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Carbon dioxide emissions and fossil fuel consumption a Canadian perspective

John Peter Doucet
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CARBON DIOXIDE EMISSIONS AND FOSSIL FUEL CONSUMPTION:

A CANADIAN PERSPECTIVE

By

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B.A., University of Toronto, 1985

THESIS

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ABSTRACT

The potential climate change due to increased loading of carbon dioxide in the atmosphere has emerged as one of the most significant environmental threats of the late twentieth century. An analysis of a variety of feasible energy demand scenarios for Canada indicates that if we continue to consume the same types and proportions of fuels as we do today, the expected demand for energy in the year 2005 would yield carbon dioxide emissions up to 52.5 per cent greater than that of 1985. On the other hand, if Canada were to alter the types and quantities of fuels required to meet its energy needs by adopting a variety of non-fossil fuels and by using all energy more efficiently, Canada's output of carbon dioxide from energy consumption in the year 2005 could be as much as 51.27 per cent less than that of 1985.

In addition to the scenario analyses, this thesis provides a complete description of the calculation of carbon dioxide emissions, a matter overlooked in previous studies of carbon dioxide emissions and fossil fuel consumption. The methodology outlined in this thesis can be easily adapted to other energy demand scenarios and also to the study of fossil fuel related carbon dioxide emissions from other countries.

ACKNOWLEDGEMENTS

This thesis is dedicated with much love and gratitude to my parents, Marie Doucet and John Doucet (1921 - 1983).

I would like to thank my committee, Drs. J.H. McMurry and H. Whitney, and especially my supervisor Dr. J.A. Hall, for their patience and assistance in completing this work. I would also like to thank Dr. J.B. Robinson of the University of Waterloo for his assistance in providing information and documentation that I required.

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1.0 INTRODUCTION

The increased loading of carbon dioxide in the atmosphere and its predicted impact on climate change has emerged as one of the most significant environmental threats of this century. It is an issue that highlights the conflict between two resources and the functions they serve. The fossil fuels that heat and light our homes and work places and power our vehicles also emit a variety of substances, including carbon dioxide, that have a negative impact on the atmosphere. Earth's atmosphere must also be seen as a resource, whose functions include the screening out of harmful solar radiation and the maintenance of a stable global average surface air temperature by regulating incoming and outgoing solar radiation. In order for the atmosphere to function efficiently and as we have come to expect, its chemical composition must remain essentially the same.

The increasing conflict between the two resources of atmosphere and fossil fuels has long been recognized from annual measurements of the chemical composition of the atmosphere, and in particular from measurements of the atmospheric concentration of carbon dioxide. These measurements indicate that since we began consuming significant quantities of fossil fuels with increasing industrialization from about 1850, the atmospheric concentration of carbon dioxide has increased by approximately 25% (Canadian Climate Centre, 1986, 3). Even more disturbing is the fact that left unchecked, global annual consumption of fossil fuels is expected to continue increasing well into the next century, with an even greater reliance on coal, leading many experts to estimate that the atmospheric concentration of carbon dioxide will be double that of the pre-industrial level by around 2050 A.D. (Hengeveld, 1987, iii). Clearly, our use of fossil fuels is changing the chemical balance of Earth's atmosphere and, hence, its ability to regulate climate. This thesis will examine this problem with respect to Canada. Specifically, we will calculate Canada's current output of carbon dioxide, and by means of a variety of energy demand scenarios we will delineate the range of Canada's future output of carbon dioxide in the year 2005. Then we can determine whether or not Canada has the capability to significantly reduce its already conspicuous output of carbon dioxide from fossil fuel consumption.

Chapter 2 summarizes the current state of understanding of the relationship between carbon dioxide and climate change, and should convince the reader that this environmental problem is real and in need of immediate attention.

With the recognition that the increased loading of carbon dioxide in the atmosphere threatens to alter Earth's climate, one must then logically ask what could be done to avert this problem. Chapter 3 reviews the current literature regarding ways of averting the buildup of carbon dioxide in the atmosphere and examines proposed technological, biological and energy management solutions to this problem. Although carbon dioxide induced climate change is a global environmental problem, it is at the national level that this issue must be addressed. Calculations made in this thesis indicate that on average, Canada's per capita emission of carbon as carbon dioxide in 1985 was almost four times greater than the world average (see Section 6.3).

Because of its resource diversity, Canada more than any other fossil fuel dependent country in the world, has the capability to change. This thesis will examine Canada's options for change. At the core of this study is an examination of published energy demand scenarios that have been prepared by a variety of organizations. Chapter 4 provides the reader with a detailed analysis of the characteristics of each of the energy demand scenarios evaluated in this thesis along with a description of the organizations that developed them.

Chapter 5 provides a full account of how to calculate the potential future carbon dioxide emissions associated with each energy demand scenario and also how to standardize the differing measurements so that direct comparisons between scenarios are facilitated. Chapter 5 also provides detailed information on the calculation of the carbon dioxide emissions associated with each type of fossil fuel.

Chapter 6 discusses the results of the analysis of each of the energy demand scenarios. Specifically, the following information was calculated and discussed for each scenario:

- total energy demand in petajoules (PJ);
- total carbon dioxide emissions in teragrams (Tg);
- percentage of total energy demand met by fossil fuels, hydro and renewables, and nuclear energy;

- ratio of carbon emitted per fixed unit of energy;
- percent share of total fossil fuel demand and corresponding carbon dioxide emissions; and
- the percent increase or decrease in total energy demand and total carbon dioxide emissions for each scenario in comparison with Scenario A, the 1985 Historical Base Case.

Finally, Chapter 7 summarizes and discusses the results of this thesis. Because of Canada's disproportionate per capita consumption of fossil fuels in comparison with the world as a whole, and because of its demonstrated potential to alter its current emission patterns, Canada has an obligation to lead the way in demonstrating that the global problem of atmospheric carbon dioxide accumulation can be dealt with effectively and without economic constraint.

One should note that the results of this thesis are by no means precise predictions of what Canada's future energy demand and consequent emission of carbon dioxide will be. Rather, it is hoped that by incorporating a variety of diverse yet feasible options in this study, the range of potential carbon dioxide emission levels will be evident. As an exercise in resource management, this thesis will provide an indication of the scope of choice available in Canada with respect to energy demand and consequent emission of carbon dioxide. As it has been said, "we cannot know the future, but we can design it" (Brooks et al.,1983,197).

No study can do everything. This study has set limits to the time in the future it considers, and to the kind of anthropogenic emissions it considers. A twenty year (1985 - 2005) time frame has been adopted for the energy demand scenarios. By limiting the outlook to twenty years in the future, one of the most serious limitations of energy demand scenarios will be somewhat diminished, the problem of realistically projecting into the increasingly uncertain future. Also, the twenty year period coincides with the projection period of one group of energy demand scenarios used in this thesis. From a planning or resource management perspective, the twenty year time frame is distant enough to allow sufficient time to develop and implement policy and technology changes that may be advisable.

This thesis will not examine anthropogenic carbon dioxide emissions from non-combustive processes such as deforestation, land use change, incineration of rural and urban waste and the production of cement, nor will this thesis examine the role in climate change of other anthropogenically produced greenhouse gases (methane, nitrous oxide, chlorofluorocarbons and tropospheric ozone). The reader should note that both the non-combustive sources of carbon dioxide and the other greenhouse gases are likely to contribute significantly to the global problem of anthropogenically induced climate change. So the environmental problem is likely even greater than that documented here. But let us zero in on fossil fuels, carbon dioxide, and climate.

2.0 CARBON DIOXIDE AND CLIMATE CHANGE

2.1 Introduction

In order to begin to understand the role of fossil fuel consumption in potential climate change one must first understand something about the nature of the causative agent in this relationship, carbon dioxide. The present chapter contains information on the current state of understanding with respect to the relationship between carbon dioxide and climate change.

We begin by examining carbon dioxide's role in the global cycle of carbon (Section 2.2). In particular, we will learn of the human interference in the natural cycling of this element. The greatest source of human interference in this process, and the source of concern in this thesis, is the combustion of fossil fuels. We also note that there are other, non-fossil, anthropogenic sources of carbon dioxide that lie beyond the specific bounds of interest of this research. In addition, an analysis of past and present trends with respect to atmospheric carbon dioxide concentration is given, indicating that current atmospheric concentrations are approximately 25% greater than pre-industrial (ca. 1850) levels.

We next examine carbon dioxide's role as a greenhouse gas with a discussion of its radiative properties (Section 2.3). With these properties understood, one can then evaluate the potential role of increased atmospheric concentrations of carbon dioxide in climate change (Section 2.4). The best computer models have indicated that a doubling of the pre-industrial concentration of atmospheric carbon dioxide will yield an increase of between 1.5 and 4.5 degrees Celsius in the global mean surface air temperature.

Finally, we acknowledge that although carbon dioxide is considered the greenhouse gas of most concern, there are anthropogenically induced greenhouse gases other than carbon dioxide that are likely to contribute to climate change (Section 2.5).

2.2 Carbon Dioxide and the Global Cycle of Carbon

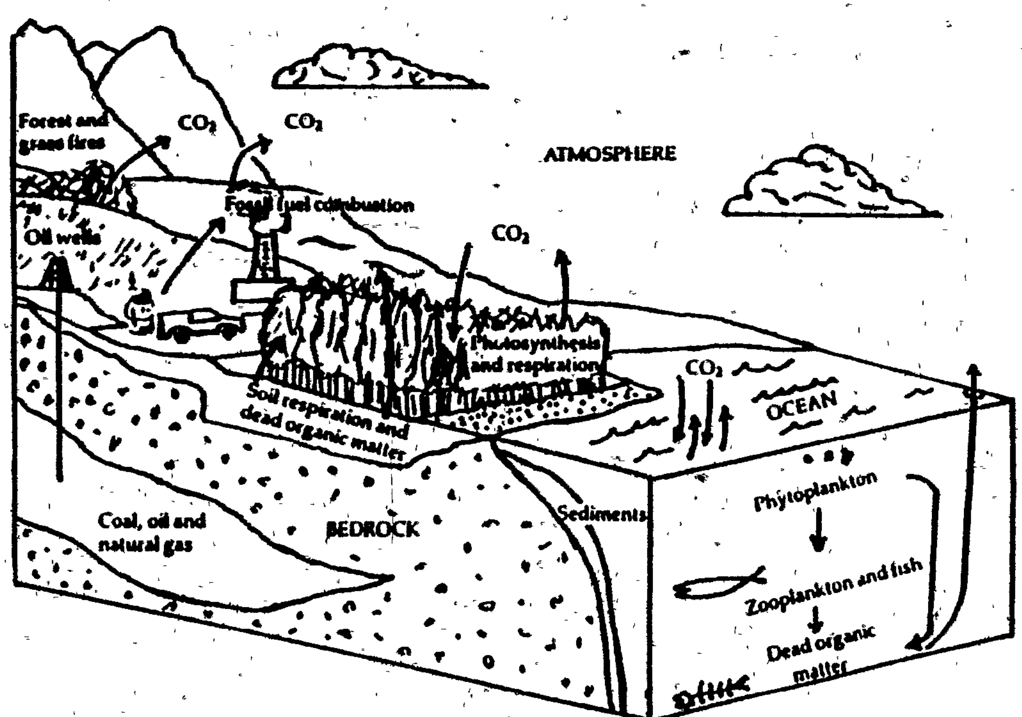
In terms of Earth's atmospheric composition, carbon dioxide (CO_2) is the fourth most abundant gas, currently present at a concentration of approximately 345 parts per million (ppm) or 0.0345% by volume (nitrogen, oxygen and argon are the most abundant atmospheric components, with shares of 78%, 21% and 0.93% by volume respectively) (Canadian Climate Centre,1986,4). A clear, odourless and at low concentrations a nontoxic gas, carbon dioxide is thought to be chemically inert, that is to say, it is not believed to participate significantly in any photochemical reactions (Manahan,1975,341).

Carbon dioxide is a radiatively active gas, with the ability to absorb and re-radiate long-wave radiation. In particular, carbon dioxide is effective at absorbing and re-transmitting long-wave radiation between the wavelength of 12-20 micrometers (um). As a radiatively active gas, carbon dioxide contributes to the warming of Earth's surface air temperature in a process that has been termed the greenhouse effect (see Section 2.3).

As with other naturally occurring elements such as oxygen and nitrogen, carbon in its various forms is exchanged between air, sea and land in a complex process referred to as the carbon cycle (see Figures 2.1 and 2.2). Through this cycling of carbon, carbon dioxide is naturally introduced to the atmosphere through respiration by all organisms and as a by-product of forest and grass fires (Figure 2.1). Anthropogenic contributions of carbon dioxide to the atmosphere are largely the result of fossil fuel combustion. Hirschler (1981,719) notes that, "almost all of the gas (CO2 - auth.) liberated as a result of man's activities arises from combustion processes", approximately 75% (Bolin,1986,147) of anthropogenic emissions being derived from fossil fuels.

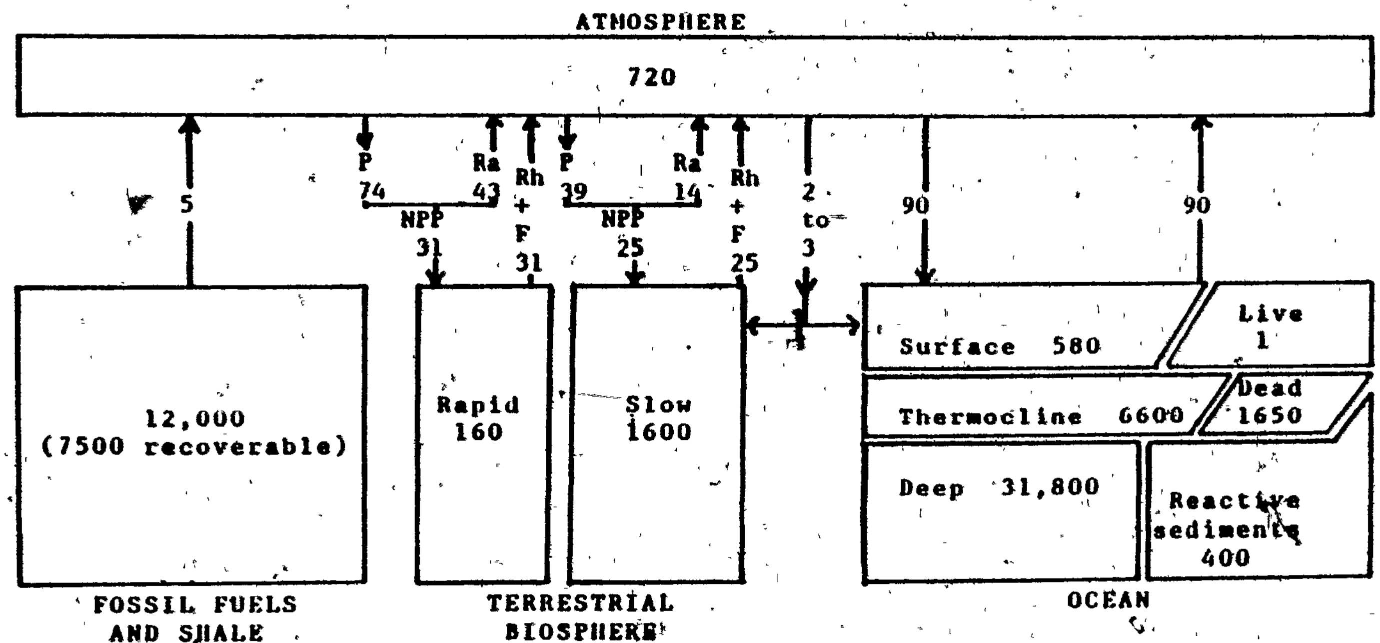
Although fossil fuel combustion undoubtedly constitutes the largest anthropogenic contribution of carbon dioxide to the atmosphere, it is by no means the only source. Estimates indicate that the net annual non-fossil input of carbon dioxide is approximately 25% of the total human-induced emissions of this gas (Bolin,1986,148). Deforestation and land use changes have certainly been important factors in atmospheric carbon dioxide increase over the past century. A net release of carbon dioxide

Figure 2.1
The Carbon Cycle



Source: Adapted from Gates (1985,16).

Figure 2.2
Sinks and Fluxes of Carbon Dioxide



Note: All values in gigatonnes (Gt) and the annual fluxes of carbon in Gt/yr.

P, gross primary production; Ra, carbon released by respiration of autotrophs; NPP, net primary production (P - Ra); Rh, carbon released by heterotrophic respiration; F, carbon released by fires.

Source: Adapted from Gates (1985,17).

to the atmosphere occurs whenever chnages in land use replace ecosystems of high carbon density with ones of lower carbon density. The prime example of such change is the conversion of forest to agricultural or grazing land (Clark et al.,1982,9). Revelle (1982,45) notes that, "the threefold growth of human populations since 1850 was probably accompanied by a roughly equivalent increase in the areas of agricultural land, in part at the expense of forested areas". Carbon dioxide is also released during the natural decomposition of organic matter in soils, a process that is accelerated through a variety of agricultural practices such as ploughing.

The incineration of both urban and rural waste, although only a fraction of fossil fuel emissions, is another anthropogenic source of carbon dioxide. Hirschler (1981,722) indicates that, as with coal, the conversion of organic matter to carbon dioxide is responsible for virtually all the heat released by incinerated waste. He estimates that the emission of carbon dioxide per tonne of refuse incinerated is approximately 35% of that of each tonne of hard coal (bituminous) burnt.

A final anthropogenic source of carbon dioxide to be considered is the production of cement and the consequent liberation of carbon dioxide from calcium carbonate. Rotty (1981,131) reports that the contribution of cement to the output of carbon dioxide is small, about 2% of all industrially generated carbon dioxide.

Other than the atmosphere, which is estimated to contain approximately 720 gigatonnes (1 GT = 10EXP9 tonnes) of carbon as carbon dioxide, important resevoirs of carbon include the world's oceans and their sediments, the terrestrial biosphere and Earth's deposits of fossil fuels and shales (Gates,1985,149)(Figures 2.1 and 2.2). The world's oceans and their sediments are estimated to contain approximately 41,000 GT of carbon, the largest of any carbon pool, while the terrestrial biosphere and fossil fuels and shale contain 1760 GT and 12,000 GT respectively (Gates,1985,149) (Figure 2.2).

As Figure 2.2 depicts, various fluxes occur between the carbon reservoirs. The most important for the purposes of this study is that which occurs between the world's fossil fuel reserves and the atmosphere. Of the 12,000 GT of carbon estimated to be contained in Earth's fossil fuel and shale deposits, approximately 7500 GT is estimated to be recoverable (Gates,1985,17) (Figure 2.2). From this recoverable pool of fossil fuels, mankind is currently emitting approximately 5 GT of carbon as carbon dioxide into the atmosphere on an annual basis (Canadian Climate Centre,1986,4)(Figure 2.2).

Since the combustion of fossil fuels accounts for approximately 75% of anthropogenic carbon dioxide emissions, the carbon dioxide 'problem' is strongly correlated with the post mid-nineteenth century industrial revolution. The most recent evaluations of the pre-industrial (ca. 1850) level of atmospheric carbon dioxide, based on measurement and analysis of carbon-dated air trapped in glacial ice, indicate a concentration of 275 +/- 10 parts per million by volume (ppmv) (WMO,1986,18). By 1986 the concentration of atmospheric carbon dioxide had risen to 345 ppmv, an increase of approximately 25% over the pre-industrial level (Canadian Climate Centre,1986,3).

