructure. Regardless of the overall economic attractiveness of these currencies, installation of the necessary pipelines will never be economically feasible for large parts of the country. As well, one can argue that for infrastructure provided

to new developments the choice of either district heat or natural gas will preclude installation of the other.

These difficulties are resolved by creating abstract energy density regions, in which natural gas and district heat compete up to a strict activity limit. The density constraint is implemented in the model by first identifying density categories, each representing the fraction of the total national energy demand which falls within certain bounds of areal energy density, in kW<sub>y</sub>/km<sup>2</sup>. Then each density region is assigned a natural gas distribution technology, with regions of decreasing density having increasing distribution costs. As well, each region has an absolute limit on the total combined natural gas and district heat service within that region.

- **Residential and Commercial District Heat** - Within the model, residential district heat is an attractive option, and is, in fact, more attractive than commercial district heat utilization. However, in reality residential district heat is unlikely to be available without a base of large commercial users to underwrite the initial infrastructure costs. For this reason it is necessary to link the use of residential district heat to that of commercial, ensuring that only when they are jointly economically feasible will district heat be implemented in the model.

### 3.4.3 The Canadian Commitment: Stabilization

The most important scenario, next to the BAU case on which it depends, represents the attainment of the Canadian Commitment: stabilization of CO<sub>2</sub> emissions in 2000 to the levels calculated for 1990. (For brevity this scenario is referred to simply as Stabilization). This emission limit is the only change in this scenario from the base case model, with the exception of minor adjustments to two parameters:

- An increase in the share of urban passenger transport available for public transit;
- A small increase in the limit on capacity additions of residential and commercial district heat.

### 3.4.4 Other Scenarios

The following scenarios are described more fully in Chapter 4:

- **Toronto Target:** The CO<sub>2</sub> emission limit is lowered by a little over 20% (to estimate a reduction with respect to 1988, rather than 1990 emissions) and the target is postponed to 2005.
- **Further Emission Reduction:** Starting from Stabilization, but with further emission reductions to 90%, 80%, 70% and 60% of 1990 levels.
- **Sectoral Limit:** A more stringent limit, in which each sector of the energy system (transmission and distribution, electricity and heat generation, industry, commerce, residential, and transport) must *individually* meet the emission stabilization criterion required by the Canadian Commitment.
- **Emission Taxes:** Replaces a CO<sub>2</sub> emission limit — the command and control approach — with a fixed emissions charge, or tax, on CO<sub>2</sub> emissions — the economic incentive approach. Tax levels from \$10 to \$120 per tonne CO<sub>2</sub> are investigated.
- **Enhanced Nuclear:** The restriction on construction of new nuclear generating capacity is relaxed without changing any other parameters, to allow up to approximately twice the base case replacement capacity, or a total of nearly 20 GW added capacity up to the end of the last reported period (2027).
- **Enhanced Hydroelectric:** The constraint on the development of new hydroelectric sites is relaxed, to allow up to 100% of the projects identified by provincial electric utilities (NEB 1991) to be constructed. This adds approximately 15 GW to the available potential additions to hydroelectric capacity.
- **Enhanced Demand Reduction:** Investigates the potential role to be played by more aggressive demand reduction measures. Within the model this means reducing somewhat the costs of all demand reduction technologies, and loosening (though not removing) their constraints on market penetration.

### 3.5 Uncertainty

Uncertainty is a “lack of sureness,” and in modeling one wants to be sure:

1. the model really answers the question that is asked, and in a reasonable way, and
2. the model results are robust to small changes in input parameters.

The physical basis of techno-economic modeling allows the first issue to be readily resolved. One can easily check that physical constraints and requirements are met, that demands are satisfied, and that emissions correctly relate to activities. The reasonableness issue is a matter of judgement, but it can also be easily addressed in a physical model.

The second issue, the robustness of the solution, is more difficult to address. For models of a few tens or even a few hundreds of parameters it is possible to use one of a variety of formal methods to analyze the sensitivity of the model’s outputs to specified changes in its key inputs (see, e.g., Iman & Helton 1988, Ford & McKay 1985). Such approaches most commonly use statistical techniques based on a Monte Carlo approach.

However, when a model has many thousands of parameters the time and computing resources for a formal analysis become prohibitive. The only remaining option then is to use an informal approach to sensitivity testing. Variations in those input parameters which are judged most important are compared to variations in the resulting model outputs. In essence the sensitivity analysis becomes an extension of the scenario analysis.

This scenario-based approach to sensitivity analysis is the one followed in this work. Most of the scenarios discussed in Section 3.4 are, in fact, tests of the sensitivity of CO<sub>2</sub> emissions to:

- economic climate, represented through the forecast demand for services (which in turn, is examined indirectly via changes in emission reduction levels);
- societal preferences regarding further hydroelectric and nuclear development;
- political and societal behavior in the area of energy service demand reduction;

### 3.6 Limitations

Every model and every modeling approach has limitations. Limitations in this specific model are more appropriately addressed as part of a discussion of results, and so are deferred to Chapter 4. Two limitations in the chosen methodology have already been discussed:

- The partial-equilibrium nature of the model. The energy system is optimized, but the interactions between the energy system and the larger national economy are ignored.
- The use of a linear programming approach, leading to difficulties in modeling non-linear effects, e.g., economies of scale.

## Chapter 4

# Results

The results below are organized by scenario. Key figures for the BAU and Stabilization scenarios are presented together for ease of comparison, but are discussed separately in their respective sections. As before, all costs quoted here are in Canadian dollars at 1990 prices and exchange rates.

(It is not feasible to include in this thesis all of the numerical model results, or even a significant fraction. Appendix B includes a representative listing of results for the BAU scenario, and information on obtaining results for the other scenarios.)

Finally, although it cannot be presented here, the model itself is an important result of this work. The model has value not only for the refinement and extension of the results presented here, but also in addressing other questions related to the development of the Canadian energy system.

### 4.1 The Base Case: Business as Usual

The key elements of the Business as Usual (BAU) scenario are:

- increases in energy service demands are conservative, to reflect expectations of lower growth rates over the next two decades compared to most of the seventies and eighties;
- constraints are imposed on hydropower and nuclear expansion to reflect current socio-political concerns over energy sources;

- biomass is considered CO<sub>2</sub>-neutral, with utilization beyond industrial process requirements constrained to reflect assumed sustainable rates of harvesting;
- newly commercialized renewable energy technologies are limited to estimated real-world market penetration rates;
- SO<sub>2</sub> emissions corresponding to Eastern Canada are limited according to the joint federal-provincial Eastern Canadian Control Program (Government of Canada 1991b, p. 12-17);
- modal shifts in transport are restricted to account for the widespread preference for automobile travel, despite the cost and emission advantages of public travel modes;
- penetration of natural gas and district heating are constrained within energy density regions, reflecting economic limits on the spread of distribution networks.

As a group, these constraints are necessary to reflect factors which strongly affect the development of the Canadian energy system, but which cannot be represented directly by standard techno-economic parameters.

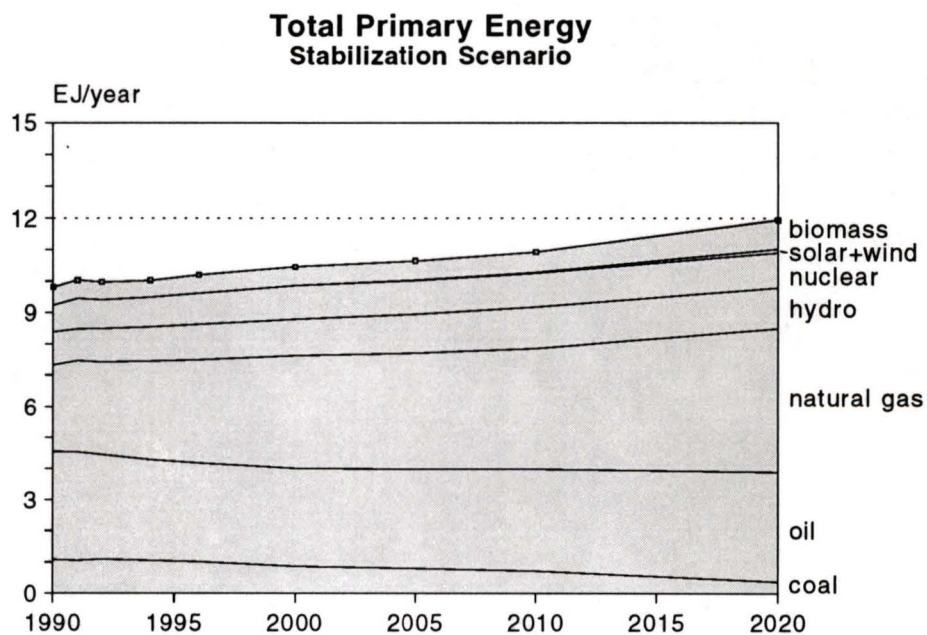
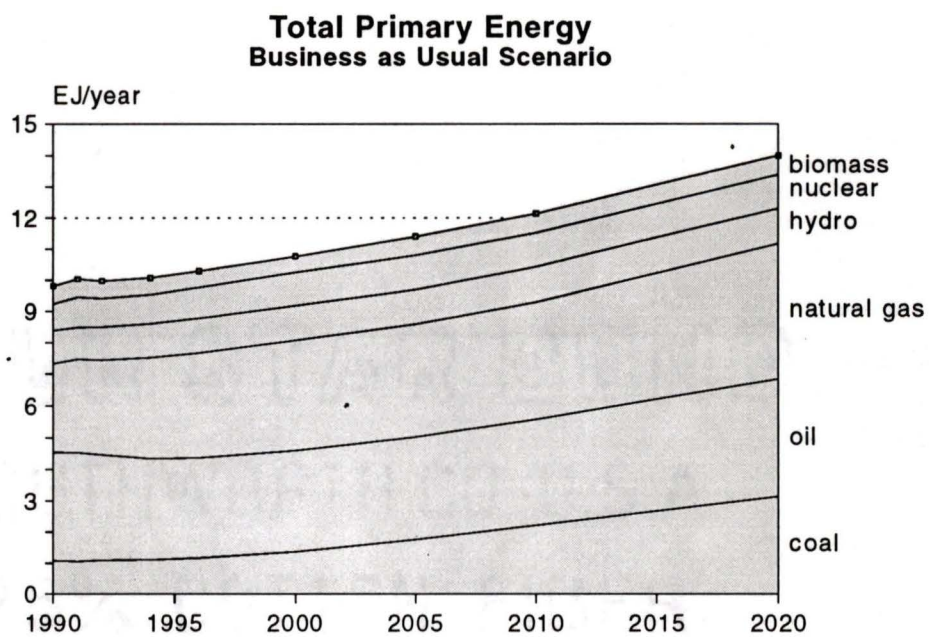
The broad trends for future BAU development determined by the model are shown through the evolution of:

- primary energy, by source, to reflect production;
- final energy, by currency, to reflect final utilization;
- electricity production, by source, since it is a key energy system element of industrialized countries;
- CO<sub>2</sub> emissions, by sector.

#### **4.1.1 Energy and Emission Trends**

##### **Primary Energy**

Figure 4.1 shows the trends in primary energy, by energy source, from the base year 1990 through to 2020. Features worth noting are:



**Figure 4.1:** Total primary energy, by source, for the BAU and Stabilization scenarios. Here biomass includes municipal waste as well.

- The majority of growth occurs in coal, and to a lesser extent in natural gas.
- Except for a small shift from oil to natural gas in the early years of the model, no source exhibits a decline in share.
- Included in the biomass component of Figure 4.1 is a small municipal waste contribution, starting in 1996 and reaching approximately 17 PJ by 2020.

### **Electricity Generation**

Electricity production by primary source is shown in Figure 4.2. The reason for the growth in primary coal in Figure 4.1 is now apparent: nearly all of the increase in electricity production is sourced by coal, although natural gas also increases its share.

### **Final Energy**

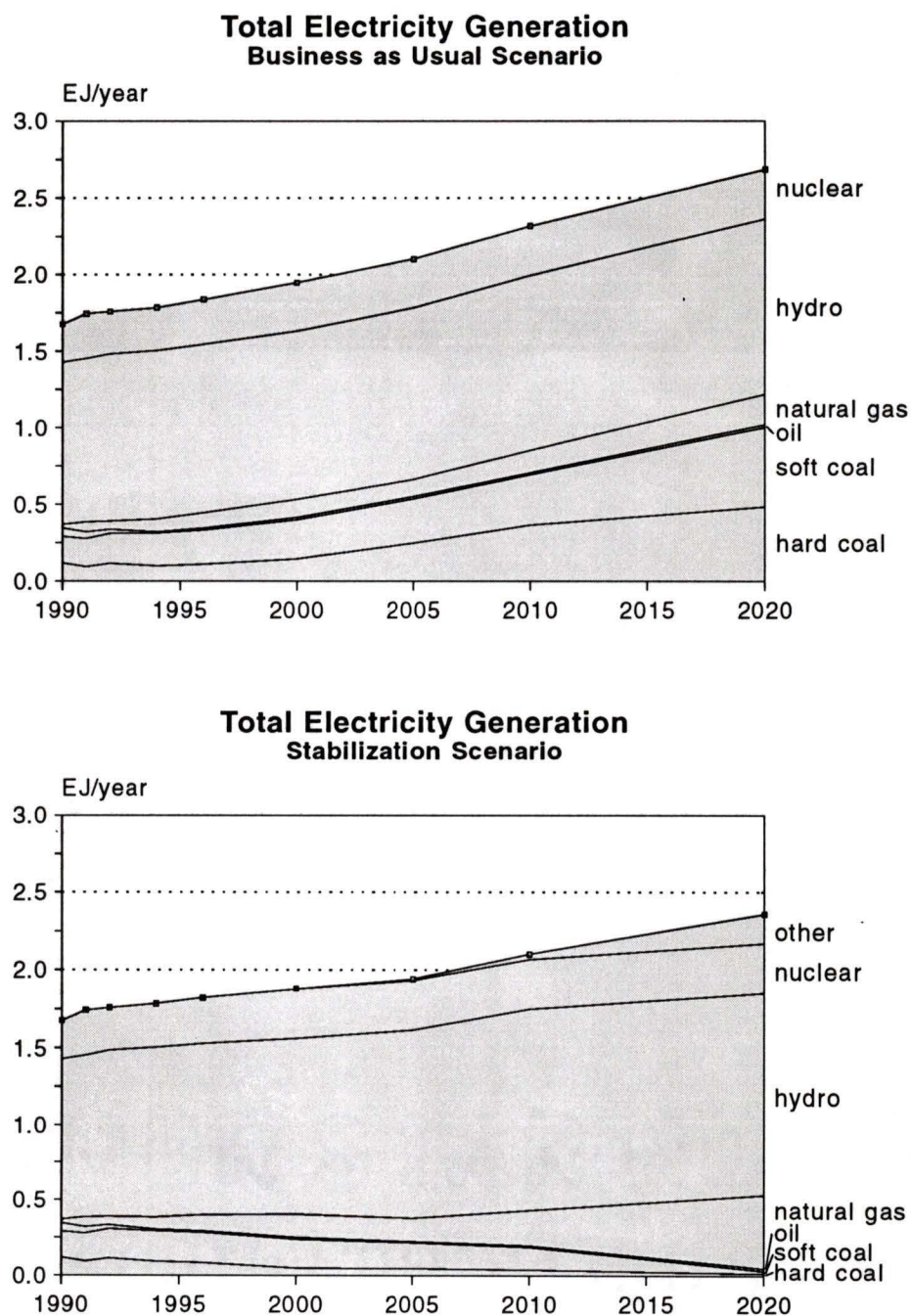
Final energy by currency is shown in Figure 4.3. Little comment is required: growth is steady, and weighted somewhat more towards natural gas and electricity. District heat provides a small but steadily-growing share, starting in 1992.

### **CO<sub>2</sub> Emissions**

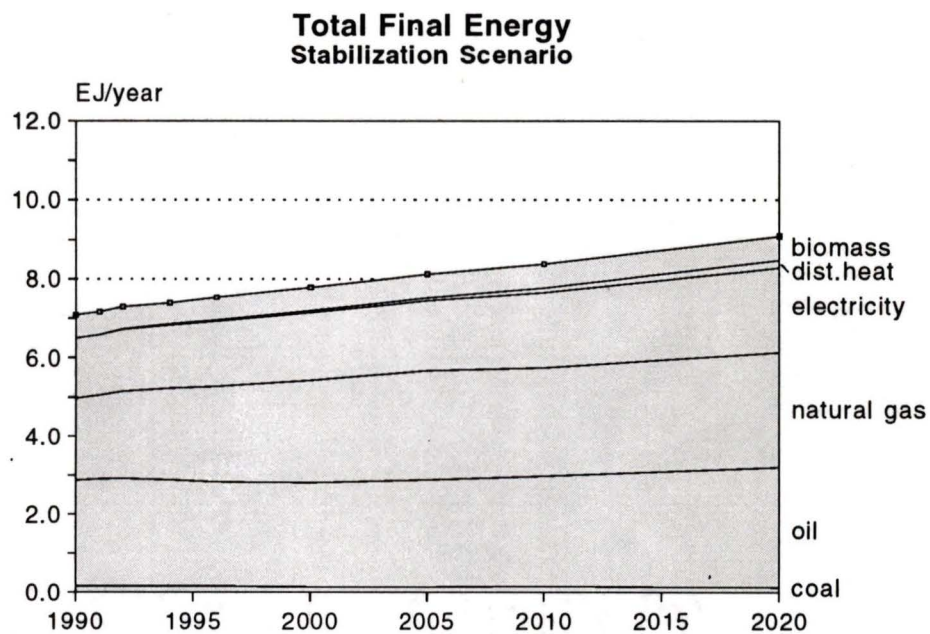
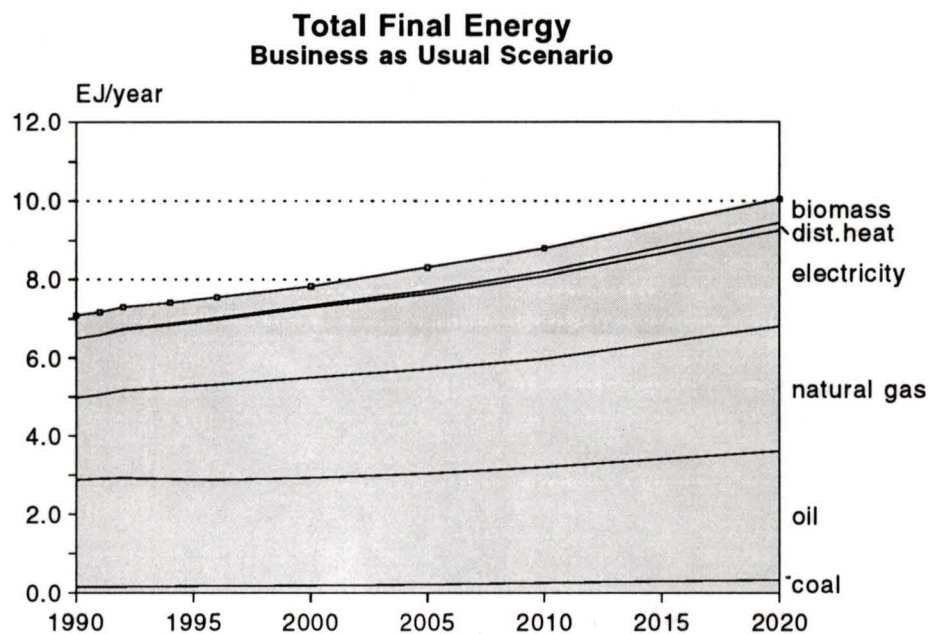
Historical energy system-related CO<sub>2</sub> emissions for 1990 were calculated by applying the emission factors listed in Table 2.1 to the quantities of energy sources and currencies tabulated by Statistics Canada (1991c); the result is approximately 454 megatonnes (Mt) CO<sub>2</sub>.

Figure 4.4 shows the BAU trend in CO<sub>2</sub> emissions, by sector, over the model time horizon. The increase in CO<sub>2</sub> emissions from the sector representing electricity and district heat generation should be expected, given the growth of coal-sourced electricity seen earlier in Figure 4.2.

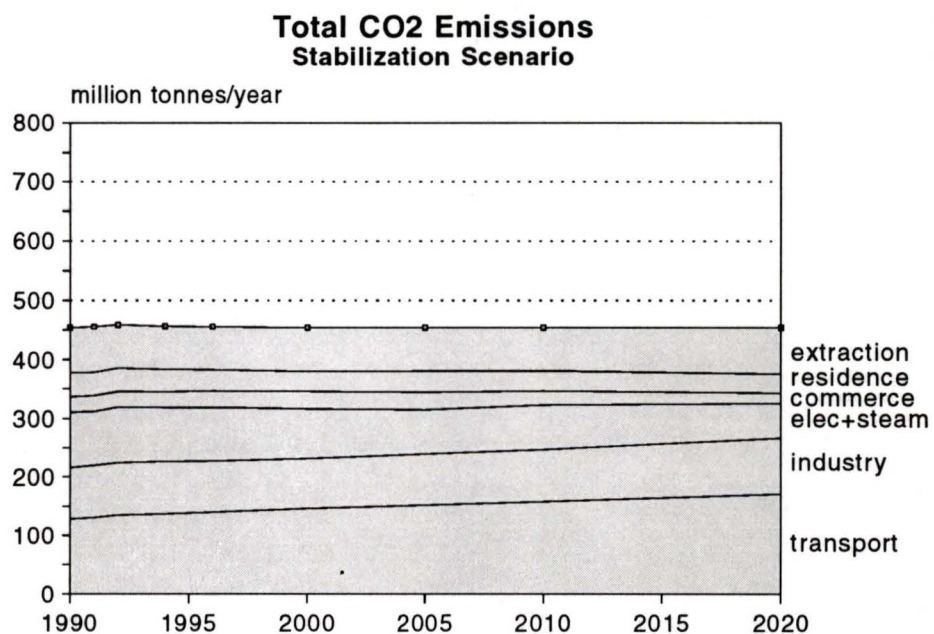
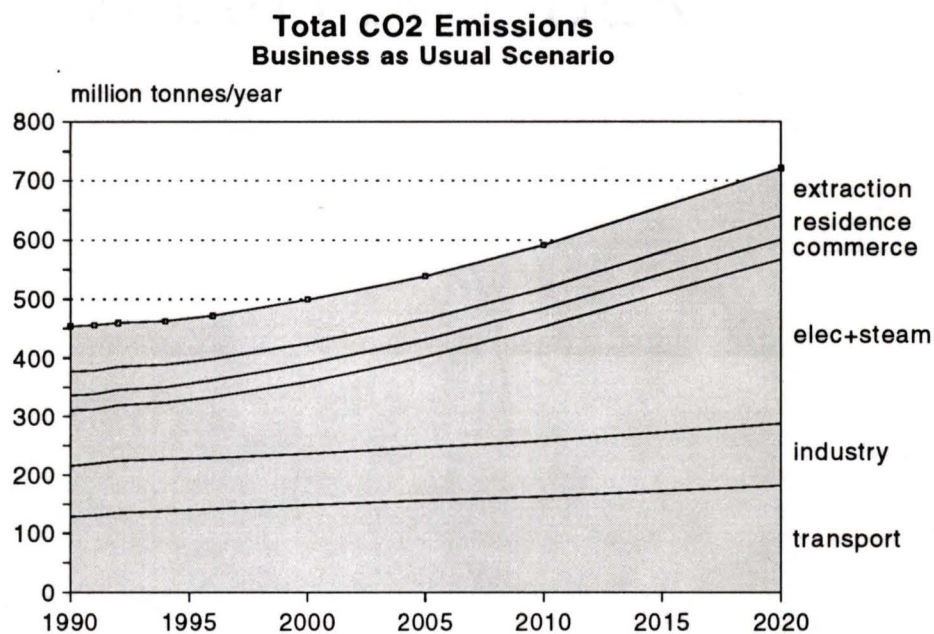
Total CO<sub>2</sub> emissions over the period 1991–2020 are 16.79 gigatonnes (Gt). The equivalent discounted emissions (which are required if emissions are to be compared to discounted costs, as they later will be) are 8.06 Gt.



**Figure 4.2:** Total electricity generation, by source, for the BAU and Stabilization scenarios. The **other** category includes biomass, municipal waste, solar photovoltaic, and wind power.



**Figure 4.3:** Total final energy, by currency, for the BAU and Stabilization scenarios. Final coal includes both coal and coke.



**Figure 4.4:** Total CO<sub>2</sub> emissions, by sector, for the BAU and Stabilization scenarios. The **extraction** sector also includes emissions from currency production, transmission, and distribution; industrial steam is included in **industry** rather than **elec+steam**.

### 4.1.2 Total System Cost

The value of the objective function corresponding to the period 1991–2020 is \$2.264 trillion ( $\$2.264 \times 10^{12}$ ). This is the total discounted cost of providing all the specified energy services for this period.

The total system cost of the BAU scenario is, by itself, not especially important. However, it serves as a benchmark against which the cost of other scenarios can be compared and thus from which their *incremental* cost can be determined.

## 4.2 The Commitment: Stabilization

The Stabilization scenario holds CO<sub>2</sub> emissions at 1990 levels, i.e., 454 Mt/year, starting in 2000. In addition, two minor modifications compared to BAU scenario reflect some of the small social changes which might result from a determined effort to meet the Canadian Commitment:

- For urban passenger transport, the upper limit on the ratio of public to private transport, i.e., bus travel versus car travel, is increased from 15% to 20% (the historical value is about 13.4%).
- The limit on capacity additions of residential and commercial district heat is increased 10% in 1996, rising to 30% in 2020.

As with the BAU scenario, the overall trends in the energy system are best shown by looking at the evolution of primary energy, final energy, and electricity generation, plus CO<sub>2</sub> emissions. For ease of comparison these figures are displayed beneath the corresponding figures for the BAU scenario, in the preceding section.

### 4.2.1 Energy and Emission Trends

#### Primary Energy

The changes in primary energy are shown in Figure 4.1, on page 77. Overall primary energy drops less than 3% in 2000, although the drop increases to about 15% by 2020. As

might be expected, coal utilization is most affected of all primary sources; 2020 utilization is down nearly 88% from BAU. On the other hand, natural gas utilization rises roughly 5%.

Newer renewable energy sources now make a tiny but noticeable contribution by 2020, with about 15 PJ of solar photovoltaic and about 100 PJ of wind power. This is in addition to the large contributions of the traditional renewables biomass and hydropower. Utilization of biomass increases, but remains below the sustainability-related limit. New hydropower capacity, however, is added at the maximum rate (see Section 3.4.2), indicating that its economic feasibility exceeds its socio-political acceptability.

### **Electricity Generation**

Differences in the structure of electricity generation are shown in Figure 4.2, on page 79. Overall, the decline in total electricity generation is comparable to the drop in primary energy utilization.

As expected from the shifts in primary energy, coal-sourced electricity nearly disappears by 2020, to be replaced by natural gas, hydropower, and, to a small degree starting in 2005, wind, biomass and solar photovoltaic. By 2020 the last three are contributing about 180 PJ/year, out of a total of 2460 PJ. A tiny quantity (4 PJ in 2020) of municipal waste-sourced electricity present in the BAU case disappears.

### **Final Energy**

Final energy utilization by currency is shown in Figure 4.3, on page 80. The most noteworthy feature of the two scenarios viewed together is how similar they are. From BAU to Stabilization final energy drops less than 1% in 2000, and about 10% by 2020, but the shifts between currencies (see Table 4.1) are relatively small, especially compared to those in electricity generation. Coal demand nearly disappears, although this is hidden by the nearly constant coke use in the metals industries. Other currencies seeing some decline are gasoline, electricity, and, perhaps surprisingly, natural gas.

Currency	Percent of total final energy in 2020	
	Business as Usual	Stabilization
Natural gas	31.8	32.2
Electricity	24.5	23.7
Motor and aviation fuel	19.0	18.7
Diesel/light oil	12.0	13.5
Biomass	5.9	6.6
Coal	2.3	0.2
District heat	1.9	2.1
Heavy oil	1.5	1.7
Coke	1.1	1.2
Liquid hydrogen (LH <sub>2</sub> )	0.0	< 0.1

**Table 4.1:** Shares of currencies making up total final energy; BAU and Stabilization scenarios compared.

More interesting, perhaps, is what Figure 4.3 does not show. In particular, the model does not utilize available energy currency options for:

- biomass-sourced methanol, for vehicles;
- district cooling of commercial buildings;
- residential and commercial solar space heating;
- liquid hydrogen (LH<sub>2</sub>), beyond a little less than 1 PJ for internal combustion engines in urban buses.<sup>1</sup>

## CO<sub>2</sub> Emissions

Figure 4.4, on page 81, confirms that CO<sub>2</sub> emissions meet the 1990 limit. Of more interest, however, is how the sectoral emissions shift—Table 4.2 shows the sectoral changes in CO<sub>2</sub> emissions compared to the BAU case. Most of the emission reduction occurs in the electricity and steam generation sector, which is consistent with the near-elimination of

<sup>1</sup>The model has the choice of producing this H<sub>2</sub> via electrolysis or steam-methane reforming (SMR) of natural gas, and chooses the latter. The SMR process outputs the carbon contained in the natural gas as CO<sub>2</sub>; the model then has the option of either emitting this to the atmosphere or disposing of it, within limits, via injection in Western Canadian gas fields. Disposal is the method chosen.

coal-sourced electricity. Other sectors see little impact in 2000, although by 2020 only Extraction and Transport show less than a 10% decline in emissions.