The longest detailed records of the increasing concentrations of carbon dioxide come from the observations made at the Mauna Loa Observatory in Hawaii and the South Pole station of the U.S. Antarctic Program. The observations were initiated in 1957-58 as part of the activities of the International Geophysical Year, and the remote locations were chosen to limit the background noise that might be expected at a point closer to the sources of anthropogenically generated carbon dioxide. The results of this program indicate that atmospheric carbon dioxide concentration has increased from approximately 315 ppmv in early 1959 to 343 ppmv in 1984, or by about 9% (WMO,1986,18).

Future carbon dioxide emissions are very much dependent on future global energy demands and the types of fuels chosen to meet these demands. These in turn depend on human decisions which are largely unpredictable. Clearly this is an extremely difficult scenario to predict over anything more than a few years. Hence, uncertainties as to future atmospheric concentrations of carbon dioxide increase significantly.

As noted previously, current anthropogenic emissions of carbon dioxide from the combustion of fossil fuels amount to some 5 GT of carbon per year. Future projections range from an upper bound of approximately 20 GT of carbon per year, to a lower bound of 2 GT of carbon per year, by the year 2050 (WMO,1986,19). The lower bound could possibly be achieved by sustained global efforts to limit the future use of fossil energy by decreasing energy demands and by increasing the use of non-fossil energy sources. Higher values than 20 GT of C/year in the year 2050 seem unlikely in view of the environmental, social and logistic constraints (WMO,1986,19).

2.3 Carbon Dioxide and the Greenhouse Effect

In the previous section it was learned that mankind's emission of carbon dioxide from the combustion of fossil fuels has been increasing steadily since the mid-nineteenth century. In turn this increased anthropogenic loading of atmospheric carbon dioxide has raised considerable concern among the scientific community. In particular, this community has recognized that as a radiatively active gas, the increasing concentration of carbon dioxide may be contributing to an enhancement of what has become commonly known as the greenhouse effect.

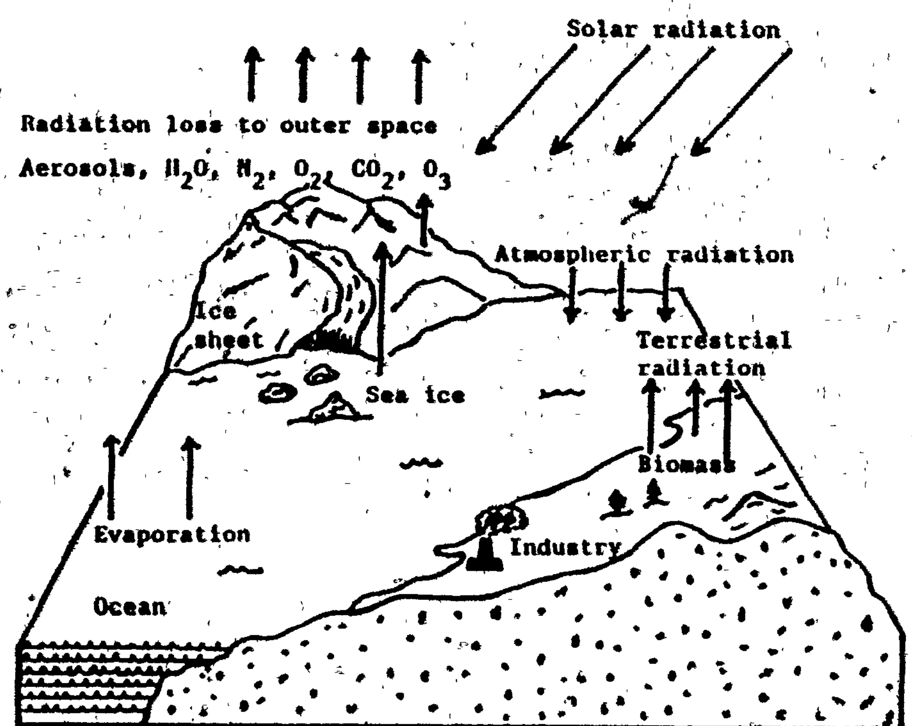
The greenhouse effect is a term used to describe the process of absorption and re-emission of radiation which warms the lower troposphere and Earth's surface. Incoming solar radiation is partly absorbed and scattered by the stratosphere and troposphere before it reaches Earth's surface. That amount which does reach the surface of the earth is again partly absorbed and partly reflected. The absorbed radiation is subsequently transferred back to the atmosphere, partly as long-wave radiation (including infra-red (IR) radiation), and partly as direct sensible heat or indirectly as latent heat. Finally, a small part of the re-radiated long-wave radiation escapes back into space while the greater portion of such radiation is absorbed by the atmosphere to be subsequently released into space or re-radiated back to the surface of the earth (see Figure 2.3).

It should be noted that the term greenhouse effect is really a misnomer, as the heating of a greenhouse occurs largely by the control of vertical convective heat flow, and only partly by the restriction of the loss of heat radiation. Although inaccurate, the term has gained some currency and it will be used in this thesis.

Certain naturally occurring atmospheric gases have the ability to absorb and re-radiate long-wave radiation. According to Watson et al. (1986,114), of these naturally occurring gases, "about 90% of the atmospheric absorption is from water vapour (H2O), carbon dioxide (CO2) and clouds in Earth's atmosphere, and the remaining 10% of the absorption is due to atmospheric ozone (O3), methane (CH4) and nitrous oxide (N2O)". The presence of these trace gases in the atmosphere is essential in order to maintain the global energy balance of the earth-atmosphere system. If the earth had no such atmosphere, the average surface temperature would be some 35 degrees K cooler (1 degree K = 1 degree C)(Chamberlain et al.,1982,255; Wang et al., 1986,120).

The greenhouse effect has gained global attention in recent years because of the realization that a variety of human activities may be enhancing this phenomenon by releasing additional amounts of greenhouse gases into the atmosphere. The

Figure 2.3
Radiation and the Greenhouse Effect



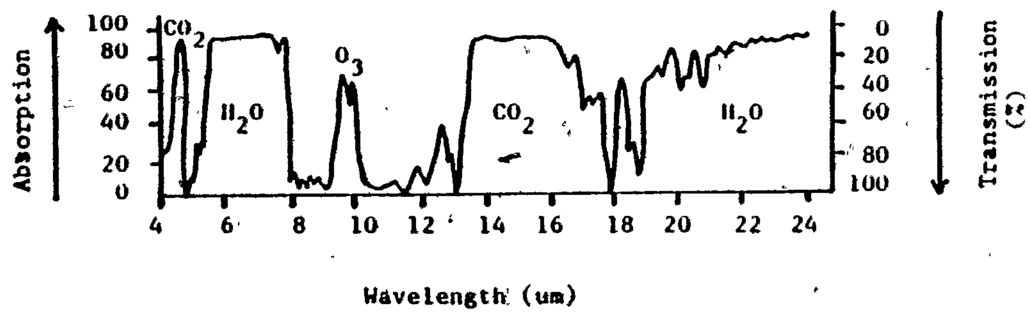
Note: "The exchange of energy between the sun, the Earth, and outer space involves many processes. Solar radiation brings energy to the atmosphere and to the ground surface. The atmosphere, containing aerosols and gases H_2O, N_2, O_2, CO_2, and O_3, reradiates energy to the ground as well as to outer space. The ground surface and sea surface radiate heat to outer space. Energy is removed from the Earth's surface by the evaporation of moisture from the ocean and from the land." (Gates,1985,146).

Source: Adapted from Gates (1985,146).

concern expressed by the scientific community is that the anthropogenic emissions of trace gases that are radiatively absorptive is likely to contribute to a significant warming of the global average surface air temperature by the middle of the next century. If extra atmospheric absorption is introduced into this system, Earth's surface air temperature must increase until the outgoing radiation once again is equal to incoming radiation, thus maintaining the radiative balance of the system.

As the Canadian Climate Centre (1986,3) notes in their annual report, Understanding CO_2 and Climate, "although molecule-by-molecule not the most powerful greenhouse gas, carbon dioxide remains the most important because of its greater abundance and rate of increase". As noted earlier, solar radiation, or shortwave radiation (300 - 2500 nanometers (nm)) that reaches Earth's surface is absorbed and re-radiated back to outer space as long-wave or infra-red radiation (4000 - 20,000 nm or 4 - 20 micrometers (um)). As a radiatively absorptive gas, carbon dioxide possesses an extremely strong, broad absorption band centred at a wavelength of 14 um, but extending from 12 um to beyond 20 um (Figure 2.4)(Gates,1985,145). As one can see, carbon dioxide's absorption band falls within that range of radiation emitted from Earth's surface, hence increased concentrations of atmospheric carbon dioxide will improve the efficiency of the atmosphere in absorbing and partially re-radiating back to Earth, radiation within carbon dioxide's absorption band. The climatic implications of increased concentrations of atmospheric carbon dioxide will be discussed in

Figure 2.4
Carbon Dioxide's Absorption Band



Source: Adapted from Gates (1985,46).

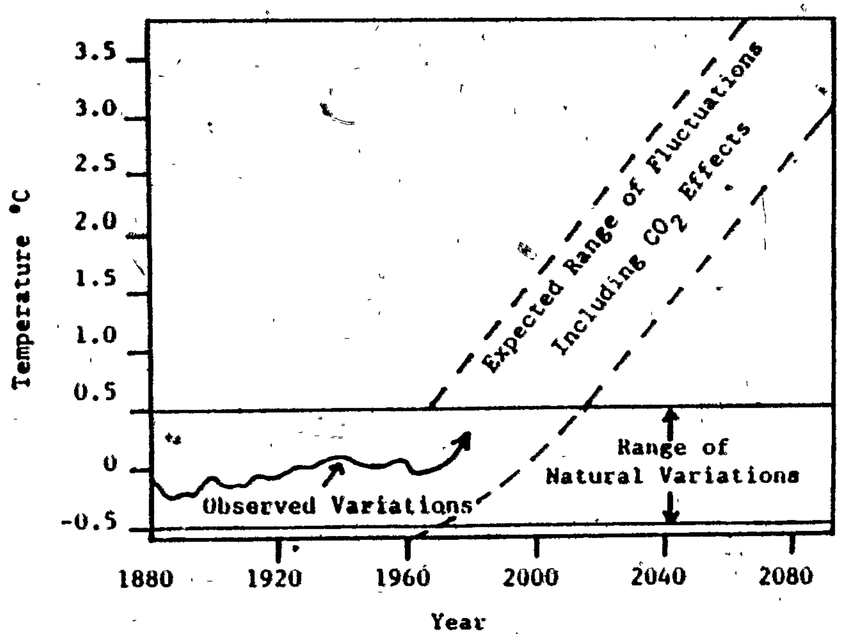
the following section.

2.4 Carbon Dioxide and Climate Change

An examination of records of the mean annual temperature of the Earth between 1880 and 1980 by Hansen et al. (1981,957) has determined that during this period the mean global temperature rose by about 0.4 degrees Celsius (Figure 2.5). In order to attempt to explain this observed temperature increase, Hansen and his group constructed a complex numerical computerized model of the global climate. Incorporated in this model were equations for radiative and convective energy exchange involving clouds, aerosols (particularly those of volcanic origin), changes in surface albedo, an increase in carbon dioxide concentration of 43 ppm over the study period, a hypothetical variability of 0.2 percent in the sun's luminosity and a 100-meter- mixed-layer ocean with thermal diffusion down to 1000m. As Figure 2.6 demonstrates, Hansen et al.'s (1981,965) climate model is in general agreement with the observed temperature fluctuations over the study period, thus suggesting that increased concentrations of atmospheric carbon dioxide have probably played some role in the observed global average temperature increase calculated over the past century.

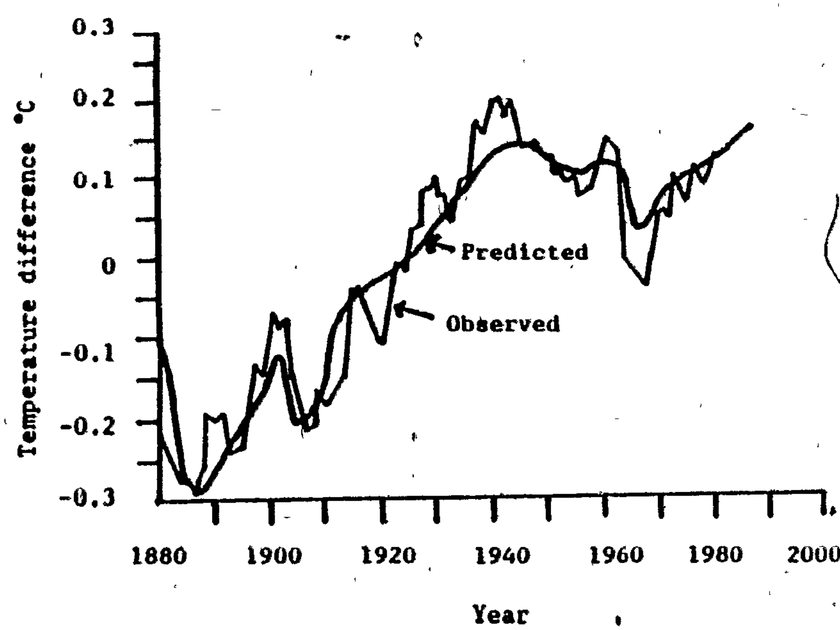
One controversial aspect of trying to draw a positive correlation between the observed increase in atmospheric carbon

Figure 2.5
Historic and Expected Changes in Global Mean Temperatures



Source: Adapted from Bruce and Hengeveld (1985,3).

Figure 2.6
Comparison of Predicted and Observed Temperature Changes Over the Past Century



Source: Adapted from Gates (1985,158).

dioxide and the increase in global mean temperature of 0.4 degrees Celsius, is that this increase falls within the range of natural variations in Earth's mean surface temperature (Figure 2.5). As Revelle (1982,38) notes, "Confidence in the carbon dioxide hypothesis will be much firmer if a warming trend exceeding the noise level becomes evident".

Although still poorly understood, the principle explanation for the inability to ascribe the increase in mean global temperature in a statistically rigorous manner to the changing carbon dioxide concentration, is the role that Earth's oceans play in climate change. Bolin et al. (1986a,15) note that, "the storage of heat in the oceans delays the warming expected for an equilibrium response to carbon dioxide-induced warming and may also significantly modify the geographical distribution of climatic change".

Despite these uncertainties, Revelle (1982,38) concludes that, "Almost any reasonable estimate of how much fossil fuel will be burned in the coming years suggests that if carbon dioxide is indeed altering climate, an unmistakeable warming trend should appear in the 1990's". Hare (1986,257) adds, "My own view is that the effect (carbon dioxide - auth.) is real, and that the anticipated warming is actually in progress. This view is now shared by the great majority of climatologists".

Unless dramatic steps are taken, global consumption of fossil fuels will continue to increase well into the next century and consequently the atmospheric concentration of carbon dioxide will also increase. In assessing the impact of increasing atmospheric carbon dioxide, much use has been made of sophisticated computer driven, three-dimensional numerical models of Earth's climate systems. Commonly known as general circulation models (GCMs), the best of these estimate that for a doubling of atmospheric carbon dioxide over the pre-industrial level, the global mean surface air temperature will increase from 1.5 to 4.5 degrees Celsius or higher (Bolin et al.,1986b,xxi). The uncertainty with respect to the magnitude of the warming is a function of the limitations of even the most advanced GCMs. In particular, "the three-dimensional GCMs are generally deficient in the treatment of ocean heat transport and dynamics and feedback between the ocean and the atmosphere" (National Research Council,1983,27).

Should the global average surface air temperature increase by the amounts indicated by the GCMs, the anticipated changes in global climate would be unprecedented in human history. The World Meteorological Association (WMO,1986,57) notes that, "although quantitative uncertainty in model results persists it is highly probable that increasing concentration of the greenhouse gases will produce significant climatic change". These anticipated climatic changes may be summarized as follows (WMO,1986,2):

> The major climatic effects in low latitudes are probably an increase in both precipitation and evaporation over the tropical rainbelt and maybe a strengthening of the monsoon over some land areas.
>
> The major climatic effect in mid-latitude land areas is a lengthening of the warm season and shortening of the cold season. Snow accumulation will occur later and snow melt earlier; the snowline in mountain areas will rise. Summer dryness may become more frequent.

The major climatic effects in high sub-polar latitudes are a shortening of the winter season; a shrinking of the sea ice extent; and an increase in precipitation that may substantially increase runoff.

In Canada, climate change associated with a doubling of atmospheric carbon dioxide concentration over pre-industrial levels is expected to have the following impacts (Canadian Climate Centre,1986,1-2):

Agriculture will benefit significantly from warmer and longer growing seasons, particularly in northern regions;

Direct effects of increased CO_2 could enhance field crop growth by up to 15% (CO_2 is an essential plant nutrient - auth.);

Agriculture in southern regions may be significantly affected by increased frequency and severity of drought;

Great Lakes winter ice seasons may disappear, with a potential increase in shipping of 15% to 30%;

Decreased Great Lakes Basin water runoff could reduce lake levels by 20cm, with a net decrease in seasonal shipping capacity of 6%. Major ecological marshes such as Point Pelee would disappear or be significantly altered;

Downhill skiing industry could disappear in southern Ontario as reliable snow seasons retreat northward. Net effects on the related Ontario economy, possibly in excess of $50 million/year, would be at least partially offset by increased summer recreational activity.

As one can see, there are potentially both positive and negative implications associated with the magnitude of climatic change implied by a doubling of the atmospheric concentration of carbon dioxide. It is also clear that these impacts, both positive and negative, will not be distributed evenly across Canada, hence regional disparities may be further aggravated by climate change. On a global scale the impact of climate change will likely be felt the hardest by the developing countries, who are the least equiped economically and technologically to adapt to, or avert, a changing climate. Hare (1986,263) comments that:

> More generally, the impact of future climatic change is likely to be unequal as between nations and power blocs. It will introduce new elements into the geopolitical balance. World politics already has to grapple with the problem of winners and losers. Climate may well compound this inequality.

Some insight into what a warmer Canada might be like has been gained from the analysis of warm periods in the climate data records of the past 80 years. Study findings suggest a number of recurring features, including (Canadian Climate Centre,1986,9):

- A consistently amplified warming in Arctic regions, particularly in winter and spring, accompanied by increases in storminess and precipitation;
- An area of cooling off the east coast of Canada in winter and spring;
- Decreased summer precipitation and increased variability in precipitation in spring, summer and fall in interior regions of southern Canada, hence a significant increase in potential for severe drought events;
- Generally increased winter precipitation and decreased fall precipitation across Canada.

With the evidence for a carbon dioxide induced change in climate mounting, mankind is faced with two courses of action. We can either learn to adapt to an anthropogenically modified climate, or we can take steps to reduce our emissions of carbon dioxide. By adopting the latter strategy, at the very least one delays the build-up of carbon dioxide and therefore allows more time to learn to adapt to climate change.

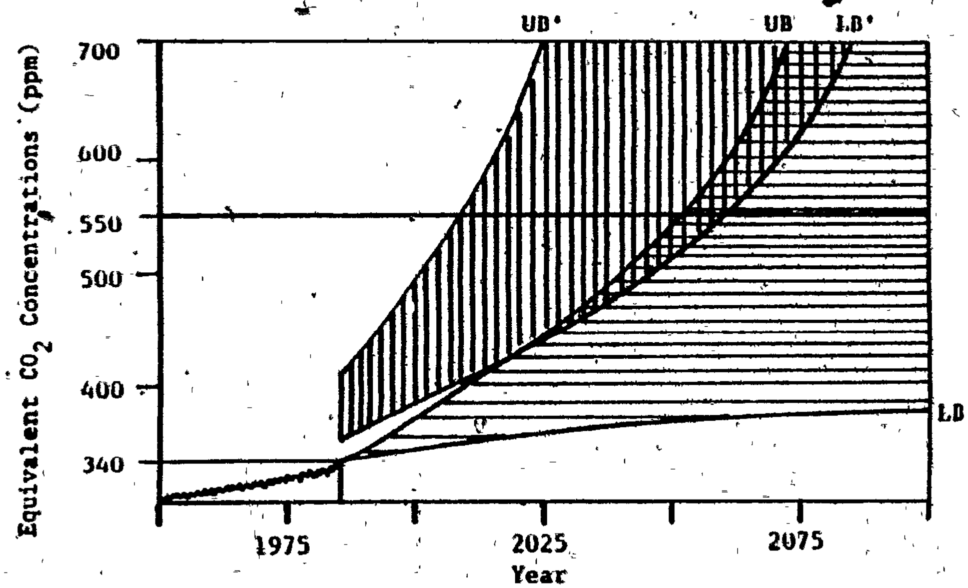
The objective of this thesis is to analyze ways in which Canada, a conspicuous consumer of fossil fuels, may reduce the emissions of carbon dioxide resulting from its demand for, and use of energy.

2.5 Other Greenhouse Gases

Although not specifically addressed in this thesis, atmospheric gases other than carbon dioxide also contribute to the greenhouse effect and hence to climate change. Anthropogenic emissions of methane (CH4), nitrous oxide (N2O), chlorofluorocarbons (CFCs) and enhancement of the generation of tropospheric ozone (O3) all contribute to the greenhouse effect. It has been suggested that the combined influence of these other radiatively active gases on climate may already be approaching that of carbon dioxide (Canadian Climate Centre,1986,5). The continued emission of these gases into the atmosphere is likely to have the effect of speeding up the time at which the climate change anticipated from the doubling of carbon dioxide will be experienced (Figure 2.7).

With the recognition that the increased loading of carbon dioxide in the atmosphere threatens to alter Earth's climate, we turn our attention to an analysis of the options available to avert this problem.

Figure 2.7
Projections for Future Concentrations of Atmospheric Greenhouse Gases



Note: "The curves UB and LB indicate range of estimates for future concentrations of CO_2 alone, while UB' and LB' represent the range of estimates for "equivalent" CO_2 concentrations when other trace gases are included. The value of 550 ppm represents a doubling of preindustrial CO_2 concentrations." (Canadian Climate Centre, 1986, 5).

Source: Adapted from Canadian Climate Centre (1986,5).

3.0 WAYS OF AVERTING THE BUILDUP OF CARBON DIOXIDE IN THE ATMOSPHERE - A REVIEW OF THE LITERATURE

3.1 Introduction

In the previous chapter we learned of the serious threat that anthropogenic emissions of carbon dioxide pose with respect to climate change. The overwhelming consensus among experts studying this global environmental problem is that if we continue to release carbon dioxide into the atmosphere at the current rate, a significant warming of the global average surface air temperature will be unavoidable. This being the case, the question arises, then, whether anything can be done to avert this potential and unprecedented change in the global environment.

The present chapter reviews current literature regarding ways of averting the buildup of carbon dioxide in the atmosphere. We begin by examining proposed technological solutions that involve the physical and/or chemical removal of carbon dioxide from combustion gases (Section 3.2). These solutions are rejected because of their high costs, limited application and inherent problems with the disposal of the recovered carbon dioxide.

We next examine proposed biological solutions to the buildup of atmospheric carbon dioxide (Section 3.3). These solutions involve the deliberate management of terrestrial and aquatic plant life, both natural sinks for carbon dioxide. These solutions offer only limited potential to reduce the accumulation of atmospheric carbon dioxide and as such cannot be viewed as permanent solutions to the problem. On the other hand, the enhancement of terrestrial plant growth through programs of reforestation and through a cessation of deforestation is in its own right highly desirable for other ecological reasons.

Finally, we examine what appears to be the only viable solution to the buildup of atmospheric carbon dioxide, better management of the types and quantities of fuels we choose to meet our energy needs (Section 3.4). This particular solution is the only one of the three proposals to directly address the very source of this global environmental problem, our dependence on fossil fuels.

3.2 Technological Solutions

A number of technological solutions to remove carbon dioxide from exhaust gases exist today. In An Analysis of Concepts for Controlling Atmospheric Carbon Dioxide, Steinberg (1983) notes that there are a variety of physical and chemical processes that can be used to extract carbon dioxide from the exhaust gases associated with the combustion of fossil fuels. For example, the removal and recovery of carbon dioxide from gas streams can be accomplished by absorption in liquid solvents such as water or aqueous sodium carbonate. The carbon dioxide is then stripped from this liquid using heat, steam or an inert gas. The concentrated CO_2 is then ready for disposal or is utilized in the manufacture of products for which it is required (Steinberg,1983,18).

Certain solids, including naturally occuring sorbents (e.g. clays, oil shale, silica, coal, and carbon), may also be used in the gas stream to absorb carbon dioxide (Steinberg,1983,20). It must be noted that in using either liquids or solids to absorb and remove carbon dioxide from spent combustion gases, either filter system reduces the total efficiency of the process (Bach,1984,201).

The high costs and nature of the systems involved limit the application of these technological solutions to large, point sources of carbon dioxide emissions. In particular, large fossil fuel powered electrical generating plants have lent themselves to the study of the feasibility of adopting a technological solution to limit carbon dioxide emissions. Steinberg et al. (1984,56) estimate that in the United States the implementation of absorption/stripping technology in fossil fuel power plants would lead to a 10% reduction in the annual incremental atmospheric CO_2 content. Depending on the region of the United States, the authors estimate that the production cost of electricity would increase by 56% to 100% (Steinberg et al.,1984,62).

Regardless of the costs involved with installing and operating a physical or chemical removal system, the greatest problem associated with these solutions is how to dispose of the recovered carbon dioxide. Three types of disposal sites have been suggested; the deep ocean, spent oil and gas wells and salt caverns (Steinberg et al., 1984,62; Kellogg and Schware,1981,106). With spent oil and gas well and salt cavern disposal one is faced with the possibility of leakage of the stored gas because of geologic instability (Kellogg and Schware, 1981,111).

Disposal of carbon dioxide in the deep ocean is the most commonly discussed solution but it also poses a number of serious problems. The recovered carbon dioxide must first be transported by pipeline or truck to one or more collection centres. The possibility of the leakage of the gas in transport must be considered. The carbon dioxide can then be introduced into the deep ocean in one of a number of forms; a concentrated CO2-seawater solution, liquid CO2 or dry ice (solid CO2) (Bach, 1984,202). According to Kellogg and Schware (1981,110), "given the right temperature and pressure, carbon dioxide becomes a liquid more dense than water", hence, under the right conditions the carbon dioxide would sink to the bottom of the ocean and remain there.

The greatest shortcoming of deep ocean disposal of carbon dioxide is related to the very nature of the role of the oceans in the carbon cycle. As Kellogg and Schware (1981,110) note, "storage in the oceans can effect the rate of increase of carbon dioxide but not the ultimate value of the atmospheric concentration, since oceanic and atmospheric carbon levels will eventually come to equilibrium". Clearly, deep ocean disposal of anthropogenically generated carbon dioxide is a very expensive and complex temporary solution to the problem of the increasing buildup of atmospheric carbon dioxide.

3.3 Biological Solutions

Since deforestation has been partially responsible for the carbon dioxide buildup in the atmosphere, reforestation has been proposed as a method of controlling this accumulation. Dyson (1977) has been credited as the first to suggest the formation of a biological "carbon bank" of fast-growing trees or water plants as a means of controlling the concentration of atmospheric carbon dioxide (Bach,1984,206).

Recall that in our discussion of carbon sinks and fluxes (Section 2.2.2) the terrestrial and oceanic biosphere were noted to be important natural sinks for atmospheric carbon dioxide. As Steinberg (1983,46) notes, "the photosynthetic fixation of atmospheric CO_2 in plants and trees could be of great value in maintaining a CO_2 balance in the atmosphere". He also notes that, "the biological fixation of CO_2 from the atmosphere by marine organisms in the ocean especially near the continental shelves could extract and reduce atmospheric CO_2" (Steinberg,1983,47).

Cooper (1978,510) reports that an increase of one percent in the mass of plant life on earth, especially the forests, would be sufficient to absorb and sequestor one year's release of carbon dioxide at the current global rate of 5 GT per year. As Bach

(1984,206) notes, the storage of carbon dioxide in land plants is only a short-term solution, lasting only as long as suitable land is available and the trees grow. As the trees mature and growth rates slow, the amount of carbon dioxide required by the aging biomass decreases and hence this carbon sink becomes smaller. Thus Bach (1984,206) correctly argues that with a program of reforestation, "one would have several decades for the development of alternative, CO2-free technologies, and, in any case, reforestation is, in its own right, an ecological necessity". In order to highlight the complexity of this problem one must also consider that a large-scale program of reforestation may, in itself, contribute to regional climate change. Kellogg and Schware (1981,113) note that changed vegetation patterns could enhance the absorption of solar radiation reaching Earth's surface and hence contribute to a warming of the surface air temperature.

Storage of carbon dioxide in water plants also raises a number of concerns. In order for such a program to be effective, large quantities of nutrients, such as nitrogen and phosphorus, must be added to the oceans to encourage and support increased plant growth. The toxicity of such a massive influx of nutrients to other marine organisms is not known, nor are the ecological impacts of such a dramatic increase in aquatic biomass. The overall effectiveness of such a program in removing atmospheric carbon dioxide has also been questioned. Dyson and Marland (1979,115) report that the addition of 10 million tons of phosphorus would only give a deposition of about 300 million tons of organic carbon (only 6% of current annual fossil fuel contribution of carbon dioxide of 5 gigatonnes).

Clearly, the biological solutions to the buildup of atmospheric carbon dioxide that are currently being proposed, do not offer a permanent solution to the problem, particularly if emissions of carbon dioxide continue to increase. Rather, these solutions offer the means to slow down the accumulation of atmospheric carbon dioxide and thus allow more time to develop long-term solutions to the problem. It should also be noted that a program of reforestation along with a cessation of deforestation may be attractive for other ecological reasons such as the reestablishment of lost habitat and as protection against soil erosion.

3.4 Energy Management Solutions

Recall that in Section 2.2.3 we learned that the combustion of fossil fuels accounts for about 75% of anthropogenic carbon dioxide emissions. Hence, the carbon dioxide problem is most strongly associated with our dependence on fossil fuels to meet our evergrowing demand for energy.

With the latter relationship in mind, it is reasonable to suggest that the most effective way to deal with the carbon dioxide problem is not to physically or chemically remove carbon dioxide from exhaust gases once it has been created, nor is the solution to plant more vegetation to remove the excess carbon dioxide from the atmosphere. Indeed, the most realistic way of averting the buildup of carbon dioxide in the atmosphere may be to address the problem at its source. In other words, the most effective solution to this problem is to limit our production of the gas.

In terms of energy consumption and the carbon dioxide problem, emissions may be reduced in one of two ways. Firstly, by improving the efficiency of the devices which require fossil fuels we can achieve the same productive output with less energy input, and therefore emit less carbon dioxide. Secondly, carbon dioxide emissions may be reduced by replacing fossil fuels with sources of energy that do not emit carbon dioxide. Examples of such forms of energy include; hydro and nuclear generated electricity, active and passive solar systems, wind and tidal power, and renewable biomass that is grown as a crop with replanting following harvest. Even our choice of what types of fossil fuels we use has an effect on our output of carbon dioxide. As we will learn in Section 5.2, for an equivalent output of energy, natural gas releases less carbon dioxide than oil, which in turn releases less than coal. Clearly, by managing both the types of fuels we use, and the efficiency with which we use them, we can decrease our output of carbon dioxide while still maintaining a similar or improved level of production.

Early studies (Keeling and Bascatow,1977; Siegenthaler and Oeschger,1978) of global carbon dioxide emissions made use of time trend analysis techniques to generate a single "best guess" scenario and estimated that future carbon dioxide emission growth rates would increase up to 4% per year. More recently, Clark et al. (1982) cited more numerous and more sophisticated studies that generally agreed that future CO_2 emission rates would be about 2% per year.

In 1983, Nordhaus and Yohe abandoned the traditional extrapolative techniques in favour of a new approach for estimating future carbon dioxide emissions. Referred to as probabilistic scenario analysis, the technique "extends the scenario approach to include modern developments in aggregate energy and economic modelling in a simple and transparent model of the global economy and carbon dioxide emissions" (Nordhaus and Yohe,1983,88). In particular, this technique "attempts to recognize the intrinsic uncertainty about future economic, energy, and carbon cycle developments" (Nordhaus and Yohe,1983,88). In this manner, probabilistic scenario analysis replaces the "best guess" scenario with a median probability scenario bracketed by confidence intervals. As Nordhaus and Yohe (1983,89) note, the policymaker "can assess not only a policy along a most likely trajectory but also along other trajectories that cannot be ruled out with some degree of statistical significance".

With their technique, Nordhaus and Yohe (1983,91) estimate that global carbon dioxide emissions will probably grow at a median rate of about 1.6% annually to 2025, then slowly to slightly under 1% annually after 2025. The authors cite two factors as to why their estimate is considerably lower than previous ones. Firstly, they include the expectation that the growth of the global economy is now thought to be slower than had earlier been assumed, and secondly, their work also includes the tendency to substitute nonfossil for fossil fuels as a result of the increasing relative prices of fossil fuels (Nordhaus and Yohe,1983,91).

Most recently, Edmonds et al. (1986a) have followed in Nordhaus and Yohe's path by also employing quantitative uncertainty analysis in the study of future global energy and carbon dioxide emissions. By making use of a more detailed model, the authors lower still further the median growth rate of global carbon dioxide emissions to between 1.0% and 0.5% per year. In general, Edmonds et al. (1986a,84) conclude that "CO2 emissions are likely to grow, but that the possibility of a dramatic buildup of atmospheric CO2 from fossil fuel emissions is smaller than previously thought".

These authors caution that model structure is extremely important in determining model results. In addition to model structure, they also note from their results that three variables play dominant roles in determining CO2 emissions (Edmonds et al.,1986,85):

1. Labor Productivity Growth Rate
2. Exogenous Energy Efficiency Growth Rate
3. Income Elasticity of Demand for Aggregate Energy in Developing Regions.

Note that conspicuously absent from this list is the rate of interfuel substitution which Nordhaus and Yohe found to be the most important determinant of carbon dioxide emissions. This discrepancy may highlight the aforementioned importance of model structure determining model results. While interfuel substitution is not explicitly mentioned as being an important factor in determining CO2 emissions by Edmonds et al., they do consider the cost of biomass fuels to be important. Hence, indirectly, the importance of interfuel substitution is implied in their model.

In general, these recent modelling exercises seem to highlight the fact that both interfuel substitution and improvements in the efficiency with which we use energy are key factors in reducing our output of carbon dioxide. Bach (1984,208) strongly advocates such rational use of energy as the most practical means of averting the CO2 problem. While these global studies do provide an indication of the general direction one must take in order to avert a buildup of atmospheric CO2, they lack the resolution necessary to address this problem at a national level. Since energy and environmental policy must ultimately be addressed by each individual country, there is a need for studies to be undertaken at this scale in order to address the capabilities and options available to a particular country to deal with this issue.

To date, only one such study has been completed that specifically addresses Canada's contribution to the carbon dioxide issue. Completed in 1983, by Acres Consulting Services Limited, for the Atmospheric Environment Service of Environment Canada, it was updated in 1987. Acres' (1983;1987) study largely concentrates on documenting Canada's historic contribution to carbon dioxide emissions from 1945 to 1985. Their study also makes use of National Energy Board data to make projections of potential carbon dioxide emissions to the year 2005. It is at this point that this thesis attempts to make a significant improvement over the Acres study. By providing not just one viewpoint of what potential energy use and carbon dioxide emissions in Canada may be, this thesis offers the reader a wide variety of opinions as to what Canada's contribution to the carbon dioxide issue might be.

3.5 Conclusions

Both the technological and biological solutions to the carbon dioxide problem that are currently being proposed offer limited hope with respect to averting this problem. While these techniques may possess desirable characteristics for certain applications they are, in their present states of development, insufficient in themselves to avert a buildup of carbon dioxide in the atmosphere.

Clearly, at present, the most efficient and perhaps most desirable means of averting this problem is to direct our efforts in reducing the amount of carbon dioxide we release in the first place. Sophisticated energy models and intuition tell us that improvements in energy efficiency and interfuel substitution offer practical means to this end.

While the carbon dioxide issue is clearly global in nature, each member nation of our global community will eventually have to come to grips with its contribution to this problem on its own terms, based on each country's endowment of energy resources and their technological capabilities. As a conspicuous consumer of fossil fuels that is also blessed with a rich variety of energy alternatives, Canada has a responsibility and may be in the best position to demonstrate that interfuel substitution and continued improvement in energy efficiency offer the most desirable and efficient means of averting a buildup of atmospheric carbon dioxide.

But what options does Canada have? Let us turn to the analysis of a number of current yet differing energy demand scenarios.

4.0 ENERGY DEMAND SCENARIOS

4.1 Introduction

If, as this thesis suggests, the most viable solution to the buildup of atmospheric carbon dioxide is to limit our output of the gas in the first place, then we must next decide what type of framework is best suited to the analysis of alternative energy paths. The framework adopted in this thesis involves the use of a variety of existing energy demand scenarios from which the analysis of potential carbon dioxide emission is made.

We begin the present chapter by examining the pros and cons associated with the use of energy demand scenarios (Section 4.2). In particular, special note is made of the care taken to minimize the negative aspects and enhance the positive aspects of the use of these analytical tools.

The bulk of the chapter is taken up with detailed descriptions of the energy demand scenarios used in this thesis and the organizations that developed them (Section 4.3).

Finally, we examine the differences between forecasting and backcasting, two analytical techniques that are used to develop energy demand scenarios (Section 4.4).

4.2 Energy Demand Scenarios: Prediction of Future Demand or Delineation of Potential Future Demand?

The title of this section highlights the controversy that surrounds the development and use of energy demand projections. In the design and construction of these scenarios, the analysts make every attempt to ensure that their projection is as accurate as possible, given the data set they have to work with.

As with any design exercise, the energy demand analyst is influenced directly and indirectly by any number of internal and external influences. Hence, the outcome of the analysis is very much dependent on these factors. In particular, energy demand forecasts tend to strongly reflect the philosophy of the organizations that developed them. As Baumgartner and Midttun (1986,13) note, "Social and institutional linkages and political cultures influence assumptions about nature and society, - assumptions that in turn underlie the cognitive and normative framework that produce the variety of competing models".

Given the fact that energy demand forecasts tend to be naturally biased and subject to changes beyond their control, it becomes evident that an individual forecast cannot be used to accurately predict future energy demand over anything more than one or two years. One might then justly ask, why does one bother to develop such forecasts in the first place? The answer to this question is alluded to in the second half of the title of this section. It can be argued that the usefulness of energy demand projections lies not in their ability to predict future energy demand but, taken collectively as a diversified group, in their ability to give some insight into what future energy demand may be, given a variety of different yet feasible conditions.