Sector	Percent reduction in CO <sub>2</sub> emissions from BAU scenario	
	2000	2020
Extraction	<1	<1
Electricity and Steam	31	79
Industry	3	10
Residence	<1	20
Commerce	7	46
Transport	2	6

**Table 4.2:** Changes in CO<sub>2</sub> emissions, by sector, from BAU to Stabilization, showing the sectors most affected by emission constraints.

Total CO<sub>2</sub> emissions over the period 1991–2020 are 13.41 Gt, a reduction of 3.38 Gt from BAU.

#### 4.2.2 Emission Reduction Costs

For the Stabilization scenario, the total objective function representing the period 1991–2020 is approximately  $\$2.290 \times 10^{12}$ , or about  $\$26 \times 10^9$  above the corresponding value for BAU.

#### Calculation of Unit Reduction Costs

It is perhaps tempting now to quickly calculate the unit cost of CO<sub>2</sub> abatement as  $\$26 \times 10^9 / 3.38 \times 10^9 \text{ tCO}_2 \approx \$7.7/\text{tCO}_2$ . However, this calculation ignores the time value of money (Section 3.2.1) by assigning the same cost to each tonne of CO<sub>2</sub>, regardless of when it was emitted.

To correctly allocate the total abatement to the difference in total discounted costs, it is necessary to also discount the emissions. While it may seem unusual to discount physical flows, this is necessary if a discounted monetary value (e.g., the value of the objective

eries of physical flows spread over time, as a 10/kg penalty or tax must be paid, at the time ; emitted today and 1 kg emitted 20 years from 0 penalty paid 20 years from now is worth only lay at 5% is sufficient to cover all present and

of emission reduction today, an additional 1 kg oday to bring about the total reduction. If each he time of reduction, then the \$13.77 cost cannot be allocated equally between the 2 kg of emissions (which would result in a charge of \$6.89/kg); rather, the future emission must be discounted back to the present, to give 0.377 kg, and the total cost of \$13.77 allocated to the total discounted abatement of  $(1 + 0.377) = 1.377$  kg. The result is the expected \$10/kg.

Discounting the emissions in this-way for the BAU and Stabilization scenarios gives a discounted emission reduction of 1.13 GtCO<sub>2</sub>. Thus the *average* cost of abatement for this scenario, calculated as the total increase in discounted system costs divided by the total discounted emissions, is  $\$26 \times 10^9 / 1.13 \times 10^9 \text{ tCO}_2 \approx \$23/\text{tCO}_2$ .

By comparison, the *marginal* cost of abatement<sup>2</sup>, represented by the shadow price of the CO<sub>2</sub> emissions constraint in the model, is \$42.7/tCO<sub>2</sub> in 2000 and \$98.9/t in 2020. The system costs and emissions are summarized in Table 4.3.

The CO<sub>2</sub> emission reduction costs can be put in context through expression in terms of the equivalent costs of common energy currencies. Table 4.4 lists the equivalent values per natural unit of natural gas, gasoline and coal which are equivalent to \$100/tCO<sub>2</sub>.

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<sup>2</sup>The distinction between average and marginal cost is critical. On one hand, the average cost is often a more comprehensible measure of overall cost. However, the marginal cost

- indicates the cost of making any change from the status quo, and as such
- is the appropriate value to use in any comparison involving costs and benefits of abatement, and in particular, in the setting of any emission tax or charge.

From BAU to Stabilization	
CO <sub>2</sub> emission reduction	3.38 Gt
Discounted emission reduction	1.13 Gt
Incremental system cost	\$26 × 10 <sup>9</sup>
Average CO <sub>2</sub> reduction cost	\$23/t
Marginal CO <sub>2</sub> reduction cost	
in 2000	\$43/t
in 2020	\$99/t

**Table 4.3:** Incremental costs and CO<sub>2</sub> emission reductions for the Stabilization scenario, compared to BAU. The marginal CO<sub>2</sub> reduction cost in 2000 and 2020 is given for comparison.

Energy Currency	Cost equivalent to \$100/tCO <sub>2</sub>
Natural gas	\$5.0/GJ
Gasoline	\$0.24/l
Hard coal	\$240/tonne
Soft coal	\$160/tonne

**Table 4.4:** The cost per natural unit of common energy currencies which is equivalent to \$100/tCO<sub>2</sub>, i.e., the value of each currency if the CO<sub>2</sub> produced by it were valued at \$100/t. Based on the emission factors given in Table 2.1.

Thus, using these values and assuming that all reduction costs are paid out of levies on energy currencies in proportion to their carbon content (however unlikely such a scenario might be in reality), the average reduction cost for this scenario of \$23/tCO<sub>2</sub> is equivalent to a surcharge of about \$1.25/GJ natural gas or about \$0.06/litre gasoline. Coal is hit harder: for the hard coal used in central and eastern Canada, a \$23/tCO<sub>2</sub> levy is equivalent to a near-doubling of the average \$62/t utility price, while for the soft coal used in the West the same levy leads to a more than threefold increase in the \$11/t average price (Statistics Canada 1992b).

### 4.2.3 Observations

Energy-related CO<sub>2</sub> emissions can be stabilized at 1990 levels by the year 2000. Moreover, no sweeping macro-level changes to the energy system are required. The only major impact, at least for electric utilities (and, no doubt, for coal miners, investors, and delivery industries) is the replacement of coal-sourced electricity generation by natural gas, hydroelectric and by some demand reduction.

That the electricity generation sector is the first to adapt should be expected. This sector is by far the largest consumer of coal, and coal is the energy currency with the highest CO<sub>2</sub> emission factor.<sup>3</sup> Moreover, electricity is also the sector with the widest range of abatement options, including (at a cost) a variety of carbon-free energy sources.

On the other hand, the relatively minor changes in the structure of final energy utilization are also to be expected; here the emission reductions to be gained by currency-switching are smaller, and the opportunities to do so are more limited.

To maintain CO<sub>2</sub> emissions stabilized through to 2020, with an additional 30 years of demand growth to accommodate, is more difficult than simply meeting the target in 2000. However, except for the decline in coal use, the degree of structural economic change is surprisingly low.

#### Costs

The costs of meeting the Canadian Commitment are not trivial. They are equivalent, for example, to the retail price of natural gas rising by about 20% or to the price of gasoline rising about 10%. However (except, again, for coal), neither are such costs onerous.

By focussing at the macro level, this work necessarily ignores many micro-level changes and impacts. However, any full accounting of costs and benefits must include the effects of such impacts, two examples of which follow.

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<sup>3</sup>Referring back to Table 2.1, coal has the highest emission factor on the basis of simple complete combustion. Accounting for emissions from the complete energy currency production process, as MESSAGE does, complicates comparisons since emission factors are now process dependent. However, the rankings don't change (Grubb 1989).

- One means by which CO<sub>2</sub> emissions are stabilized is the construction in Quebec of an additional 10 GW of hydroelectric capacity by the year 2010 (over and above that constructed in the BAU scenario). Given the increasing public concern over the construction of large hydroelectric projects, this may be viewed as entailing a considerable non-monetary cost.

However, it should not be thought that this increase in hydroelectric capacity is necessary for attainment of the emission stabilization target—only that this was determined to be the least-cost approach, within the context of this scenario.

- Only about 15% of the coal used for electricity generation in Canada is imported; the rest is produced domestically. Given the near-disappearance of coal-sourced electricity (and for coal use in general) in this scenario, the impact on the thermal coal industry in Canada is a significant non-monetary cost.

However, as discussed in the following section, there are considerable external costs<sup>4</sup> associated with coal extraction and use; CO<sub>2</sub> emission reductions can be viewed as a process of indirectly internalizing those costs, i.e., incorporating them into the prices of coal. From this perspective, any impact of emission reductions on the coal industry is not a cost which must be paid by the industry now, but rather an external cost which other third parties no longer have to pay.

## Benefits

With the costs laid out, one may ask if there are any benefits to this scenario, aside from the presumed, but unknown reduction to the threat of global climate change.<sup>5</sup>

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<sup>4</sup>The internal costs of an economic activity are those which are reflected in the prices paid by the consumers of the activity. The external costs are those which are

- *not* reflected in the prices paid by the consumers of the activity, and
- paid by other, third parties, who are not otherwise involved in the activity.

Air pollution in general is a classic example of an external cost; it is imposed on third parties by polluters, but it is not reflected in the prices of the polluters' products. See Ottinger et al. (1991) for an extensive review of the external costs associated with one sector of the energy system: electricity generation.

<sup>5</sup>Which, it must be noted again, will only come about as part of a global CO<sub>2</sub> emission reduction strategy.

One certain, but difficult-to-quantify collateral benefit is the reduction of other emissions to the atmosphere. MESSAGE currently accounts for emissions of:

- methane ( $\text{CH}_4$ ), also a GHG;
- sulphur dioxide ( $\text{SO}_2$ ), the major contributor to the problem of acid deposition or “acid rain”;
- nitrogen oxides ( $\text{NO}_x$ ), a precursor to ground-level ozone as well as a source of acid deposition;
- carbon monoxide ( $\text{CO}$ ), affecting local air quality;
- volatile organic compounds (VOCs), precursors to ground-level ozone.

However, except for  $\text{SO}_2$  these emissions are strongly process dependent; e.g., small changes in combustion parameters can have significant effects on emissions. (See, e.g., Alson, Adler & Baines (1991) for the variation in emissions of alternate fuel vehicles.) For this reason, and because these emissions are not the focus of this work, they are not reported here. However, one value is worth noting: compared to the BAU scenario, the Stabilization scenario shows an average annual reduction of more than 450,000 tonnes  $\text{SO}_2$ , or about 28% of total energy-system  $\text{SO}_2$  emissions.

What is 450 kt $\text{SO}_2$ /year worth? Putting a monetary value on any emission is an uncertain undertaking, yet as Ottinger et al. (1991) put it in their extensive review of the field, “one always has to come back to the basic tenet that a ‘crude approximation’ of these damage costs is closer to an accurate accounting for resource costs than is a value of zero.” (p. 14)

Ottinger et al. estimate the damage cost of  $\text{SO}_2$  at just over US\$2/pound, or about Cdn\$5200/t,<sup>6</sup> leading to a value for a 450 kt annual  $\text{SO}_2$  emission reduction of more than  $\$2.3 \times 10^9$ /year. The corresponding total discounted  $\text{SO}_2$  emission reduction for the model time frame is approximately 4.8 Mt, which at \$5200/t gives a present value on the order of  $\$25 \times 10^9$ .

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<sup>6</sup>Any number of this type is necessarily an average, and is based on numerous assumptions including ones about the environment into which the  $\text{SO}_2$  is emitted. Thus, separate from the issue of whether the value is reasonable given the underlying assumptions, there is the question of whether the value can be applied in a different environment, e.g., Western Canada versus the North-eastern United States.

Thus, the collateral SO<sub>2</sub> abatement associated with meeting the Canadian Commitment leads to a reduction in SO<sub>2</sub> damage costs comparable to the total CO<sub>2</sub> emission reduction cost. While this comparison ignores

- whether there exist less costly means to reduce SO<sub>2</sub> emissions,
- whether the damage cost used is, in general, applicable to SO<sub>2</sub> emissions in Canada, and
- whether the damage cost used is applicable to *all* SO<sub>2</sub> emissions in Canada,

nonetheless SO<sub>2</sub> reduction is only one potential collateral benefit to CO<sub>2</sub> reduction; one can expect others.

### Implementation Issues

- In terms of implementation, the CO<sub>2</sub> emission constraint imposed on the model is framed in terms of a limit, but only one overall, national, limit. Thus the scenario might be better interpreted as representing a national tradable permit scheme, in which those who can most easily reduce emissions do so, and those who can't need not.

Whether such a system is, in practice, feasible remains an open question.

- While stabilization does not depend on large scale implementation of new technologies, the model does utilize systems which are not yet in commercial use, at least in Canada: wind power, large-scale solar photovoltaic, and disposal of CO<sub>2</sub> by injection in abandoned gas wells. The question remains as to whether these technologies will be commercially available "on schedule" to meet the commitment.

Similarly, stabilization requires the construction of considerable new hydroelectric capacity, starting immediately and continuing through 2010. It is an open question whether construction could, in reality, be completed as required, given both the long lead times required and the inevitable socio-political inertia.

### 4.3 Sensitivities: Alternate Scenarios

While this thesis focusses on attainment of the Canadian Commitment, other scenarios have value

- as tests of the sensitivity of the main scenario results,
- as indicators of the feasibility of extending CO<sub>2</sub> emission reductions beyond the current government commitment, and
- as means to examine issues relating to implementation of CO<sub>2</sub> emission reductions.

The following seven scenarios, representing a total of 21 separate analyses, are not discussed as extensively as the BAU and Stabilization scenarios. The intent is only to present the key points illuminated by each variant or set of variants. Unless noted otherwise, all assume the Stabilization scenario as a starting point.

#### 4.3.1 The Toronto Target

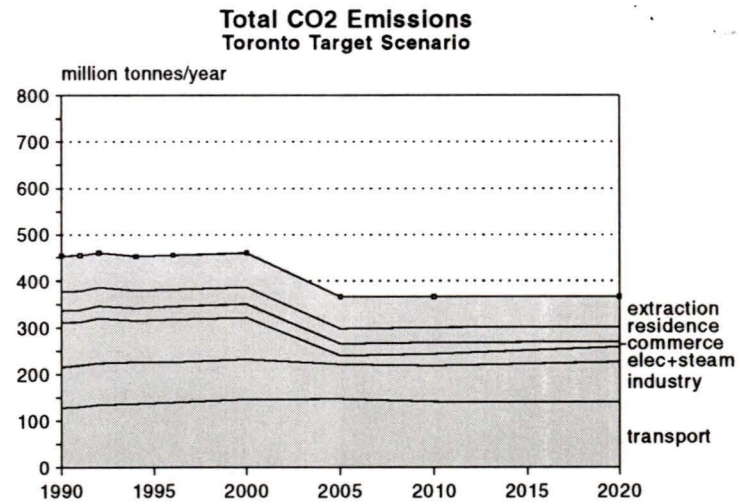
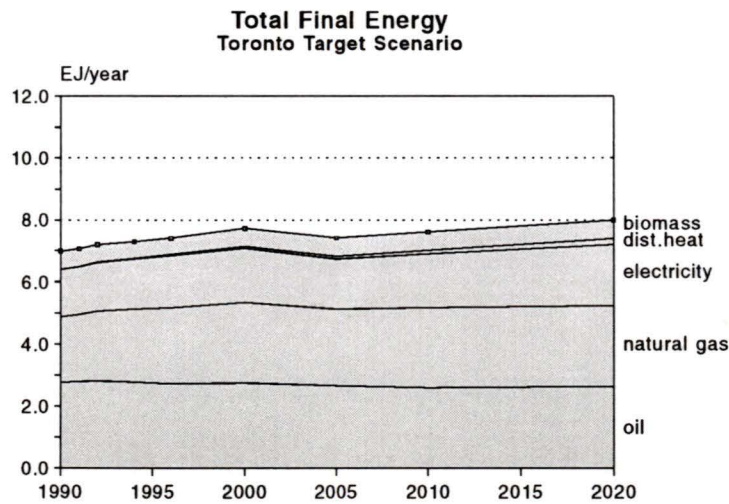
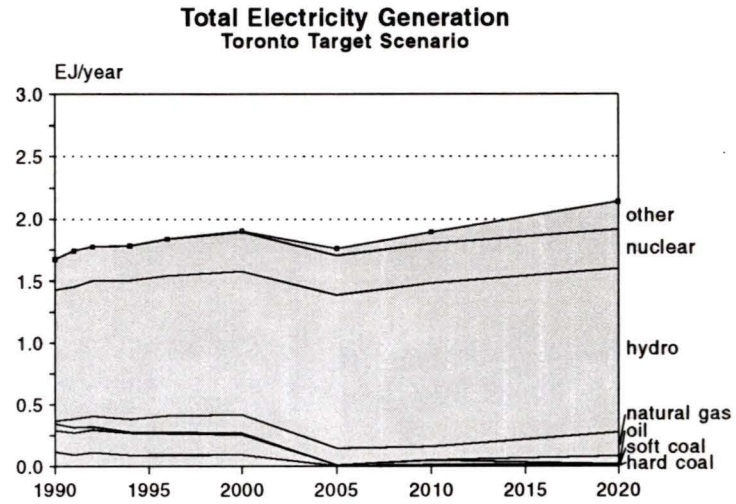
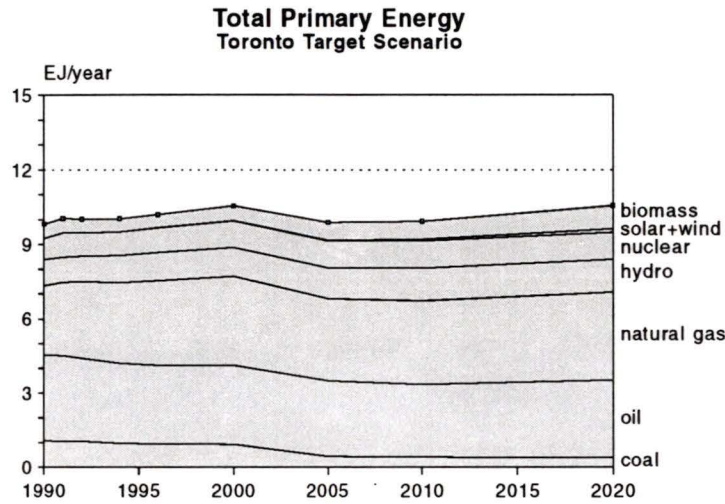
Compared to the Stabilization scenario, the Toronto Target reduces CO<sub>2</sub> emissions a further 20% to 366 Mt/year, and postpones the target date five years, to 2005. It is included to investigate the costs of implementing an emission reduction target which many believe is the minimum Canada should aim for and which all industrialized countries will eventually have to attain.

#### Other Assumptions

One other change has been made compared to the Stabilization scenario: for urban passenger transport, the upper limit on the ratio of public to private transport is increased yet again from 20% to 25%, to represent a key behavioral change which might come about as part of the process of aiming for the limit.

#### Results

The energy and emission trends for the Toronto Target scenario are shown in Figure 4.5, for comparison to the corresponding figures for the BAU and Stabilization scenarios.



**Figure 4.5:** Energy and emission trends for the Toronto Target scenario (final coal is negligible). Compare to the BAU and Stabilization scenario results shown in Figures 4.1 through 4.4; refer to those figures for details on the corresponding figures here.

The key results from this scenario are:

- Moving from BAU to the Stabilization uses all the “easy” CO<sub>2</sub> emission reduction opportunities—the continued reductions required by the Toronto Target are more difficult and more expensive, e.g., with coal utilization already minimized, cuts must now be made in the growth of other fossil fuels’ use, including natural gas.
- Table 4.5 shows the incremental system costs, incremental CO<sub>2</sub> emission abatement, and the resulting abatement costs, compared to both the BAU and the Stabilization scenarios. Not surprisingly, all costs are up compared to Stabilization; the marginal abatement cost in 2020 is roughly doubled.

To the Toronto Target:	
From BAU	
CO <sub>2</sub> emission reduction	4.89 Gt
Discounted emission reduction	1.65 Gt
Incremental system cost	$\$52 \times 10^9$
Average CO <sub>2</sub> reduction cost	$\$31/t$
From Stabilization	
CO <sub>2</sub> emission reduction	1.51 Gt
Discounted emission reduction	0.53 Gt
Incremental system cost	$\$26 \times 10^9$
Average CO <sub>2</sub> reduction cost	$\$49/t$
Marginal CO <sub>2</sub> reduction cost	
in 2000	$\$103/t$
in 2020	$\$199/t$

**Table 4.5:** Incremental costs and CO<sub>2</sub> emission reductions for the Toronto Target scenario, compared to BAU and Stabilization. The marginal CO<sub>2</sub> reduction cost for the Toronto Target in 2000 and 2020 is given for comparison.

## Summary

The model is able to reach the Toronto Target with surprisingly few structural changes. As with the Stabilization scenario, the impacts are greatest in the electricity generation sector, although the increased reductions require greater changes in technologies used to provide end-use services: both increased efficiency and increased demand reduction.

The cost of reaching the target can be viewed two ways. On one hand the average reduction cost compared to BAU is about \$31/t; referring back to Table 4.4, this is equivalent to an approximate increase in natural gas prices of \$1.6/GJ, or a \$0.07 per litre increase in gasoline prices. While 35% higher than the corresponding cost of Stabilization, such increases are not beyond consideration.

On the other hand, the marginal abatement cost is nearly \$200/t, which indicates clearly that the model has run out of inexpensive emission reduction measures.

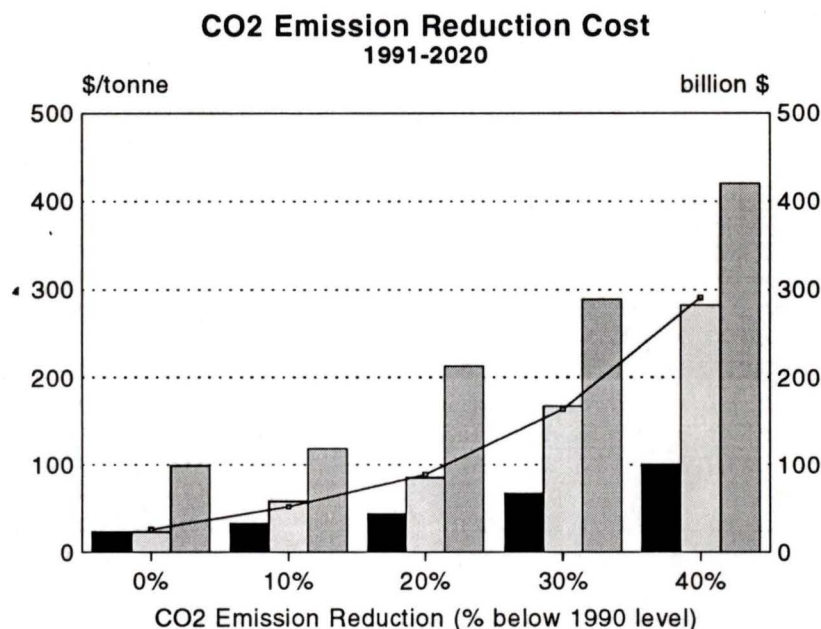
### 4.3.2 Increased Abatement

The Toronto Target scenario represents one particular emission reduction target which goes beyond the current government commitment. To investigate more generally the implications of increasing the level of CO<sub>2</sub> emission abatement, four additional scenarios are included, representing emission reductions of 10%, 20%, 30% and 40% below 1990 levels in the year 2000.

These scenarios also serve as proxies for the investigation of different scenarios of energy service demand growth; rather than a constant limit in the face of increased demand, these scenarios look at reduced limits for the case of constant demand.

## Results

The emissions in this scenario are fixed; beyond the issue of feasibility, what is of interest is the cost required to meet the emission limits. To this end, Figure 4.6 shows the trends in:



**Figure 4.6:** Four different measures of the cost of CO<sub>2</sub> emission reduction, starting at Stabilization (0% below 1990 levels in 2000) and reducing further to 40% below 1990 levels: a curve of total discounted cost, the average unit cost ■ (compared to BAU), the average incremental unit cost □ (compared to the previous reduction step), and the 2020 marginal cost ■.

- the total emission reduction cost, i.e., the difference in the total discounted system cost over the period 1991–2020, compared to the BAU scenario;
- the average unit emission reduction cost, i.e., the increase in total discounted cost divided by the total discounted emission reduction (both with respect to BAU);
- the incremental average unit emission reduction cost, i.e., the increase in the total discounted system cost divided by the decrease in discounted emissions, both compared to the next higher absolute emission limit scenario; this represents the average unit cost required to make each incremental emission reduction, i.e., to go from 20% below to 30% below 1990 levels;
- the marginal unit emission reduction cost in 2020, i.e., the 2020 shadow price on the CO<sub>2</sub> emission constraint.

## Summary

Figure 4.6 makes two key points:

1. Average abatement costs, even at \$100/tCO<sub>2</sub> (or, say, 24 cents per litre gasoline) for reduction to 40% below 1990 levels, should be feasible; most Europeans pay higher energy prices already.
2. Marginal abatement costs, however, rise to over \$400/tCO<sub>2</sub>; *additional* abatement becomes very expensive. Conversely, the returns from a dollar spent on emission reduction diminish quickly. While  $\$50 \times 10^9$  (discounted) is sufficient to meet the original stabilization target, spending another  $\$50 \times 10^9$  cuts emissions only a further 10%.

What isn't shown in Figure 4.6 is the considerable structural change brought about by reducing CO<sub>2</sub> emissions to 40% below 1990 levels. By 2020 fossil energy sources are reduced to providing only 5% of electricity, and nearly half the urban passenger-kilometres are met by demand reduction, i.e. in ways other than travelling. Also, it is worth remembering that this level of emissions is still higher than the minimum 60% cut estimated by the IPCC (1990) as being required to stabilize atmospheric CO<sub>2</sub> concentrations at current levels.

### 4.3.3 Sectoral Limit

The application of an emission constraint to the nation as a whole represents the results of implementing an ideal tradeable permit system, as described in Chapter 2. With only a single overall limit to meet, those within the system who can most easily reduce their emissions do so, and those who can't, don't.

The Sectoral Limit scenario investigates the impact of a more stringent emission limit, in which each sector of the energy system (extraction, transmission and distribution, processing, electricity and heat generation, industry, commerce, residential, and transport) must *individually* stabilize emissions at 1990 levels.

## Results

Table 4.6 compares the costs of the Stabilization scenario to this Sectoral Stabilization, the costs of which are clear: while total emissions are further reduced in Sectoral Stabilization (the reason will become clear shortly), the average reduction cost more than doubles to \$51/t, compared to \$23/t for overall Stabilization. Referring back to Figure 4.6, one can see that if the sectoral constraint is removed, i.e., only an overall limit is imposed, total emissions can be reduced nearly 20% beyond Sectoral Stabilization at a considerably lower overall average reduction cost (the lowest bar in the 20% reduction group represents about \$35/t).

From BAU To:	Stabilization	Sectoral Stabilization
CO <sub>2</sub> emission reduction	3.38 Gt	3.79 Gt
Discounted emission reduction	1.13 Gt	1.31 Gt
Incremental system cost	\$26 × 10 <sup>9</sup>	\$67 × 10 <sup>9</sup>
Average CO <sub>2</sub> reduction cost	\$23/t	\$51/t

**Table 4.6:** Incremental costs, and CO<sub>2</sub> emission reductions for Sectoral Stabilization, as compared to overall Stabilization. Marginal costs are given in Table 4.7

Marginal costs, which are now calculated on a sectoral basis, are shown separately in Table 4.7. These values demonstrate one of the key drawbacks to Sectoral Stabilization: some emitters will find it *much* more expensive than others to meet the constraint.

In Table 4.7 the extraction sector finds it very difficult to meet its limit, as indicated by the marginal reduction cost of over \$1000/tCO<sub>2</sub>. It can be presumed that the only way for the constraint to be met is to reduce the final utilization of certain currencies, with the result that the processing, transmission and residence sectors don't even reach their emissions limits (as indicated by the zero marginal cost). Thus, as a side effect, because no sector can exceed its limit, overall emissions will be below the overall limit; this is the effect seen in Table 4.6.