In developing a framework for their own energy demand projections, Energy, Mines and Resources Canada (1977,2) noted the following:

> There are, of course, risks in making projections of future energy demands. The projections can be only as good as the assumptions which underlie them (and the data on which they are based). Because almost all assumptions about the future turn out, after the fact, to be wrong, so do the projections. This does not mean, however, that all projections are useless or that resources devoted to making projections are wasted. On the contrary, these kinds of analyses can provide ranges of possible outcomes and quantitative indications of cause and effect which are extremely useful in formulating appropriate policies to manage Canada's energy resources. They emphasize the need to retain flexibility to be able to adapt to patterns of future events which, almost certainly, will turn out to be different than those now thought to be probable. In a sense, the analytic process is more important than any specific projection.

From a scholarly viewpoint it is clear that the analytical function that energy demand projections serve is highly desirable. In reality, as Baumgartner and Midttun (1986,29) quite accurately note, models and forecasting generally serve a dual function; "They may serve as analytical tools to explore premises for and consequences of policy options. Or they may serve as instruments for political legitimation". The authors also note that in many cases these two functions are closely interlinked.

The use, or should one say the misuse, of models and forecasting for political legitimation constitutes the most serious abuse of these techniques. In particular, this abuse tends to manifest itself in two ways (Baumgartner and Midttun,1986,30):

> (1) Reference to advanced mathematical and technical properties is an important political argument used by groups possessing a model monopoly to silence critical questions and challenges from groups without access to models.
>
> (2) Conflicts and arguments can be shifted from the political to the technical field. This is one method to reduce the circle of "legitimate" challengers, a reduction which limits the challengers to the group of professionalized and socialized people.

In their analysis of energy policy and modelling in Canada, Robinson and Hooker (1986,312) comment that; "Forecasts used as predictive tools are seen to be related in a particularly complex way to the policy-making process. They are both cause and consequence of policy decisions. Forecasts do not reliably reveal the future but they often justify the attempt to create (or prevent) a particular future". Commenting on the positive role of energy forecasting, these authors note that, "Under conditions of great uncertainty and when considerable choice as to the future direction of energy policy is available, the most useful, or at least most honest, role of forecasts may not be to predict the future but to test the feasibility and implications of different futures" (Robinson and Hooker,1986,313).

With the latter statement in mind, let us remind ourselves that part of the purpose of this thesis is to test the impact of a number of feasible future energy demand scenarios on the potential emission of carbon dioxide in Canada. In using energy demand scenarios to fulfill this purpose, no attempt whatsoever is made by the author of this thesis to predict Canada's actual future output of carbon dioxide associated with energy demand and use. Rather, by making use of a variety of different, yet feasible, energy demand scenarios the results of this thesis will give some indication of the bounds in which Canada's future emissions of carbon dioxide, from energy demand and use, may lie. In this manner, the energy demand scenarios chosen for this thesis are not used as predictive tools, but instead reflect their value in delineating the potential future implications of energy demand on carbon dioxide emissions.

The remainder of this chapter will examine the energy demand scenarios used in this thesis. Each scenario and the organization that developed them will be described in detail with particular attention paid to their characteristic attributes.

4.3 Description of the Energy Demand Scenarios and the Organizations That Developed Them

4.3.1 The National Energy Board (NEB)

The National Energy Board (NEB) was established by the Federal Government of Canada in July, 1959, through the passing in Parliament of the National Energy Board Act. According to the NEB Act, the NEB was established to primarily fulfill two mandates. Firstly, the NEB is a regulatory body who's powers include, "the licensing of the export of oil, gas and electricity, the issuance of certificates of public convenience and necessity for interprovincial and international pipelines and international power lines and the setting of just and reasonable tolls for pipelines under federal jurisdiction" (NEB,1986, i). Secondly, "The Act also requires that the Board keep under review the outlook for Canadian supply of all major energy commodities, including electricity, oil and natural gas and their by-products, and the demand for Canadian energy in Canada and abroad" (NEB,1986,i).

The NEB currently consists of eleven members, all of whom are appointed by the federal government, supported by a staff of about 450 people (Robinson and Hooker,1986,283). Since its inception, the NEB has prepared a number of reports on Canadian energy supply and demand, the most recent of which were published in September, 1984 and October, 1986. It is from these publications that the NEB scenarios used in this thesis were extracted.

Being a regulatory body, the NEB theoretically should act as an independent and impartial body in preparing its forecasts. Robinson and Hooker (1986,294) have criticized the NEB for straying from this ideal when they note that, "the forecasts prepared by the NEB often served clear political functions and closely reflected the general policy context prevailing at the time the forecast was prepared".

Criticism notwithstanding, the forecasts prepared by the NEB serve two functions in this thesis. Firstly, NEB data was used to construct Scenario A - the 1985 historical base case. This is the data set from which all the other Scenarios (B-G) are compared and analyzed with respect to improvement, or lack thereof, over current levels of emissions of carbon dioxide from energy use in Canada. Secondly, the NEB forecasts are representative of the conservative side of energy demand analysis in Canada. The NEB forecasts are strongly rooted in the extrapolation of current energy demand into the future. Their econometric demand models adopt a laissez-faire attitude in terms of energy demand growth and the choice of fuels used to meet that demand.

4.3.1.1 Characteristics of Scenario A

As mentioned previously, Scenario A represents Canada's actual total energy demand for 1985 and serves as the historical base case from which the other scenarios are compared. In this thesis, total energy demand is defined as total primary demand for all types of energy less any non-energy demand. With respect to fossil fuels, total energy demand only takes into account that amount of fuel that will undergo combustion and hence release carbon dioxide into the atmosphere. For a complete description of total energy demand refer to Section 5.3.1.

The data used in constructing Scenario A was obtained from Table A3-3 (Total Energy Balance - Canada), of the National Energy Board's (NEB,1986,160) report, Canadian Energy: Supply and Demand 1985-2005 (Appendix C). Details with respect to the methodology used in developing this scenario can be found in Section 5.3.3.

4.3.1.2 Characteristics of Scenario B

Scenario B, the 2005 Low Oil Price Case, represents the National Energy Board's vision of what the future demand for energy in Canada may be should the world price of oil remain low. The data used in constructing Scenario B was also obtained from Table A3-3 of the NEB's 1986 (175) report. Of all the scenarios examined in this thesis, Scenario B is the most strongly rooted in the technique of extrapolating present socio-economic conditions into the future. Scenario B is a product of the unusually low oil prices that have been characteristic of the energy market since the world price of oil began to decline in 1984.

As with any forecasting exercise, the NEB's energy demand models are strongly based on a number of key assumptions. First among these is the way in which the NEB views Canada's role in the world energy picture. According to the NEB (1986,2): "On a world scale Canada is a relatively small producer and consumer of oil. Therefore we (the NEB - auth.) assume that Canada will be a price taker on the world oil market, exporting and importing oil at world market prices. We assume continuation of the current policy whereby domestic oil prices are not regulated, and there are no export taxes, import duties or other charges of equivalent effect on crude oil or most internationally traded oil products".

Assumptions with respect to the world price of oil are key to the NEB's forecasting. The NEB (1986,7) notes that: "The pricing assumptions are central to the whole overview because the cost of energy affects total energy demand and supply".

In particular, in developing their low price scenario the NEB (1986,9) have made the following assumptions:

> Excess supply and flat demand in 1986 will at best allow for a weak OPEC agreement on export quotas for each member; therefore prices will remain relatively low for the rest of the year, yielding a 1986 average price of about $US 14 per barrel.

Moderate real economic growth occurs in major consuming countries over the outlook period, but there is a low degree of responsiveness in demand for oil; low prices and increasing incomes do not lure consumers back to considerably increased oil dependence for fear of future price effects.

At prices around $US 18 (1986) per barrel, there continues to be economic incentive to implement additional conservation measures, constraining both oil demand growth and the scope for sustained price increases above about $US 18 (1986) per barrel.

With low demand growth, non-OPEC supply continues to satisfy over half of international demand, it being assumed in this scenario that sufficient non-OPEC supplies of oil, gas or alternative energy could be made available as needed over the long-term at equivalent oil prices of up to $US 18 (1986) per barrel.

With relatively flat demand, weak prices and competitive energy supply alternatives, OPEC countries are unable to exercise much discipline over supply. Price increases are constrained by market forces. If producers tried to increase cash flow by increasing volume beyond the market share available at the going price they would depress prices. Under the circumstances, appropriate quota balancing within the OPEC group is not easily manageable.

In conclusion, of all the scenarios examined in this thesis, Scenario B demonstrates the largest total energy demand in the year 2005. Hence Scenario B delineates the upper bound for total energy demand in Canada in the year 2005, and coincidentally the upper bound for potential carbon dioxide emissions (see Section 6.2.2).

4.3.1.3 Characteristics of Scenario C

Scenario C, the 2005 High Oil Price Case, represents the National Energy Board's vision of what the future demand for energy in Canada may be should the world price of oil increase over the projection period to a peak of $US 27 (1986) per barrel. The data used in constructing Scenario C was also obtained from Table A3-3 of the NEB's 1986 (176) report.

The NEB's (1986,9) higher oil price outlook is based on a number of key assumptions:

> Low short-term oil prices stimulate economic growth in major consuming countries. Income responsiveness of demand for oil is higher than in the low price case. As oil prices increase, the economic growth stimulus of lower prices is dampened, but demand for oil remains relatively strong in response to the economic growth which does occur.
>
> Non-OPEC supplies of oil, gas and alternative energy are more expensive and less abundant than presumed in the low price case. Furthermore, they dwindle more quickly than under the low price case due to investor pessimism and financing problems created by low prices in the mid-to-late 1980s.
>
> American natural gas prices increase as the U.S. gas deliverability surplus is worked off and new reserves become available, but at increasing marginal cost.
>
> Increasing demand, falling non-OPEC supply in the late 1980s/ early 1990s and the higher cost of alternative energy provide a higher share of the world oil market to OPEC and more room for OPEC to coordinate markets and influence prices.

A peak price of $US 27 (1986) per barrel was set by the NEB (1986,9) in recognition of the fact that, "around this price energy resources other than OPEC oil should be available, constraining OPEC's ability to sustain price levels much beyond this range".

Having examined the assumptions that underlie both the NEB's (1986) High and Low Price Cases, it should be noted that not even the NEB expect that either of their energy demand scenarios will be followed precisely. In fact, the NEB (1986,3) recognize that:

> The definition of the lower and higher price paths does not mean that oil prices will remain on either one of these paths year after year. The oil price will most likely fluctuate above or below each of these paths in any year, but it is not possible to forecast these fluctuations. The meaning of these two scenarios is that each is a 'qualitatively' different long-term view emerging from different behavioural assumptions sustaining either relatively lower or higher prices. Moreover, it is possible that the actual path could be a composite of the two projections, for example close to the low path in the earlier years, drifting up over time toward the higher path by the end of the study period.

In conclusion, it would appear that the NEB's (1986) High and Low Price Cases represent their own delineation of where future Canadian energy demand may lie. Given the conservative nature of the NEB's energy demand models, even Scenario C, the High Price Case, indicates that total energy demand in Canada in the year 2005, will still be at the high end of the spectrum (see Section 6.2.3) in comparison with the other scenarios examined in this thesis.

4.3.1.4 Characteristics of Scenario D

Scenario D represents the National Energy Board's (1984) vision of what the future demand for energy in Canada may be should the world price of oil rise over the projection period to a peak of $US 38 (1983) per barrel. The NEB (1984,8) developed this scenario when world oil prices were still under the influence of the 1979-80 price shock, when the cost of a barrel of crude oil reached a staggering peak of $US 34 (1981). The data used in constructing Scenario D was obtained from Table A10-3 (Total Energy Balance - Canada 2005), of the National Energy Board's (NEB,1984,A-205) report, Canadian Energy: Supply and Demand 1983-2005.

Once again the NEB emphasizes their opinion that energy supply and demand are inextricably linked to the cost of energy. They note that "Energy supply and demand are influenced by numerous factors some of which relate to a particular energy form and others of which are pervasive. Among the latter, the prices of energy commodities relative to each other and to other goods and services, and the level of economic activity, are critical." (NEB,1984,5)

In their 1984 report, the NEB assumed that existing federal and provincial policies relating to the pricing and taxation of energy commodities would remain in force over the projection period. The NEB (1984,9) also assumed that the Canadian economy would continue to grow at a modest rate (approx. 3% p.a.) over the projection period. The latter assumption is consistent with the NEB's view that renewed upward pressure on the world price of oil tends to be influenced by an optimistic view of world economic growth (NEB,1984,7).

The NEB's 1984 and 1986 energy supply and demand reports provide an interesting comparison. The former was developed under the influence of the highest oil prices the global economy had ever witnessed, while only two years later, the latter was developed under the influence of extremely low oil prices. These two reports emphasize the inherent instabilty that surrounds the supply of, and demand for, conventional energy. The NEB's reports also serve to highlight the fact that many of the elements that influence the cost of conventional energy are largely beyond the control of any one country.

In conclusion, despite the large degree of uncertainty that surrounds the availability of fossil fuels, and in particular oil, both NEB reports assume that the types and percent share of fossil fuels we use today will remain essentially the same over the projection period (see Sections 6.2.1 - 6.2.4). This observation serves to emphasize the conservative nature of the NEB energy demand forecasts. In general, the NEB energy demand forecasts serve as an indication of what our future output of carbon dioxide from the combustion of fossil fuels may be if we choose to maintain our current trends in energy consumption. The NEB forecasts assume that our consumption of energy is largely influenced by economic factors and little or no attempt is made to inject any degree of concern about the quality of the environment.

4.3.2 Cheng, H.C., Steinberg, M. and M. Beller

Cheng et al. are members of the Process Science Division of the Department of Applied Science at Brookhaven National Laboratory in Upton, New York. They were commissioned by the Carbon Dioxide Research Division of the United States Department of Energy to investigate the effects of energy technology on global CO2 emissions. The results of their investigation have been summarized in their report entitled, Effects of Energy Technology on Global CO2 Emissions (Cheng et al.,1986).

The purpose of Cheng et al.'s study was to, "explore the potential for more effective use of energy through improvements in energy technology and to determine the consequent reduction in future buildup of atmospheric CO2 (which would mitigate the expected climatic and environmental changes)" (Cheng et al.,1986,1). The perspective of the study is from the physical sciences rather than the social and political sciences. As the authors note, the study "focussed on how energy is consumed for a specific energy service rather than on technical trade-offs such as use of mass transit instead of automobiles" (Cheng et al.,1986,1).

In their study, Cheng et al. (1986,1) first grouped energy technologies by stage of evolution as (1) now in use, (2) emerging, and (3) advanced or far-out, and the associated energy-efficiency levels were evaluated in terms of (1) present, (2) achievable, and (3) theoretical maximum. The authors then estimated the potential energy savings from introduction of efficiency improvements in the future.

Energy savings in the residential and commercial sector are estimated to be achievable through efficiency improvements in space heating, water heating, lighting and miscellaneous electric (e.g. appliances). In the industrial sector improvements in energy efficiency are expected in process heat, electric drive, aluminium electrolytic process, iron and steel and petrochemical feedstock. Efficiency improvements are also expected in the transportation sector through continued improvement in vehicle design. Because of the limitations of time and space, I recommend that those interested in the specific technologies involved in achieving these efficiency improvements consult Cheng et al's. work directly.

In assessing the suitability of this largely American study for this 'Canadian' thesis, the authors themselves note that:

> Since Canada and Western Europe and the OECD (Organization for Economic Cooperation and Development - auth.) Pacific are industrially developed, having a technological basis and economic growth trends generally similar to those in the U.S., the same efficiency gains through technology improvements are thought to apply to these regions as to the U.S. Thus the energy savings obtainable by applying higher-efficiency technologies in these regions can be calculated by applying the relative percentage fuel savings (i.e., technology improvement factor) in the U.S. for each fuel type and end-use sector. ... The energy savings by fuel type in Region 2 (Canada and Western Europe) over the fuel demand in year 2050 with mid-1970's technological efficiency are 55% for liquids, 61% for gases, 70% for solids, and 43%

for electricity (Cheng et al.,1986,31-32).

The precise details as to how these values were adapted to fit the format of this thesis can be found in Section 5.3.4.

Cheng et al's. (1986) study serves as a middle ground between the conservative NEB scenarios (Scenarios B-D) and the call for a new approach to energy use by Friends of the Earth Canada (Scenarios F and G). Scenario E represents a situation in which the total energy balance (see Section 5.3.2) does not change significantly over the present situation. In other words, the fuel mix remains much as it is today. This scenario adopts a strong conservation ethic without resorting to significant fuel substitution. By stressing fuel efficiency over absolute cutbacks in consumption, economic productivity is not necessarily hindered.

As the authors note, "the fact that improved technologies are sufficiently well known for use today plus the finding that the potential for energy savings and CO2 reduction is very large indicate the great importance of technology improvement in determining future energy consumption and CO2 emissions (Cheng et al., 1986,5). Moreover, they add that, "More efficient use of energy not only would extend the period for using known finite energy resources and allow time for a smooth transition to alternatives, but also would reduce the strain on the environment due to both energy production and consumption and allow more time for remedial action" (Cheng et al.,1986,7). The latter statement is consistent with the idea that the scenario developed from

Cheng et al's (1986) data forms a middle ground of opinion in this thesis.

4.3.2.1 Characteristics of Scenario E

Scenario E incorporates the potential reductions in energy demand from the adoption of improved energy technology as outlined by Cheng et al. (1986,32). By implementing this strategy, Cheng et al. (1986,32) have concluded that mid-1970's productivity can be sustained with significantly less energy input than was required at that time.

Scenario E simulates a situation in which stringent energy conservation is practiced for all fuel types among all sectors. So strong is the conservation ethic that it is even applied to renewable fuels. The total energy balance remains essentially as it is today.

4.3.3 Friends of the Earth Canada

In May 1978, Canada's major environmental groups joined together to establish Friends of the Earth Canada, a sister group of the world-wide environmental organization Friends of the Earth International. The fundamental objective of Friends of the Earth

Canada is, "to encourage and promote Canada's movement towards a 'Conserver Society'" (Friends of the Earth Canada,1979,2). A Conserver Society is defined as one that:

> Recognizes that the world is both finite and interdependent - and behaves accordingly. A Conserver Society cares for the future, in the knowledge that erroneous decisions in such areas as energy and resources often have irreversible and destructive impacts in the long term. A Conserver Society is, on principle, opposed to waste, pollution and destruction of the environment. Last, but certainly not least, a Conserver Society is built on a framework of social justice and political democracy (Friends of the Earth Canada,1979, 2-3).

One of the key objectives of this organization was to design and promote a soft energy path (SEP) for Canada. The term 'soft energy path' was introduced by Lovins (1977,38) to describe energy policy paths or strategies directed towards achieving principle reliance upon 'soft energy technologies'. In turn, soft energy technologies are defined by the following characteristics (Brooks et al.,1984,59-60):

> They rely on renewable energy flows that are always there whether we use them or not, such as sun and wind and vegetation: on energy income, not on depletable energy capital.
>
> They are divers, so that as a national treasury runs on many small tax contributions, so national energy supply is an aggregate of very many individually modest contributions, each designed for maximum effectiveness in particular circumstances.
>
> They are flexible and relatively low technology - which does not mean unsophisticated, but rather, easy to understand and use without esoteric skills, accessible rather than arcane.
>
> They are matched in 'scale' and in geographic distribution to end-use needs, taking advantage of the free distribution of most natural energy flows.

They are matched in 'energy quality' to end-use needs. Finally,

They are as environmentally benign as possible, given the inherent interactions with renewable resources that all production, transportation and use of energy involve.

In contrast to soft energy paths are 'hard energy paths', which are characterized by, "an emphasis upon increasing energy supply and by increasing scale, electrification, and centralization of energy production" (Brooks et al.,1984,59). In general, hard paths tend to be more typical of traditional views of likely energy futures, while soft path studies tend to represent challenges to the status quo. Brooks et al. (1984,26) also note that, "with either hard paths or soft, the most important environmental impacts from the primary production stage affect land and water resources. At later production and end-use stages, impacts on air become the most significant". In their preliminary assessment of the relative impacts of hard and soft energy paths the authors also note that, "hard paths tend to be characterized by environmental problems related to emissions, and soft paths by those related to land use. Thus, the two paths offer a trade-off in kind as well as in magnitude of impact" (Brooks et al., 1984,26).

In meeting their objective to promote soft energy paths, in 1980 Friends of the Earth Canada was commissioned by the Department of Energy, Mines & Resources and Environment Canada to prepare a report on the feasibility of adopting a soft energy strategy in Canada. The national study took over three years to complete, and in 1983 their report entitled, <u>2025: Soft Energy</u>

Futures for Canada - Volume 1: National Report, was published (Brooks et al.,1983). In addition, the group also published a more popular (less technical) version of the report entitled, Life After Oil: A Renewable Energy Policy for Canada (Bott et al.,1983).

In their study, Friends of the Earth Canada prepared two energy demand scenarios, projected to the years 2000 and 2025. The scenarios, referred to as 'Business as Usual' (BU) and 'Consumer Saturation' (CS), were developed using Statistics Canada's Long Term Simulation Model (LTSM). The LTSM is a materials balance model of the Canadian economy based upon input-output tables (Brooks et al.,1983,10). The authors emphasize that, "this simulation model was used to project the economic characteristics of the society, but not the energy characteristics; the latter were developed independently -- indeed, they formed the core of the study -- and they were grafted onto the framework provided by the former" (Brooks et al.,1983,15).

In order to strengthen their study, a number of major conservatisms were incorporated into the analysis. These include (Brooks et al.,1983,270-275):

No major changes in values or lifestyles are assumed;

No significant technological changes are assumed;

No improvements in the efficiency of materials use are included;

Market-determined interest rates are assumed to reflect meaningful resource discount rates;

The social and environmental costs of all fuels have been ignored;

Only modest reductions in the real costs of soft energy technologies are assumed;

No transportation modal shifts or substitution effects and few load factor improvements were included in the analysis;

Potential savings from cogeneration or energy cascading in industry are not analyzed;

Population projection is high;

Solar pre-heating of industrial process heat requirements is excluded;

Potential savings from district heating or changes in urban form are not analyzed; Finally,

Conservation savings in the energy supply sector were largely ignored..

In addition, certain energy options were excluded, (e.g. arctic oil and new nuclear power stations) while other options were de-emphasized (e.g. large-scale coal and hydro projects).

Although filled with deliberate conservatisms to strengthen the validity of their report, the Friends of the Earth Canada study is a radical departure from the conservative nature of those prepared by the NEB. In borrowing their terminology, Friends of the Earth Canada call on us to follow a new 'path' towards energy demand and consumption. This new path is characterized by a strong conservation ethic and a movement towards the increased adoption of renewable fuels.

The Friends of the Earth Canada study is unique in that from the outset, "it was designed as a national study, with a consistent set of national parameters for population and economic growth, appliance efficiencies, transportation technology, etc."

(Brooks et al.,1983,9). This national consistency provides a good framework for their analysis.

4.3.3.1 Characteristics of Scenario F

Scenario F, also referred to as the 'Business as Usual' (BU) scenario, was adapted from Table CA-12 and CA-13 of the Friends of the Earth Canada study (Brooks et al.,1983,193-194). Full details on the methodology used in adapting this information to the framework of this study can be found in Section 5.3.5.

In developing their Business as Usual scenario, the authors incorporated a number of key assumptions, including (Brooks et al.,1983,16):

Maintenance of full employment by keeping constant labour hours worked per person per year.

Strong economic growth - an increase of more than 200% in Gross Domestic Product (GDP) over Friends of the Earth Canada's study period (1978 - 2025).

Moderate population growth - an increase of over 50% (approx. 1% per annum) over their study period.

No supply or demand measure or energy conservation or renewable technique was introduced until it was proven cost effective in comparison with conventional fuels.

No lifestyle changes are required.

Should the conditions characteristic of Scenario F be realized, the authors conclude that "it would be technically feasible and cost-effective to operate the Canadian economy in 2025 with 12% less energy than it requires today (1978 - auth.), and, over the same 47 year period to shift from 16% reliance on renewable sources to 77% (Brooks et al.,1983,11).

Under the conditions of the Business as Usual scenario, low energy growth is realized not because of a decline in the economy nor in productivity but rather, because of gains in energy efficiency, which, according to the authors, "have exactly the same positive economic effects as gains in labour productivity" (Brooks et al.,1983,85).

While time and space do not permit a complete examination of the techniques proposed by the authors to improve energy efficiency, in brief, these techniques generally advocate the following: the importance of matching energy sources to end-use needs in terms of the quality of energy required; the adoption of the best available energy technology for a given task; and finally, the gradual adoption of three general renewable sources of energy (active solar heating and electricity, biomass solids and biomass fluids)(Brooks et al.,1983,128). The objective of "matching" energy sources to end-use needs, "is to increase system efficiency by matching sources of energy to uses of energy in ways that, so far as possible, minimize conversion losses and transportation and transmission losses (with "losses" being interpreted in both its thermodynamic and its economic senses)" (Brooks et al.,1983,150). For those interested in a more detailed examination of the energy conservation techniques advocated by Brooks et al. (1983), please consult 2025: Soft Energy Futures for Canada - National Report.

In conclusion, Scenario F represents a situation in which not only are strong energy conservation measures advocated but also, Canadian society begins a transition towards the adoption of non-conventional forms of energy, which, for the most part, are renewable. These changes take place without hurting the economy and without any changes in lifestyle. By using energy more efficiently and by matching appropriate energy forms to end-use needs, Canadians in 2005 will be doing much the same as they do today with much less fossil energy required.

4.3.3.2 Characteristics of Scenario G

Scenario G, also referred to as the 'Consumer Saturation' (CS) scenario, was adapted from Tables CA-14 and CA-15 of the Friends of the Earth Canada study (Brooks et al.,1983,195-196). Full details on the methodology used in adapting this information to the framework of this study can be found in Section 5.3.5.

In developing their Consumer Saturation scenario, the authors incorporated a number of key assumptions, including (Brooks et al.,1983,16):

Maintenance of full employment by trading income for leisure so that labour hours per person per year fall by about 30%.

Moderate economic growth - an increase of 140% in Gross Domestic Product (GDP) to 2025.

Same population growth as incorporated in Scenario F.

Somewhat less than fully cost-effective efficiency improvement techniques were incorporated.

Modest lifestyle changes were allowed to be incorporated at the provincial study level.

Should the conditions characteristic of Scenario G be realized, the authors conclude that, "it would be feasible and cost-effective to use 34% less energy in 2025 than in 1978, with 82% of that energy provided by renewable sources" (Brooks et al.,1983,11). They also add that, "technical feasibility is defined in terms of the availability today of either off-the-shelf or prototype technology. Cost-effectiveness is defined in terms of the long-run marginal costs of alternative ways of supplying energy in Canada." (Brooks et al.,1983,11).

The same techniques used in Scenario F to improve energy efficiency are also used in Scenario G. The difference between the two scenarios is that in Scenario G, many of these techniques are adopted before they become fully cost effective. The implementation of Scenario G also necessitates a number of moderate lifestyle changes, such as, working fewer hours in exchange for more leisure time. Because the individual works fewer hours, disposable income is gradually reduced, hence demand for goods and services decreases, and therefore the demand for the energy required to provide these goods and services also decreases (Brooks et al.,1983,84).

In general, the authors note that their Consumer Saturation scenario does not represent an all-out conserver society, nor does their Business as Usual scenario approach all-out growth. Rather, they note that, "the two bracket a range of moderate growth possibilities under assumptions that seem reasonable about the nature of industrial production and the use of consumer incomes" (Brooks et al., 1983,25).

In conclusion, Scenario G represents a situation in which the adoption of strong energy conservation techniques, non-conventional, renewable fuels and a less energy-intensive lifestyle are advocated. Of all the scenarios examined in this thesis, Scenario G demonstrates the smallest total energy demand in the year 2005. Hence, Scenario G delineates the lower bound for total energy demand in Canada in the year 2005, and coincidentally the lower bound for potential carbon dioxide emissions (see Section 6.2.8). Of all the energy demand scenarios studied in this thesis, Scenario G represents the greatest challenge to conventional energy demand and use in Canada. In terms of the types and quantity of energy used, and indeed how it is used, Scenario G represents the most radical departure from our present situation (Scenario A).

4.4 Forecasting Vs. Backcasting

Two terms that are inextricably linked to the concept of energy demand analysis are forecasting and backcasting. Forecasts of future energy demand are based upon the analysis of past trends and the extrapolation of these trends into the future. Forecasting is inherently conservative and as a technique, does not lend itself easily to the analysis of new trends and developments. Forecasts also tend to be deterministic in that because of their limited data base, they may often become nothing more than self-fulfilling prophecies. The strength of forecasting is in its ability to predict short-term patterns in a manner that is relatively straightforward to understand. Examples of forecasts in this thesis include all scenarios developed by the National Energy Board (Scenarios B-D) and, to a certain extent, that adapted from Cheng et al. (1986)(Scenario E) which simply projects potential improvements in current energy technology into the future.

By definition, backcasting is concerned, "not with what energy futures are likely to happen, but with how desirable futures can be obtained. They are thus explicitly normative, involving 'working backwards' from a particular chosen future end-point to the present in order to determine what policy measures would be required to reach that future" (Robinson,1982,337). The only true backcasts used in this thesis are the scenarios (F and G) prepared by Friends of the Earth Canada.

Brooks et al. (1983,5) note that, "the outcome of a good forecast is an indication of the likely results of certain specified conditions" while, "the outcome of a good backcast is an indication of what policy measures would have to be taken in order to reach a specified goal". They also note that:

> The difference between forecasting and backcasting is thus as much one of approach as of methods. Both techniques must incorporate policy changes; both must also make use of some predictions; both can be highly quantitative. The value of backcasting, which in contrast to forecasting, increases as the time horizon of the study is extended, is that it makes possible the exploration of the feasibility and viability of a wide range of possible energy futures rather than, as Rene Dubos stated, elevating trend to destiny (Brooks et al.,1983,5).

In general, backcasting is concerned with how desirable energy futures can be obtained, while forecasting is concerned with what futures are likely to happen.

4.5 Conclusions

As one can see, the energy demand scenarios considered in this thesis range from the conservative to the challenging. By incorporating such a wide spectrum of viewpoints in this study, the author of this thesis hopes that the chosen energy demand scenarios delineate Canada's potential future energy demand in the year 2005, and hence, delineate our potential future emissions of carbon dioxide from energy use.

The individual scenarios were chosen not only for their philosophical differences, but also for the credibility of the individuals or organizations that developed them. Although it is unlikely that Canada's energy demand in the year 2005 will be exactly the same as outlined in any one of the scenarios discussed in this thesis, it is likely that it will fall within the range of these projections.

Clearly, since energy policy is a matter of choice, the energy demand scenarios in this thesis provide a variety of options with respect to the types and amount of fuel we choose to meet our energy demand. In turn, these decisions on energy policy have a direct impact on the amount of carbon dioxide we choose to introduce to the atmosphere.

The next chapter will examine the methodology used to apply the energy demand scenarios to a study of potential carbon dioxide emissions.

5.0 METHODOLOGY

5.1 Introduction

Now that we have described the energy demand scenarios that will be examined in this thesis, we must now discuss the methodology used to carry out the analysis. We begin by describing the calculations required to derive the carbon dioxide emission factors (Section 5.2). These are the values that when applied to the energy demand scenarios will indicate the expected emission of carbon dioxide.

We next examine the calculation of total energy demand for each scenario (Section 5.3) In addition, an explanation as to how each scenario was standardized to fit the format of this study is included.

Finally, we examine the calculation of the carbon dioxide emissions associated with each scenario (Section 5.4). In general, the methodology adopted in this thesis offers several improvements over earlier examples. Firstly, a full description of the calculation of the carbon dioxide emission factors is included. These values were calculated from data which reflects the carbon content of the fuels used in Canada. Secondly, three carbon dioxide emission factors were applied to coal consumption, reflecting the significant differences in carbon dioxide emission associated with the three different grades of coal. Thirdly, the difficulties met in standardizing energy demand scenarios of different formats are discussed in order to assist others in their attempts to analyze other scenarios in similar studies.

5.2 Calculation of Carbon Dioxide Emission Factors

Carbon dioxide emission factors are simply numerical expressions of the amount (by weight) of carbon, as carbon dioxide, liberated when a fuel undergoes combustion. The factors are standardized such that the amount of carbon released is related to the quantity of a given fuel required to generate a fixed unit of energy, such as, a petajoule (1 PJ = 10EXP15 J) or an exajoule (1 EJ = 10EXP18 J).

While published carbon dioxide emission factors do exist (Edmonds et al.,1986a & b; Rotty & Reister,1986; Acres,1983; Schware,1981; Keeling,1973; Niehaus, 1976; Parry & Landsburg,1977; Zimen et al.,1977; Rotty,1978 and Woodwell et al.,1979), they are generally lacking in two areas. Firstly, they tend to be too general, only providing emission factors for three types of fossil fuels; gas, liquids and solids, in other words, natural gas, oil products and coal. This generalization inadequately addresses the fact that the amount of carbon released as carbon dioxide from the burning of fossil fuels does vary between the specific types of fossil fuels, and in particular, between the various grades of coal. The second shortcoming associated with the published emission data is the lack of information given as to how the values were derived.

Because of the aforementioned weaknesses in the published values and in order to provide a better understanding of the relationship between fossil fuel consumption and carbon dioxide emissions, it has been deemed necessary to determine the carbon dioxide emission factor for each fossil fuel from what might be referred to as 'first principles'. This approach takes into account the fact that the amount of carbon released as carbon dioxide from the burning of a given type of fossil fuel is dependent on two factors:

(i) the gross energy content of the fuel, expressed as the energy content of that fuel for a given quantity (e.g. MJ/m3, GJ/tonne or GJ/m3). The value is then standardized to express the amount of fuel required to generate a fixed amount of energy. For example, the amount of fuel (expressed in teragrams, Tg) required to generate one exajoule (EJ) of energy (1 Tg = 10exp12 g; 1 EJ = 10exp18 J).

(ii) the carbon content of a given fuel, expressed as a proportion of its mass (or volume).

Hence, by knowing the gross energy content of a given fuel (i), one can determine the mass (or volume) of that fuel required to generate a fixed amount of energy. In a similar manner, if the carbon content of a given fuel is known (ii), that fuel's carbon dioxide emission factor can be determined by multiplying the carbon content of that fuel by the mass/volume of that fuel required to generate a fixed amount of energy [(i) * (ii)]. By following this procedure one obtains a carbon dioxide emission factor for each fuel, expressed as the amount of carbon released as carbon dioxide, in teragrams, for every exajoule of energy produced from the combustion of that fuel. By standardizing the emission factors for a fixed unit of energy, inter-fuel comparisons are facilitated. This standardization also makes it easier to apply these emission factors to published energy demand forecasts, which more frequently adopt the metric unit of energy measurement, the Joule.

The detailed calculations as to how the carbon dioxide emission factors used in this thesis were determined are to be found in Appendix A. Table 5.1 summarizes the essential pieces of data required to determine the carbon dioxide emission factor for each fuel.

The gross energy content factors for each fuel were obtained from the National Energy Board's (1986,130) report, Canadian Energy Supply and Demand: 1985-2005. By making use of this particular set of data the Canadian aspect of this study is further enhanced, as these values reflect the gross energy content of the fuels used in Canada. Because the energy content of a given fuel does vary from source to source, the use of recognized Canadian gross energy content factors enhances the accuracy of this national study.

The proportion of carbon by unit mass for each fuel was obtained from various sources. Keeling (1973,191) calculated that the average proportion of carbon by volume for natural gas was 524g of C/m3. Campbell (1986,55) gives the typical carbon content of bituminous or hard coal to be 70% by mass, while lignite

Table 5.1. Calculation of Carbon Emission Factors by Fuel Type.

Fuel Type	Gross Energy Content Factor (a)	Mass of Fuel Tg/EJ (b)	Proportion of C Converted to CO_2 by Mass (volume) (c)	Carbon Emission Factor Tg of C as CO_2/EJ (b)	Carbon Emission Factor Tg of C as CO_2/PJ (b)
Natural Gas	38.03 MJ/m3 (d)	524g of C/m3		13.78	0.01378
Bituminous Coal	29.30 GJ/tonne	34.13	0.700	23.89	0.02389
Subbituminous Coal	19.76 GJ/tonne	50.61	0.513	25.95	0.02595
Lignite	15.35 GJ/tonne	65.15	0.430	28.01	0.02801
Motor Gasoline	34.66 GJ/m3	21.35	0.869	18.55	0.01855
Kerosene	37.68 GJ/m3	21.51	0.869	18.69	0.01869
Aviation Gasoline	33.52 GJ/m3	22.08	0.869	19.18	0.01918
Natural Gas Liquids	24.17 GJ/m3 (e)	22.36	0.869	19.43	0.01943
Light Fuel Oil	38.68 GJ/m3	22.49	0.869	19.55	0.01955
Aviation Turbo	35.93 GJ/m3	22.56	0.869	19.60	0.01960
Heavy Fuel Oil	41.73 GJ/m3	22.77	0.869	19.79	0.01979
Average Carbon Emission from Combustion of Refined Petroleum Products				19.26 (f)	0.01926

(a) source NEB, 1986.
(b) for detailed calculations refer to Appendix A.
(c) source Keeling, 1973; Zimen et al., 1977 and Campbell, 1986.
(d) national average, n = 8, std. dev. = 0.95
(e) average of the gross energy content of three NGLs; ethane, propane and butane, std. dev. = 4.30.
(f) based on average carbon emission Tg/EJ of Motor Gasoline to Heavy Fuel Oil, n = 7, std. dev. = 0.44

contains only 43% carbon by mass. The carbon content of subbituminous coal,an intermediate grade, was estimated to be approximately 51% by mass (see Appendix A). Finally, Zimen et al. (1977,1545) indicate that the average carbon content by mass of refined petroleum products is approximately 87%.

The results of the calculations indicate that per exajoule of energy generated, the combustion of natural gas releases the least amount of carbon (C), only 13.78 Tg of C as CO_2/EJ. This is followed by refined petroleum products, which upon combustion emit on average 19.26 Tg of C as CO_2/EJ, approximately 1.4 times more than natural gas. By far the worst offenders in terms of carbon emissions are the various grades of coal. The combustion of high-grade or bituminous coal releases 23.89 Tg of C as CO_2/EJ, medium-grade or subbituminous coal releases 25.56 Tg of C as CO_2/EJ, while low-grade coal or lignite releases 28.01 Tg of C as CO_2/EJ. The latter carbon emission factors for coal are respectively approximately 1.7, 1.9 and 2.0 times more than natural gas. These values are comparable with those published by Gates (1985, 150) who also found that the combustion of oil products released 1.4 times more carbon than the combustion of natural gas per unit of energy consumed and coal (unspecified grade) 1.7 times more.