Sector	Marginal reduction cost (\$/tCO <sub>2</sub> )	
	2000	2020
Resource extraction	1122	560
Currency processing	0	0
Transmission/distribution	0	0
Electricity and steam	61	81
Industry	68	112
Residence	0	39
Commerce	28	6
Transport	229	198
Overall stabilization scenario	43	99

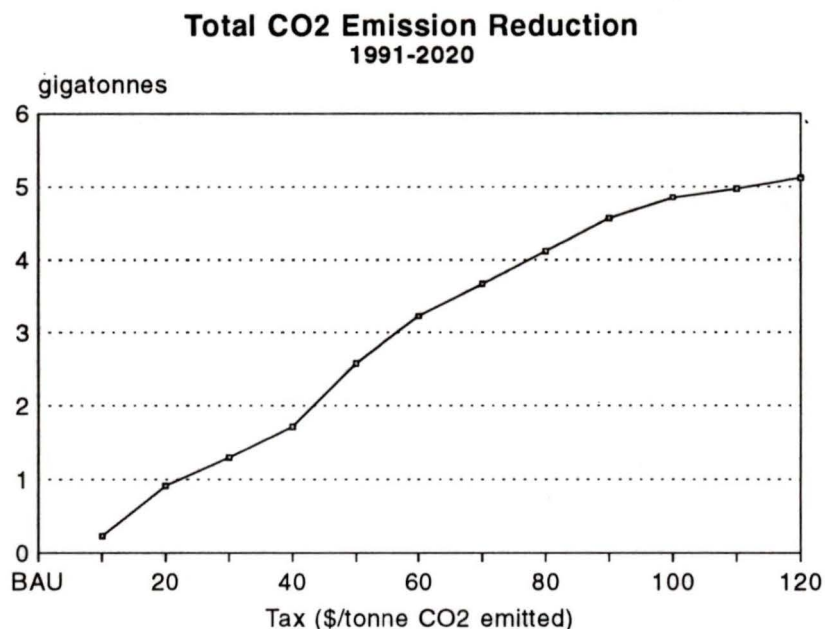
**Table 4.7:** Marginal emission reduction costs for 2000 and 2020, for each individual sector in Sectoral Stabilization scenario.

The marginal reduction cost for the Transport sector indicates that it, too, has difficulty meeting its constraint.

### Summary

From an implementation perspective, it is difficult to defend the imposition of sectoral limits. While in this scenario total emissions are reduced somewhat below the overall Stabilization scenario, a greater increase in abatement could be accomplished for a lower average reduction cost by instead imposing an overall limit 20% below 1990 levels (i.e., the third variant of the Increasing Abatement scenario).

One attraction to some a sectoral type of limit is as an appeal to (perceived) equity: that everyone should have to meet the same limit. However, the one clear result of this scenario is that such an approach is, in fact, very inequitable: some pay nothing, and others pay a great deal.



**Figure 4.7:** Total CO<sub>2</sub> emission reduction for CO<sub>2</sub> taxes varying from \$10 to \$120/tCO<sub>2</sub> emitted.

#### 4.3.4 Emission Taxes

This scenario, based also on Stabilization as a starting point, investigates the effect of replacing the limit—the command and control approach—with a fixed emissions charge, or tax, on CO<sub>2</sub> emissions—the economic incentive approach. Tax levels from \$10 to \$120 per tonne CO<sub>2</sub> (assumed constant over time) are investigated, to determine the level which most closely meets the emission reductions required by Stabilization, and how the two resulting systems differ as the tax is varied.

#### Results

Figure 4.7 shows the effect of varying the tax rate on the total CO<sub>2</sub> reduction. Total abatement increases steadily as the tax is increased, although diminishing returns are clearly visible as the tax exceeds \$100/tCO<sub>2</sub>.

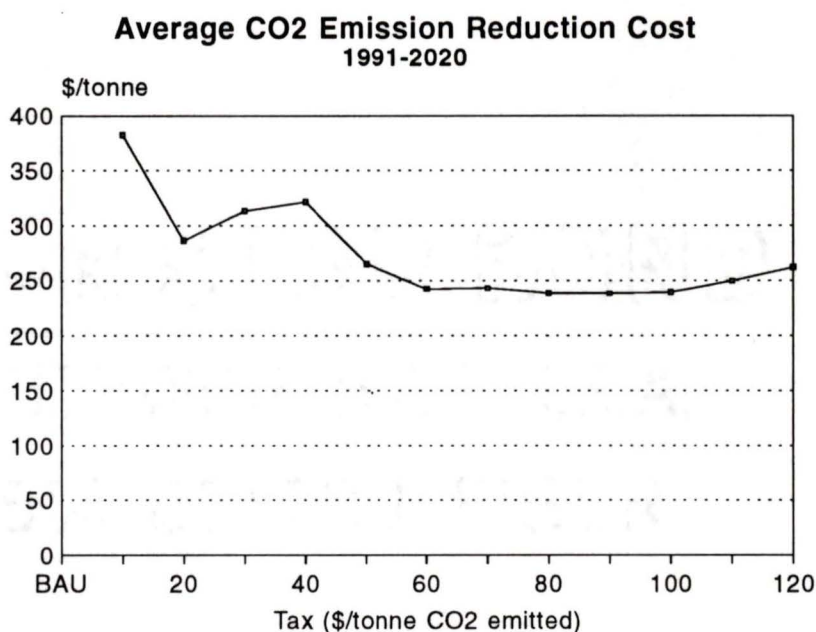
One data point of interest in Figure 4.7 is the tax which results in the same overall reduction as is achieved in the Stabilization scenario, i.e., 3.38 Gt less than BAU. (Recognizing, however, that the timing of particular reductions may differ between the two scenarios.) This reduction corresponds to a tax of approximately \$65/t. Table 4.8 compares the cost of emission reduction between the Stabilization scenario and emissions charges of \$60/t and \$70/t. Note that for an approximately equal level of emission reduction, the \$60/t emission charge has an incremental system cost over eight times higher.

From BAU To:	Stabilization	\$60/tCO <sub>2</sub>	\$70/tCO <sub>2</sub>
CO <sub>2</sub> emission reduction	3.38 Gt	3.23 Gt	3.67 Gt
Discounted emission reduction	1.13 Gt	1.14 Gt	1.30 Gt
Incremental system cost	\$26 × 10 <sup>9</sup>	\$277 × 10 <sup>9</sup>	\$317 × 10 <sup>9</sup>
Average CO <sub>2</sub> reduction cost	\$23/t	\$242/t	\$243/t

**Table 4.8:** Incremental costs, and CO<sub>2</sub> emission reductions for Stabilization, and two CO<sub>2</sub> emissions charges.

Figure 4.8 shows the effect of tax rate on the average cost of emission reduction. One can see at least three interesting features:

- Most striking is, again, the generally high cost of emission reduction. The minimum cost, corresponding to a tax of \$90/t emitted, is approximately \$240/t abated; this is well over twice the average cost associated with the 40%-below-1990 reduction examined earlier (Figure 4.6), for which total emissions are reduced an additional 18%, or 3 Gt.
- The highest abatement cost corresponds to the lowest tax. While this may initially appear counterintuitive, one need only consider the effect of a tax which is too small to result in any emission reduction—such a tax will have an infinite reduction cost. This scenario starts, instead, at a tax which results in some reduction, but at a level small enough to give a very high average abatement cost.



**Figure 4.8:** Average cost of CO<sub>2</sub> emission reduction as a function of the level of a CO<sub>2</sub> emission tax.

- The curve is not monotonic. Although exacerbated somewhat by the use of a linear programming framework, this feature is not inconsistent with real world behavior. At any given tax rate there likely exists some abatement measure which is not quite economically feasible, i.e., for which it remains cheaper to pay the tax than to reduce emissions. As the tax rate is increased, however, it must eventually equal the measure's abatement cost; once this point is exceeded abatement will be preferred to paying the tax, and emissions will now drop by whatever amount the particular abatement measure can achieve. While prior to this tax level the average abatement cost has been rising (due to an increasing tax causing no increased abatement), at this tax the average cost will suddenly drop.

### Summary

Looking at the high abatement costs associated with an emissions tax, one may well wonder why such a measure has any appeal. The answer lies in recognizing that the tax is

an indirect measure, and achieves more than just emission abatement. Most of abatement costs are tax revenues which will be then spent on other things; e.g., in the \$60/tCO<sub>2</sub> tax case,  $\$253 \times 10^9$  of the  $\$277 \times 10^9$  incremental cost represents revenues to the tax collector. The benefits of these expenditures should also be credited to the emission tax (although it may be difficult to do so in this type of modeling framework).

From an implementation perspective, the difficulty with the tax approach is that the appropriate level of tax to achieve a desired level of emission reduction can only be determined through trial and error.

#### 4.3.5 Enhanced Nuclear, Hydroelectric, and Demand Reduction

These three variations on the Stabilization scenario are grouped together for brevity.

- **Enhanced Nuclear** - This variation on the Stabilization scenario differs only in that the restriction on construction of nuclear generating capacity is relaxed, to allow up to approximately twice the base case replacement capacity, or a total of nearly 20 GW added capacity up to the end of the last reported period (2027).
- **Enhanced Hydroelectric** - This scenario is similar to Enhanced Nuclear, except that the relaxed constraint is on the development of hydroelectric sites. The only change is the removal of the base case limit on hydroelectric development, to allow up to 100% of the projects identified by provincial electric utilities to be constructed. This adds approximately 15 GW to the potential additions to hydroelectric capacity.
- **Enhanced Demand Reduction** - This scenario uses many small changes to the Stabilization scenario to investigate the potential role to be played by more aggressive demand reduction measures, or more precisely, by more aggressive efforts to overcome the barriers (discussed in Section 2.3.2) to widespread adoption of the many existing demand reduction options. Such measures could include:
  - moving towards rational, i.e., marginal pricing of energy;
  - improving access to capital, e.g., through utility financing;

- reducing the “information gap” between what is commercially available and what consumers are aware of;
- eliminating legal and administrative barriers.

While these measures would involve additional expenditures, the underlying assumption is that from a social perspective these would be more than offset by the reduction in energy systems costs. Thus, in the model these types of measures are interpreted as reductions in the cost of demand reduction “technologies,” or measures, and a relaxation of constraints on their adoption.

## Results

The point to these scenarios is to examine their impact on the cost of abatement. These results are presented together in Table 4.9, below.

From BAU To:	Stabilization	Enhanced Nuclear	Enhanced Hydro	Enhanced Demand Reduction
CO <sub>2</sub> reduction	3.38 Gt	3.38 Gt	3.40 Gt	3.78 Gt
Discounted reduction	1.13 Gt	1.13 Gt	1.14 Gt	1.32 Gt
Incremental system cost	$\$26 \times 10^9$	$\$19 \times 10^9$	$\$28 \times 10^9$	$\$-122 \times 10^9$
Average CO <sub>2</sub> cost	\$23/t	\$16/t	\$24/t	\$-92/t
Marginal CO <sub>2</sub> cost				
in 2000	\$43/t	\$44/t	\$25/t	\$0/t
in 2020	\$99/t	\$75/t	\$78/t	\$46/t

**Table 4.9:** Incremental costs and CO<sub>2</sub> emission reductions for the Enhanced Nuclear, Enhanced Hydroelectric and Enhanced Demand Reduction scenarios, compared to Stabilization. The marginal CO<sub>2</sub> reduction cost in 2000 and 2020 is also given.

## Summary

Given that these scenarios represent the relaxation of constraints, it is not surprising that all have lower costs than the Stabilization scenario. Similarly, since the limit remains the

same for all cases, one would expect that the total CO<sub>2</sub> reduction would be the same for all.

One interesting point is that the Enhanced Demand Reduction scenario actually has lower costs than the BAU scenario, and results in greater emission reduction than Stabilization. The reasons for this are:

- It represents a scenario in which there exist negative-cost abatement measures, i.e., measures which reduce both emissions and total costs.<sup>7</sup>
- The zero marginal cost for Enhanced Demand Reduction in 2000 indicates that the emission limit can be reached at no additional cost; this, in turn implies that the limit has been exceeded, leading to a higher degree of abatement.

#### 4.4 Limitations

Section 3.6 has discussed the limitations in this work which are due to the chosen methodology. However, limitations also exist which are due to the particular choices made in the formulation of the current model.

- **Energy Service Demand Aggregation** - Section 3.3.3 discussed the difficulties in determining, and thus modeling, true energy services; final energy must often be used as a proxy. Nonetheless, it would be useful to disaggregate some of the current energy service demand categories, e.g. the industrial thermal and electric categories.
- **Demand Reduction Aggregation** - While all energy service demand categories have available at least two demand reduction options, none of these options are identifiable technologies—they are simply non-specific demand reductions which are available at a certain cost. For the current level of aggregation this is both necessary and appropriate. However, both the formulation of scenarios and the interpretation

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<sup>7</sup>Such measures certainly exist, e.g., travelling by bus is less expensive and has fewer emissions than travelling by private car. The question is what value people put on the other attributes of the private car, such as privacy, flexibility, prestige, etc., and thus what cost must be incurred to encourage a switch from private car to bus travel.

of results would be improved by disaggregating the demand reduction “technologies” into actual identifiable technologies or policy measures.

- **Allocation of Energy Service Demands** - The structure and base case data of the current model is based on that of the national statistics tabulated by Statistics Canada (1991c). However, because of limits in the disaggregation of these statistics, the upstream activities of all currencies are not treated equally.

For example, the statistics for natural gas clearly identify the transmission losses and producer consumption, allowing a reasonably accurate representation of this chain. The production losses and requirements for crude oil, on the other hand, are rarely identified separately; instead they are included within the various industrial and transportation end-use demand categories. Similarly, natural gas distribution can be easily identified as a separate activity, while the distribution of gasoline is just part of the total freight transport service demand.

Thus one improvement would be to estimate the upstream requirements for the sources and currencies (other than natural gas), so that the competition between them takes full account of their costs and benefits.

- **Geographic Constraints** - The current model does not deal directly with issues of spatial distribution—recall the earlier discussion on the need to implement natural gas energy density region constraints. Similar issues arise concerning the distribution of electricity.

Coal is currently used for electricity generation not only because of its low cost, but also because it is the only reasonable option for base load generation capacity in areas of the country where hydropower and natural gas are not available, and where the institutional infrastructure for nuclear generation does not exist. The current energy system representation does not address such geographic issues, i.e., whether the electricity in the Stabilization scenario which replaces the coal-sourced electricity in BAU can be distributed from where it is generated (e.g., in Quebec for the added hydroelectricity) to where it is required (e.g., the prairie provinces).

For the current scenarios this is not a serious problem; one can reasonably assume that Quebec hydroelectricity supplies Eastern Canada, while Alberta natural gas supplies the West. However, this would be better dealt with by explicitly modeling, for some currencies at least, separate regions of Canada.

## Chapter 5

# Conclusions

### 5.1 Meeting the Target

The key conclusions from this work can best be expressed as answers to the questions posed in the Introduction:

- *Can the emission stabilization target be reached?*

Yes. CO<sub>2</sub> emissions from the energy system can be stabilized at 1990 levels by the year 2000, and can be maintained at these levels through to 2020.

- *If it can be reached, what are the costs?*

The costs depend on the policy instrument used to achieve the target (see the next question).

- *How does the energy system respond to either an absolute limit on emissions, or an increasing emissions tax?*

The changes to the system are similar in either case; the key difference is the cost of meeting the target.

The least-cost solution is one overall, national emission limit; in practice this is equivalent to a national system of tradeable emissions permits. For this case, the total discounted cost of meeting the target is approximately \$26 billion (1990 Canadian dollars). This works out to about \$23/tCO<sub>2</sub> abated, which in terms of common energy currencies is equivalent to a levy of

- \$1.2/GJ natural gas,
- \$0.06/litre gasoline, or
- \$55/tonne hard coal.

While this is a cost-effective solution, it is not clear how a *universal* system of tradeable emission permits might be implemented.

Alternately, implementation is relatively straightforward if an emissions charge, or tax, on each unit of CO<sub>2</sub> emitted is introduced. A tax of \$60/tCO<sub>2</sub> results in a total reduction in emissions approximately equal to that of an imposed Stabilization limit, although at a much higher total cost. At this level of tax the cost of emission reduction is \$277/tCO<sub>2</sub> abated, or over eight times the cost of the Stabilization scenario. However, of the total \$277 billion cost, about \$253 billion represents tax revenues available to be spent on other services, the value of which should also be credited to the tax.

In general, the cost of meeting the target is minimized when the energy system is allowed maximum flexibility in doing so. Emission stabilization for the energy system as a whole costs \$41 billion less than the same limit applied individually to each energy system sector.

- *What are the collateral benefits?*

Reduction of other pollutants is one certain collateral benefit. In particular, the reduction in SO<sub>2</sub> emissions due to CO<sub>2</sub> emission stabilization leads to a considerable reduction in SO<sub>2</sub> damage costs. Accounting for all other emission reductions as well could lead to collateral benefits equalling or exceeding the cost of CO<sub>2</sub> emission reduction.

- *What structural changes are brought about?*

The sector most affected is electricity and central steam generation. In 1990 17% of electricity is generated from coal; under BAU this grows to 27% by 2020. Under CO<sub>2</sub> stabilization this falls by 2020 to 1.4%.

- *How do these issues change as emission reductions are increased? In particular, what are the implications of aiming for the Toronto Target?*

For reduction to the Toronto Target (20% below 1988 CO<sub>2</sub> emission levels by 2005) the average cost of abatement is \$31/tCO<sub>2</sub>, or about 35% above the cost of Stabilization. There are no sweeping changes in the structure of the energy system, although efficiency improvements and demand reduction measures are used to a greater degree.

The cost of CO<sub>2</sub> emission reduction rises quickly as the target is reduced below this level. For a level of reduction 40% below stabilization, the average cost of reduction is \$100/tCO<sub>2</sub> abated, or over four times higher than stabilization. This can be compared to the equivalent increase in energy currency prices (according to their carbon content)

- \$5/GJ natural gas,
- \$0.24/litre gasoline, or
- \$240/tonne hard coal.

Such increases, while considerable, would nonetheless result in energy prices comparable to those paid by many Europeans today.

At this level of emission reduction there are also considerable structural changes in the utilization of energy. For example, nearly half of the total demand for urban passenger-km of travel are met by demand reduction, i.e., they are trips not taken.

It should be kept in mind that these conclusions reflect the assumptions underlying the scenarios, particularly:

- conservative increases in the demand for energy services;
- significant socio-political resistance to large-scale hydroelectric and nuclear development;
- a preference for travel via private automobile;
- limits on the penetration of new energy technologies to estimated real-world rates;

## 5.2 Other Lessons

This work suggests additional useful conclusions:

- The cost of CO<sub>2</sub> emission reduction is lowered by the removal of constraints on development of hydro and/or nuclear electricity. Nonetheless, there may be significant socio-political costs associated with removing these constraints.
- The reduction of energy service demands, particularly through the removal of existing barriers to efficient energy utilization, has the potential to reduce CO<sub>2</sub> emissions at relatively low cost. The cost of implementing such measures is unclear.
- Applying the same emission limit to each sector of the energy system, so that each sector must *individually* stabilize CO<sub>2</sub> emissions, has the appearance of equity. However, in terms of the costs paid by each sector this is a highly inequitable approach, since some sectors (e.g., resource extraction) have much higher reduction costs than other sectors (e.g., electricity generation). In the end, the sectoral approach leads to an average cost of emission reduction, at \$51/tCO<sub>2</sub> abated, which is more than twice that of the same emission reduction applied to the system as a whole.

While outside the scope of this work, these results have interesting implications for the allocation of emission reductions:

1. **Among Canadian provinces** - Should Quebec, with its dependence on carbon-free hydroelectric power, be required to reduce CO<sub>2</sub> emissions to the same degree as the provinces which depend, instead, on coal and oil for their electricity?
2. **Among countries of the world** - Should all countries be required to reduce CO<sub>2</sub> to the same degree? Alternately (to allow for the development needs of many countries in the world) should all industrialized countries be required to reduce CO<sub>2</sub> to the same degree?

### 5.3 Directions for Future Work

There are three directions along which the work presented here can be usefully extended, either separately or in parallel.

#### Data Improvement

Every model can benefit from data refinement, and techno-economic modeling is very data intensive. The current model is certainly no exception; given its relatively early state of development, it would benefit considerably from some time devoted in this direction. A few prominent areas are:

- improved disaggregation of those energy services which are in fact delivered to upstream sectors of the energy system, e.g., quantities of energy currencies used in the extraction of crude oil;
- similarly, the disaggregation of energy services representing transport of energy currencies, i.e., the distribution of gasoline;
- improvements in emission factors for emissions other than CO<sub>2</sub>; SO<sub>2</sub> is well represented, but CO, NO<sub>x</sub>, VOCs, and particularly CH<sub>4</sub> require further work;
- costs for demand reduction which better reflect the actual costs of bringing about behavioral change.

#### Structural Improvement

The structure of the model also has many areas which could be improved:

- the disaggregation of energy service demands, particularly for industry;
- the disaggregation of demand reduction measures in all energy service demand categories;
- modeling of regional/geographic constraints, especially those representing the distribution of energy currencies.

### **Linking Energy System and Economic Models**

There are many potential pitfalls in the linking of bottom-up, techno-economic models with top-down, econometric ones; this has been discussed in Section 1.3.2. Yet, one key benefit of the top-down, economic approach remains: it applies the same systematic approach to the specification of energy service demands which the techno-economic modeling approach applies to the rest of the energy system. For this reason, it is a task deserving further work.

## Bibliography

- Alson, J. A., Adler, J. M. & Baines, T. M. (1991). Motor vehicle emission characteristics and air quality impacts of methanol and compressed natural gas, *in* Sperling (1991), pp. 109–143.
- American Wind Energy Association (AWEA) (1993, 17 May). Wind energy weekly, Electronic Newsletter, Issue 557. Contact [awea@mcimail.com](mailto:awea@mcimail.com).
- Avallone, E. A. & Baumeister III, T. (eds) (1987). *Mark's Standard Handbook for Mechanical Engineers*, ninth edn, McGraw-Hill, New York.
- Ayres, R. U. (1993). Eco-restructuring: The transition to an ecologically sustainable economy, Working Paper 93/35/EPS, INSEAD, Centre for Management of Environmental Resources, Fontainebleau, France.
- Barclay, J. (1992, 24 September). Nova natural gas specification, Portion of a Presentation.
- Beaujean, J. M., Charpentier, J. P. & Nakićenović, N. (1977). Global and international energy models: A survey, *Annual Review of Energy* **2**: 153–170.
- Beaver, R. D. (1993). Structural comparison of the models in EMF 12, *Energy Policy* **21**(6): 238–248.
- Beaver, R. D. & Huntington, H. G. (1992). A comparison of aggregate energy demand models for global warming policy analyses, *Energy Policy* **20**(8): 568–574.
- Berger, C. et al. (1992a). CO<sub>2</sub> control in Quebec and Ontario: A systems analysis using MARKAL, Les Cahiers du GERAD G-92-21, Groupe d'études et de recherche en analyse des décisions, Montreal, Canada.
- Berger, C. et al. (1992b). Canadian MARKAL: An advanced linear programming system for energy and environmental modelling, *INFOR* **30**(3): 222–239.
- Blok, K., Hendriks, C. A. & Turkenburg, W. C. (1989). The role of carbon dioxide removal in the reduction of the greenhouse effect, *Energy Technologies for Reducing Emissions of Greenhouse Gases: Proceedings of an Experts' Seminar, Volume II*, Organization for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, pp. 135–152.
- British Petroleum (BP) (1991, June). BP statistical review of world energy.

- British Petroleum (BP) (1992, June). BP statistical review of world energy.
- Brookes, D. B., Robinson, J. B. & Torrie, R. D. (1983). 2025: Soft energy futures for Canada, Report, Friends of the Earth Canada, Ottawa.
- Brookes, W. T. (1989, 25 December). The global warming panic, *Forbes* pp. 96–102.
- Canadian Automobile Association (CAA) (1992). Energy efficiency strategy for road transportation in Canada, Ottawa.
- Carlsmith, R. S., Chandler, W. U., McMahon, J. E. & Santini, D. J. (1990). Energy efficiency: How far can we go?, Report ORLN/TM-11441, Oak Ridge National Laboratory, National Technical Information Service, Springfield, VA.
- Climate Institute (1992). 154 nations sign climate change accord, *Climate Alert* 5(2): 1.
- DeLuchi, M. A. (1989). Hydrogen vehicles: An evaluation of fuel storage, performance, environmental impacts and cost, *International Journal of Hydrogen Energy* 14(2): 81–130.
- DeLuchi, M. A. (1990, 3 June). State-of-the-art assessment of emissions of greenhouse gases from the use of fossil and nonfossil fuels, with emphasis on alternative transportation fuels, Draft Report.
- DeLuchi, M. A., Johnston, R. A. & Sperling, D. (1988). Methanol vs. natural gas vehicles: A comparison of resource supply, performance, emissions, fuel storage, safety, costs, and transitions, SAE Technical Paper 881656, Society of Automotive Engineers, Warrendale, Pennsylvania.
- DeLuchi, M. A., Wang, Q. & Sperling, D. (1989). Electric vehicles: Performance, life-cycle costs, emissions, and recharging requirements, *Transportation Research A* 23A(3): 255–278.
- EcoPlan International (1990). *Choosing Europe's Energy Future*, EcoPlan International, Paris. Prepared for the Norwegian Ministry of Petroleum and Energy.
- Edmonton Power (1993, 10 August). District heat study, Unpublished study of district heat feasibility.
- European Conference of Ministers of Transport (ECMT) (1991). *Freight Transport and the Environment*, Organization for Economic Cooperation and Development (OECD), Paris.
- Foat, K. D., Protti, G. J. & Douglas, G. W. (1981). Models for energy policy analysis: A survey, Client Report 81-1, Canadian Energy Research Institute (CERI), Calgary, Alberta.
- Ford, A. & McKay, M. D. (1985). Quantifying uncertainty in energy model forecasts, *Energy Systems and Policy* 9(3): 217–247.

- Government of Canada (1990). *Canada's Green Plan*, Supply and Services Canada, Ottawa.
- Government of Canada (1991a). *Getting There: The Interim Report of the Royal Commission on National Passenger Transportation*, Supply and Services Canada, Ottawa.
- Government of Canada (1991b). *The State of Canada's Environment - 1991*, Supply and Services Canada, Ottawa.
- Grubb, M. J. (1989). On coefficients for determining greenhouse gas emissions from fossil fuel production and consumption, *Energy Technologies for Reducing Emissions of Greenhouse Gases: Proceedings of an Experts' Seminar, Volume I*, Organization for Economic Cooperation and Development (OECD)/International Energy Agency (IEA), Paris, pp. 537-555.
- Grubb, M. J. (1990). *Energy Policies and the Greenhouse Effect, Volume I: Policy Appraisal*, Dartmouth, Gower House, Aldershot.
- Grubb, M. J. (1993). Policy modelling for climate change, *Energy Policy* 21(3): 203-208.
- Grubb, M. J. et al. (1991). *Energy Policies and the Greenhouse Effect, Volume II: Country Studies and Technical Options*, Dartmouth, Gower House, Aldershot.
- Häfele, W. (1981). *Energy in a Finite World, Volume 2: A Global Systems Analysis*, Ballinger, Cambridge, Massachusetts. Report by the Energy Systems Group of the International Institute for Applied Systems Analysis (IIASA), Wolf Häfele, Program Leader.
- Häfele, W. & Rogner, H.-H. (1984). A technical appraisal of the IIASA energy scenarios? A rebuttal, *Policy Sciences* 17: 341-365.
- Haites, E. (1990). Canada, in W. U. Chandler (ed.), *Carbon Emissions Control Strategies: Case Studies in International Cooperation*, World Wildlife Fund & The Conservation Foundation, Baltimore, Maryland, chapter 8, pp. 173-192.
- Hoffman, K. C. & Wood, D. O. (1976). Energy system modeling and forecasting, *Annual Review of Energy* 1: 423-453.
- Hoffman, P. (1993, April). *The Hydrogen Letter*.
- Hollins, J. G. et al. (1992). Technology options to meet environmental requirements: Insight from MARKAL modeling, Presented at the Workshop and Conference on Global Change and Environmental Considerations for Energy System Development, 21 April - 8 May 1992, Trieste, Italy.
- Horlock, J. H. (1987). *Cogeneration—Combined Heat and Power (CHP): Thermodynamics and Economics*, Pergamon, Oxford.

- Houghton, J. T., Callander, B. A. & Varney, S. K. (eds) (1992). *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment*, Cambridge University Press, Cambridge.
- Houghton, J. T., Jenkins, G. J. & Ephraums, J. J. (eds) (1990). *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press, Cambridge.
- Idso, S. B. (1989). Carbon dioxide: A contrarian point of view, Presented at Annual Meeting of the Alternate Fuels Industry in Tucson, Arizona.
- Iman, R. L. & Helton, J. C. (1988). An investigation of uncertainty and sensitivity analysis techniques for computer models, *Risk Analysis* 8(1): 71–90.
- Intergovernmental Panel on Climate Change (IPCC) (1991). *Climate Change: The IPCC Response Strategies*, Island Press, Washington, D.C.
- International Energy Agency (IEA) (1991b). *Greenhouse Gas Emissions: The Energy Dimension*, Organization for Economic Cooperation and Development (OECD), Paris.
- International Energy Agency (IEA) (1991a). *Energy Balances of OECD Countries: 1980–1989*, Organization for Economic Cooperation and Development (OECD), Paris.
- International Energy Agency (IEA) (1992a). *Energy Balances of OECD Countries: 1989–1990*, Organization for Economic Cooperation and Development (OECD), Paris.
- International Energy Agency (IEA) (1992b). *Energy Statistics of OECD Countries: 1989–1990*, Organization for Economic Cooperation and Development (OECD), Paris.
- International Institute for Applied Systems Analysis (IIASA) (1993). CO<sub>2</sub>DB: CO<sub>2</sub> Database. Electronic Database, Laxenburg, Austria.
- Isaksen, I. S. A., Ramaswamy, V., Rodhe, H. & Wigley, T. M. L. (1992). Radiative forcing of climate, in Houghton et al. (1992), appendix 2, pp. 47–67.
- Jaques, A. P. (1992). Canada's greenhouse gas emissions: Estimates for 1990, Report EPS 5/AP/4, Environment Canada, Conservation and Protection, Ottawa.
- Jochem, E. & Gruber, E. (1990). Obstacles to rational electricity use and measures to alleviate them, *Energy Policy* 18(4): 340–350.
- Klass, L. (1978). Fuels from biomass, *Kirk-Othmer Encyclopedia of Chemical Technology*, third edn, Wiley-Interscience, pp. 334–392.
- Lave, L. B. (1990). Comment, *The Energy Journal* 11(4): 61–62.
- Ledbetter, M. & Ross, M. (1992). Light vehicles: Policies for reducing their energy use and environmental impact, in J. Byrne & D. Rich (eds), *Energy and Environment: The Policy Challenge*, Transaction, New Brunswick, New Jersey, pp. 187–234.

- Levine, M. D. et al. (1992, March). Electricity end-use efficiency: Experience with technologies, markets, and policies throughout the world. Draft report to the Energy and Industry Subcommittee of the Policy Response Panel of the IPCC.
- Lind, R. C. et al. (1982). *Discounting for Time and Risk in Energy Policy*, Resources for the Future, Washington, D.C.
- Lovins, A. B. & Lovins, L. H. (1991). Least-cost climatic stabilization, *Annual Review of Energy and the Environment* 16: 433–531.
- Mader, G. H. & Bevilacqua, O. M. (1991). Electric vehicle commercialization, in Sperling (1991), pp. 235–246.
- Manne, A. S. & Richels, R. G. (1990). CO<sub>2</sub> emission limits: An economic cost analysis for the USA, *The Energy Journal* 11(2): 51–74.
- Manne, A. S. & Richels, R. G. (1991). Buying greenhouse insurance, *Energy Policy* 19(6): 543–552.
- Marbek Resource Consultants (1992a). City of Toronto study 1: Potential for electricity conservation — Commercial/institutional buildings sector, Technical report, Marbek Resource Consultants, Toronto, Ontario. A Submission to the Ontario Hydro Demand/Supply Plan Environmental Assessment Board Hearings.
- Marbek Resource Consultants (1992b). City of Toronto study 1: Potential for electricity conservation — Residential sector, Technical report, Marbek Resource Consultants, Toronto, Ontario. A Submission to the Ontario Hydro Demand/Supply Plan Environmental Assessment Board Hearings.
- Marbek Resource Consultants (1992c). City of Toronto study 1: Potential for electricity conservation — Residential sector appendices, Technical report, Marbek Resource Consultants, Toronto, Ontario. A Submission to the Ontario Hydro Demand/Supply Plan Environmental Assessment Board Hearings.
- Marbek Resource Consultants (1992d). City of Toronto study 1: Potential for electricity conservation — Commercial/institutional buildings sector appendices, Technical report, Marbek Resource Consultants, Toronto, Ontario. A Submission to the Ontario Hydro Demand/Supply Plan Environmental Assessment Board Hearings.
- Marchetti, C. & Nakićenović, N. (1979). The dynamics of energy systems and the logistic substitution model, Technical Report RR-79-13, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
- Margolick, M. et al. (1992). Energy efficiency and fuel substitution in Canadian industry under greenhouse gas regulation, Accepted for publication in Proceedings of the 1992 World Energy Conference.

- George C. Marshall Institute (1989). Scientific perspectives on the greenhouse problem, Report, George C. Marshall Institute, Washington, D.C. Cited in SCE (1991, p. 7) and Schneider (1991).
- Messner, S. (1984a). User's guide for the matrix generator of MESSAGE II, Part I: Model description and implementation guide, Working Paper WP-84-71a, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. The model actually used is a more recent, but undocumented version of this system.
- Messner, S. (1984b). User's guide for the matrix generator of MESSAGE II, Part II: Appendices, Working Paper WP-84-71b, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
- Meyers, S. & Schipper, L. (1992). World energy use in the 1970s and 1980s: Exploring the changes, *Annual Review of Energy and the Environment* 17: 463–505.
- Nakićenović, . et al. (1993). Long-term strategies for mitigating global warming, *Energy—The International Journal* 18(5): 401–609. Also reprinted July 1993 as RR-93-11, by the International Institute for Applied Systems Analysis (IIASA).
- National Energy Board (NEB) (1985): *The Social Discount Rate: Is 10 Percent Too High?*, Supply and Services Canada, Ottawa.
- National Energy Board (NEB) (1991). *Canadian Energy: Supply and Demand 1990–2010*, Supply and Services Canada, Ottawa.
- OECD Nuclear Energy Agency/IEA (OECD-NEA) (1989). *Projected Costs of Generating Electricity from Power Stations for Commissioning in the Period 1995–2000*, Organization for Economic Cooperation and Development (OECD), Paris.
- O'Brien, B. (1992). The greenhouse holy war, *Global Warming and Climate Change*, pp. 15–24. Proceedings of a Panel Discussion Sponsored by B.C. Hydro, B.C. Environmental Network, and Torrie and Associates, held 12 May 1992 in Victoria, B.C., Canada.
- Ogden, J. M. & Williams, R. H. (1989). Solar hydrogen: Moving beyond fossil fuels, Technical report, World Resources Institute, Washington, DC.
- Ontario Hydro (1989). Providing the balance of power: Ontario Hydro's plan to serve customer's electricity needs, Demand/supply plan report, Ontario Hydro, Toronto, Ontario.
- Ontario Nuclear Cost Inquiry (ONCI) (1989). Report to the Minister of Energy, Technical report, Province of Ontario, Toronto, Ontario.
- Ottinger, R. L. et al. (1991). *Environmental Costs of Electricity*, Oceana, New York.
- Ouellette, N. (1992, 9 March). Notes on energy density data, Notes for Mechanical Engineering 590, based on Statistics Canada Census Data.

- Perreault, J. (1990, March). Population projections for Canada, provinces and territories 1989–2011, Catalogue 91-520, Statistics Canada, Supply and Services Canada, Ottawa.
- Perry, R. H. & Chilton, C. H. (1973). *Chemical Engineers' Handbook*, fifth edn, McGraw-Hill, New York.
- Prakash, C. B., Song, G. S. & Adams, W. A. (1991). The environmental impact of electric vehicles based on Canadian experience, Technical report, Conservation and Protection, Environment Canada. Presented at the AIEC Conference, Automotive Industry in Expanding Countries, Buenos Aires, Argentina, 3–6 September 1991.
- Ramanathan, V. (1988). The greenhouse theory of climate change: A test by an inadvertent global experiment, *Science* **240**: 293–299.
- Roberts, L. (1991). Report nixes “geritol” fix for global warming, *Science* **253**: 1490–1491.
- Rogner, H.-H. (1989). Natural gas as the fuel for the future, *Annual Review of Energy* **14**: 14–73.
- Rogner, H.-H. (1992, January). Cost breakdown of North American fossil reserves and resources, Lecture Notes for Mechanical Engineering 590.
- Rogner, H.-H. & Britton, F. E. K. (1991). *Toward a Framework for an Energy Strategy*, EcoPlan International, Paris. Commissioned by DG XVII, Commission of the European Communities.
- Schneider, S. H. (1991). Three reports of the Intergovernmental Panel on Climate Change, *Environment* **33**(1): 25–30.
- Scott, D. S. & Häfele, W. (1990). The coming hydrogen age: Preventing world climatic disruption, *International Journal of Hydrogen Energy* **15**(10): 727–737.
- Scott, D. S. & Rogner, H.-H. (1993). Fuel cell locomotives in Canada, *International Journal of Hydrogen Energy* **18**(3): 253–264.
- Shine, K. P., Derwent, R. G., Wuebbles, D. J. & Morcrette, J.-J. (1990). Radiative forcing of climate, in Houghton et al. (1990), chapter 2, pp. 41–68.
- Simon, H. A. (1988). Prediction and prescription in system modelling, Presented at International Institute for Applied Systems Analysis (IIASA) 1988 Annual Conference, Laxenburg, Austria.
- Sperling, D. (1988). *New Transportation Fuels: A Strategic Approach to Technological Change*, University of California Press, Berkeley, California.
- Sperling, D. (ed.) (1991). *Alternative Transportation Fuels: An Environmental and Energy Solution*, Quorum, New York.
- Staff (1990a, February). Clean fuels report.

- Staff (1990b, 31 December). Worldwide report, *Oil and Gas Journal* 88(53): 41-91.
- Staff (1991, June). Clean fuels report.
- Staff (1992, September). Clean fuels report.
- Staff (1993, June). Hercules receives ARB certification, *Natural Gas Fuels* p. 6.
- Standing Committee on the Environment (SCE) (1991). *Out of Balance: The Risks of Irreversible Climate Change, Part III of Our Changing Atmosphere*, House of Commons, Ottawa.
- Statistics Canada (1989, April). Gas utilities, December 1990, Catalogue 55-002, Supply and Services Canada, Ottawa.
- Statistics Canada (1990a, February). Fuel consumption survey, Passenger cars, Annual reports: 1984-1988, Catalogue 53-226, Supply and Services Canada, Ottawa.
- Statistics Canada (1990b, November). Trucking in Canada, 1988, Catalogue 53-222, Supply and Services Canada, Ottawa.
- Statistics Canada (1991a, November). Canadian civil aviation, 1990, Catalogue 51-206, Supply and Services Canada, Ottawa.
- Statistics Canada (1991b, December). Electric power statistics, Volume III: Inventory of prime mover and electric generator equipment as of December 91, 1990, Catalogue 57-206, Supply and Services Canada, Ottawa.
- Statistics Canada (1991c, July). Quarterly report on energy supply-demand in Canada: 1990-IV, Catalogue 57-003, Supply and Services Canada, Ottawa.
- Statistics Canada (1992a, January). Electric power statistics, Volume I: Annual electric power survey of capability and load, 1990 actual, 1991-2000 forecast, Catalogue 57-204, Supply and Services Canada, Ottawa.
- Statistics Canada (1992b, May). Electric power statistics, Volume II: Annual statistics 1990, Catalogue 57-202, Supply and Services Canada, Ottawa.
- Statistics Canada (1992c, July). Rail in Canada, 1990, Catalogue 52-216, Supply and Services Canada, Ottawa.
- Statistics Canada (1992d, March). Shipping in Canada, 1990, Catalogue 54-205, Supply and Services Canada, Ottawa.
- Statistics Canada (1993a, February). Passenger bus and urban transit statistics, 1990, Catalogue 53-215, Supply and Services Canada, Ottawa.
- Statistics Canada (1993b, February). Trucking in Canada, 1990, Catalogue 53-222, Supply and Services Canada, Ottawa.

- Steinmetz, G. F. (1984). Review presentation for transmission, distribution and bulk storage of hydrogen relative to natural gas supplementation, in T. N. Veziroglu & J. B. Taylor (eds), *Hydrogen Energy Progress V. Proceedings of the Fifth World Hydrogen Energy Conference*, Vol. 3, International Association for Hydrogen Energy, Pergamon, New York, pp. 1187–1200. Held 15–20 July 1984 in Toronto, Canada.
- Strubegger, M. (1984). User's guide for the post processor of MESSAGE II, Working Paper WP-84-72, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.
- Torrie Smith Associates (1992a). City of Toronto study 1: Potential for electricity conservation — Industrial sector, Technical report, Torrie Smith Associates, Toronto, Ontario. A Submission to the Ontario Hydro Demand/Supply Plan Environmental Assessment Board Hearings.
- Torrie Smith Associates (1992b). City of Toronto study 1: Potential for electricity conservation — Industrial sector appendices, Technical report, Torrie Smith Associates, Toronto, Ontario. A Submission to the Ontario Hydro Demand/Supply Plan Environmental Assessment Board Hearings.
- Transportation Energy Division (TED-EMR) (1986). Incremental cost to Canadians of the proposed heavy duty engine regulations to limit emissions from trucks and buses, Internal Report TE-86-4, Energy, Mines and Resources Canada (EMR), Ottawa.
- Treasury Board Secretariat (1976). Benefit-cost analysis guide, Technical report, Supply and Services Canada, Ottawa.
- U.S. Congress, Office of Technology Assessment (US-OTA) (1991). *Changing by Degrees: Steps to Reduce Greenhouse Gases*, U.S. Government Printing Office, Washington, DC.
- U.S. Department of Energy (US-DOE) (1990a). *The Potential of Renewable Energy: An Interlaboratory White Paper*, Solar Energy Research Institute (SERI), Golden, Colorado.
- U.S. Department of Energy (US-DOE) (1990b). *Technical Report Four: Vehicle and Fuel Distribution Requirements, Assessment of Costs and Benefits of Flexible and Alternative Fuel Use in the U.S. Transportation Sector*, U.S. Department of Energy (US-DOE), Washington, DC.
- Watson, R. T., Rodhe, H., Oeschger, H. & Siegenthaler, U. (1990). Greenhouse gases and aerosols, in Houghton et al. (1990), chapter 1, pp. 1–40.
- Wene, C.-O. (1993). Top down – bottom up: A system engineer's view, in Y. Kaya, N. Nakićenović, W. D. Nordhaus & F. L. Toth (eds), *Costs, Impacts, and Benefits of CO<sub>2</sub> Mitigation*, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, pp. 355–370. Proceedings of a Workshop, held 28–30 September 1992.

- Williams, H. P. (1985). *Model Building in Mathematical Programming*, second edn, Wiley-Interscience.
- Williams, R. H. (1990). Low-cost strategies for coping with CO<sub>2</sub> emission limits, *The Energy Journal* **11**(3): 35–59.
- Wilson, D. & Swisher, J. (1993). Exploring the gap: Top-down versus bottom-up analyses of the cost of mitigating global warming, *Energy Policy* **21**(3): 249–263.
- World Meteorological Organization (WMO) (1989). Conference statement, *The Changing Atmosphere: Implications for Global Security*, number WMO 710, World Meteorological Organization (WMO), Secretariat of the World Meteorological Organization, Geneva, Switzerland, pp. 292–299. Proceedings of a World Conference, held 27–30 June 1988 in Toronto, Canada.
- World Meteorological Organization (WMO) (1991). Ministerial declaration, in J. Jäger & H. L. Ferguson (eds), *Climate Change: Science, Impacts and Policy. Proceedings of the Second World Climate Conference*, World Meteorological Organization (WMO), Cambridge University Press, Cambridge, pp. 535–542.

## Appendix A

# Model Description

### A.1 Input Files

Two sets of files contain the majority of the input data for the models underlying this work:

1. the actual MESSAGE input files, and
2. a set of spreadsheet files used to calculate parameters for the MESSAGE files.

#### A.1.1 MESSAGE Input Files

For each scenario, the actual model parameters are contained in two files:

- the <model>.adb file, e.g., can.adb which contains most of the input data, and which, more or less, defines the Business as Usual (BAU) scenario;
- the <model>\_<scenario>.ldb file, e.g., can\_hyd.ldb which contains the parameters which distinguish this particular scenario from BAU. For all scenarios, the most important element of this file is the specification of the energy service demands.

The following set of files define the model input parameters for all scenarios. They are available on the Internet via anonymous ftp at [iesvic.uvic.ca](ftp://iesvic.uvic.ca) in the directory `pub/iesvic/jdwthesis/message`.

<i>File</i>	<i>Description</i>
can.adb	the input data common to all scenarios, and essentially defining BAU
Scenario-specific data for:	
bau.ldb	BAU
lim_00.ldb	Stabilization, i.e., 0% below 1990 levels in 2000
lim_tor.ldb	Toronto Target, i.e., 20% below 1988 levels in 2005
lim_90.ldb	90% below 1990 levels in 2000
lim_80.ldb	80% below 1990 levels in 2000
lim_70.ldb	70% below 1990 levels in 2000
lim_60.ldb	60% below 1990 levels in 2000
lim_sect.ldb	Sectoral Stabilization
lim_dmr.ldb	Enhanced Demand Reduction
lim_hyd.ldb	Enhanced Hydroelectric Generation
lim_nuc.ldb	Enhanced Nuclear Generation
tax_nnn.ldb	Emission Tax, with particular level set by changing -999 on one line of the file to the tax level, e.g., to 90 for a \$90/tCO <sub>2</sub> tax

### A.1.2 Spreadsheet Calculation Files

The following spreadsheet files are used to calculate many of the parameters contained in the model input files, as well as providing background data. Note that:

- Many of the files are linked to others, to facilitate data transfer. If only certain files are retrieved it should still be possible to view them, but automatic inter-file updating may not work.
- The original files are in the format used by Microsoft Excel Version 4, and have names ending in *.XLS*, as shown in the table. There should be no difficulties in using these files with either the Apple Macintosh or Microsoft Windows versions of Excel.
- For compatibility, the spreadsheet files have also been provided in Lotus 123 format. For this there are two additional files for each scenario (beyond the *.XLS* files listed in the table below) having the same root name, but with one file ending in *.WK1* and the other file ending in *.FMT*. The file conversion was performed using Excel, and thus no guarantees can be made regarding the correctness or completeness of the Lotus-format files. (At the same time, there is no reason to expect problems, except perhaps with inter-file linkages).

<i>File</i>	<i>Description</i>
COMMERCE.XLS	Commerce and public administration; division of totals into energy service demand categories
DEMAND.XLS	Energy service demands; used as input to .ldb files, above
DENSITY.XLS	Energy density regions
ELEC.XLS	Existing electric generation capacity and historical activity; also load curve calculations
ELEC2.XLS	Future hydroelectric resources
ELEC3.XLS	Generation options for Ontario Hydro, and associated emissions
EMIT.XLS	CO <sub>2</sub> emissions; also CH <sub>4</sub> emissions from oil and gas production
EMIT-NEB.XLS	Emission factors for energy currencies
EMIT-PP.XLS	Emissions from power plants
EMIT-SCE.XLS	Emissions, as presented in Government of Canada (1991b, Table 14.1)
EMIT-SO2.XLS	Division of SO <sub>2</sub> emissions between East (limited) and West (unlimited)
EMIT-TRN.XLS	Emissions from transportation
GAS.XLS	Natural gas load curves
H2.XLS	Hydrogen transportation systems
HC-COAL.XLS	Coal reserves and resources
HC-COAL2.XLS	Coal consumption, overall and for electricity generation
HC-O&G.XLS	Crude oil and natural gas reserves and resources
INDUSTRY.XLS	Industry; division of totals into energy service demand categories
REFINE.XLS	Oil refinery balances
RESIDENT.XLS	Residential; division of totals into energy service demand categories
STATCAN.XLS	Energy flows and accounting, based on Statistics Canada Quarterly Report 57-003, 1990
TRANS.XLS	Transportation; division of totals into modal energy service categories
URANIUM.XLS	Historic nuclear generation capacity

### A.1.3 Citations for Data Sources

The following citations are the data sources used in the preparation of the files described above:

- General (used throughout)
  - Statistics Canada (1991c)
  - IEA (1992a)

**Electricity Generation**

Statistics Canada (1992b)  
Statistics Canada (1992a)  
Statistics Canada (1991b)  
NEB (1991)  
Ontario Hydro (1989)

**Emissions**

Jaques (1992)  
Government of Canada (1991b)  
NEB (1991)  
Hollins et al. (1992)  
Ontario Hydro (1989)  
OECD-NEA (1989)  
Perry & Chilton (1973)  
Avallone & Baumeister III (1987)  
DeLuchi (1990)  
DeLuchi, Johnston & Sperling (1988)  
IEA (1991b)  
Ledbetter & Ross (1992)  
Prakash, Song & Adams (1991)  
CAA (1992)  
Sperling (1988)  
TED-EMR (1986)  
ECMT (1991)  
Staff (1993)  
Barclay (1992)  
Klass (1978)

**Resources**

NEB (1991)  
BP (1991)  
BP (1992)  
Rogner (1992)

**Energy Service Demands**

Marbek (1992b)  
Marbek (1992c)  
Perreault (1990)  
NEB (1991)  
Ontario Hydro (1989)

**Transportation**

Statistics Canada (1991a)  
Statistics Canada (1992c)  
Statistics Canada (1993b)  
Statistics Canada (1990a)  
Statistics Canada (1993a)  
Statistics Canada (1990b)  
Statistics Canada (1993b)  
Statistics Canada (1992d)  
Sperling (1988)  
Government of Canada (1991a)  
Mader & Bevilacqua (1991)  
Prakash et al. (1991)  
DeLuchi, Wang & Sperling (1989)  
Staff (1990a)  
Staff (1991)  
Staff (1992)  
US-DOE (1990b)

**Refineries**

Staff (1990b)  
IIASA (1993)

**Uranium**

Ontario Hydro (1989)  
Statistics Canada (1992b)  
OECD-NEA (1989)

**Density Regions**

Ouellette (1992)

**Industrial**

Torrie Smith (1992a)  
Torrie Smith (1992b)

**Residential**

Marbek (1992b)  
Marbek (1992c)  
Ouellette (1992)  
IEA (1992a)

**Commerce and Public Administration**

Marbek (1992a)  
Marbek (1992d)  
Edmonton Power (1993)

**Load Curves**

Statistics Canada (1989)  
Ontario Hydro (1989)

**CO<sub>2</sub> Recovery, Disposal**

- Blok, Hendriks & Turkenburg (1989)  
Nakićenović et al. (1993)

**Hydrogen Systems**

- Scott & Rogner (1993)  
DeLuchi (1989)  
Hoffman (1993)  
Steinmetz (1984)

**Renewable Energy Systems**

- US-DOE (1990a)  
DeLuchi (1989)  
DeLuchi et al. (1988)  
Avallone & Baumeister III (1987)  
Sperling (1988)  
OECD-NEA (1989)  
AWEA (1993)  
Ogden & Williams (1989)

## A.2 Summary of BAU Input Parameters

The following report summarizes the input parameters for the BAU case. It is, however, a static picture: it presents techno-economic data for the starting point of the model, but does not show the dynamics which are included in, and are key to the model (and which are specified in the model input files, above):

start of file:

Report of Inputs to MESSAGE II Run for: can\_ref  
 \*\*\*\*\*

produced at 2.19, on 1993-10- 4

General Inputs  
 =====

Labels of Time Periods:  
 -----

1991 1992 1994 1996 1998 2003 2008 2013 2028

Length of Historic Periods: 1 Years

Definition of Load Regions  
 -----

Identifiers	nr of sub peaks	nr per time unit
s-ason	4	1

Length (fraction per year) :

0.050 0.150 0.500 0.300

Discount Rate  
 -----

Constant 5.0 %

Demands  
 =====

Annual Demand Figures:  
 -----

Years	H-ResEl	h-ResTh	S-ComEl
1991	9.88	20.07	8.25
1992	10.43	20.26	8.61
1994	11.00	20.47	9.02
1996	11.59	20.61	9.52

1998	12.53	20.82	10.49
2003	14.19	21.03	12.15
2008	16.07	21.24	14.07
2013	20.11	20.92	18.86
2028	20.11	20.92	18.86

Years	s-ComTh	v-ComVent	a-ComCool
1991	12.34	2.32	1.92
1992	12.72	2.40	1.99
1994	13.14	2.50	2.07
1996	13.68	2.62	2.18
1998	14.75	2.87	2.38
2003	16.47	3.28	2.72
2008	18.40	3.75	3.11
2013	22.96	4.89	4.05
2028	22.96	4.89	4.05

Years	B-MetEl	G-PaPEl	C-ChEl
1991	4.49	4.75	1.79
1992	4.46	4.72	1.86
1994	4.44	4.70	1.93
1996	4.46	4.71	2.02
1998	4.55	4.81	2.18
2003	4.63	4.90	2.46
2008	4.72	4.99	2.77
2013	4.89	5.17	3.53
2028	4.89	5.17	3.53

Years	O-IndEl	P-FAgEl	b-MetTh
1991	7.22	0.98	2.64
1992	7.48	0.95	2.60
1994	7.76	0.93	2.56
1996	8.12	0.92	2.54
1998	8.79	0.91	2.55
2003	9.91	0.89	2.54
2008	11.17	0.86	2.52
2013	14.20	0.82	2.48
2028	14.20	0.82	2.48

Years	A-MetCoke	g-PaPTh	c-ChTh
1991	3.08	8.51	3.81
1992	3.03	8.37	3.95
1994	2.99	8.25	4.10
1996	2.97	8.19	4.29
1998	2.98	8.24	4.65
2003	2.96	8.18	5.24
2008	2.94	8.12	5.91
2013	2.90	8.02	7.51
2028	2.90	8.02	7.51

Years	o-IndTh	p-FAgTh	j-TrIC
1991	13.88	1.80	251.73
1992	14.38	1.75	264.22
1994	14.93	1.71	277.32
1996	15.61	1.69	290.22
1998	16.90	1.68	310.71
2003	19.05	1.63	345.58
2008	21.48	1.59	384.37

2013	27.30	1.50	459.43
2028	27.30	1.50	459.43

Years	k-TrUrb	r-TrRFrt	w-TrSFrt
1991	222.95	416.83	371.94
1992	236.30	414.05	369.45
1994	250.45	412.10	367.72
1996	264.67	413.46	368.93
1998	287.53	421.77	376.34
2003	327.70	429.52	383.26
2008	373.49	437.42	390.31
2013	468.85	453.65	404.79
2028	468.85	453.65	404.79

Years	f-TrAFrt	F-SpecFeed	L-SpecLiq
1991	1.85	14.99	7.34
1992	1.93	15.54	7.33
1994	2.02	16.13	7.33
1996	2.14	16.86	7.39
1998	2.35	18.26	7.59
2003	2.73	20.59	7.82
2008	3.16	23.21	8.05
2013	4.23	29.50	8.54
2028	4.23	29.50	8.54

Distribution of Demands to Load Regions:

for Demand	1. lr	2. lr	3. lr	4. lr
H-ResEl	0.070	0.180	0.500	0.250
h-ResTh	0.090	0.270	0.540	0.100
S-ComEl	0.070	0.180	0.500	0.250
s-ComTh	0.090	0.270	0.540	0.100
v-ComVent	0.070	0.180	0.500	0.250
a-ComCool	0.090	0.270	0.540	0.100
B-MetEl	0.070	0.180	0.500	0.250
G-PaPEl	0.070	0.180	0.500	0.250
C-ChEl	0.070	0.180	0.500	0.250
O-IndEl	0.070	0.180	0.500	0.250
P-FAgEl	0.070	0.180	0.500	0.250
x-ResDuct	0.050	0.150	0.500	0.300
b-MetTh	0.050	0.150	0.500	0.300
A-MetCoke	0.050	0.150	0.500	0.300
g-PaPTh	0.050	0.150	0.500	0.300
c-ChTh	0.050	0.150	0.500	0.300
o-IndTh	0.050	0.150	0.500	0.300
p-FAgTh	0.050	0.150	0.500	0.300
j-TrIC	0.050	0.150	0.500	0.300
k-TrUrb	0.050	0.150	0.500	0.300
r-TrRFrt	0.050	0.150	0.500	0.300
w-TrSFrt	0.050	0.150	0.500	0.300
f-TrAFrt	0.050	0.150	0.500	0.300
F-SpecFeed	0.050	0.150	0.500	0.300
L-SpecLiq	0.050	0.150	0.500	0.300

Power Level Relative to Average Load:

for Demand	1. lr	2. lr	3. lr	4. lr
H-ResEl	1.400	1.200	1.000	0.833

h-ResTh	1.800	1.800	1.080	0.333
S-ComEl	1.400	1.200	1.000	0.833
s-ComTh	1.800	1.800	1.080	0.333
v-ComVent	1.400	1.200	1.000	0.833
a-ComCool	1.800	1.800	1.080	0.333
B-MetEl	1.400	1.200	1.000	0.833
G-PaPEl	1.400	1.200	1.000	0.833
C-ChEl	1.400	1.200	1.000	0.833
O-IndEl	1.400	1.200	1.000	0.833
P-FAgEl	1.400	1.200	1.000	0.833
x-ResDuct	1.000	1.000	1.000	1.000
b-MetTh	1.000	1.000	1.000	1.000
A-MetCoke	1.000	1.000	1.000	1.000
g-PaPTh	1.000	1.000	1.000	1.000
c-ChTh	1.000	1.000	1.000	1.000
o-IndTh	1.000	1.000	1.000	1.000
p-FAgTh	1.000	1.000	1.000	1.000
j-TrIC	1.000	1.000	1.000	1.000
k-TrUrb	1.000	1.000	1.000	1.000
r-TrRFrt	1.000	1.000	1.000	1.000
w-TrSFrt	1.000	1.000	1.000	1.000
f-TrAFrt	1.000	1.000	1.000	1.000
F-SpecFeed	1.000	1.000	1.000	1.000
L-SpecLiq	1.000	1.000	1.000	1.000