The carbon dioxide emission factors that have been calculated in this section are also comparable with published values, and this information is summarized in Table 5.2. The calculated value for natural gas is in very good agreement with the published emission factors, as are the calculated values for

Table 5.2. Comparison of Calculated Values With Published Carbon Dioxide Emission Factors.

Source	Carbon Dioxide Emission Factors (Tg of C as CO2/EJ)				
	Natural Gas	Coal			Refined Petroleum Products
		Bituminous	Subbituminous	Lignite	
Thesis Calculations	13.78	23.89	25.95	28.02	19.26
Edmonds et al. (1986a & b)	13.70	23.80			19.20
Rotty & Reister (1986)	14.10	23.90			19.70
Acres (1983)	13.55		25.00		21.93
Schware (1981)	13.57	23.99			18.94
Keeling (1973) (a)	13.76	23.95			16.70
Niehaus (1976) (a)			25.94	31.88	20.64
Parry & Landsburg (1977) (a)	13.85	24.21			19.34
Ziemen et al. (1977) (a)	13.57	24.33			
Rotty (1978) (a)	13.57	23.95			17.93-20.48
Woodwell et al. (1979) (a)	13.67	23.58			18.87

(a) summarized in Kellogg and Schware, 1981.

the three grades of coal and their published counterparts. The published emission factors for oil products demonstrate the greatest variation from the value calculated in this thesis. This is no doubt the result of the wide variety of fuels represented in this category, and the probability that the authors based their calculations on only one type of fuel, or an unspecified combination of fuels.

As mentioned previously, a significant problem with the published carbon dioxide emission factors is the lack of information as to how, and from what information the values were derived. It is hoped that the information presented in this section helps the reader to overcome these problems and thus come to a better understanding of the relationship between fuel type and carbon dioxide emission.

5.2.1 Biomass Fuels and Carbon Dioxide Emissions

Biomass fuels include organic materials such as wood, mill waste, crop waste and crops produced for the production of energy. These fuels already play a small role in Canada's total energy balance and most energy demand scenarios project that they will play a much larger role in Canada's energy future (see Chapter 6).

Because biomass fuels are carbon based, during combustion carbon dioxide is formed and released. It must also be remembered that carbon dioxide is an essential plant nutrient, transformed by plants from the gaseous state into carbohydrates and other organic materials by photosynthesis. This process represents one component of the biogeochemical cycling of carbon.

If plant material is harvested for energy production, it is assumed that the production of any biomass fuels will be done on a strictly renewable basis. Hence, from a carbon dioxide emissions perspective the carbon cycle is essentially balanced, though somewhat accelerated. Therefore, no net emission of carbon dioxide is assumed from the combustion of renewable biomass fuels. This in no way implies that the emission of other substances (e.g. particulates) from the combustion of biomass fuels is in a similar balance.

5.2.2 Other Fuels and Carbon Dioxide Emissions

No carbon dioxide emissions result from the generation of energy from the following fuel sources: hydro, nuclear, solar, wind or tidal electricity, nor from geothermal or hydrogen based energy production.

5.2.3 Carbon Dioxide Emissions from Non-Combustive Processes

Because the author has restricted this research to the study of carbon dioxide emissions resulting from the use of energy, emissions of carbon dioxide from non-combustive processes have been excluded. Non-combustive sources of carbon dioxide include the production of cement and ammonia. Carbon dioxide is also released as a result of the oxidation of organic matter in soils. The latter process is accelerated whenever a soil is disturbed as is the case with certain agricultural practices.

5.3 Calculation of Total Energy Demand

5.3.1 Definition of Total Energy Demand

When speaking of energy demand, one generally refers to either primary or secondary demand. By definition, secondary energy demand (also referred to as end use demand for energy) refers to the "energy used by final consumers for residential, commercial, industrial and transportation purposes, and hydrocarbons used for such non-energy purposes as petrochemical feedstock" (NEB,1986,132).

On the other hand, primary energy demand includes not only end use demand for energy, but also energy used by the energy supply industry to transform one energy form to another (e.g. coal to electricity) and the energy used by suppliers in transporting energy to the market (e.g. pipeline fuel)(NEB,1986,134).

It is clear that neither of these standard definitions is adequate for the purpose of this study. In the case of secondary energy demand, the energy required to produce and deliver the secondary product is not taken into account, hence emissions of carbon dioxide from these sources are overlooked. In both cases the use of fossil fuels for non-energy purposes such as petrochemical feedstock, asphalt production and the manufacture of lubricants, greases and petroleum coke is taken into account. Since the latter products do not undergo combustion, no carbon dioxide is released from their use, hence the use of unadjusted primary energy demand figures would result in an overestimate of carbon dioxide emissions.

From a carbon dioxide emissions perspective, one is only interested in the total demand for fossil fuels that will definitely undergo combustion. This value can be determined from published energy demand reports by simply subtracting non-energy demand for a given fuel from the primary demand for that fuel. The specific values used do vary among the energy demand scenarios utilized in this study, and these differences are discussed under the sections devoted to each specific case (Sections 5.3.3 - 5.3.5).

5.3.2 Total Energy Balance Approach

In order to give a better understanding of the changing role of fossil fuels among the different energy demand scenarios examined in this study, Canada's complete energy balance is examined. In other words, a total energy balance approach looks at total demand for all types of energy: fossil fuel based, renewable, and hydro and nuclear generated electricity. Quite simply, the value derived expresses Canada's total demand for energy, less our demand for fuels for non-energy purposes.

This approach allows for the calculation of the following useful statistics:

(i) Percentage of total energy demand (TED) met by fossil fuels. This statistic indicates the overall importance of fossil fuels in meeting Canada's total energy balance among the different scenarios.

(ii) Percentage of total energy demand met by hydro and renewables. This statistic indicates the overall importance of what might be considered the more environmentally benign forms of energy to Canada's total energy balance.

(iii) Percentage of total energy demand met by nuclear generated electricity. Once again this statistic indicates the overall importance of this controversial form of energy to Canada's total energy balance.

(iv) Ratio of total carbon emission to total energy demand, expressed as Tg of carbon emitted per PJ or EJ of energy generated. This value provides a useful means to compare the various energy demand scenarios with respect to the total amount of carbon generated given the total amount of energy produced.

(v) Percent increase or decrease in total energy demand for each scenario over 1985 historical total energy demand (Scenario A). Net change and per annum change calculated (see Appendix B for details of calculations).

(vi) Percent increase or decrease in total carbon emission for each scenario over 1985 historical total carbon emission. Net change and per annum change calculated (see Appendix B for details of calculations).

By making use of the latter statistics it is hoped that comparisons between energy demand scenarios will be facilitated.

5.3.3 Calculation of Total Energy Demand for Scenarios A,B,C and D

Scenario A, the 1985 Historical Base Case, was derived from Table A3-3 (Total Energy Balance - Canada), of the National Energy Board's (NEB,1986,160) report, <u>Canadian Energy: Supply and Demand 1985-2005</u>. Total energy demand was calculated by subtracting any non-energy use and petrochemical demand from the total primary demand indicated for each fuel type. The energy demand values are given in petajoules (PJ). The results of these calculations can be found in Chapter 6.

The National Energy Board has chosen to amplify the demand for nuclear generated electricity, using a conversion factor of 12.1 gigajoules per megawatt-hour (GJ/MW.h). The NEB (1986,111) chose to enhance the demand for nuclear generated electricity in order to reflect "the reality that Canada will not likely revert to fossil fuels to generate the quantities of electricity now being generated by CANDU reactors." Because this study is interested in conveying the true demand for energy, the NEB's values for total demand for nuclear energy were recalculated to reflect the standard conversion factor of 3.6 GJ/MW.h.

Scenario B, the 2005 Low Price Case and Scenario C, the 2005 High Price Case were also derived from Table A3-3 of the National Energy Board's report (NEB,1986,175-6). The same methodology used to determine the total energy demand for Scenario A was also used for Scenarios B and C. The results of these calculations can be found in Chapter 6.

Scenario D, a projection of energy demand in the year 2005, was obtained from Table A10-3 of the National Energy Board's (NEB,1984, A-205) report, <u>Canadian Energy: Supply and Demand 1983-2005</u>. Total energy demand was calculated as above and the energy demand values are given in petajoules (PJ). The results of these calculations can be found in Chapter 6.

In its 1984 report, the NEB also chose to enhance the demand for nuclear generated electricity, using a conversion factor of 10.5 GJ/MW.h. This particular value was used by the NEB in order to ascribe a fossil fuel equivalency to nuclear generated electricity. Once again, in order to reflect the real demand for nuclear generated electricity, the value for total demand for this fuel was recalculated to reflect the standard conversion factor of 3.6 GJ/MW.h.

The raw data used in developing Scenarios A,B,C and D can be found in Appendix C.

5.3.4 Calculation of Total Energy Demand for Scenario E.

In their report, Effects of Energy Technology on Global CO2 Emissions, H.C. Cheng, M. Steinberg and M. Beller (1986,32) estimated that by the year 2050, Canada could improve its fuel consumption efficiency over mid-1970s rates by 55% for liquids, 61% for gases, 70% for solids and 43% for electricity. These values represent a net improvement in efficiency over a seventy-five year period. Improvements in fuel consumption efficiency have an equivalent benefit in reducing total energy demand and consequently a reduction in CO2 emissions.

In order to adopt these values to the format of this study, an assumption of a linear improvement in efficiency over the seventy-five year period was made. With this assumption made, a simple compound interest formula can be applied to Cheng et al.'s (1986,32) data in order to determine the annual rate of improvement in efficiency.

The following compound interest formula was used:

Xp(1 + r)EXPn = Xf

Where Xp = present value, arbitrarily assumed to be 1000 units for simplicity of calculation.

n = 75 years.

Xf = future demand, calculated by multiplying improvement in efficiency by present value and subtracting this value from xP.
e.g. if efficiency improvement = .55% then,
xP(.55) = 1000(.55) = 550 therefore,
1000 - 550 = 450 = Xf.

r = calculated annual rate of improvement.

EXP = exponential function.

In order to calculate the net improvement in energy use efficiency over the twenty year period examined in this study, the calculated annual rate of improvement was incorporated in the same compound interest formula in which the following values were utilized:

Xp = 1985 historical total energy demand for the fuel in question (obtained from Scenario A).

n = 20 years.

Xf = demand in the year 2005.

r = calculated annual rate of improvement in energy use efficiency for the fuel in question.

A more detailed account of the calculations used to develop Scenario E can be found in Appendix D. The calculated annual rates of improvement in fuel consumption efficiency for each fuel are as follows:

Natural Gas	-1.25% p.a.
Refined Petroleum Products	-1.05% p.a.
Coal (solids)	-1.60% p.a.
Electricity (nuclear)	-0.75% p.a.

In Scenario E the total demand for hydro electricity is assumed to remain at 1985 levels. This assumption was made in order to reflect the fact that once in place, hydro generating capacity remains essentially fixed. Improvements in efficiency in the consumption of electricity are reflected in decreased demand

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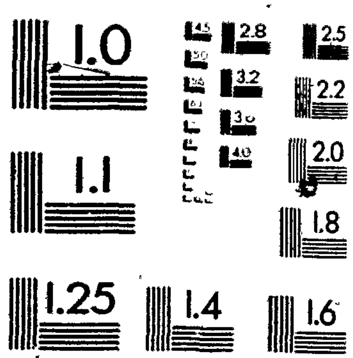


for nuclear generated electricity.

In Scenario E, the same rate of improvement in consumption efficiency for refined petroleum products is also applied to renewable fuels. The results of these calculations can be found in Chapter 6.

5.3.5 Calculation of Total Energy Demand for Scenarios F and G

In their report, 2025: Soft Energy Futures for Canada, D.B. Brooks, J.B. Robinson and R.D. Torrie (1983) provide projections for future energy demand in Canada for the years 2000 and 2025, under two distinct scenarios (F: Business as Usual and G: Consumer Saturation). Their tables provide energy demand values in petajoules (PJ) for a similar range of fuels as the National Energy Board's projections (NEB 1984 & 1986). The only real difference between Brooks et al.'s (1983) and the NEB's (1984 & 1986) range of fuels is that the former chose to subdivide renewable fuels into three distinct categories; active solar, wind and biomass. For reasons of simplicity and comparison between the different scenarios, Brooks et al.'s three categories were simply combined to form one category for total energy demand for renewable fuels.

Total energy demand for each fuel type was calculated by subtracting non-energy use from the sum of primary production plus net primary and secondary inflow (i.e. net imports). The raw data used in developing Scenarios F and G can be found in Appendix E.

As noted above, Brooks et al. (1983) have provided projections for only two future data points, the years 2000 and 2025, neither meeting the chosen twenty year projection period of this study. The authors note that their "study represents an energy version of what economists call comparative statics" and as such, "provides results for specific years but does not deal with the pattern of activity between those years" (Brooks et al., 1983,209). They also note that for the purpose of studying the implementation of their proposals, "the projected soft path results could, on the average, be achieved by implementation policies yielding equal changes from one year to the next", in other words, linear change between the comparative statics (Brooks et al.,1983,209).

With the latter statement in mind, Brooks et al.'s (1983) data can be manipulated to provide a data set meeting the requirements of this study by calculating the equation of the line between the two data points (the years 2000 and 2025) for each fuel. The total energy demand for each fuel for the study year 2005 can then be determined by substituting the year 2005 into the linear demand equation for each fuel.

Specifically, the slope (m) of the linear demand equation for each fuel can be determined as follows:

$$m = \frac{Y2 - Y1}{X2 - X1}$$

Where Y2 = total energy demand for a specific fuel in 2025.

Y1 = total energy demand for a specific fuel in 2000.
X2 = 2025.
X1 = 2000.

The y-intercept (b) of the line can then be determined by substituting the calculated slope (m) and one known point on the line [(X1,Y1) or (X2,Y2)] into the standard linear equation, Y = mX + b, as follows:

$$Y_n = m(X_n) + b$$

$$b = Y_n - [m(X_n)].$$

To determine the total energy demand for each fuel in 2005, one simply lets Y be the total energy demand for that fuel and solve the equation of the line by letting X = 2005 and b and m equal the calculated values for that fuel:

$$Y = m(2005) + b.$$

The detailed calculations used in developing Scenarios F and G are to be found in Appendix F and the results of the calculations can be found in Chapter 6.

5.3.6 Subdivision of Total Energy Demand Values for Coal Into Three Distinct Categories: Bituminous, Subbituminous and Lignite

All of the energy demand projections examined in this study treat coal as a single value, yet as noted in Section 5.2, the carbon dioxide emission factors do differ between the various grades of coal. These values range from a low of 23.89 Tg of C as CO2/EJ for bituminous grade coal to a high of 28.01 Tg of C as CO2/EJ for lignite.

The National Energy Board (Bowers,1987,personal communication) has provided the author of this thesis with their actual (1985) and estimated (2005 High Price and Low Price Cases) coal share values. In 1985 demand for coal was divided as follows among the three principle grades:

1985	Bituminous	44.6%
	Subbituminous	35.2%
	Lignite	20.2%
		100.0%

The latter values were only applied to the total demand for coal in Scenario A, the results of which can be found in Chapter 6.

Under the NEB's (1986) Low Price Case (LPC) (Scenario B) the demand for coal was divided as follows:

2005 LPC	Bituminous	49.9%
	Subbituminous	29.9%
	Lignite	20.2%
		100.0%

These values were only applied to the total demand for coal in Scenario B, the results of which can be found in Chapter 6.

Under the NEB's (1986) High Price Case (HPC) (Scenario C) the demand for coal was divided as follows:

2005 HPC	Bituminous	42.8%
	Subbituminous	37.5%
	Lignite	19.7%
		100.0%

These values were applied to Scenarios C through G. This blanket approach was adopted in recognition of the fact that high oil prices were either built into the scenarios (Scenarios C & D) or would be one of many factors that would prompt a move towards greater efforts to conserve fuel and/or substitute non-conventional sources of energy (Scenarios E through G). The results of this application can be found in Chapter 6.

It is hoped that by providing this extra detail greater clarity in terms of specific energy demand and carbon emissions can be attained.

5.4 Calculation of Carbon Dioxide Emissions

The calculation of the carbon dioxide emissions resulting from the total demand for a given fuel is straightforward. For each scenario, the total demand for each carbon dioxide emitting fuel was multiplied by its appropriate carbon dioxide emission factor. The individual values were added together, the total representing gross carbon dioxide emissions for each scenario. The results of these calculations can be found in Chapter 6.

The technique of applying carbon dioxide emission factors to energy demand values is standard among carbon dioxide emission studies. It is a technique that has been used to estimate past emission trends (Acres,1983 & Keeling,1973) as well as future trends (Edmonds et al.,1986a & b; Zimen et al.,1977; Rotty and

Reister, 1986; Niehaus,1976 and Schware,1981).

What this study hopefully adds to this body of literature is a more detailed description of the methodology which in turn has been applied at a more precise scale, national as opposed to global. In addition, Scenarios E through G have not previously been analyzed from a carbon dioxide emissions perspective.

6.0 RESULTS

6.1 Introduction

With the methodology having been applied, we now turn our attention to the results of the analysis which are summarized for each scenario (Section 6.2). We conclude this chapter with a brief analysis of current Canadian emissions of carbon dioxide in comparison with global emissions in order to place Canada's contribution into perspective (Section 6.3).

6.1.1 General Notes on Tables and Figures

The tables and figures presented in this chapter summarize the results of the analysis for each scenario. Each scenario is referred to by its alphabetic designation as follows:

A: 1985 Historical Case (actual values)(NEB,1986)

B: 2005 Low Price Case (NEB,1986)

C: 2005 High Price Case (NEB,1986)

D: 2005 High Oil Prices (NEB,1984)

E: 2005 All Fuels Efficiency Improvement (Cheng et al.,1986)

F: 2005 Business as Usual (Brooks et al.,1983)

G: 2005 Consumer Saturation (Brooks et al.,1986)

6.2 Results - By Scenario

6.2.1 Scenario A

Scenario A represents Canada's actual total energy demand and consequent carbon dioxide emissions for the year 1985. As the only historical case, Scenario A is the base from which the other scenarios are compared.

Table 6.1 and Figures 6.1 and 6.2 indicate that in 1985, Canada's total energy demand was 7212 petajoules (PJ) and the consequent emission of carbon as carbon dioxide was 102.4 teragrams (Tg). Of the 7212 PJ of total energy demand, 76.3% was met by fossil fuels, 20.7% by hydro and renewables, and 3.0% by nuclear (Table 6.2 and Figure 6.3).

Canada's emission of 102.4 Tg of carbon for a total energy demand of 7212 PJ is equivalent to an emission rate of 0.01420 Tg of carbon (C) as carbon dioxide (CO2) emitted per PJ of total energy demand (Table 6.2 and Figure 6.4).

Of the 102.4 Tg of total carbon emission, 23.5% is attributed to natural gas, 24.3% to coal, and the majority, 52.2%, to refined petroleum products (Table 6.3 and Figure 6.6). Natural gas, coal and refined petroleum products account for

Table 6.1. Total Energy Demand and Carbon Dioxide Emissions - Canada

Fuel Type: Total Energy Demand (PJ)/Carbon Dioxide Emissions (Tg)

Scenario	Natural Gas	Coal: Bitum.	Coal: Subbitum.	Coal: Lignite	Refined Petroleum Products	Renewable	Hydro	Nuclear	TOTAL
A: 1985 Historical (NEB, 1986)	1751.0 24.1	437.0 10.4	345.0 9.0	198.0 5.5	2774.0 53.4	517.0 0.0	977.0 0.0	213.0 0.0	7212.0 102.4
B: 2005 LPC (NEB, 1986)	2902.0 40.0	981.0 23.4	588.0 15.3	397.0 11.1	3448.0 66.4	670.0 0.0	1422.0 0.0	456.0 0.0	10864.0 156.2
C: 2005 HPC (NEB, 1986)	2518.0 34.7	785.0 18.8	688.0 17.9	361.0 10.1	2900.0 55.9	667.0 0.0	1388.0 0.0	477.0 0.0	9784.0 137.4
D: 2005 (NEB, 1984)	2687.0 37.0	628.0 15.0	550.0 14.3	289.0 8.1	2758.0 53.1	704.0 0.0	1544.0 0.0	534.0 0.0	9694.0 127.5
E: 2005 AFEI (Cheng et al., 1986)	1362.0 18.8	305.0 7.3	270.0 7.0	135.0 3.8	2241.0 43.2	417.0 0.0	977.0 0.0	183.0 0.0	5890.0 80.1
F: 2005 BU (Brooks et al., 1983)	1703.0 23.5	411.0 9.8	361.0 9.4	189.0 5.3	1360.0 26.2	2778.0 0.0	1238.0 0.0	164.0 0.0	8224.0 74.2
G: 2005 CS (Brooks et al., 1983)	1055.0 14.5	290.0 6.9	255.0 6.6	134.0 3.8	939.0 18.1	2415.0 0.0	1197.0 0.0	145.0 0.0	6430.0 49.9

Table 6.2. Selected Statistics for Scenario Analysis

Scenario	%age of Total Energy Demand Met by Fossil Fuels	%age of Total Energy Demand Met by Hydro & Renewables	%age of Total Energy Demand Met by Nuclear Energy	Tg of C Emitted per PJ of Total Energy Demand
A: 1985 Historical (NEB, 1986)	76.3	20.7	3.0	0.01420
B: 2005 LPC (NEB, 1986)	76.5	19.3	4.2	0.01438
C: 2005 HPC (NEB, 1986)	74.1	21.0	4.9	0.01404
D: 2005 (NEB, 1984)	71.3	23.2	5.5	0.01315
E: 2005 AFEI (Cheng et al., 1986)	73.2	23.7	3.1	0.01360
F: 2005 BU (Brooks et al., 1983)	48.9	48.8	2.3	0.00902
G: 2005 CS (Brooks et al., 1983)	41.6	56.2	2.2	0.00776

Figure 6.1
Energy Balance and Total Energy Demand — Canada

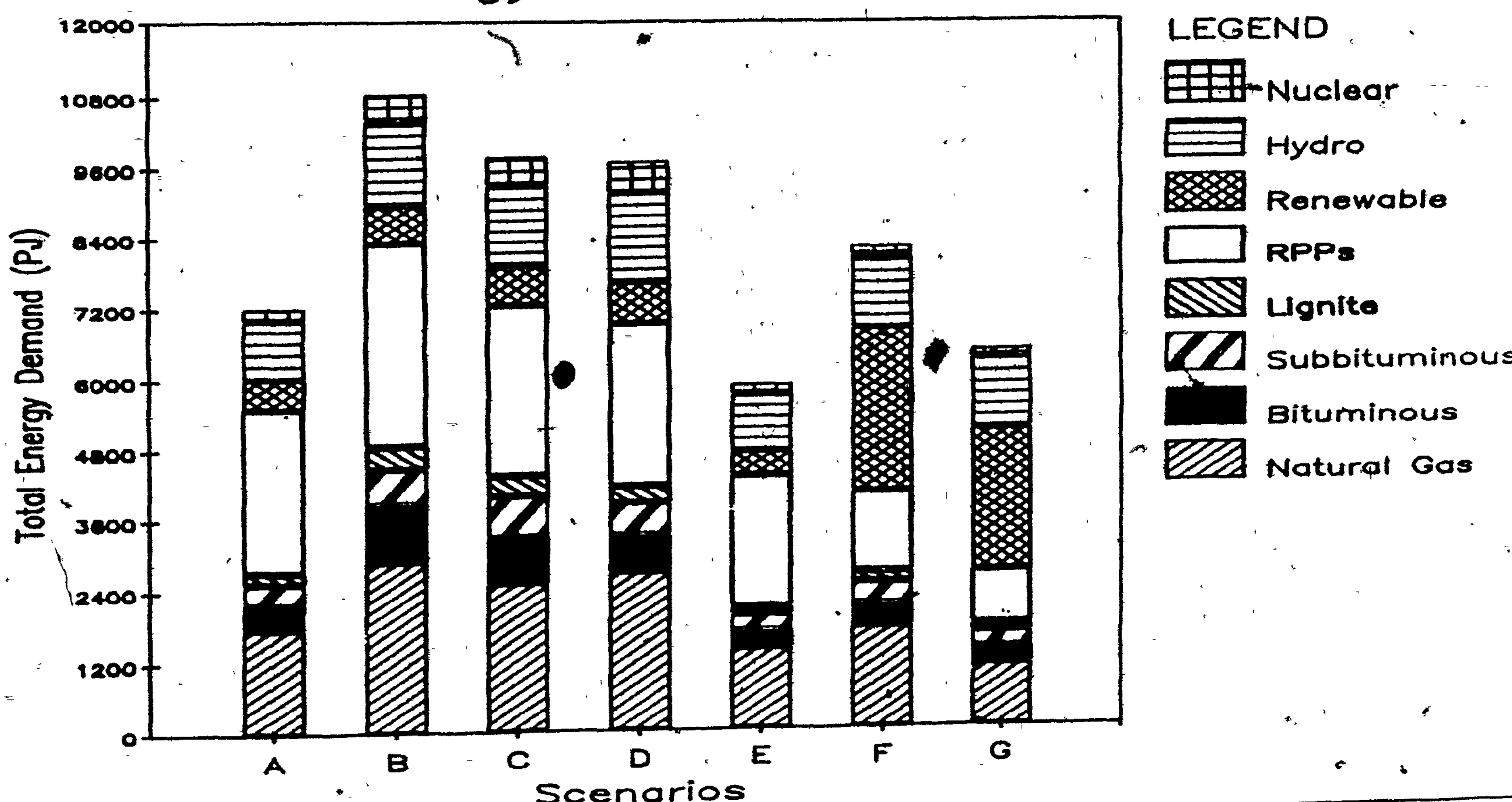


Figure 6.2
Energy Balance and Carbon Dioxide Emissions — Canada

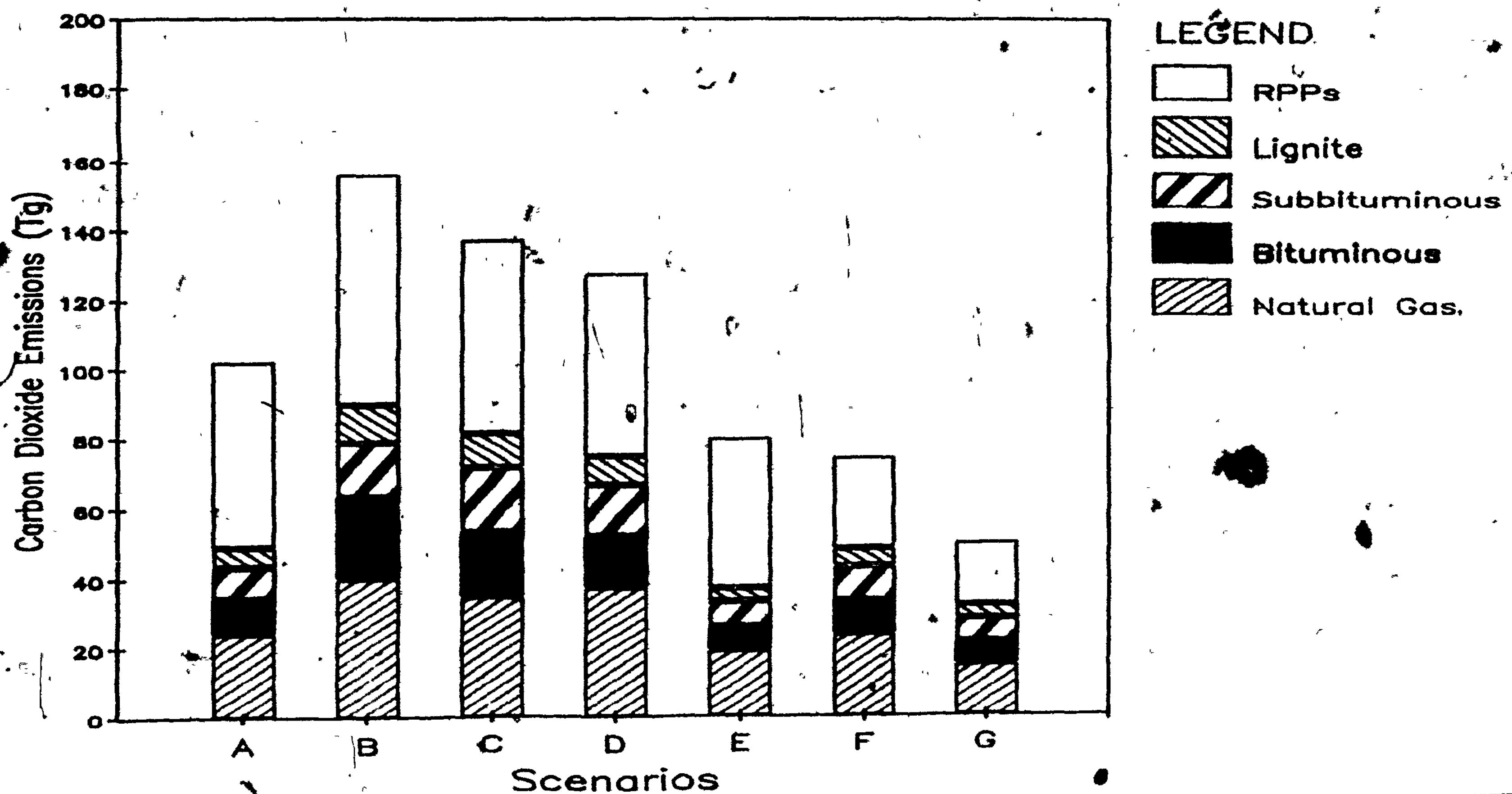


Figure 6.3
Per Cent Share of Total
Energy Demand by Fuel Type

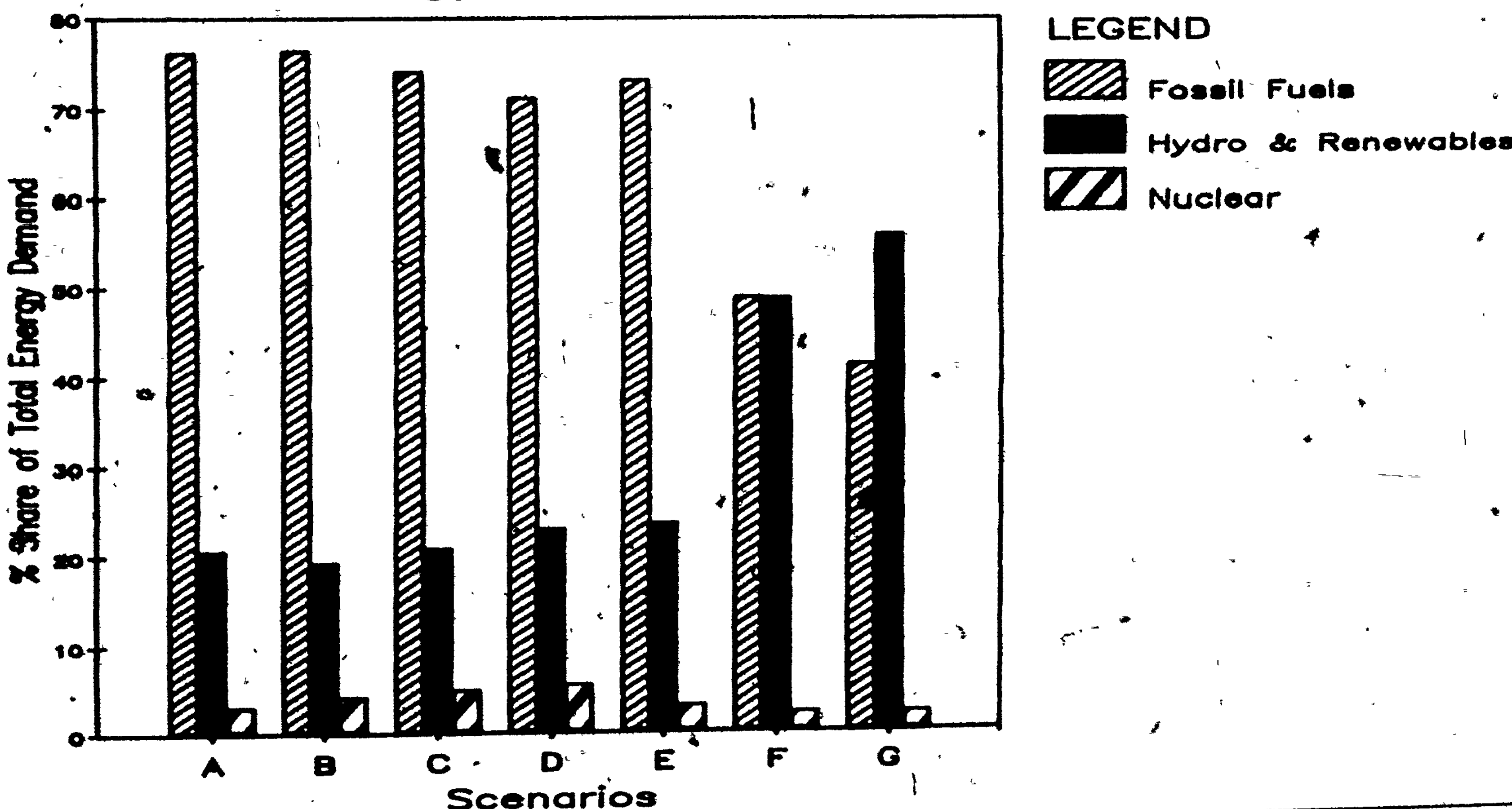
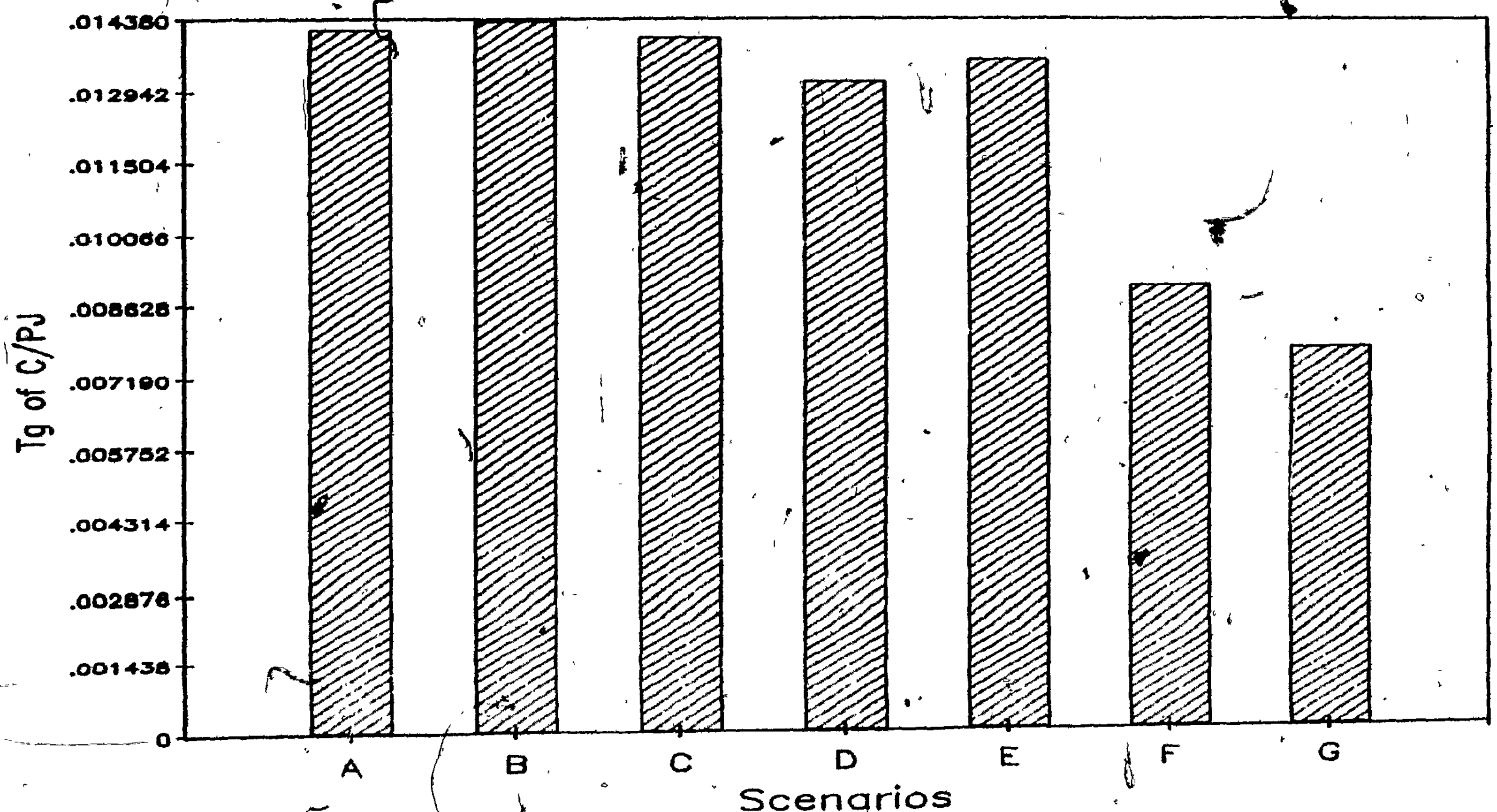


Figure 6.4
Tg of Carbon Emitted per
PJ of Total Energy Demand



31.8%, 17.8% and 50.4% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5). It is important to note that because of the large differential in carbon dioxide emission rates between natural gas and coal (Table 5.1), the former provides a significantly larger share of total fossil fuel demand than the latter (31.8% vs 17.8%), yet natural gas still manages to contribute a smaller portion of total carbon dioxide emissions than coal (23.5% vs 24.3%) (Table 6.3). This particular contrast between natural gas and coal is demonstrated among all the scenarios, except E, examined in this thesis.

Clearly, Canada's total energy demand for 1985 is characterized by an overwhelming dependence on fossil fuels and in particular, refined petroleum products and natural gas. Very little of our total energy demand is met by nuclear energy, while a more significant proportion is met by hydro electricity and renewables.