#### Lists of Energy Form Names

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#### Energy Forms:

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Level: r	Level: a	Level: x	Level: t	Level: f	Level: u
h RHCool	a PNGas	A SNGas	a DNGas	e FElec	H ResEl
b RSCool	h PHCoal	a SNGasL	e DElec	M LiqMet	h ResTh
o ROnCrude	b PSCoal	d SDHeat	z DElecD	P LiqPaP	S ComEl
O ROnCrude	o PCrude	e SElec	w DMeth	E LiqCh	s ComTh
i ROnCrude	f PNGasOn	x SHElec	h DHCoal	I LiqInd	v ComVent
j ROffCrud	z PNGasOff	n SNGLL	b DSCoal	F LiqFAG	a ComCool
k ROffCrud	l PLtOil	w SMeth	l DLtOil	a FNGas	B MetEl
t RTarsand	y PresOil	c SCoke	y DResOil	w FMeth	G PaPEl
a RNGasOn1	w PMWaste	m SMFuel	m DMFuel	d FDHeat	C ChEl
n RNGasOn2	u PUranium	k SAVFuel	q DBiomass	h FHCoal	O IndEl
N RNGasOn2	q PBiomass	4 SElecExp	t DLH2	l FLtOil	P FAgEl
f RNGasOn3	2 PCrudeEx	u SURanium		y FResOil	x ResDuct
z RNGasOnN	3 PLtOilEx	t SLH2		m FMFuel	b MetTh
m RNGasOff	5 PMFuelEx	T SH2		s FMFLiq	A MetCoke
p RNGasOff	7 PNGasExp			q FBiomass	g PaPTh
c RBiomass	8 PCoalExp			t FLH2	c ChTh
u URanium	n PEXNOx				o IndTh
	s PEXSO2				p FAgTh
	c PEXCO2				j TrIC
					k TrUrb
					r TrRFrt
					w TrSFrt
					f TrAFrt
					F SpecFeed
					L SpecLiq

#### Stock Piles: (Level q)

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id name	Stock in Base Year
n E0nCrude	269.00

Definition of Additional Relations

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Used for Accounting only :

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c2ex-EmC02\_Ext  
CO2 emissions from resource extraction

c2pr-EmC02\_Proc  
CO2 emissions from processing

c2di-EmC02\_Dist  
CO2 emissions from transmission and distribution

c2pp-EmC02\_PP  
CO2 emissions from power plants

c2in-EmC02\_Ind  
CO2 emissions from industrial sectors

c2rs-EmC02\_Res  
CO2 emissions from residential sector

c2cm-EmC02\_Com  
CO2 emissions from commercial and public admin sectors

c2tr-EmC02\_Tran  
CO2 emissions from transport systems

c2-EmC02  
total CO2 emissions

coex-EmC0\_Ext  
CO emissions from resource extraction

copr-EmC0\_Proc  
CO emissions from processing

codi-EmC0\_Dist  
CO emissions from transmission and distribution

copp-EmC0\_PP  
CO emissions from power plants

coin-EmC0\_Ind  
CO emissions from industrial sectors

cors-EmC0\_Res  
CO emissions from residential sector

cocm-EmC0\_Comm  
CO emissions from commercial and public admin sectors

cotr-EmC0\_Tran  
CO emissions from transport systems

co-EmC0

total CO emissions

nxex-EmNOx\_Ext  
NOx emissions from resource extraction

nxpr-EmNOx\_Proc  
NOx emissions from processing

nxdi-EmNOx\_Dist  
NOx emissions from transmission and distribution

nxpp-EmNOx\_PP  
NOx emissions from power plants

nxin-EmNOx\_Ind  
NOx emissions from industrial sectors

nxrs-EmNOx\_Res  
NOx emissions from residential sector

nxcm-EmNOx\_Comm  
NOx emissions from commercial and public admin sectors

nxtr-EmNOx\_Tran  
NOx emissions from transport systems

nx-EmNOx  
total NOx emissions

c4ex-EmCH4\_Ext  
CH4 emissions from resource extraction

c4pr-EmCH4\_Proc  
CH4 emissions from processing

c4di-EmCH4\_Dist  
CH4 emissions from transmission and distribution

c4pp-EmCH4\_PP  
CH4 emissions from power plants

c4in-EmCH4\_Ind  
CH4 emissions from industrial sectors

c4rs-EmCH4\_Res  
CH4 emissions from residential sector

c4cm-EmCH4\_Comm  
CH4 emissions from commercial and public admin sectors

c4tr-EmCH4\_Tran  
CH4 emissions from transport systems

c4-EmCH4  
total CH4 emissions

voex-EmVOC\_Ext  
VOC emissions from resource extraction

vopr-EmVOC\_Proc  
VOC emissions from processing

vodi-EmVOC\_Dist

VOC emissions from transmission and distribution

vopp-EmVOC\_PP  
VOC emissions from power plants

voin-EmVOC\_Ind  
VOC emissions from industrial sectors

vors-EmVOC\_Res  
VOC emissions from residential sector

vocm-EmVOC\_Comm  
VOC emissions from commercial and public admin sectors

votr-EmVOC\_Tran  
VOC emissions from transport systems

vo-EmVOC  
total VOC emissions

s2ex-EmS02\_Ext  
S02 emissions from resource extraction

s2pr-EmS02\_Proc  
S02 emissions from processing

s2di-EmS02\_Dist  
S02 emissions from transmission and distribution

s2pp-EmS02\_PP  
S02 emissions from power plants

s2in-EmS02\_Ind  
S02 emissions from industrial sectors

s2rs-EmS02\_Res  
S02 emissions from residential sector

s2cm-EmS02\_Com  
S02 emissions from commercial and public admin sectors

s2tr-EmS02\_Tran  
S02 emissions from transport systems

s2-EmS02  
total S02 emissions

Used as Constraints :

-----

Years	xinv (le)	sinv (le)	hydq (le)	hydo (le)
1991	none	none	0.00	0.00
1992	none	none	0.00	0.00
1994	none	none	0.00	0.00
1996	none	none	0.00	0.00
1998	none	none	0.00	0.00
2003	none	none	0.00	0.00
2008	none	none	0.00	0.00
2013	none	none	0.00	0.00
2028	none	none	0.00	0.00

## Comments:

-----

xinv-InvRes  
upper bounds on investments in residential sector

sinv-InvCom  
upper bounds on investments in commercial sector

hydq-PlfHydQue  
average plant factor limit on Quebec hydro power plants

hydo-PlfHydOnt  
average plant factor limit on Ontario hydro power plants

Years	hydb (le)	hydt (le)	dcap (le)	dpip (le)
1991	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00

Years	hydb (le)	hydt (le)	dcap (le)	dpip (le)
1991	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00

## Comments:

-----

hydb-PlfHydBC  
average plant factor limit on BC hydro power plants

hydt-PlfHydOth  
average plant factor limit on Other hydro power plants

dcap-CapHPlant  
average plant factor of district heating plants: 0.45

dpip-DuctPipe  
link residential ducts/piping capacity with heating system capacity

Years	mcar (le)	purb (le)	rfrt (le)	rtrk (eq)
1991	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00

Years	mcar (le)	purb (le)	rfrt (le)	rtrk (eq)
1991	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00

## Comments:

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mcar-TranCar  
constraint on minimum private car transport

purb-TranPub  
constraint on maximum public urban transport

rrft-TranRdFrt  
constraint on minimum road freight transport

rtrk-TranRdTrk  
constraints on road freight fuel type

Years	cgtp (le)	oiie (le)	lgd1 (le)	lgd2 (le)
1991	44.60	0.00	7.00	12.00
1992	44.60	0.00	7.07	12.30
1994	44.60	0.00	7.21	12.92
1996	44.60	0.00	7.36	13.58
1998	44.60	0.00	7.50	14.26
2003	44.60	0.00	7.89	16.14
2008	44.60	0.00	8.29	18.26
2013	44.60	0.00	8.71	20.66
2028	44.60	0.00	10.12	29.92

Comments:

cgtp-TmNGasChp  
limit for cheap gas transmission lines

oiie-OilImpExp  
force exports to exceed imports

lgd1-DHDense1  
gas distribution and district heat energy density region 1

lgd2-DHDense2  
gas distribution and district heat energy density region 2

Years	lgd3 (le)	lgd4 (le)	lgd5 (le)	hpsf (le)
1991	20.00	10.00	20.50	10.00
1992	20.60	10.20	20.55	10.00
1994	21.85	10.61	20.65	10.00
1996	23.19	11.04	20.76	10.00
1998	24.60	11.49	20.86	10.00
2003	28.52	12.68	21.12	10.00
2008	33.06	14.00	21.39	10.00
2013	38.32	15.46	21.66	10.00
2028	59.70	20.81	22.48	10.00

Comments:

lgd3-DHDense3  
gas distribution and district heat energy density region 3

lgd4-DHDense4  
gas distribution and district heat energy density region 4

lgd5-DHDense5  
gas distribution and district heat energy density region 5

hpsf-HPumpSolar  
limit on heat pumps and solar in residential and commercial

Years	hplt (le)	dhdc (le)	dhrc (le)	h2ng (le)
1991	10.00	0.00	0.00	0.00
1992	10.00	0.00	0.00	0.00
1994	10.00	0.00	0.00	0.00
1996	10.00	0.00	0.00	0.00
1998	10.00	0.00	0.00	0.00
2003	10.00	0.00	0.00	0.00
2008	10.00	0.00	0.00	0.00
2013	10.00	0.00	0.00	0.00
2028	10.00	0.00	0.00	0.00

Comments:

-----

hplt-HPumpInd

limit on heat pumps in other ind & chemicals

dhdc-LinkDHeat

link commercial district heat and district cooling capacities

dhrc-DHComsRes

link residential and commercial district heating capacities

h2ng-H2Mix

limits injection of hydrogen into natural gas system

Years	dsc (ge)	dncc (ge)	dsci (ge)	dncci (ge)
1991	0.00	0.00	0.00	0.00
1992	0.00	0.00	0.00	0.00
1994	0.00	0.00	0.00	0.00
1996	0.00	0.00	0.00	0.00
1998	0.00	0.00	0.00	0.00
2003	0.00	0.00	0.00	0.00
2008	0.00	0.00	0.00	0.00
2013	0.00	0.00	0.00	0.00
2028	0.00	0.00	0.00	0.00

Comments:

-----

dsc-DeSO2\_PP

balance emissions and reductions of SO2 from power plants

dncc-DeNOx\_PP

balance emissions and reductions of NOx from power plants

dsci-DeSO2\_HI

balance emissions and reductions of SO2 from industry

dncci-DeNOx\_HI

balance emissions and reductions of NOx from industry

Years	dc2 (le)	s2ea (le)
1991	0.00	606.00
1992	0.00	606.00
1994	0.00	465.00
1996	0.00	465.00

1998	0.00	465.00
2003	0.00	465.00
2008	0.00	465.00
2013	0.00	465.00
2028	0.00	465.00

## Comments:

-----

## dc2 -DeCO2

allows disposal of separated CO2 (from IGCC2, and SMR)

## s2ea-EMS02\_East

allows fraction of disposed CO2 to be used, at lower cost, in enhanc

## Annual Cost Figures :

-----

years	xinv	sinv	oilp
1991	1.50	1.50	104.70
1992	1.50	1.50	104.70
1994	1.50	1.50	110.00
1996	1.50	1.50	121.00
1998	1.50	1.50	130.70
2003	1.50	1.50	141.30
2008	1.50	1.50	165.00
2013	1.50	1.50	165.00
2028	1.50	1.50	165.00

## Comments:

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## xinv-InvRes

upper bounds on investments in residential sector

## sinv-InvCom

upper bounds on investments in commercial sector

## oilp-OilPrices

crude oil import prices

-

taxes for households

## Resources - Imports - Exports

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1. h-RHCoal on level: 1

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## Domestic Resources

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annual	total		1. grade		cost	2. grade		cost
	lolim	uplim	lolim	uplim		lolim	uplim	
1991	0.		0.		0.	0.	15.	
1992	0.		0.		0.	0.	15.	
1994	0.		0.		0.	0.	15.	

1996	0.	0.	0.	0.	15.	
1998	0.	0.	0.	0.	15.	
2003	0.	0.	0.	0.	15.	
2008	0.	0.	0.	0.	15.	
2013	0.	0.	0.	0.	15.	
2028	0.	0.	0.	0.	15.	
-----						
total	0.	70460.	0.	3260.	0.	67200.

hard coal (bituminous)

2. b-RSCoal on level: 1

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Domestic Resources

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	total			1. grade			2. grade		
annual	lolim	uplim	lolim	uplim	cost	lolim	uplim	cost	
1991	0.		0.		0.	0.		9.	
1992	0.		0.		0.	0.		9.	
1994	0.		0.		0.	0.		9.	
1996	0.		0.		0.	0.		9.	
1998	0.		0.		0.	0.		9.	
2003	0.		0.		0.	0.		9.	
2008	0.		0.		0.	0.		9.	
2013	0.		0.		0.	0.		9.	
2028	0.		0.		0.	0.		9.	
-----									
total	0.	47700.	0.	1600.		0.	46100.		

lignite/soft coal (mix of lignite and sub-bituminous)

3. o-ROnCrude1a on level: 1

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Domestic Resources

-----

	total			1. grade		
annual	lolim	uplim	lolim	uplim	cost	
1991	0.		0.		0.	
1992	0.		0.		0.	
1994	0.		0.		0.	
1996	0.		0.		0.	
1998	0.		0.		0.	
2003	0.		0.		0.	
2008	0.		0.		0.	
2013	0.		0.		0.	
2028	0.		0.		0.	
-----						
total	0.	385.	0.	385.		

oil onshore less expensive reserves -- category Ia

4. O-ROnCrude1b on level: 1

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## Domestic Resources

annual	total		1. grade		cost
	lolim	uplim	lolim	uplim	
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.
1996	0.		0.		0.
1998	0.		0.		0.
2003	0.		0.		0.
2008	0.		0.		0.
2013	0.		0.		0.
2028	0.		0.		0.
total	0.	373.	0.	373.	

oil onshore more expensive reserves -- category Ib

5. i-R0nCrude2 on level: 1

## Domestic Resources

annual	total			1. grade			2. grade			3. grade		
	lolim	uplim	cost	lolim	uplim	cost	lolim	uplim	cost	lolim	uplim	cost
1991	0.		0.	0.		0.	0.		84.	0.		151.
1992	0.		0.	0.		0.	0.		84.	0.		151.
1994	0.		0.	0.		0.	0.		84.	0.		151.
1996	0.		0.	0.		0.	0.		84.	0.		151.
1998	0.		0.	0.		0.	0.		84.	0.		151.
2003	0.		0.	0.		0.	0.		84.	0.		151.
2008	0.		0.	0.		0.	0.		84.	0.		151.
2013	0.		0.	0.		0.	0.		84.	0.		151.
2028	0.		0.	0.		0.	0.		84.	0.		151.
total	0.	1743.		0.	525.		0.	564.		0.	654.	

oil onshore discovered and undiscovered resources -- category

6. j-R0ffCrude1 on level: 1

## Domestic Resources

annual	total		1. grade		cost
	lolim	uplim	lolim	uplim	
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.
1996	0.		0.		0.
1998	0.		0.		0.
2003	0.		0.		0.
2008	0.		0.		0.
2013	0.		0.		0.
2028	0.		0.		0.

total 0. 134. 0. 134.

oil offshore reserves -- category I

7. k-ROffCrude2 on level: 1

-----  
Domestic Resources

total		1. grade			2. grade			
annual	lolim	uplim	lolim	uplim	cost	lolim	uplim	cost
1991	0.		0.		0.	0.		84.
1992	0.		0.		0.	0.		84.
1994	0.		0.		0.	0.		84.
1996	0.		0.		0.	0.		84.
1998	0.		0.		0.	0.		84.
2003	0.		0.		0.	0.		84.
2008	0.		0.		0.	0.		84.
2013	0.		0.		0.	0.		84.
2028	0.		0.		0.	0.		84.
total	0.	4025.	0.	625.		0.	3400.	

oil offshore discovered and undiscovered resources -- categ

8. t-RTarsand on level: 1

-----  
Domestic Resources

total		1. grade			
annual	lolim	uplim	lolim	uplim	cost
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.
1996	0.		0.		0.
1998	0.		0.		0.
2003	0.		0.		0.
2008	0.		0.		0.
2013	0.		0.		0.
2028	0.		0.		0.
total	0.	82500.	0.	82500.	

tarsands/bitumen reserves and resources

9. a-RNGas0n1 on level: 1

-----  
Domestic Resources

total		1. grade			
annual	lolim	uplim	lolim	uplim	cost
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.

1996	0.		0.		0.
1998	0.		0.		0.
2003	0.		0.		0.
2008	0.		0.		0.
2013	0.		0.		0.
2028	0.		0.		0.
-----					
total	0.	1710.	0.	1710.	

gas onshore cheap reserves -- category I

10. n-RNGasOn2a            on level: 1

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Domestic Resources

		total		1. grade		
annual	lolim	uplim	lolim	uplim	cost	
1991	0.		0.		0.	
1992	0.		0.		0.	
1994	0.		0.		0.	
1996	0.		0.		0.	
1998	0.		0.		0.	
2003	0.		0.		0.	
2008	0.		0.		0.	
2013	0.		0.		0.	
2028	0.		0.		0.	
-----						
total	0.	854.	0.	854.		

gas onshore more expensive reserves -- category IIa

11. W-RNGasOn2b            on level: 1

-----  
Domestic Resources

		total		1. grade		
annual	lolim	uplim	lolim	uplim	cost	
1991	0.		0.		0.	
1992	0.		0.		0.	
1994	0.		0.		0.	
1996	0.		0.		0.	
1998	0.		0.		0.	
2003	0.		0.		0.	
2008	0.		0.		0.	
2013	0.		0.		0.	
2028	0.		0.		0.	
-----						
total	0.	925.	0.	925.		

gas onshore most expensive reserves -- category IIb

12. f-RNGasOn3            on level: 1

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## Domestic Resources

	total			1. grade			2. grade		
	lolim	uplim	cost	lolim	uplim	cost	lolim	uplim	cost
annual									
1991	0.		0.	0.		0.	0.		15.
1992	0.		0.	0.		0.	0.		15.
1994	0.		0.	0.		0.	0.		15.
1996	0.		0.	0.		0.	0.		15.
1998	0.		0.	0.		0.	0.		15.
2003	0.		0.	0.		0.	0.		15.
2008	0.		0.	0.		0.	0.		15.
2013	0.		0.	0.		0.	0.		15.
2028	0.		0.	0.		0.	0.		15.
total	0.	3750.		0.	1700.		0.	2050.	

gas onshore undiscovered resources -- category III

13. z-RNGasOnNC on level: 1

## Domestic Resources

	total			1. grade			2. grade		
	lolim	uplim	cost	lolim	uplim	cost	lolim	uplim	cost
annual									
1991	0.		0.	0.		0.	0.		50.
1992	0.		0.	0.		0.	0.		50.
1994	0.		0.	0.		0.	0.		50.
1996	0.		0.	0.		0.	0.		50.
1998	0.		0.	0.		0.	0.		50.
2003	0.		0.	0.		0.	0.		50.
2008	0.		0.	0.		0.	0.		50.
2013	0.		0.	0.		0.	0.		50.
2028	0.		0.	0.		0.	0.		50.
total	0.	10960.		0.	4110.		0.	6850.	

gas onshore nonconventional resources

14. m-RNGasOff1 on level: 1

## Domestic Resources

	total			1. grade			2. grade		
	lolim	uplim	cost	lolim	uplim	cost	lolim	uplim	cost
annual									
1991	0.		0.	0.		0.	0.		3.
1992	0.		0.	0.		0.	0.		3.
1994	0.		0.	0.		0.	0.		3.
1996	0.		0.	0.		0.	0.		3.
1998	0.		0.	0.		0.	0.		3.
2003	0.		0.	0.		0.	0.		3.
2008	0.		0.	0.		0.	0.		3.
2013	0.		0.	0.		0.	0.		3.
2028	0.		0.	0.		0.	0.		3.
total	0.	1413.		0.	413.		0.	1000.	

## gas offshore reserves and discovered resources -- category

15. p-RNGasOff2 on level: 1

-----  
Domestic Resources

	total		1. grade		
annual	lolim	uplim	lolim	uplim	cost
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.
1996	0.		0.		0.
1998	0.		0.		0.
2003	0.		0.		0.
2008	0.		0.		0.
2013	0.		0.		0.
2028	0.		0.		0.
total	0.	9170.	0.	9170.	

## gas offshore undiscovered resources -- category II

16. c-RBiomass on level: 1

-----  
Domestic Resources

	total		1. grade		
annual	lolim	uplim	lolim	uplim	cost
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.
1996	0.		0.		0.
1998	0.		0.		0.
2003	0.		0.		0.
2008	0.		0.		0.
2013	0.		0.		0.
2028	0.		0.		0.
total	0.		0.		

biomass resource

17. u-RUranium on level: 1

-----  
Domestic Resources

	total		1. grade		
annual	lolim	uplim	lolim	uplim	cost
1991	0.		0.		0.
1992	0.		0.		0.
1994	0.		0.		0.
1996	0.		0.		0.

1998	0.	0.	0.
2003	0.	0.	0.
2008	0.	0.	0.
2013	0.	0.	0.
2028	0.	0.	0.
-----			
total	0.	0.	

natural uranium resource

### Short Description of Technologies

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nr	name	capcost US\$/kw	var o+m US\$/kWa	fix o+m US\$/kw/a	tot eff %	pllife years	plfct fr	avg cst US\$/kWa	technology name
1	a.ww	0.00	195.00	0.00	1.00	1.	1.00	195.00	ExMWaste
2	auuu	0.00	9.90	0.00	1.00	1.	1.00	9.90	ExUranium
3	accq	0.00	95.00	0.00	1.00	1.	1.00	95.00	ExBiomass
4	ahhh	100.00	50.00	11.00	1.00	20.	0.90	71.14	ExHCoal
5	abbb	40.00	12.00	4.00	1.00	20.	0.90	20.01	ExSCoal
6	aaaa	370.69	25.86	13.79	1.00	15.	0.90	80.87	ExOilOn1a
7	a00o	275.86	57.76	13.79	1.00	15.	0.90	102.61	ExOilOn1b
8	aiao	422.41	31.03	7.76	1.00	15.	0.90	84.87	ExOilOn2
9	anno	740.00	54.00	25.00	1.00	15.	0.90	160.99	ExOilOnE
10	ajjo	330.00	34.00	18.00	1.00	15.	0.90	89.33	ExOilOff1
11	akko	690.00	46.00	25.00	1.00	15.	0.90	147.64	ExOilOff2
12	atto	690.00	76.00	55.00	1.00	15.	0.90	210.97	ExTarsand
13	aaaf	200.00	5.00	3.00	1.00	15.	0.90	29.74	ExNGasOn1
14	annf	250.00	8.00	5.00	1.00	15.	0.90	40.32	ExNGasOn2a
15	aNnf	250.00	12.00	8.00	1.00	15.	0.90	47.65	ExNGasOn2b
16	afff	600.00	15.00	15.00	1.00	15.	0.90	95.89	ExNGasOn3
17	azzf	1400.00	40.00	50.00	1.00	15.	0.90	245.42	ExNGasOnNC
18	ammz	800.00	6.00	9.00	1.00	15.	0.90	101.64	ExNGasOff1
19	appz	1200.00	30.00	20.00	1.00	15.	0.90	180.68	ExNGasOff2
20	afxa	86.00	0.62	1.70	1.00	15.	1.00	10.61	PipeOnNGas
21	azgf	180.00	1.50	2.30	0.98	15.	1.00	21.14	PipeOffNGas
22	xagA	210.00	1.00	6.50	0.91	40.	1.00	19.74	NGasPlant
23	ao22	0.00	0.00	0.00	1.00	1.	1.00	0.00	ExpCrude
24	al33	0.00	0.00	0.00	1.00	1.	1.00	0.00	ExpLtOil
25	xei4	1.00	-320.00	15.00	0.99	1.	1.00	-303.95	ExpElec
26	am55	0.00	0.00	0.00	1.00	1.	1.00	0.00	ExpMFuel
27	aa77	1.00	2.00	0.00	1.00	1.	1.00	3.05	ExpNGas
28	ah88	0.00	0.00	0.00	1.00	1.	1.00	0.00	ExpHCoal
29	a.io	0.00	0.00	0.00	1.00	1.	1.00	0.00	ImpCrude
30	a.6y	0.00	0.00	0.00	1.00	1.	1.00	0.00	ImpResOil
31	a.ih	0.00	0.00	0.00	1.03	1.	1.00	0.00	ImpHCoal
32	xnna	100.00	2.00	0.00	1.00	40.	1.00	7.83	NGasMix
33	xhsc	420.00	31.00	15.00	0.65	30.	0.90	78.02	Coking
34	ao11	35.78	1.97	2.47	0.91	25.	0.88	7.66	Refinery1
35	ao21	29.78	1.65	1.99	0.96	25.	0.88	6.31	Refinery2
36	ay11	37.23	2.98	3.72	0.91	20.	0.88	10.61	Cracker1
37	ay21	20.55	0.41	0.82	0.94	20.	0.88	3.22	Cracker2
38	x13m	29.01	1.93	4.84	0.85	20.	0.88	10.07	Cracker3
39	xqww	890.00	70.00	210.00	0.53	25.	0.85	391.35	MethBio
40	xufu	0.00	7.20	0.00	1.00	1.	1.00	7.20	FabUranium
41	xaTT	345.00	65.50	17.40	0.78	30.	0.90	109.77	H2SMR
42	xeTT	600.00	65.50	17.40	0.77	30.	0.95	124.90	H2Elec
43	xTaa	0.00	0.00	0.00	1.00	1.	1.00	0.00	H2Mix
44	xTtt	460.00	5.70	17.30	0.77	30.	0.90	58.17	H2Liquefy

45	xAba	315.86	4.69	7.85	0.97	40.	1.00	30.95	TmNGasL
46	taba	100.00	3.50	6.00	1.00	40.	1.00	15.33	TmNGas1
47	taca	200.00	5.20	8.60	1.00	40.	1.00	25.46	TmNGas2
48	xxke	0.00	0.00	0.00	0.98	1.	1.00	0.00	TmElecLink
49	tebz	840.00	16.00	25.00	0.95	60.	1.00	85.38	TmElec
50	tmtm	0.00	20.00	0.00	1.00	1.	1.00	20.00	TmMFuel
-----									
nr	name	capcost US\$/kw	var o+m US\$/kWa	fix o+m US\$/kw/a	tot eff %	pllife years	plfct fr	avg cst US\$/kWa	technology name
-----									
51	tltl	0.00	20.00	0.00	1.00	1.	1.00	20.00	TmLOil
52	tyty	0.00	20.00	0.00	0.87	1.	1.00	20.00	TmROil
53	twww	0.00	20.00	0.00	1.00	1.	1.00	20.00	TmMeth
54	tttt	0.00	30.00	0.00	0.95	1.	1.00	30.00	TmLH2
55	tqtq	0.00	21.00	0.00	1.00	1.	1.00	21.00	TmBio
56	thth	0.00	10.00	0.00	1.00	1.	1.00	10.00	TmHCoal
57	tbtb	0.00	4.00	0.00	1.00	1.	1.00	4.00	TmSCoal
58	xhbe	1400.00	13.00	18.00	0.35	35.	0.80	142.38	PPHC_ST
59	xhpe		13.00		0.34			181.19	PPHC_ST
60	xhae	2000.00	15.00	18.00	0.38	35.	0.80	190.18	PPHC_FBEd
61	xhce		15.00		0.40			242.73	PPHC_FBEd
62	xhie	2300.00	16.00	22.00	0.40	30.	0.80	230.52	PPHC_IGCC
63	xhie	3160.00	21.00	29.00	0.36	30.	0.80	314.20	PPHC_IGCC2
64	xbpe	1600.00	6.40	26.00	0.34	35.	0.80	161.04	PPSC_ST
65	xqpe	1700.00	3.70	18.00	0.20	35.	0.70	177.73	PPBio_ST
66	xAae	660.00	1.80	2.10	0.35	35.	0.80	54.81	PPNGas_ST1
67	xape	660.00	1.80	2.10	0.35	35.	0.80	54.81	PPNGas_ST2
68	xabe	810.00	11.00	8.70	0.48	30.	0.90	79.21	PPNGas_CC
69	xahe	340.00	2.40	2.00	0.26	30.	0.90	29.20	PPNGas_CT
70	xlpe	350.00	2.20	2.00	0.29	30.	0.85	31.34	PPLoil_CT
71	xybe	660.00	9.30	2.10	0.34	35.	0.80	62.31	PPROil_ST
72	xhme	1600.00	14.00	20.00	0.34	35.	0.80	161.14	PPMulti_ST
73	xyme		9.20		0.37			156.34	PPMulti_ST
74	xame		4.20		0.31			151.34	PPMulti_ST
75	xwie	490.00	13.00	18.00	0.26	35.	0.70	81.46	PPMW_ST
76	x.cx	5300.00	3.00	15.00	1.00	60.	0.80	371.74	PPHydQue
77	x.ex	4000.00	3.00	15.00	1.00	60.	0.80	285.89	PPHydOnt
78	x.fx	4500.00	3.00	15.00	1.00	60.	0.95	269.03	PPHydBC
79	x.gx	3100.00	3.00	16.00	1.00	60.	0.80	227.71	PPHydOther
80	xupe	2100.00	11.00	15.00	0.29	35.	0.59	253.80	PPCandu
81	x.se	7500.00	60.00	0.00	1.00	25.	0.25	2188.57	PPSolarPV
82	x.pe	1700.00	25.00	0.00	1.00	15.	0.40	434.45	PPWind
83	xaqe	604.55	5.61	7.77	0.88	30.	0.90	57.95	CogenMulti
84	xyre		4.53		0.83			54.48	CogenMulti
85	xamd	115.00	5.00	3.50	0.86	25.	0.70	21.66	DHMulti
86	xyod		13.00		0.85			29.66	DHMulti
87	xwpd	170.00	7.50	5.30	0.65	30.	0.80	27.95	DHMWaste
88	tzbe	660.00	13.00	19.00	0.99	40.	1.00	70.46	DistElec1
89	febe	1700.00	43.00	52.00	0.98	40.	1.00	194.07	DistElec2
90	fa1a	300.00	3.50	30.00	1.00	40.	0.90	56.26	DistNGas1
91	fa2a	410.00	3.80	38.00	1.00	40.	0.95	68.95	DistNGas2
92	fa3a	470.00	4.20	43.00	1.00	40.	0.95	78.30	DistNGas3
93	fa4a	530.00	4.60	49.00	1.00	40.	0.95	88.69	DistNGas4
94	fa5a	610.00	5.00	61.00	1.00	40.	0.95	106.63	DistNGas5
95	fd1d	530.00	0.00	24.00	0.96	40.	0.35	156.82	DistDHeat1
-----									
nr	name	capcost US\$/kw	var o+m US\$/kWa	fix o+m US\$/kw/a	tot eff %	pllife years	plfct fr	avg cst US\$/kWa	technology name
-----									

96	fmfm	0.00	80.00	0.00	1.00	1.	1.00	80.00	DistMFuel
97	fmFs	0.00	80.00	0.00	1.00	1.	1.00	80.00	DistMLiq
98	flfl	0.00	80.00	0.00	1.00	1.	1.00	80.00	DistLOil
99	fygy	0.00	80.00	0.00	1.00	1.	1.00	80.00	DistROil
100	fwfm	0.00	80.00	0.00	1.00	1.	1.00	80.00	DistMeth
101	fttt	0.00	120.00	0.00	0.95	1.	1.00	120.00	DistLH2
102	fqdq	0.00	9.00	0.00	1.00	1.	1.00	9.00	DistBio
103	fheh	0.00	93.00	0.00	1.00	1.	1.00	93.00	DistHCoal
104	a.rs	1.00	0.00	0.03	1.00	10.	0.40	0.40	DeSO2_PP1
105	a.qs	1.10	0.00	0.03	1.00	10.	0.40	0.44	DeSO2_PP2
106	a.ps	2.30	0.00	0.07	1.00	10.	0.40	0.92	DeSO2_PP3
107	a.sn	1.35	0.00	0.05	1.00	10.	0.40	0.57	DeNOx_PP1
108	a.tn	2.00	0.00	0.08	1.00	10.	0.40	0.85	DeNOx_PP2
109	a.ss	4.20	2.00	0.17	1.00	10.	0.80	2.89	DeSO2_Ind1
110	a.ts	8.40	3.00	0.32	1.00	10.	0.80	4.76	DeSO2_Ind2
111	a.nn	4.70	0.00	0.25	1.00	10.	0.80	1.07	DeNOx_Ind1
112	a.cc	47.10	0.00	4.70	1.00	25.	0.95	8.47	DeCO2
113	u.1b	5681.00	0.00	0.00	1.00	10.	1.00	735.72	TIndCons1
114	u.2b	7647.50	0.00	0.00	1.00	10.	1.00	990.39	TIndCons2
115	u.3b	9832.50	0.00	0.00	1.00	1.	1.00	10324.13	TIndCons3
116	ucsA	0.00	30.00	0.00	1.00	1.	1.00	30.00	MetCoke
117	uesB	0.00	55.00	0.00	1.00	1.	1.00	55.00	MetEl
118	flMM	0.00	100.00	0.00	1.00	1.	1.00	100.00	MetLiq
119	uesb	37.00	2.21	1.10	0.90	15.	0.82	7.86	MetThEl
120	uabb	48.00	2.47	1.07	0.61	35.	0.80	7.47	MetThNGas
121	uybb	58.40	5.26	2.46	0.54	35.	0.76	13.14	MetThROil
122	uhbb	185.00	31.40	8.68	0.50	35.	0.75	58.04	MetThCoal
123	uesG	0.00	55.00	0.00	1.00	1.	1.00	55.00	PaPEl
124	flPP	0.00	100.00	0.00	1.00	1.	1.00	100.00	PaPLiq
125	uesg	37.00	2.21	1.10	0.90	15.	0.82	7.86	PaPThEl
126	uagg	48.00	2.47	1.07	0.61	35.	0.80	7.47	PaPThNGas
127	uygg	58.40	5.26	2.46	0.54	35.	0.76	13.14	PaPThROil
128	uhgg	185.00	31.40	8.68	0.50	35.	0.75	58.04	PaPThCoal
129	u.Bg	300.00	24.00	14.00	0.40	30.	0.75	68.69	PaPBio
130	uesC	0.00	55.00	0.00	1.00	1.	1.00	55.00	ChEl
131	flEE	0.00	100.00	0.00	1.00	1.	1.00	100.00	ChLiq
132	uecc	36.70	2.21	1.10	0.90	15.	0.82	7.83	ChThEl
133	uacc	73.30	4.55	2.72	0.72	30.	0.80	13.91	ChThNGas
134	uycc	89.00	5.97	3.30	0.60	30.	0.80	17.33	ChThROil
135	ues0	0.00	55.00	0.00	1.00	1.	1.00	55.00	IndEl
136	flII	0.00	100.00	0.00	1.00	1.	1.00	100.00	IndLiq
137	ueoo	36.70	2.21	1.10	0.95	15.	0.82	7.83	IndThEl
138	uaoo	73.30	4.55	2.72	0.72	30.	0.54	18.42	IndThNGas
139	uloo	84.00	5.63	3.10	0.66	30.	0.54	21.49	IndThLOil
140	uyoo	84.00	11.37	3.10	0.63	30.	0.54	27.23	IndThROil
<hr/>									
nr	name	capcost	var o+m	fix o+m	tot eff	pllife	plfct	avg cst	technology name
		US\$/kw	US\$/kWa	US\$/kw/a	%	years	fr	US\$/kWa	
<hr/>									
141	uhoo	184.70	31.40	8.68	0.52	35.	0.54	68.36	IndThCoal
142	udoo	44.00	2.64	1.32	0.96	30.	0.54	10.38	IndThDH
143	ueto	93.85	15.96	4.41	3.00	30.	0.54	35.43	IndThHPEl
144	uesP	0.00	55.00	0.00	1.00	1.	1.00	55.00	FAGel
145	flFF	0.00	100.00	0.00	1.00	1.	1.00	100.00	FAGLiq
146	uepp	36.70	2.21	1.10	0.80	30.	0.20	19.65	FAGThEl
147	uapp	73.30	4.55	2.72	0.72	30.	0.45	21.19	FAGThNGas
148	ulpp	84.00	5.63	3.10	0.57	30.	0.45	24.66	FAGThLOil
149	uypp	84.00	11.40	3.10	0.54	30.	0.45	30.43	FAGThROil
150	u.Bp	300.00	24.00	14.00	0.50	30.	0.45	98.48	FAGBio
151	uesH	0.00	110.00	0.00	1.00	1.	1.00	110.00	RsEl
152	u.lH	3500.00	0.00	0.00	1.00	10.	1.00	453.27	RsElConsL

153	u.hh	4500.00	0.00	0.00	1.00	10.	1.00	582.77	RsElConsH
154	u.hx	300.00	0.00	0.00	1.00	50.	0.20	82.17	RsDuct
155	uehh	75.00	0.00	6.76	0.99	20.	0.30	42.59	RsThElec
156	ualh	220.00	1.00	12.00	0.56	20.	0.20	149.27	RsThNGasL
157	uahh	400.00	1.00	21.00	0.80	20.	0.20	266.49	RsThNGasH
158	ullh	245.00	1.00	15.00	0.54	20.	0.20	174.30	RsThLOilL
159	ulhh	425.00	1.00	18.00	0.75	20.	0.20	261.52	RsThLOilH
160	uhhh	400.00	2.00	30.00	0.40	20.	0.25	250.39	RsThCoal
161	uqhh	400.00	2.00	30.00	0.35	20.	0.25	250.39	RsThBio
162	ueph	510.00	0.00	30.00	2.15	15.	0.30	263.78	RsThHPEL
163	uaph	590.00	0.00	33.80	1.12	15.	0.30	302.14	RsThHPG
164	udhh	50.00	0.00	1.00	0.98	40.	0.30	13.05	RsThDH
165	u.sh	1800.00	0.00	25.00	1.00	20.	0.20	847.18	RsThSol
166	u.lh	700.00	0.00	0.00	1.00	10.	0.15	616.69	RsThConsL
167	u.hh	900.00	0.00	0.00	1.00	10.	0.15	792.89	RsThConsH
168	uesS	0.00	80.00	0.00	1.00	1.	1.00	80.00	CmEl
169	u.lS	3500.00	0.00	0.00	1.00	10.	1.00	453.27	CmElConsL
170	u.hS	4500.00	0.00	0.00	1.00	10.	1.00	582.77	CmElConsH
171	uess	60.00	0.00	3.00	0.99	20.	0.35	22.33	CmThEl
172	ueps	360.00	0.40	18.00	4.50	25.	0.30	145.54	CmThHPE
173	uals	150.00	1.00	6.00	0.65	20.	0.30	61.12	CmThNGasL
174	uahs	280.00	1.00	17.00	0.80	20.	0.30	132.56	CmThNGasH
175	ulls	200.00	2.00	7.50	0.60	20.	0.30	80.50	CmThLOilL
176	ulhs	350.00	2.00	17.00	0.75	20.	0.30	152.28	CmThLOilH
177	uyss	200.00	2.27	10.00	0.55	20.	0.30	89.10	CmThROil
178	uaps	410.00	0.40	20.50	1.12	15.	0.30	200.40	CmThHPG
179	udss	50.00	0.00	1.00	0.98	40.	0.30	13.05	CmThDH
180	u.vs	2200.00	0.00	25.00	1.00	20.	0.20	1007.67	CmThSol
181	u.ls	1500.00	0.00	0.00	1.00	40.	0.30	291.39	CmThConsL
182	u.hs	2000.00	0.00	0.00	1.00	40.	0.30	388.52	CmThConsH
183	uelv	280.00	1.00	17.00	1.00	30.	0.50	71.43	CmVentL
184	uehv	580.00	1.00	15.00	1.50	30.	0.50	106.46	CmVentH
185	uela	360.00	0.40	18.00	3.20	20.	0.20	234.84	CmCoolL
-----									
nr	name	capcost	var o+m	fix o+m	tot eff	pllife	plfct	avg cst	technology name
		US\$/kw	US\$/kWa	US\$/kw/a	%	years	fr	US\$/kWa	
-----									
186	ueha	560.00	0.40	18.00	4.20	20.	0.20	315.08	CmCoolH
187	udca	500.00	0.00	1.50	0.98	40.	0.30	102.13	CmCoolDC
188	u.la	2000.00	0.00	0.00	1.00	10.	1.00	259.01	CmCoolConsL
189	u.ha	3000.00	0.00	0.00	1.00	10.	1.00	388.51	CmCoolConsH
190	umlr	76.70	12.30	37.30	17.18	10.	1.00	59.53	RTkRoad
191	ulhr	84.50	12.30	37.30	24.80	10.	1.00	60.54	RTkRdDies
192	umhr	80.50	12.30	37.30	7.17	10.	1.00	60.03	RTkRdMF
193	uahr	88.20	12.30	37.30	7.17	10.	1.00	61.02	RTkRdNG
194	ulLr	11.10	1.27	11.40	87.70	30.	1.00	13.39	RTkRailL
195	ulHr	11.70	1.27	11.40	92.10	30.	1.00	13.43	RTkRlDiesH
196	uaHr	13.10	1.27	11.40	87.70	30.	1.00	13.52	RTkRlLNGH
197	utHr	117.00	2.92	26.20	111.00	15.	1.00	40.39	RTkRlLH2H
198	uylw	6.76	0.46	4.15	109.87	30.	1.00	5.05	STkShipL
199	uyhw	7.10	0.46	4.15	114.91	30.	1.00	5.07	STkShipH
200	uklf	226.00	64.90	195.00	1.58	15.	1.00	281.67	ATkAirL
201	ukhf	237.00	64.90	195.00	2.45	15.	1.00	282.73	ATkAirH
202	u.lr	0.99	69.30	0.00	1.00	1.	1.00	70.34	TkConsL
203	u.hr	0.99	79.20	0.00	1.00	1.	1.00	80.24	TkConsH
204	umlj	692.00	15.90	46.20	14.62	10.	1.00	151.72	ICUCar
205	umlk		22.00		7.65			209.43	ICUCar
206	umhj	727.00	15.90	46.20	22.40	10.	1.00	156.25	ICUCarMF
207	umhk		22.00		11.80			215.68	ICUCarMF
208	ulhj	761.00	15.90	46.20	24.70	10.	1.00	160.65	ICUCarDies
209	ulhk		22.00		13.20			221.76	ICUCarDies

210	uahj		796.00	15.90	46.20	22.70	10.	1.00	165.19		ICUCarWG
211	uahk			22.00		11.90			228.01		ICUCarWG
212	uehk		1450.00	22.00	46.20	58.00	10.	1.00	255.98		UrbCarEl
213	ulLj		142.00	16.30	99.30	53.10	20.	1.00	126.99		ICSrf
214	ulHj		149.00	16.30	99.30	60.40	20.	1.00	127.56		ICSrfDies
215	uaHj		163.00	16.30	99.30	41.20	20.	1.00	128.68		ICSrfWG
216	uklj		22.60	9.54	28.60	15.80	15.	1.00	40.32		ICAirL
217	ukhj		23.80	9.54	28.60	24.50	15.	1.00	40.43		ICAirH
218	u.lj		1.00	190.00	0.00	1.00	1.	1.00	191.05		ICConsL
219	u.hj		1.00	200.00	0.00	1.00	1.	1.00	201.05		ICConsH
220	ulLk		63.70	27.00	81.00	31.48	15.	1.00	114.14		UrbBus
221	ulHk		66.90	27.00	81.00	37.10	15.	1.00	114.45		UrbBusDies
222	uaHk		73.30	27.00	81.00	39.40	15.	1.00	115.06		UrbBusWG
223	ueHk		127.00	27.00	81.00	37.00	15.	1.00	120.24		UrbBusEL
224	utHk		80.30	28.40	85.00	41.60	15.	1.00	121.14		UrbBusLH2
225	u.lk		1.00	265.00	0.00	1.00	1.	1.00	266.05		UrbConsL
226	u.hk		1.00	280.00	0.00	1.00	1.	1.00	281.05		UrbConsH
227	uaFF		0.00	0.00	0.00	1.00	1.	1.00	0.00		SpecFeed
228	uMLL		0.00	0.00	0.00	1.00	1.	1.00	0.00		SpecLiq

:end of file

## Appendix B

### Model Results

#### B.1 Available Files

The complete results from any particular execution of the MESSAGE model are contained in a machine-readable solution file. Particular values from this file can be extracted and formatted as reports. The core set of reports used in this thesis consists of a set of 75 tables for each scenario, covering all aspects of the modeled energy system.

Section B.2 is a listing of this set of 75 tables for the BAU scenario. It is included both to make this information available, as well as to indicate the information available in the other tables.

The following sets of tables, for the corresponding analysis, are available on the Internet via anonymous ftp at [iesvic.uvic.ca](ftp://iesvic.uvic.ca) in the directory `pub/iesvic/jdwthesis/results`.

<i>File</i>	<i>Description</i>
bau.tab	BAU, Business as Usual
lim_00.tab	Stabilization, i.e., 0% below 1990 levels in 2000
lim_90.tab	90% below 1990 levels in 2000
lim_80.tab	80% below 1990 levels in 2000
lim_70.tab	70% below 1990 levels in 2000
lim_60.tab	60% below 1990 levels in 2000
lim_tor.tab	Toronto Target, i.e., 20% below 1988 levels in 2005
lim_sect.tab	Sectoral Stabilization
lim_hyd.tab	Enhanced Hydroelectric
lim_nuc.tab	Enhanced Nuclear
lim_dmr.tab	Enhanced Demand Reduction
tax_10.tab	\$10/tCO <sub>2</sub> Emission Charge/Tax
tax_20.tab	\$20/t Tax
tax_30.tab	\$30/t Tax
tax_40.tab	\$40/t Tax
tax_50.tab	\$50/t Tax
tax_60.tab	\$60/t Tax
tax_70.tab	\$70/t Tax
tax_80.tab	\$80/t Tax
tax_90.tab	\$90/t Tax
tax_100.tab	\$100/t Tax
tax_110.tab	\$110/t Tax
tax_120.tab	\$120/t Tax

## B.2 Results for BAU

- A full listing of the following set of tables would require over 60 pages. Since the file is available in electronic form, the following listing has been edited to remove tables containing little useful information, or containing information mainly of value during model formulation.
- The production of the following file leads to table numbers which are not sequential; do not assume that missing table numbers automatically indicate missing tables.
- The guide at the beginning of the listing has been annotated to indicate sets of tables which have been deleted or reduced in size.

start of file:

=====

CONTENTS:	Tbl
-----	
* Primary	3
* Imports, Exports	13
* Emissions	15
* Shadow Prices	19 <reduced>
* Electricity Generation (Overall)	29 <reduced>
* Electricity Generation (By Load Region)	35 <deleted>
* Natural Gas Production and Transmission	42 <deleted>
* Crude Oil Production	46 <deleted>
* Final Energy : Total	48
*           : Industry	51
*           : Residential	59
*           : Commercial	62
*           : Transport	65
* Useful Energy: Industrial	71
*           : Residential	79
*           : Commercial	81
*           : Transport	83
* Demand Reduction and Capital Investment	87
* Density Regions (Natural Gas and District Heat)	90 <reduced>
* District Heat Production	92 <deleted>

\* Refinery Inputs and Outputs 96 <deleted>

\* CO2 and Objective Function Summary 99 <reduced>

Table 3 CANADA: CO2 Model

MESSAGE II Base Case -----

Date: 01Oct93 02:06:18 Primary Energy Use

GWy

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991    -1993    -1995    -1997    -2002    -2007    -2012    2027
Mid:      (Base)  (1991)  (1992)  (1994)  (1996)  (2000)  (2005)  (2010)  (2020)
=====

```

Coal (Hard and Soft)

```

-----
PrimCoal    34.157    33.479    35.323    35.552    37.374    42.958    55.269    69.700    98.580

```

Crude Oil and Bitumen

```

-----
PrimOil     109.813    110.065    106.317    102.464    101.174    102.194    103.471    106.668    117.641

```

Natural Gas (including NGL)

```

-----
PrimGas     88.413     92.708     94.051     100.352    104.726    111.174    113.696    118.298    137.744

```

## Primary Electricity

. Hydro	33.562	33.833	34.652	34.815	34.815	34.815	35.555	36.294	36.294
. SolarPV	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
. Wind	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Production	33.562	33.833	34.652	34.815	34.815	34.815	35.555	36.294	36.294
Exports	0.052	1.818	1.212	0.606	0.000	0.000	0.000	0.000	0.000
PrimElec	33.510	32.015	33.440	34.209	34.815	34.815	35.555	36.294	36.294

## Other Primary

Uranium	26.800	31.292	29.701	30.231	31.823	34.474	34.474	34.523	34.610
Biomass	18.706	18.389	17.710	16.899	16.781	15.797	18.824	18.919	18.926
MWaste	0.000	0.000	0.000	0.000	0.032	0.138	0.298	0.657	0.534
SolarTherm	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TotalPrim	311.399	317.948	316.544	319.707	326.725	341.550	361.588	385.060	444.329

Table 4

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Primary to Final Energy

Natural Gas + NGL

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027



ThermElec	2.663	5.963	4.836	6.302	7.040	7.533	5.160	5.131	5.065
. Cogen	0.000	0.000	0.000	0.969	1.376	2.433	4.139	5.657	10.007
. DHeat	0.067	0.000	0.000	0.191	0.238	0.366	0.562	0.620	0.943
-----									
SteamHeat	0.067	0.000	0.000	1.161	1.614	2.799	4.701	6.277	10.949
Refinery	3.705	3.620	3.217	3.041	2.977	2.947	2.809	2.698	2.643
RefLPGIn	1.894	1.893	1.829	1.762	1.740	1.758	1.780	1.835	2.023
SMRFeed	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.072
H2In	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
=====									
Final&NonE	66.893	68.146	70.914	74.307	77.323	81.701	85.081	88.225	101.432
=====									
NonEnergy	9.135	9.298	9.639	10.005	10.458	11.327	12.772	14.397	18.299
=====									
Final	57.758	58.848	61.275	64.302	66.865	70.374	72.309	73.827	83.133

Table 5

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 010ct93 02:06:18

Primary to Final Energy

Electricity

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

. Hydro	33.562	33.833	34.652	34.815	34.815	34.815	35.555	36.294	36.294
. Candu	7.850	9.169	8.702	8.858	9.324	10.101	10.101	10.115	10.141
. SolarPV	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
. Wind	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Primary	41.411	43.001	43.355	43.673	44.139	44.916	45.656	46.410	46.435
Exports	0.052	1.818	1.212	0.606	0.000	0.000	0.000	0.000	0.000
=====									
Available	41.360	41.183	42.143	43.067	44.139	44.916	45.656	46.410	46.435
. Distrib	0.000	0.566	0.593	0.618	0.651	0.693	0.751	0.838	0.965
. TransSht	0.000	0.495	0.506	0.519	0.542	0.575	0.622	0.686	0.797
. TransLng	0.000	2.607	2.663	2.734	2.850	3.028	3.273	3.613	4.195
. TransLnk	0.000	0.677	0.693	0.696	0.696	0.696	0.711	0.726	0.726
-----									
TotalLoss	4.402	4.345	4.454	4.568	4.740	4.993	5.358	5.863	6.683
. NatGas	0.754	1.894	1.525	2.501	3.054	3.892	3.818	4.880	6.650
. LOilCT	0.112	0.000	0.000	0.000	0.056	0.060	0.062	0.064	0.077
. ResOil	1.579	1.360	0.853	0.316	0.359	0.395	0.375	0.383	0.537
. HardCoal	3.769	3.153	3.848	3.322	3.625	4.450	7.680	11.234	15.015
. SoftCoal	5.483	5.858	6.164	6.735	7.016	8.069	9.052	10.399	16.337
. Biomass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
. MWaste	0.000	0.000	0.000	0.000	0.008	0.030	0.071	0.131	0.132
-----									
Secondary	11.697	12.265	12.391	12.875	14.118	16.897	21.058	27.091	38.747
Refinery	0.645	0.639	0.590	0.562	0.552	0.550	0.533	0.521	0.530
=====									
Final	48.010	48.465	49.489	50.812	52.966	56.270	60.824	67.117	77.969

Table 6

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Primary to Final Energy

Crude Oil

GWy

	1990	1991	1992	1994	1996	1998	2003	2008	2013
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
. OnOil	88.969	85.469	79.789	65.744	66.077	61.690	49.080	38.068	57.929
. OffOil	0.000	0.000	0.000	8.883	8.883	15.329	31.635	43.358	18.039
. TarSands	29.225	31.596	29.884	27.836	26.214	25.176	22.757	25.242	41.673
Production	118.194	117.065	109.672	102.464	101.174	102.194	103.471	106.668	117.641
Imports	37.992	39.000	39.195	36.407	31.151	26.653	19.993	15.470	11.971
Exports	46.374	46.000	42.550	36.407	31.151	26.653	19.993	15.470	11.971
Available	109.813	110.065	106.317	102.464	101.174	102.194	103.471	106.668	117.641
Refinery	109.812	110.065	106.317	102.464	101.174	102.194	103.472	106.668	117.641
Final	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 8

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Primary to Final Energy

Hydrogen

GWy

	=====								
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
	=====								
. H2_SMR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.056
. H2_Elec	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Production	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.056
GasInject	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
=====									
Available	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.056
LH2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.056
(TransLH2)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
(DistLH2)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TotalLoss	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003
=====									
Final	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054

Table 9

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Primary to Final Energy

Biomass

GWy

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991    -1993    -1995    -1997    -2002    -2007    -2012    2027
Mid:      (Base)  (1991)  (1992)  (1994)  (1996)  (2000)  (2005)  (2010)  (2020)
=====

```

Biomass Production

```

=====
. BioPaP    11.667    11.601    11.396    11.207    11.110    11.143    11.012    10.884    10.684
. BioFag     1.332     1.367     1.330     1.295     1.271     1.257     1.211     1.167     1.094
. Biomass    5.708     5.422     4.984     4.397     4.400     3.398     6.601     6.869     7.147
=====
Available   18.706    18.389    17.710    16.899    16.781    15.797    18.824    18.919    18.926

ThermElec   0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
MethSynth   0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000

(TransBio)  0.000     5.422     4.984     4.397     4.400     3.398     6.601     6.869     7.147
(DistBio)   0.000     5.422     4.984     4.397     4.400     3.398     6.601     6.869     7.147

TotalLoss   0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000     0.000
=====
Final       18.706    18.389    17.710    16.899    16.781    15.797    18.824    18.919    18.926
=====
FinalNoInd  5.708     5.422     4.984     4.397     4.400     3.398     6.601     6.869     7.147
=====

```

Table 10

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Miscellaneous Primary Production

GWy

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991  -1993  -1995  -1997  -2002  -2007  -2012  2027
Mid:      (Base) (1991) (1992) (1994) (1996) (2000) (2005) (2010) (2020)
=====

```

Municipal Waste Production

```

-----
TotWaste    0.000    0.000    0.000    0.000    0.032    0.138    0.298    0.657    0.534
-----

```

Uranium Production

```

-----
Uranium     26.800    31.292    29.701    30.231    31.823    34.474    34.474    34.523    34.610
-----

```

Methanol Production

```

-----
Methanol    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
-----

```

Residential and Commercial Solar Thermal

```

-----
SolarTherm  0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
-----

```

Table 12

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Secondary to Final Energy

Traditional Liquid Fuels

GWy

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991  -1993  -1995  -1997  -2002  -2007  -2012  2027
Mid:      (Base) (1991) (1992) (1994) (1996) (2000) (2005) (2010) (2020)
=====

```

Residual/Heavy Oil

```

=====
Production  13.145  12.553  10.998  8.338  6.184  4.555  3.615  3.617  4.347
Imports     2.787  3.000  3.000  3.000  3.000  3.000  3.000  3.000  3.000
=====
Available   15.932  15.553  13.998  11.338  9.184  7.555  6.615  6.617  7.347

TmPipe      2.079  2.053  1.848  1.497  1.212  0.997  0.873  0.873  0.970
ThermElec   4.578  3.947  2.464  0.915  1.038  1.138  1.072  1.086  1.504
SteamHeat   0.098  0.000  0.145  0.037  0.046  0.189  0.000  0.000  0.000
=====
Final&NonE  9.177  9.553  9.541  8.889  6.888  5.230  4.670  4.658  4.874
=====

```

<b>NonEnergy</b>	0.580	0.591	0.612	0.636	0.664	0.719	0.811	0.914	1.162
=====									
<b>Final</b>	8.596	8.962	8.929	8.254	6.223	4.511	3.859	3.743	3.711

#### Diesel and Light Fuel Oil

=====									
<b>Production</b>	39.070	38.389	36.980	35.624	35.639	35.961	36.614	38.281	41.549
<b>Exports</b>	4.994	5.100	4.704	4.518	4.339	4.167	3.767	3.405	3.078
-----									
<b>Available</b>	34.075	33.289	32.276	31.106	31.300	31.794	32.847	34.876	38.472
<b>TmPipe</b>	0.075	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
<b>ThermElec</b>	0.383	0.000	0.000	0.000	0.189	0.203	0.207	0.212	0.253
-----									
<b>Final&amp;NonE</b>	33.618	33.289	32.276	31.106	31.111	31.591	32.640	34.665	38.219
<b>NonEnergy</b>	4.536	4.617	4.786	4.968	5.193	5.624	6.342	7.149	9.086
=====									
<b>Final</b>	29.082	28.672	27.490	26.138	25.918	25.966	26.298	27.516	29.133

#### Motor Fuel (Gasoline)

=====									
<b>Production</b>	40.490	42.023	42.120	42.452	43.148	44.961	45.732	46.148	50.470
<b>Exports</b>	3.172	4.000	2.940	2.824	2.712	2.604	2.354	2.128	1.924
-----									
<b>Available</b>	37.318	38.023	39.180	39.628	40.436	42.357	43.378	44.020	48.546
<b>TmPipe</b>	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
=====									



TotImports	53.738	54.500	55.195	52.407	47.151	42.653	35.993	31.470	27.971
Exports									
ExpElec	0.052	1.818	1.212	0.606	0.000	0.000	0.000	0.000	0.000
ExpNGasNGL	53.567	53.000	51.675	49.124	46.698	44.393	39.114	34.463	30.365
ExpCrude	46.374	46.000	42.550	36.407	31.151	26.653	19.993	15.470	11.971
ExpLtOil	4.994	5.100	4.704	4.518	4.339	4.167	3.767	3.405	3.078
ExpMFuel	3.172	4.000	2.940	2.824	2.712	2.604	2.354	2.128	1.924
ExpHCoal	29.904	30.000	28.275	26.879	25.552	24.290	21.402	18.857	16.615
TotExports	138.062	139.918	131.356	120.357	110.451	102.107	86.630	74.324	63.952

Table 15

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Emissions

CO2 Emissions and Disposal

Mt/y

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

Emissions

. Extract	25.410	27.931	27.927	28.632	29.004	29.777	29.310	29.306	32.243
. Process	44.827	42.252	38.902	37.617	37.341	37.668	37.365	37.428	39.204
. TranDist	6.612	6.631	6.690	6.793	6.858	6.987	7.001	7.127	7.867
Upstream	76.849	76.815	73.518	73.042	73.203	74.431	73.676	73.861	79.314
-----									
PowerPlant	95.283	93.731	96.467	97.720	104.873	123.252	154.232	194.513	278.470
Industry	86.983	88.689	89.485	89.560	88.142	87.713	90.767	95.089	106.635
Resident	40.652	40.184	39.764	38.399	36.142	34.437	33.885	34.254	40.701
Commerce	25.779	26.082	26.224	26.717	28.488	31.053	29.831	30.247	33.021
Transport	128.366	130.499	134.324	137.219	140.914	148.279	155.885	162.846	181.284
-----									
Total	453.911	456.000	459.781	462.657	471.763	499.165	538.276	590.808	719.425
TotalSum	453.912	456.000	459.781	462.657	471.763	499.165	538.276	590.808	719.425

## Disposal

CO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----	-------	-------	-------	-------	-------	-------	-------	-------	-------

Table 16

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Emissions

Non-CO2

kt/y

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

## CH4

. Extract	0.000	1220.287	1180.618	1153.743	1161.754	1198.647	1236.627	1276.711	1379.296
. Process	0.000	0.194	0.187	0.183	0.183	0.187	0.190	0.194	0.214
. TranDist	0.000	127.966	129.478	131.921	133.288	136.314	136.673	139.069	154.087
Other	1261.000	1348.446	1310.283	1285.847	1295.225	1335.148	1373.490	1415.974	1533.597
PowerPlant	1.000	0.957	1.005	1.108	1.239	1.611	2.254	3.079	4.554
Industry	3.000	56.755	55.781	54.829	54.216	54.239	53.582	52.992	52.181
Resident	2.000	5.345	4.970	4.452	4.399	3.526	6.125	6.352	6.709
Commerce	1.000	0.575	0.566	0.556	0.590	0.635	0.611	0.621	0.680
Transport	23.000	148.481	150.910	148.355	146.606	148.664	151.267	153.603	173.059
Total	1291.000	1560.559	1523.515	1495.146	1502.275	1543.823	1587.330	1632.620	1770.780
TotalSum	1291.000	1560.559	1523.515	1495.146	1502.275	1543.823	1587.330	1632.620	1770.780

## S02

. Extract	0.000	435.995	430.474	426.678	423.499	428.137	414.101	419.828	496.818
. Process	0.000	130.977	126.518	121.932	120.397	121.611	123.131	126.935	139.993
. TranDist	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.000	566.973	556.992	548.610	543.895	549.747	537.232	546.763	636.811
PowerPlant	0.000	794.455	815.773	680.340	689.288	724.588	743.612	782.640	947.999
Industry	0.000	175.929	174.650	167.665	144.706	130.041	131.211	143.223	168.133
Resident	0.000	45.949	42.418	37.633	33.708	25.593	24.055	24.303	24.815
Commerce	0.000	18.297	14.033	7.100	6.666	5.132	5.387	5.784	6.869
Transport	0.000	72.714	74.282	76.258	78.057	81.596	86.587	92.438	103.608
Total	0.000	1674.317	1678.148	1517.607	1496.320	1516.697	1528.084	1595.151	1888.235
TotalSum	0.000	1674.317	1678.148	1517.607	1496.320	1516.697	1528.085	1595.151	1888.235

Eastern	0.000	606.000	606.000	465.000	465.000	465.000	465.000	465.000	465.000
CO									
. Extract	0.000	33.465	33.429	34.220	34.662	35.509	35.191	35.217	38.736
. Process	0.000	129.877	125.455	120.908	119.385	120.589	122.096	125.868	138.816
. TranDist	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.000	163.342	158.883	155.128	154.047	156.098	157.288	161.085	177.553
PowerPlant	0.000	14.568	14.125	15.388	17.193	20.741	26.399	34.473	47.444
Industry	0.000	753.377	742.201	732.015	727.508	732.011	729.471	728.014	729.431
Resident	0.000	1141.628	1049.970	926.933	927.150	717.229	1386.482	1442.434	1501.946
Commerce	0.000	5.262	5.285	5.374	5.730	6.245	6.000	6.084	6.642
Transport	0.000	4846.496	4896.570	4746.289	4647.436	4676.335	4641.318	4557.067	5003.047
Total	0.000	6924.674	6867.034	6581.128	6479.064	6308.659	6946.957	6929.156	7466.062
TotalSum	0.000	6924.674	6867.034	6581.128	6479.064	6308.660	6946.957	6929.156	7466.063
NOx									
. Extract	0.000	204.150	204.031	208.993	211.699	217.230	214.667	215.014	237.022
. Process	0.000	35.441	34.234	32.993	32.578	32.906	33.318	34.347	37.880
. TranDist	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.000	239.591	238.265	241.987	244.276	250.137	247.985	249.361	274.902
PowerPlant	0.000	257.435	252.199	240.380	249.268	276.482	290.629	317.107	449.863
Industry	0.000	356.043	356.490	355.298	351.269	353.420	364.296	379.546	413.866
Resident	0.000	41.040	40.124	38.215	36.311	33.581	37.220	37.784	43.607
Commerce	0.000	23.325	23.349	23.639	25.016	26.756	25.764	26.166	28.640
Transport	0.000	658.748	667.180	665.191	664.340	679.180	707.146	736.904	830.221

Total	0.000	1576.183	1577.607	1564.709	1570.480	1619.556	1673.040	1746.869	2041.100
TotalSum	0.000	1576.183	1577.607	1564.709	1570.480	1619.556	1673.041	1746.869	2041.099

VOC

. Extract	0.000	29.075	27.771	24.969	23.630	23.047	22.149	22.787	27.707
. Process	0.000	46.668	45.079	43.445	42.898	43.330	43.872	45.227	49.880
. TranDist	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Other	0.000	75.743	72.849	68.414	66.528	66.377	66.021	68.015	77.587
PowerPlant	0.000	1.701	1.727	1.834	2.020	2.595	3.315	4.935	6.125
Industry	0.000	40.479	40.054	39.638	39.436	39.798	39.984	40.230	40.973
Resident	0.000	202.076	185.877	164.125	164.126	127.019	245.115	254.916	265.471
Commerce	0.000	1.034	1.084	1.178	1.257	1.370	1.314	1.331	1.450
Transport	0.000	593.288	602.611	592.716	587.926	598.856	604.529	605.787	670.042
Total	0.000	914.321	904.201	867.905	861.294	836.016	960.279	975.214	1061.648
TotalSum	0.000	914.321	904.201	867.905	861.294	836.016	960.279	975.214	1061.648

Table 17

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Emission Abatement

Non-CO2

kt/y

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

S02_PP1	0.000	0.750	1.545	1.545	1.545	0.000	0.000	0.000	0.000
S02_PP2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S02_PP3	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NOx_PP1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NOx_PP2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S02_Ind1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
S02_Ind2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NOx_Ind1	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 19

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Shadow Prices &amp; Reduced Costs

Emissions

Start:		1992	1994	1996	1998	2003	2008	2013	
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
DRate	0.000	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050
DiscPer1	0.000	1.050	1.050	1.050	1.050	1.050	1.050	1.050	1.050

CO2 (various units)

\$per-tCO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
\$per-GJ-WG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
\$per-b-Oil	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
\$per-t-HC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

\$/kg

NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 20

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Shadow Prices &amp; Reduced Costs

Demand Reduction Activity

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

Industry

Total1	0.000	0.000	0.000	0.000	317.386	291.019	160.665	241.760	297.220
Total2	0.000	0.000	0.000	0.000	566.988	553.113	393.238	512.013	580.760
Total3	0.000	0.000	0.000	0.000	9920.440	10641.893	10596.821	10569.063	13655.025

## Residential

ResElec_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ResElec_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ResTherm_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ResTherm_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

## Commercial

ComElec_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ComElec_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ComTherm_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ComTherm_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1086.844	0.000
ComAC_L	0.000	0.000	0.000	0.000	0.000	-10.567	-166.339	-5.576	-95.830
ComAC_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

## Freight Transport

Freight_L	0.000	0.000	0.000	0.000	25.634	24.727	23.729	21.436	20.444
Freight_H	0.000	0.000	0.000	0.000	35.534	34.627	33.628	31.336	30.344

## Passenger Transport

ICPers_L	0.000	0.000	0.000	0.000	23.342	19.154	28.987	15.405	10.774
ICPers_H	0.000	0.000	0.000	0.000	33.342	29.154	38.987	25.405	20.775

UrbPers_L	0.000	0.000	0.000	0.000	38.551	33.575	45.484	28.026	22.154
UrbPers_H	0.000	0.000	0.000	0.000	53.551	48.575	60.484	43.026	37.155

---

Table 21

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Shadow Prices &amp; Reduced Costs

Demand Reduction Investment

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991    -1993    -1995    -1997    -2002    -2007    -2012    2027
Mid:      (Base)  (1991)  (1992)  (1994)  (1996)  (2000)  (2005)  (2010)  (2020)
=====

```

## Industry

```

-----
Total1      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
Total2      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
Total3      0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
-----

```

## Residential

```

-----
ResElec_L   0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
ResElec_H   0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000

```





Uranium	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
---------	-------	-------	-------	-------	-------	-------	-------	-------	-------

---

After Extraction (MWaste takes from here)

---

HardCoal	0.000	0.000	50.000	50.000	50.000	57.208	66.005	74.810	79.158
SoftCoal	0.000	13.037	94.611	13.230	59.106	46.598	82.376	97.722	88.565
CrudeOil	0.000	109.160	124.437	152.044	160.504	167.093	182.515	206.043	222.052
Biomass	0.000	95.000	95.000	95.000	95.000	95.000	95.000	95.000	95.000
Uranium	0.000	9.900	9.900	9.900	9.900	9.900	9.900	9.900	9.900
MWaste	0.000	50.830	69.454	124.230	149.795	214.455	192.001	197.999	195.000

---

After Production, Refining, Fabrication, etc.

For Export (and Candu)

---

MGL	0.000	173.466	208.468	211.054	350.319	285.407	247.223	225.618	211.276
ResOil	0.000	116.585	136.549	166.143	175.849	181.124	196.520	222.640	243.921
LtOil	0.000	107.547	157.553	190.066	201.530	220.295	239.695	268.895	294.694
MFuel	0.000	110.350	149.123	179.700	190.359	194.497	212.626	240.284	263.886
AvGas	0.000	601.237	68.865	88.101	63.726	76.558	96.058	108.945	82.057
Coke	0.000	31.000	107.923	107.923	107.923	119.013	179.045	194.528	199.736
Uranium	0.000	17.100	17.100	17.100	17.100	17.100	17.100	17.100	17.100
Methanol	0.000	110.350	149.123	179.700	190.359	194.497	212.626	240.284	263.886
H2	0.000	0.000	0.000	105.458	126.523	127.605	174.972	326.148	361.740
H2Liq	0.000	0.000	0.000	0.000	0.000	0.000	209.798	522.316	548.571

---

After Transporting

For Power Plants, Industrial Users, Shipping, etc.

---

ResOil	0.000	16.144	64.099	117.270	135.284	228.669	246.406	276.498	301.015
--------	-------	--------	--------	---------	---------	---------	---------	---------	---------



End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

=====

**Metals (\$/kW<sub>y</sub>):**

-----

SpecElec	0.000	304.854	409.421	461.792	562.100	630.626	747.187	783.441	759.298
Thermal	0.000	280.142	391.591	221.777	254.537	251.045	324.156	347.299	351.345
Coke	0.000	61.000	137.923	137.923	137.923	149.013	209.045	224.528	229.736
Liquids	0.000	227.547	277.553	310.066	321.530	340.295	359.695	388.895	414.694

-----

**Pulp, Paper & Sawmills (\$/kW<sub>y</sub>):**

-----

SpecElec	0.000	304.854	409.421	461.792	562.100	630.626	747.187	783.441	759.298
Thermal	0.000	280.142	391.591	221.777	254.537	425.767	324.156	347.299	351.345
Liquids	0.000	227.547	277.553	310.066	321.530	340.295	359.695	388.895	414.694

-----

**Chemicals (\$/kW<sub>y</sub>):**

-----

SpecElec	0.000	304.854	409.421	461.792	562.100	630.626	747.187	783.441	759.298
Thermal	0.000	282.973	395.755	440.127	498.932	547.439	448.525	459.034	305.240
Liquids	0.000	227.547	277.553	310.066	321.530	340.295	359.695	388.895	414.694

-----

**Other Industry & Manufacturing (\$/kW<sub>y</sub>):**

-----

SpecElec	0.000	304.854	409.421	461.792	562.100	630.626	747.187	783.441	759.298
Thermal	0.000	265.514	195.723	196.956	225.036	224.240	286.468	306.805	309.740
Liquids	0.000	227.547	277.553	310.066	321.530	340.295	359.695	388.895	414.694

-----

## Forestry/Agriculture (\$/kWyr):

SpecElec	0.000	304.854	409.421	461.792	562.100	630.626	747.187	783.441	759.298
Thermal	0.000	314.884	316.815	373.063	270.027	424.261	289.211	309.660	312.510
Liquids	0.000	262.153	307.464	339.168	350.296	362.948	381.816	410.372	435.253

## Residential (\$/kWyr):

SpecElec	0.000	407.953	514.654	568.094	670.449	740.374	859.314	896.307	1082.857
Thermal	0.000	703.327	755.302	757.344	826.270	844.456	924.312	1091.007	1182.656
Duct	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

## Commercial (\$/kWyr):

SpecElec	0.000	377.953	484.654	538.094	640.450	710.374	829.314	866.308	1052.857
Thermal	0.000	772.404	429.971	481.118	433.640	432.988	492.077	654.070	717.564
VentPump	0.000	393.001	1314.962	529.454	600.428	618.492	698.298	726.604	826.429
AirCond	0.000	532.191	556.121	566.460	624.154	676.966	757.672	692.713	816.755

## Freight Transport (\$/kt-km):

RdRlFrt	0.000	38.590	39.948	40.985	41.905	42.877	43.774	46.017	47.525
SeaFrt	0.000	5.640	6.091	6.497	6.641	7.119	7.285	7.552	7.724
AirFrt	0.000	662.315	325.120	336.499	321.930	324.337	335.358	342.512	323.348

## Passenger Transport (\$/kp-km):





. GasCogen	0.000	0.000	0.000	0.372	0.531	0.944	1.630	2.262	4.062
-----									
MatGas	0.754	1.894	1.525	2.501	3.054	3.892	3.818	4.880	6.650
LOilCT	0.112	0.000	0.000	0.000	0.056	0.060	0.062	0.064	0.077
. RDCov	1.579	1.270	0.496	0.223	0.227	0.245	0.255	0.264	0.323
. ROMulti	0.000	0.000	0.083	0.000	0.000	0.000	0.000	0.000	0.000
. ROCogen	0.000	0.090	0.274	0.093	0.133	0.150	0.121	0.119	0.214
-----									
ResOil	1.579	1.360	0.853	0.316	0.359	0.395	0.375	0.383	0.537
. CoalConv	3.769	3.137	3.848	3.070	3.034	2.913	2.561	2.182	1.700
. CoalFB	0.000	0.000	0.000	0.020	0.112	0.435	1.764	2.049	2.049
. CoalIGCC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
. Coal2IGC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
. CoalMult	0.000	0.016	0.000	0.232	0.479	1.102	3.355	7.003	11.265
-----									
HardCoal	3.769	3.153	3.848	3.322	3.625	4.450	7.680	11.234	15.015
SoftCoal	5.483	5.858	6.164	6.735	7.016	8.069	9.052	10.399	16.337
Biomass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MWaste	0.000	0.000	0.000	0.000	0.008	0.030	0.071	0.131	0.132
SolarPV	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Wind	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total	53.109	55.266	55.746	56.548	58.258	61.814	66.714	73.501	85.182

Table 33

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Electric Generation: All Load Regions

Annual Capacity Additions

GW(e)

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991    -1993    -1995    -1997    -2002    -2007    -2012    2027
Mid:      (Base)  (1991)  (1992)  (1994)  (1996)  (2000)  (2005)  (2010)  (2020)
=====
. HydQue      0.000    0.504    0.586    0.000    0.000    0.000    0.000    0.000    0.000
. HydOnt      0.000    0.000    0.000    0.000    0.000    0.000    0.100    0.100    0.000
. HydBC       0.000    0.000    0.000    0.000    0.000    0.000    0.071    0.071    0.000
. HydOth      0.000    0.160    0.160    0.160    0.000    0.000    0.079    0.079    0.000
-----
Hydro         0.000    0.664    0.746    0.160    0.000    0.000    0.250    0.250    0.000
Candu        0.000    0.000    0.000    0.000    0.000    0.000    0.090    0.500    0.460
. GasConvW    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
. GasConv     0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.000
. GasCT       0.000    0.000    0.000    0.000    0.000    0.039    0.143    0.253    0.167
. GasCC       0.000    0.020    0.042    0.093    0.154    0.145    0.336    0.483    0.000
-----
NatGas       0.000    0.020    0.042    0.093    0.154    0.184    0.479    0.735    0.167
LOilCT       0.000    0.050    0.050    0.050    0.050    0.050    0.050    0.050    0.050
ROilConv     0.000    0.118    0.200    0.200    0.200    0.200    0.200    0.200    0.200
. CoalConv    0.000    0.000    0.000    0.000    0.000    0.000    0.000    0.034    0.176

```

. CoalFB	0.000	0.000	0.000	0.013	0.057	0.111	0.302	0.071	0.000
. CoalIGCC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
. Coal2IGC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
HardCoal	0.000	0.000	0.000	0.013	0.057	0.111	0.302	0.105	0.176
SoftCoal	0.000	0.281	0.315	0.388	0.276	0.345	0.388	0.518	0.679
MultiFuel	0.000	0.020	0.042	0.093	0.154	0.229	0.490	0.912	0.356
CogenMult	0.000	0.100	0.102	0.106	0.110	0.115	0.127	0.140	0.155
Biomass	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
MWaste	0.000	0.000	0.000	0.040	0.081	0.123	0.231	0.345	0.001
SolarPV	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Wind	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total	0.000	1.253	1.497	1.143	1.083	1.357	2.607	3.756	2.244

Table 48

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Total

All Demand Sectors (including Feedstocks)

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

TurboFuel	5.873	6.110	6.406	6.718	7.045	7.587	8.535	9.645	11.888
MFuelLiq	0.000	1.780	1.777	1.778	1.792	1.840	1.895	1.952	2.072
MotorFuel	37.305	36.243	37.403	37.851	38.644	40.517	41.482	42.068	46.474
(Methanol)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LH2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
Elec	48.010	48.465	49.489	50.812	52.966	56.270	60.824	67.117	77.951
NatGas	66.893	68.146	70.914	74.307	77.323	81.701	85.081	88.225	101.432
LOil/Dies	33.614	33.289	32.276	31.106	31.111	31.591	32.640	34.665	38.219
ResOil	9.177	9.553	9.541	8.889	6.888	5.230	4.670	4.658	4.874
Coal	1.664	1.767	1.891	2.087	2.324	2.660	3.564	4.827	7.226
Coke	3.398	3.378	3.337	3.305	3.299	3.342	3.368	3.400	3.485
DistCool	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DistHeat	0.000	0.000	0.512	0.816	1.128	1.941	2.783	3.687	6.200
Biomass	18.706	18.389	17.710	16.899	16.781	15.797	18.824	18.919	18.926
SolarTherm	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	224.641	227.119	231.257	234.567	239.301	248.474	263.666	279.163	318.801

Table 51

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Metals

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Elec	5.010	4.919	4.758	4.584	4.598	4.688	4.771	4.855	5.028
Gas	2.521	2.553	2.628	2.838	3.089	3.227	3.033	2.812	2.540
Residual	0.877	0.904	0.933	0.823	0.444	0.235	0.232	0.229	0.225
Coal	0.398	0.422	0.436	0.472	0.516	0.571	0.720	0.908	1.138
Coke	3.107	3.081	3.030	2.985	2.965	2.980	2.960	2.940	2.901
Liq(Dies)	0.059	0.059	0.059	0.059	0.059	0.061	0.063	0.064	0.068
Total	11.972	11.938	11.843	11.762	11.672	11.762	11.779	11.809	11.900

Table 52

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Pulp, Paper and Sawmills

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Elec	5.299	5.145	4.900	4.791	4.806	4.901	4.989	5.078	5.262
Gas	3.224	3.280	3.377	3.646	3.969	4.372	4.878	4.710	4.500
Residual	2.612	2.680	2.765	2.458	1.998	1.518	0.748	0.740	0.726
Coal	0.131	0.146	0.176	0.190	0.208	0.230	0.290	0.366	0.459
Biomass	11.667	11.601	11.396	11.207	11.110	11.143	11.012	10.884	10.684

Liq(Dies)	0.334	0.330	0.330	0.330	0.333	0.341	0.352	0.362	0.384
-----									
Total	23.266	23.183	22.944	22.623	22.423	22.505	22.269	22.140	22.015

Table 53

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Chemicals

GWy

=====									
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
Elec	2.071	2.089	2.143	2.180	2.231	2.364	2.519	2.840	3.610
Gas	4.570	4.663	4.841	5.046	5.296	5.759	6.558	7.467	9.566
Residual	0.281	0.318	0.332	0.351	0.374	0.412	0.481	0.311	0.122
Liq(Dies)	0.011	0.011	0.011	0.011	0.011	0.011	0.012	0.012	0.013
-----									
Total	6.934	7.080	7.328	7.588	7.913	8.547	9.570	10.630	13.311

Table 54

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Other Industry and Manufacturing

GWy

	=====								
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
Elec	7.463	7.451	7.555	7.892	8.354	9.282	10.694	12.252	15.737
Gas	15.450	15.808	16.285	16.407	17.247	17.196	17.246	17.209	18.395
LtOil	0.414	0.400	0.109	0.113	0.118	0.127	0.143	0.160	0.202
Residual	2.208	2.423	2.308	2.094	0.948	0.266	0.299	0.335	0.424
Coal	0.871	0.934	1.015	1.160	1.334	1.589	2.275	3.258	5.258
DistHeat	0.000	0.000	0.512	0.816	1.128	1.941	2.609	3.419	5.671
Liq(Dies)	2.680	2.678	2.674	2.675	2.697	2.769	2.852	2.938	3.118
-----									
Total	29.085	29.695	30.458	31.157	31.825	33.171	36.117	39.571	48.805

Table 55

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Forestry and Agriculture

GWy

	=====								
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
Elec	1.099	1.024	0.975	0.952	0.938	0.932	0.907	0.883	0.836
Gas	0.964	0.974	0.995	1.065	1.150	1.252	1.268	1.216	1.135
LtOil	0.387	0.375	0.326	0.185	0.059	0.150	0.057	0.055	0.052

Residual	0.282	0.300	0.307	0.306	0.287	0.031	0.030	0.029	0.027
Biomass	1.332	1.367	1.330	1.295	1.271	1.257	1.211	1.167	1.094
Liq(Dies)	2.484	2.479	2.475	2.476	2.496	2.563	2.640	2.719	2.885
Liq(MF)	1.778	1.780	1.777	1.778	1.792	1.840	1.895	1.952	2.072
-----									
Total	8.326	8.298	8.184	8.057	7.993	8.023	8.007	8.021	8.101

Table 56

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Feedstocks

GWy

=====									
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
NatGas	9.135	9.298	9.639	10.005	10.458	11.327	12.772	14.397	18.299
LOil/Waph	4.536	4.617	4.786	4.968	5.193	5.624	6.342	7.149	9.086
Coal	0.185	0.189	0.196	0.203	0.212	0.230	0.259	0.292	0.372
ResOil	0.580	0.591	0.612	0.636	0.664	0.719	0.811	0.914	1.162
Coke	0.291	0.297	0.308	0.319	0.334	0.362	0.408	0.460	0.584
-----									
TotalSum	14.728	14.992	15.542	16.132	16.862	18.262	20.592	23.212	29.503
Total	14.728	14.992	15.542	16.132	16.862	18.262	20.592	23.212	29.503

Table 57

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Industry

Specific Liquids (Overall)

GWy

			1992	1994	1996	1998	2003	2008	2013
Start:									
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Metals	0.059	0.059	0.059	0.059	0.059	0.061	0.063	0.064	0.068
PulpPaper	0.334	0.330	0.330	0.330	0.333	0.341	0.352	0.362	0.384
Chemicals	0.011	0.011	0.011	0.011	0.011	0.011	0.012	0.012	0.013
OtherInd	2.680	2.678	2.674	2.675	2.697	2.769	2.852	2.938	3.118
ForestryAg	4.262	4.259	4.252	4.253	4.288	4.402	4.535	4.672	4.957
TotalSum	7.346	7.337	7.325	7.328	7.387	7.585	7.813	8.048	8.541
Total	7.346	7.337	7.325	7.328	7.387	7.585	7.813	8.048	8.541

Table 59

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Residential

By Currency

GWy

			1992	1994	1996	1998	2003	2008	2013
Start:									

End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Elec	14.850	15.353	16.232	17.463	18.764	20.520	20.869	22.463	22.223
NGas	17.151	17.360	17.761	17.787	17.237	17.676	18.802	19.068	23.256
LtOil	5.830	5.515	5.069	4.472	3.879	2.862	1.886	1.886	1.839
ROil	0.049	0.044	0.041	0.036	0.031	0.023	0.015	0.015	0.015
Coal	0.079	0.075	0.069	0.061	0.053	0.039	0.019	0.002	0.000
Biomass	5.708	5.422	4.984	4.397	4.400	3.398	6.601	6.869	7.147
DHeat	0.000	0.000	0.000	0.000	0.000	0.000	0.079	0.127	0.251
Solar	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	43.618	43.724	44.114	44.179	44.333	44.495	48.256	50.415	54.716

Table 60

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Residential

By Technology

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Elec	5.233	5.474	5.802	6.463	7.174	7.990	6.679	6.393	2.113
Elec_HP	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gas_L	17.151	17.360	17.761	17.787	17.237	17.676	18.802	19.068	21.703

Gas_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gas_HP	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.552
. LOilLOil	5.830	5.515	5.069	4.472	3.879	2.862	1.886	1.886	1.839
. LOilRes	0.049	0.044	0.041	0.036	0.031	0.023	0.015	0.015	0.015
LtOil_L	5.879	5.559	5.110	4.508	3.911	2.885	1.901	1.901	1.854
LtOil_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Coal	0.079	0.075	0.069	0.061	0.053	0.039	0.019	0.002	0.000
DistHeat	0.000	0.000	0.000	0.000	0.000	0.000	0.079	0.127	0.251
Biomass	5.708	5.422	4.984	4.397	4.400	3.398	6.601	6.869	7.147
Solar	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total_Th	34.050	33.889	33.725	33.215	32.774	31.988	34.081	34.360	34.621
=====									
DuctPipe	13.546	13.499	13.493	13.231	12.696	12.401	12.974	13.362	16.972
=====									
SpecElec	9.617	9.880	10.430	11.000	11.590	12.530	14.190	16.070	20.110
=====									
TotalElec	14.850	15.353	16.232	17.463	18.764	20.520	20.869	22.463	22.223
=====									

Table 62

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Commercial

By Currency

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Elec	12.120	12.379	12.811	12.826	13.148	13.448	15.841	18.426	24.737
NGas	12.971	13.289	14.340	16.235	17.434	19.264	18.427	18.629	20.242
LtOil	1.982	1.881	1.260	0.229	0.225	0.241	0.265	0.291	0.358
ROil	0.380	0.394	0.363	0.321	0.279	0.133	0.148	0.164	0.204
DHeat	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.141	0.279
DCool	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Solar	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	27.454	27.943	28.774	29.611	31.086	33.086	34.776	37.651	45.820

Table 63

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Commercial

By Technology

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Elec	0.874	0.885	0.818	0.355	0.138	0.149	0.166	0.186	0.232
Elec_HP	0.317	0.329	0.354	0.400	0.379	0.342	0.743	1.033	1.605

Gas_L	12.971	13.289	14.340	16.235	17.434	19.264	18.427	18.629	20.242
Gas_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gas_HP	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LtOil_L	1.982	1.881	1.260	0.229	0.225	0.241	0.265	0.291	0.358
LtOil_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Residual	0.380	0.394	0.363	0.321	0.279	0.133	0.148	0.164	0.204
DistHeat	0.000	0.000	0.000	0.000	0.000	0.000	0.095	0.141	0.279
Solar	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total(Th)	16.524	16.778	17.136	17.539	18.455	20.129	19.844	20.444	22.919
=====									
SpecElec	8.068	8.246	8.613	9.016	9.520	10.490	12.150	14.070	18.860
=====									
Vent_L	2.276	2.318	2.402	2.246	2.090	0.000	0.000	0.000	0.000
Vent_H	0.000	0.000	0.000	0.164	0.344	1.875	2.110	2.373	3.049
-----									
Total(Vnt)	2.276	2.318	2.402	2.410	2.434	1.875	2.110	2.373	3.049
=====									
AirCond_L	0.585	0.601	0.623	0.646	0.677	0.591	0.672	0.764	0.991
AirCond_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DistCool	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total(AC)	0.585	0.601	0.623	0.646	0.677	0.591	0.672	0.764	0.991
=====									
TotalElec	11.804	12.050	12.457	12.427	12.769	13.105	15.098	17.393	23.132
=====									

Table 65

CANADA: C02 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Transport

Freight

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
RFrt_MFuel	1.816	1.810	1.818	1.844	1.905	2.006	2.159	2.233	2.238
RFrt_Dies	10.705	10.677	10.734	10.942	11.261	11.807	12.615	13.164	13.553
RFrt_MGas	0.190	0.190	0.210	0.255	0.301	0.336	0.407	0.502	0.634
RFrt_LH2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
RoadRailFr	12.710	12.677	12.761	13.041	13.467	14.149	15.181	15.899	16.478
SFrt_Dies	1.495	1.488	1.475	1.461	1.460	1.483	1.494	1.505	1.543
SFrt_ROil	1.907	1.898	1.881	1.864	1.862	1.892	1.906	1.920	1.968
MarineFrt	3.403	3.385	3.355	3.325	3.322	3.375	3.401	3.425	3.510
AirFrt	1.144	1.171	1.209	1.238	1.279	1.381	1.516	1.661	2.108
TotalFrt	17.257	17.233	17.326	17.604	18.068	18.905	20.097	20.986	22.096

Table 66

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Transport

InterCity Persons

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
IC_MFuel	10.072	10.235	10.557	10.689	10.788	11.138	11.214	11.086	11.502
IC_Diesel	1.151	1.170	1.202	1.208	1.211	1.245	1.231	1.178	1.155
IC_AFuel	4.729	4.939	5.196	5.480	5.765	6.206	7.019	7.984	9.781
IC_MGas	0.220	0.224	0.231	0.234	0.237	0.246	0.254	0.261	0.283
ICPass	16.173	16.567	17.186	17.611	18.002	18.835	19.718	20.509	22.721

Table 67

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Transport

Urban/IntraCity Persons

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Urb_MFuel	23.640	24.198	25.028	25.318	25.951	27.373	28.109	28.749	32.734
Urb_Diesel	1.546	1.610	1.767	1.978	2.111	2.307	2.690	3.181	3.962

Urb_NGas	0.496	0.507	0.607	0.789	0.904	1.046	1.437	1.954	2.584
Urb_Elec	0.099	0.106	0.115	0.123	0.127	0.135	0.234	0.320	0.518
Urb_LH2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
UrbanPass	25.781	26.422	27.518	28.208	29.093	30.861	32.470	34.203	39.798

Table 68

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Final Energy: Transport

Total

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
MotorFuel	35.528	36.243	37.403	37.851	38.644	40.517	41.482	42.068	46.474
Diesel	14.897	14.944	15.177	15.589	16.043	16.842	18.030	19.028	20.213
ROil	1.907	1.898	1.881	1.864	1.862	1.892	1.906	1.920	1.968
AvFuel	5.873	6.110	6.406	6.718	7.045	7.587	8.535	9.645	11.888
NGas	0.906	0.921	1.048	1.278	1.442	1.628	2.098	2.717	3.501
Elec	0.099	0.106	0.115	0.123	0.127	0.135	0.234	0.320	0.518
LH2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.054
-----									
Total	59.210	60.222	62.030	63.422	65.163	68.600	72.285	75.697	84.615
=====									

Table 71

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Metals

GWy

			1992	1994	1996	1998	2003	2008	2013
Start:									
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
SpecElec	4.509	4.493	4.463	4.442	4.457	4.547	4.630	4.715	4.890
Thermal	2.662	2.639	2.596	2.557	2.540	2.553	2.536	2.519	2.485
SpecCoke	3.107	3.081	3.030	2.985	2.965	2.980	2.960	2.940	2.901
SpecLiq	0.059	0.059	0.059	0.059	0.059	0.061	0.063	0.064	0.068
SpecElec	0.000	4.493	4.463	4.442	4.457	4.547	4.630	4.715	4.890
ThermElec	0.000	0.383	0.265	0.128	0.127	0.128	0.127	0.126	0.124
Gas	0.000	1.557	1.608	1.747	1.913	2.010	1.918	1.805	1.655
Residual	0.000	0.488	0.504	0.446	0.241	0.128	0.127	0.126	0.124
Coal	0.000	0.211	0.218	0.237	0.259	0.287	0.364	0.462	0.582
Coke	0.000	3.081	3.030	2.985	2.965	2.980	2.960	2.940	2.901
Liq(Dies)	0.000	0.059	0.059	0.059	0.059	0.061	0.063	0.064	0.068
Conserv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 72

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Pulp, Paper and Sawmills

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
SpecElec	4.769	4.753	4.721	4.699	4.715	4.809	4.898	4.988	5.173
Thermal	8.586	8.514	8.373	8.250	8.195	8.235	8.180	8.125	8.016
SpecLiq	0.334	0.330	0.330	0.330	0.333	0.341	0.352	0.362	0.384
SpecElec	0.000	4.753	4.721	4.699	4.715	4.809	4.898	4.988	5.173
ThermElec	0.000	0.352	0.161	0.083	0.082	0.082	0.082	0.081	0.080
Gas	0.000	2.001	2.066	2.244	2.458	2.723	3.084	3.023	2.932
Residual	0.000	1.447	1.495	1.331	1.084	0.826	0.409	0.406	0.401
Coal	0.000	0.073	0.088	0.096	0.105	0.116	0.147	0.186	0.234
Biomass	0.000	4.640	4.563	4.496	4.466	4.488	4.458	4.428	4.369
Liq(Dies)	0.000	0.330	0.330	0.330	0.333	0.341	0.352	0.362	0.384
Conserv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 73

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Chemicals

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
SpecElec	1.760	1.792	1.857	1.928	2.016	2.183	2.461	2.775	3.526
Thermal	3.747	3.815	3.953	4.104	4.291	4.647	5.239	5.906	7.506
SpecLiq	0.011	0.011	0.011	0.011	0.011	0.011	0.012	0.012	0.013
SpecElec	0.000	1.792	1.857	1.928	2.016	2.183	2.461	2.775	3.526
ThermElec	0.000	0.267	0.257	0.227	0.194	0.163	0.052	0.059	0.075
Gas	0.000	3.357	3.496	3.666	3.871	4.235	4.895	5.657	7.356
Residual	0.000	0.191	0.200	0.211	0.225	0.249	0.292	0.190	0.075
Liq(Dies)	0.000	0.011	0.011	0.011	0.011	0.011	0.012	0.012	0.013
Conserv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SpecFeed	0.000	14.990	15.540	16.130	16.860	18.260	20.590	23.210	29.500

Table 74

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Other Industry and Manufacturing

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
SpecElec	7.090	7.217	7.479	7.764	8.117	8.792	9.911	11.170	14.200

Thermal	13.630	13.880	14.380	14.930	15.610	16.900	19.050	21.480	27.300
SpecLiq	2.680	2.678	2.674	2.675	2.697	2.769	2.852	2.938	3.118
-----									
SpecElec	0.000	7.217	7.479	7.764	8.117	8.792	9.911	11.170	14.200
ThermElec	0.000	0.222	0.072	0.224	0.546	1.307	2.191	3.115	4.505
Gas	0.000	11.382	11.760	11.920	12.605	12.644	12.872	13.038	14.147
LtOil	0.000	0.264	0.072	0.075	0.078	0.085	0.095	0.107	0.137
Residual	0.000	1.527	1.456	1.323	0.600	0.169	0.191	0.215	0.273
Coal	0.000	0.486	0.528	0.605	0.697	0.832	1.197	1.723	2.795
DistHeat	0.000	0.000	0.492	0.784	1.083	1.863	2.505	3.282	5.444
Liq(Dies)	0.000	2.678	2.674	2.675	2.697	2.769	2.852	2.938	3.118
Conserv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 75

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Forestry and Agriculture

GWy

=====									
Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
SpecElec	0.989	0.977	0.953	0.931	0.917	0.911	0.886	0.863	0.817
Thermal	1.821	1.798	1.754	1.714	1.689	1.677	1.632	1.588	1.505
SpecLiq	4.262	4.259	4.252	4.253	4.288	4.402	4.535	4.672	4.957
-----									
SpecElec	0.000	0.977	0.953	0.931	0.917	0.911	0.886	0.863	0.817

ThermElec	0.000	0.038	0.018	0.017	0.017	0.017	0.016	0.016	0.015
Gas	0.000	0.701	0.718	0.774	0.841	0.920	0.947	0.921	0.873
LtOil	0.000	0.214	0.186	0.106	0.034	0.086	0.033	0.032	0.030
Residual	0.000	0.162	0.166	0.166	0.156	0.017	0.016	0.016	0.015
Biomass	0.000	0.683	0.666	0.651	0.642	0.637	0.620	0.604	0.572
Liq(Dies)	0.000	2.479	2.475	2.476	2.496	2.563	2.640	2.719	2.885
Liq(MF)	0.000	1.780	1.777	1.778	1.792	1.840	1.895	1.952	2.072
Conserv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 76

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Feedstocks

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
MatGas	0.000	9.297	9.639	10.004	10.457	11.326	12.771	14.396	18.297
LOil/Waph	0.000	4.616	4.786	4.968	5.192	5.624	6.341	7.148	9.085
Coal	0.000	0.189	0.196	0.203	0.212	0.230	0.259	0.292	0.372
ResOil	0.000	0.591	0.612	0.635	0.664	0.719	0.811	0.914	1.162
Coke	0.000	0.297	0.308	0.319	0.334	0.362	0.408	0.460	0.584
TotalSum	14.728	14.990	15.540	16.130	16.860	18.260	20.590	23.210	29.500
Total	14.728	14.990	15.540	16.130	16.860	18.260	20.590	23.210	29.500

Table 77

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Industrial

Specific Liquids (Overall)

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Metals	0.000	0.059	0.059	0.059	0.059	0.061	0.063	0.064	0.068
PulpPaper	0.000	0.330	0.330	0.330	0.333	0.342	0.352	0.362	0.385
Chemicals	0.000	0.011	0.011	0.011	0.011	0.011	0.012	0.012	0.013
OtherInd	0.000	2.679	2.675	2.676	2.698	2.770	2.853	2.939	3.119
ForestryAg	0.000	4.260	4.254	4.255	4.289	4.404	4.537	4.673	4.959
Conserv	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
TotalSum	7.346	7.340	7.328	7.331	7.390	7.588	7.816	8.052	8.544
Total	7.346	7.340	7.328	7.331	7.390	7.588	7.816	8.052	8.544

Table 79

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Residential

By Technology



CnsrvEl_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total_Elec	9.617	9.880	10.430	11.000	11.590	12.530	14.190	16.070	20.110
=====									

Table 81

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Commercial

By Technology

GWy

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
=====									
Elec	0.874	0.876	0.810	0.351	0.137	0.148	0.165	0.184	0.230
Elec_HP	1.425	1.481	1.603	1.825	1.749	1.594	3.549	5.061	8.060
Gas_L	8.431	8.638	9.349	10.648	11.503	12.787	12.416	12.741	14.053
Gas_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Gas_HP	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LtOil_L	1.189	1.129	0.758	0.139	0.137	0.147	0.165	0.184	0.230
LtOil_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Residual	0.228	0.217	0.200	0.177	0.154	0.074	0.082	0.092	0.115
DistHeat	0.000	0.000	0.000	0.000	0.000	0.000	0.093	0.138	0.273

Solar	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CnsrvTh_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CnsrvTh_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total(Th)	12.148	12.340	12.720	13.140	13.680	14.750	16.470	18.400	22.960
=====									
SpecElec	8.068	8.246	8.613	9.016	9.520	10.490	12.150	14.070	18.860
CnsrvEl_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CnsrvEl_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total(El)	8.068	8.246	8.613	9.016	9.520	10.490	12.150	14.070	18.860
=====									
Vent_L	2.276	2.318	2.405	2.253	2.101	0.000	0.000	0.000	0.000
Vent_H	0.000	0.000	0.000	0.248	0.524	2.872	3.280	3.746	4.885
-----									
Total(Vnt)	2.276	2.318	2.405	2.500	2.624	2.872	3.280	3.746	4.885
=====									
AirCond_L	1.888	1.923	1.995	2.074	2.177	1.906	2.177	2.486	3.242
AirCond_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DistCool	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CnsrvAC_L	0.000	0.000	0.000	0.000	0.000	0.476	0.544	0.621	0.810
CnsrvAC_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Total(AC)	1.888	1.923	1.995	2.074	2.177	2.382	2.721	3.107	4.052
=====									

Table 83

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Transport

Freight (gigatonne-km)

Gt-km

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991    -1993    -1995    -1997    -2002    -2007    -2012    2027
Mid:      (Base)  (1991)  (1992)  (1994)  (1996)  (2000)  (2005)  (2010)  (2020)
=====
Trk_TotalL  169.864  169.306  166.639  162.368  161.110  162.885  160.639  154.999  146.397
Trk_MFH     0.000   0.000   0.000   0.000   0.000   0.000   0.149   0.377   0.757
Trk_DiesH   0.000   0.000   1.500   4.893   6.659   8.219   13.480  22.109  36.928
Trk_MGH     0.000   0.000   0.038   0.124   0.169   0.208   0.193   0.184   0.179

Rail_DiesL  248.371  247.524  243.473  238.362  236.300  236.938  228.099  215.532  192.352
Rail_DiesH   0.000   0.000   1.200   2.563   2.563   5.300   13.480  22.109  35.203
Rail_LH2     0.000   0.000   0.000   0.000   0.000   0.000   0.000   0.000   6.631

-----
RoadRail    418.235  416.830  412.850  408.310  406.801  413.551  416.040  415.311  418.447

Mar_TotalL  373.190  371.940  367.650  362.826  362.988  369.007  371.232  370.581  371.840
Mar_TotalH   0.000   0.000   1.800   4.894   5.942   7.334   12.028  19.728  32.951

-----
Marine      373.190  371.940  369.450  367.721  368.930  376.341  383.260  390.309  404.791

AirL        1.810   1.850   1.925   2.000   2.101   2.309   2.641   2.997   3.925
AirH        0.000   0.000   0.007   0.023   0.034   0.046   0.086   0.160   0.306

-----
Air         1.810   1.850   1.932   2.023   2.136   2.355   2.726   3.156   4.231

```

ConsL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ConsH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Conserve	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
=====									
Total	793.236	790.620	784.232	778.054	777.866	792.246	802.026	808.776	827.469

Table 84

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Transport

Inter-City (gigaperson-km)

Gp-km

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)

Car_TotalL	165.849	168.570	174.958	179.225	183.391	192.380	200.597	203.097	211.138
Car_MFH	0.000	0.000	0.890	2.978	4.674	6.055	10.846	19.428	37.399
Car_DiesH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Car_NGH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

CarLtTrk	165.849	168.570	175.848	182.203	188.065	198.435	211.443	222.525	248.537
----------	---------	---------	---------	---------	---------	---------	---------	---------	---------

Srf_TotalL	5.034	5.124	5.273	5.299	5.271	5.334	4.824	3.652	2.626
Srf_DiesH	0.000	0.000	0.036	0.120	0.223	0.349	0.801	1.556	2.113
Srf_NGH	0.000	0.000	0.036	0.120	0.223	0.349	0.801	1.556	2.815

BusTrain	5.034	5.124	5.345	5.538	5.716	6.031	6.427	6.764	7.554
AirL	74.827	78.036	82.727	88.574	94.557	103.268	120.717	141.115	177.276
AirH	0.000	0.000	0.300	1.004	1.882	2.975	6.994	13.966	26.062
Air	74.827	78.036	83.027	89.578	96.439	106.244	127.710	155.081	203.338
Consl	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Consh	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Conserve	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Total	245.710	251.730	264.220	277.319	290.220	310.710	345.580	384.370	459.430

Table 85

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Useful Energy: Transport

Urban (gigaperson-km)

Gp-km

Start:			1992	1994	1996	1998	2003	2008	2013
End:	1990	1991	-1993	-1995	-1997	-2002	-2007	-2012	2027
Mid:	(Base)	(1991)	(1992)	(1994)	(1996)	(2000)	(2005)	(2010)	(2020)
Car_Totall	190.946	195.527	203.508	208.528	217.360	233.217	248.960	263.616	312.454
Car_MFH	0.000	0.000	1.000	3.092	4.263	5.603	10.285	17.437	25.943

Car_DiesH	0.000	0.000	1.000	3.092	4.263	5.603	10.285	17.437	25.943
Car_MGH	0.000	0.000	1.000	3.071	4.263	5.603	10.285	16.846	24.273
Car_Elec	0.000	0.000	0.000	0.000	0.000	0.000	5.142	9.439	19.083
-----									
CarLtTrk	190.946	195.527	206.508	217.783	230.148	250.026	284.956	324.774	407.697
-----									
Pub_TotalL	22.141	27.423	29.792	31.940	33.035	35.224	38.327	41.918	51.700
Pub_DiesH	0.000	0.000	0.000	0.424	0.867	1.330	2.576	3.966	5.515
Pub_MGH	0.000	0.000	0.000	0.303	0.620	0.950	1.840	2.833	3.939
Pub_ElecH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pub_LH2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
BusMetro	22.141	27.423	29.792	32.667	34.522	37.504	42.743	48.716	61.154
-----									
Conservation									
-----									
ConsL	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ConsH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-----									
Conserve	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
=====									
Total	213.087	222.950	236.300	250.450	264.670	287.530	327.700	373.490	468.851
=====									

Table 87

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Price Induced Technology

Demand Reductions

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991    -1993    -1995    -1997    -2002    -2007    -2012    2027
Mid:      (Base)  (1991)  (1992)  (1994)  (1996)  (2000)  (2005)  (2010)  (2020)
=====

```

Industry (GWy)

```

=====
TotalInd1  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
TotalInd2  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
TotalInd3  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
=====

```

Residential (GWy):

```

=====
ResElec_L  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
ResElec_H  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000

ResTherm_L 0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
ResTherm_H 0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
=====

```

Commercial (GWy):

```

=====
ComElec_L  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
ComElec_H  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000

ComTherm_L 0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
ComTherm_H 0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000  0.000
=====

```

ComAC_L	0.000	0.000	0.000	0.000	0.000	0.476	0.544	0.621	0.810
ComAC_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

=====

Freight Transport (Gt-km):

=====

RdRlFrt_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
RdRlFrt_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SeaFrt_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SeaFrt_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AirFrt_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
AirFrt_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

=====

Passenger Transport (Gp-km):

=====

ICPers_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ICPers_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
UrbPers_L	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
UrbPers_H	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

=====

(shadow prices for demand reduction are given with the other Shadow Prices)

Table 88

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Energy Capital Investment

(Including Demand Reduction)

\$

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991  -1993  -1995  -1997  -2002  -2007  -2012  2027
Mid:      (Base) (1991) (1992) (1994) (1996) (2000) (2005) (2010) (2020)
=====
Residence  0.000 1392.847  921.099  921.094  708.838  716.673  1874.104  1561.682  1514.951
Commercial 0.000  721.380  686.056 1095.517  848.606 1033.923  1101.269  1373.400  1044.673
=====

```

Table 99

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

Objective Function

Overall and Components

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991  -1993  -1995  -1997  -2002  -2007  -2012  2027
Mid:      (Base) (1991) (1992) (1994) (1996) (2000) (2005) (2010) (2020)
=====
DRate      1.050    1.050    1.050    1.050    1.050    1.050    1.050    1.050    1.050
Disc2Strt  0.000    1.000    0.952    0.864    0.784    0.711    0.557    0.436    0.342
Disc2Mid   0.000    0.976    0.907    0.823    0.746    0.629    0.493    0.386    0.237
=====

```

## Objective Function Values

(and fractions for end and middle of each period)

```

-----
ThisObjFn  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316
EndFracObj    0.000    60.295   180.884   301.473   422.062   723.534  1025.007  1326.480  2230.898
MidFracObj  -30.147    30.147   120.589   241.178   361.767   572.798   874.271  1175.743  1778.689

```

Table100

CANADA: CO2 Model

MESSAGE II

Base Case -----

Date: 01Oct93 02:06:18

CO2 Emissions

Shadow Prices and Abatement

Mt/y

```

=====
Start:                1992    1994    1996    1998    2003    2008    2013
End:      1990    1991   -1993   -1995   -1997   -2002   -2007   -2012   2027
Mid:      (Base)  (1991) (1992) (1994) (1996) (2000) (2005) (2010) (2020)
=====

```

(time = 0 is the start of first modelled period; ignore base period)

```

CurPLen    1.000    1.000    2.000    2.000    2.000    5.000    5.000    5.000   15.000
Years2End   0.000    1.000    3.000    5.000    7.000   12.000   17.000   22.000   37.000
Years2Strt  -1.000    0.000    1.000    3.000    5.000    7.000   12.000   17.000   22.000
Years2Mid   -0.500    0.500    2.000    4.000    6.000    9.500   14.500   19.500   29.500
DRate       1.050    1.050    1.050    1.050    1.050    1.050    1.050    1.050    1.050
Disc2Strt   0.000    1.000    0.952    0.864    0.784    0.711    0.557    0.436    0.342
Disc2Mid    0.000    0.976    0.907    0.823    0.746    0.629    0.493    0.386    0.237
=====

```

CO2 Shadow Price (various units)

-----

\$per-tCO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
\$per-GJ-WG	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
\$per-b-Oil	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
\$per-t-HC	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

CO2 Shadow Price (annual value, discounted back to 1990)

-----

\$per-t-dis	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
-------------	-------	-------	-------	-------	-------	-------	-------	-------	-------

Other Emission Shadow Prices (\$/kg)

-----

NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SO2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Specified CO2 Tax (\$/t)

-----

CO2TaxRate	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
------------	-------	-------	-------	-------	-------	-------	-------	-------	-------

=====  
Emission Abatement  
=====

Base Case Values (from .fil file)

undiscounted

-----

BaseCO2	0.000	455.500	459.200	462.100	471.300	499.300	538.700	591.300	720.200
CumBCO2	0.000	455.500	1373.900	2298.100	3240.700	5737.200	8430.700	11387.200	22190.199

discounted back to 1990

-----

DiscBC02	0.000	444.522	416.508	380.171	351.691	314.096	265.523	228.358	170.753
CumDBC02	0.000	444.522	1277.539	2037.881	2741.262	4311.745	5639.358	6781.150	9342.451

=====

**This Case Values**

undiscounted

TotalC02	0.000	456.000	459.781	462.657	471.763	499.165	538.276	590.808	719.425
CumTC02	0.000	456.000	1375.562	2300.876	3244.402	5740.227	8431.605	11385.648	22177.023

discounted back to 1990

DiscTC02	0.000	445.010	417.036	380.629	352.036	314.011	265.314	228.169	170.570
CumTDC02	0.000	445.010	1279.081	2040.339	2744.412	4314.469	5641.038	6781.880	9340.425

=====

**Abatement (Base Case - This Model)**

undiscounted

DeltaC02	0.000	-0.500	-0.581	-0.557	-0.463	0.135	0.424	0.492	0.775
CumDC02	0.000	-0.500	-1.662	-2.777	-3.703	-3.027	-0.906	1.552	13.178

discounted back to 1990

DiscDC02	0.000	-0.488	-0.527	-0.458	-0.346	0.085	0.209	0.190	0.184
CumDDC02	0.000	-0.488	-1.542	-2.459	-3.150	-2.725	-1.679	-0.730	2.026

=====

**Objective Function Values**

(and fractions for end and middle of each period)

Base Case

```

-----
BaseObjFn  3135.539  3135.539  3135.539  3135.539  3135.539  3135.539  3135.539  3135.539  3135.539  3135.539
EndFracObj  0.000    60.299  180.896  301.494  422.092  723.586  1025.080  1326.574  2231.057
MidFracObj -30.149   30.149  120.598  241.195  361.793  572.839  874.333  1175.827  1778.815

```

This Case

```

-----
ThisObjFn  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316  3135.316
EndFracObj  0.000    60.295  180.884  301.473  422.062  723.534  1025.007  1326.480  2230.898
MidFracObj -30.147   30.147  120.589  241.178  361.767  572.798  874.271  1175.743  1778.689

```

Net Cost (This Case - Base Case)

```

-----
DeltaObjFn  -0.223   -0.223   -0.223   -0.223   -0.223   -0.223   -0.223   -0.223   -0.223   -0.223
EndFracObj  0.000   -0.004   -0.013   -0.021   -0.030   -0.051   -0.073   -0.094   -0.159
MidFracObj  0.002   -0.002   -0.009   -0.017   -0.026   -0.041   -0.062   -0.084   -0.127

```

```

=====
:end of file

```

## VITA

Surname: Wells Given Names: John David

Place of Birth: Toronto, Ontario Date of Birth: 58/04/13

### Educational Institutions Attended:

University of Victoria	1991 to 1993
University of Waterloo	1976 to 1982

### Degrees Awarded:

B.A.Sc.	University of Waterloo	1982
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### Publications:

1. Wells, J. D. & Scott, D. S. (In Press). Fuel cells for telephone networks, *International Journal of Hydrogen Energy*.
2. Wells, J. D. & Scott, D. S. (1992). Fuel cells for telephone networks, in T. N. Veziroglu, C. Derive & J. Pottier (eds), *Hydrogen Energy Progress IX: Proceedings of the Ninth World Hydrogen Energy Conference, held 22-25 July 1992 in Paris, France*, Societe des Ingenieurs et Scientifiques de France, Paris, France, pp. 1531-1537.
3. Gifford, R. D. & Wells, J. D. (1991). FISH: A commons dilemma situation., *Behavior Research Methods, Instruments, & Computers* **23**: 437-441.
4. Verburg, G., Sim, J., Field, D., Balfour, L., Bowles, J. & Wells, J. D. (1986). Towards improved accessibility of the icon educational microcomputer, in M. Donath, H. Friedman & M. Carlson (eds), *Proceedings of the Ninth Annual Conference on Rehabilitation Technology*, RESNA - Association for the Advancement of Rehabilitation Technology, Minneapolis, MN, pp. 439-441.
5. Wells, J. D. (1984). Automated ultrasonic testing system for the characterization of defects in weldments, Paper presented at the Fifth Canadian Conference on Non-destructive Testing, Toronto, Ontario.