Table 6.3. Per Cent Share of Total Fossil Fuel Demand and Corresponding Carbon Dioxide Emissions

Scenario	% Share of Total Fossil Fuel Demand/ % Share of Total Carbon Dioxide Emissions		
	Natural Gas	Total Coal (a)	Refined Petroleum Products
A: 1985 Historical (NEB, 1986)	31.8 23.5	17.8 24.3	50.4 52.2
B: 2005 LPC (NEB, 1986)	34.9 25.6	23.7 31.9	41.4 42.5
C: 2005 HPC (NEB, 1986)	34.7 25.2	25.3 34.1	40.0 40.7
D: 2005 (NEB, 1984)	38.9 29.0	21.3 29.4	39.8 41.6
E: 2005 AFEI (Cheng et al., 1986)	31.5 23.4	16.5 22.6	52.0 54.0
F: 2005 BU (Brooks et al., 1983)	42.3 31.7	23.9 32.9	33.8 35.4
G: 2005 CS (Brooks et al., 1983)	39.5 29.0	25.3 34.7	35.2 36.3

(a) total coal includes bituminous, subbituminous and lignite.

Figure 6.5
Per Cent Share of Total Fossil Fuel Demand by Fuel Type

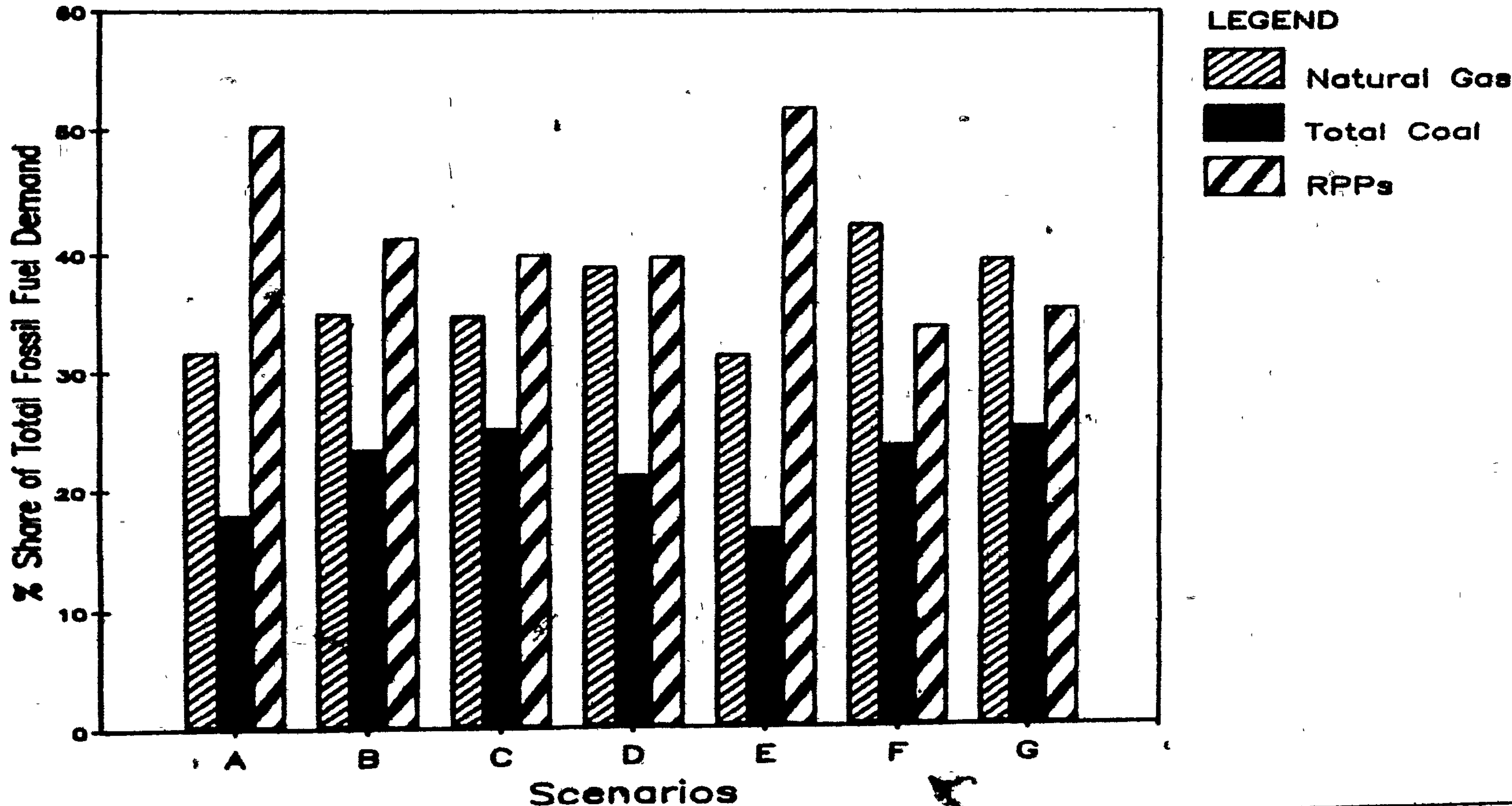
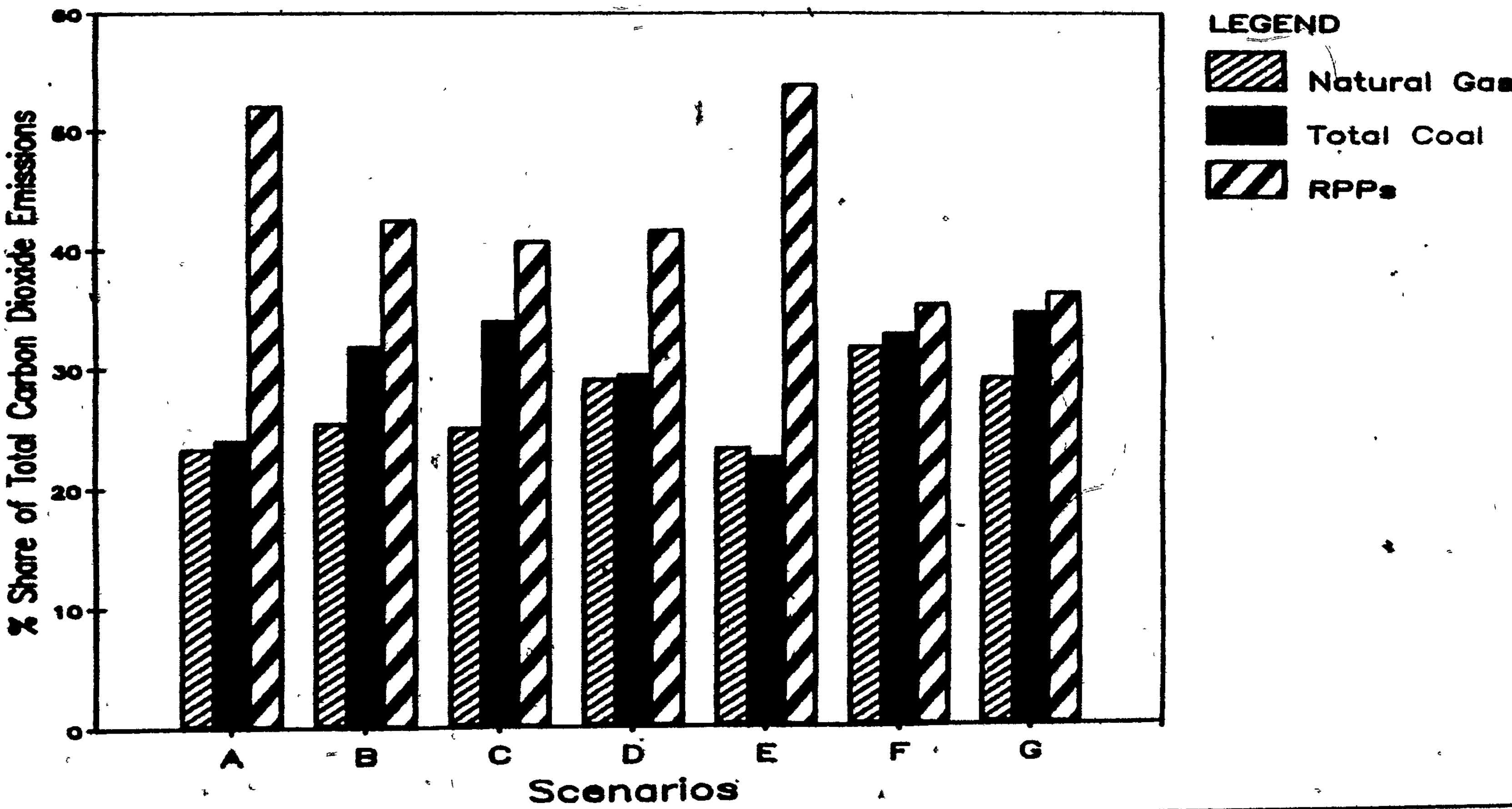


Figure 6.6
Per Cent Share of Total
Carbon Dioxide Emissions by Fuel Type



6.2.2 Scenario B

Scenario B represents the National Energy Board's (1986) vision of what Canada's total energy demand and consequent carbon dioxide emissions might be should the world price of oil remain low (between $US 14 (1986) and $US 18 (1986) per barrel) over the projection period. Under such favourable pricing conditions the demand for conventional fuels rises and the development of non-conventional fuels is suppressed.

Table 6.1 and Figures 6.1 and 6.2 indicate that should the conditions governing Scenario B be realized, Canada's total energy demand in the year 2005 may rise to 10,864 PJ and the consequent emission of carbon as carbon dioxide to 156.2 Tg. The latter values represent increases of 50.6% (2.07% per annum) in total energy demand and 52.5% (2.13% p.a.) in total carbon emissions over 1985 levels (Table 6.4). Of all the scenarios analyzed in this thesis, Scenario B demonstrates the greatest increase over 1985 values for both total energy demand and carbon emission. Of the 10,864 PJ of total energy demand, 76.5% is met by fossil fuels, 19.3% by hydro and renewables and 4.2% by nuclear (Table 6.2 and Figure 6.3).

The projected emission of 156.2 Tg of carbon for a total energy demand of 10,864 PJ is equivalent to an emission rate of 0.01438 Tg of C as CO_2 emitted per PJ of total energy demand (Table 6.2 and Figure 6.4). Although this value is the largest

Table 6.4. Changes in Scenarios Over 1985 Historical Base Case (Scenario A)

Scenario	Per Cent Increase/ Decrease in Total Energy Demand 1985-2005	Per Annum %age Increase/ Decrease in Total Energy Demand 1985-2005	Per Cent Increase/ Decrease in Total Carbon Dioxide Emissions 1985-2005	Per Annum %age Increase/ Decrease in Total Carbon Dioxide Emissions 1985-2005
B: 2005 LPC (NEB,1986)	50.60	2.07	52.54	2.13
C: 2005 HPC (NEB,1986)	35.70	1.54	34.18	1.48
D: 2005 (NEB,1984)	34.40	1.49	24.51	1.10
E: 2005 AFEI (Cheng et al.,1986)	-18.30	-1.01	-21.78	-1.22
F: 2005 BU (Brooks et al.,1983)	14.00	0.66	-27.54	-1.60
G: 2005 CS (Brooks et al.,1983)	-10.80	-0.57	-51.27	-3.53

calculated among the scenarios analyzed in this thesis, it is only slightly higher than that calculated for 1985. This slight increase can be attributed to the overall increase in the percentage of total energy demand met by fossil fuels; 76.5% in 2005 compared with 76.3% in 1985 (Table 6.2). More importantly, the percentage of total fossil fuel demand met by coal rises to 23.7% in 2005 from 17.8% in 1985 (Table 6.3).

Of the projected 156.2 Tg of total carbon dioxide emission, 25.6% is attributed to natural gas, 31.9% to coal and 42.5% to refined petroleum products (Table 6.3 and Figure 6.6). Natural gas, coal and refined petroleum products account for 34.9%, 23.7% and 41.4% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5).

As with Scenario A, Canada's total energy demand remains overwhelmingly dominated by fossil fuels under the low oil price conditions characteristic of Scenario B. The low oil prices in turn have a similar impact on the price of the other fossil fuels, hence increased demand for natural gas and coal are demonstrated in Scenario B. The most dramatic change in demand occurs for coal (three grades combined), increasing from 980 PJ in 1985 to 1966 PJ in 2005, an increase of approximately 100% (Table 6.1). Demand for natural gas increases by 65.7% over 1985 levels, while demand for refined petroleum products increases by only 24.3% over the same period (Table 6.1). The National Energy Board (1986,9) explains this comparatively "low degree of responsiveness in demand for oil" as being a function of low prices, increasing incomes and competitive energy supply alternatives not luring consumers back to "considerably increased oil dependence for fear of future price effects".

Scenario B stands out in the analysis in that of all the scenarios examined in this thesis, it demonstrates both the largest total energy demand and greatest potential emission of carbon dioxide.

6.2.3 Scenario C

Scenario C represents the National Energy Board's (1986) vision of what Canada's total energy demand and consequent carbon dioxide emissions might be should the world price of oil increase over the projection period to a peak of $US 27 (1986) per barrel. The NEB (1986,9) set this limit in recognition of the fact that "around this price energy resources other than OPEC oil should be available, constraining OPEC's ability to sustain price levels much beyond this range".

Table 6.1 and Figures 6.2 and 6.3 indicate that should the conditions governing Scenario C be realized, Canada's total energy demand in 2005 may rise to 9784 PJ and the consequent emission of carbon as carbon dioxide to 137.4 Tg. The latter values represent increases of 35.7% (1.54% p.a.) in total energy demand and 34.18% (1.48% p.a.) in total carbon emissions over 1985 levels (Table 6.4). Of the 9784 PJ of total energy demand, 74.1% is met by fossil fuels, 21.0% by hydro and renewables and

4.9% by nuclear (Table 6.2 and Figure 6.3). Clearly, although fossil fuels still dominate Canada's energy balance, under the high oil price conditions governing Scenario C there is some growth in both hydro and renewables and nuclear energy's share of the balance compared with Scenarios A and B.

The projected emission of 137.4 Tg of carbon for a total energy demand of 9784 PJ is equivalent to an emission rate of 0.01404 Tg of C as CO2 emitted per PJ of total energy demand (Table 6.2 and Figure 6.4). This value is slightly less than that calculated for 1985 because of the reduced share of the total energy balance met by fossil fuels; 74.1% in 2005 compared with 76.3% in 1985 (Table 6.2).

Of the projected 137.4 Tg of total carbon dioxide emission, 25.2% is attributed to natural gas, 34.1% to coal and 40.7% to refined petroleum products (Table 6.3 and Figure 6.6). Natural gas, coal and refined petroleum products account for 34.7%, 25.3% and 40.0% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5). The high price of oil would seem to make coal an attractive alternative, as its 25.3% share of total fossil fuel demand is the highest among the scenarios (tied with Scenario G, Table 6.3).

6.2.4 Scenario D

Scenario D represents the National Energy Board's (1984) vision of what Canada's total energy demand and consequent carbon dioxide emissions might be should the world price of oil rise over the projection period to a peak of $US 38 (1983) per barrel. The NEB (1984) developed this scenario when world oil prices were still under the influence of the 1979-80 price shock, when the price of crude oil reached a staggering peak of $US 34 (1981) per barrel.

Table 6.1 and Figures 6.1 and 6.2 indicate that should the conditions governing Scenario D be realized, Canada's total energy demand in the year 2005 may rise to 9694 PJ and the consequent emission of carbon as carbon dioxide to 127.5 Tg. The latter values represent increases of 34.4% (1.49% p.a.) in total energy demand and 24.51% (1.10% p.a.) in total carbon emissions over 1985 levels (Table 6.4). Of the 9694 PJ of total energy demand, 71.3% is met by fossil fuels, 23.2% by hydro and renewables and 5.5% by nuclear (Table 6.2 and Figure 6.3). Once again, fossil fuels still dominate Canada's energy balance, yet under the extremely high oil prices characteristic of Scenario D, the share of the energy balance met by hydro and renewables and nuclear rise to their highest levels of any of the National Energy Board's energy demand scenarios analyzed in this thesis.

The projected emission of 127.5 Tg of carbon for a total energy demand of 9694 PJ is equivalent to an emission rate of

0.01315 Tg of C as CO2 emitted per PJ of total energy demand (Table 6.2 and Figure 6.4). This value is somewhat less than that calculated for 1985, a result which can be attributed to the reduced share of the total energy balance met by fossil fuels in Scenario D (71.3%) compared with Scenario A (76.3%).

Of the projected 127.5 Tg of total carbon dioxide emission, 29.0% is attributed to natural gas, 29.4% to coal and 41.6% to refined petroleum products (Table 6.3 and Figure 6.6). Natural gas, coal and refined petroleum products account for 38.9%, 21.3% and 39.8% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5). The demand for refined petroleum products in Scenario D (2758 PJ) actually decreases by -0.58% below the demand for the same products in 1985 (2774 PJ)(Table 6.1). Natural gas demand increases in Scenario D (2687 PJ) by 53% over demand for natural gas in 1985 (1751 PJ)(Table 6.1). The demand for total coal in Scenario D (1467 PJ) increases by 50% over demand for total coal in 1985 (980 PJ)(Table 6.1).

6.2.5 Scenario E

Scenario E incorporates the potential reductions in energy demand from the adoption of improved energy technology as outlined by Cheng et al. (1986). By implementing a number of improvements in energy technology, Cheng et al. (1986) have concluded that mid-1970s productivity can be sustained with significantly less energy input than was required at that time. In order to simulate a situation in which stringent energy conservation is practiced, Scenario E extends the calculated improvements in energy consumption for liquid fuels to renewable fuels. Scenario E represents a situation in which the total energy balance does not change significantly over the present situation. In other words, the fuel mix remains much as it is today.

Table 6.1 and Figures 6.1 and 6.2 indicate that should the conditions governing Scenario E be realized, Canada's total energy demand in the year 2005 may fall to 5890 PJ and the consequent emission of carbon as carbon dioxide to 80.1 Tg. The latter values represent decreases of -18.3% (-1.01% p.a.) in total energy demand and -21.78% (-1.22% p.a.) in total carbon emissions over 1985 levels (Table 6.4). Of the 5890 PJ of total energy demand, 73.2% is met by fossil fuels, 23.7% by hydro and renewables and 3.1% by nuclear (Table 6.2 and Figure 6.3).

The projected emission, of 80.1 Tg of carbon for a total energy demand of 5890 PJ is equivalent to an emission rate of 0.01360 Tg of C as CO2 emitted per PJ of total energy demand (Table 6.2 and Figure 6.4). Note that because the total energy balance demonstrated in Scenario E does not differ significantly from that of the National Energy Board's scenarios (Scenarios A-D), the carbon dioxide emission rate calculated for Scenario E falls within the range of the rates calculated for the NEB scenarios (Table 6.2 and Figure 6.4).

Of the projected 80.1 Tg of total carbon dioxide emission, 23.4% is attributed to natural gas, 22.6% to coal and 54.0% to refined petroleum products (Table 6.3 and Figure 6.6). Natural gas, coal and refined petroleum products account for 31.5%, 16.5% and 52.0% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5). These values are similar to those calculated for 1985 (Scenario A).

6.2.6 Scenario F

Scenario F represents Friends of the Earth Canada's vision of what Canada's total energy demand and consequent carbon dioxide emissions might be should we follow what has become known as a 'soft energy future' (Brooks et al.,1983). Scenario F is based on the Business as Usual (BU) scenario developed by Brooks et al. (1983) for their report on the feasibility of moving towards a soft energy future in Canada. In terms of their energy analysis, "no energy conservation or renewable energy technique was introduced into the Business as Usual scenario until it was cost-effective, nor was any lifestyle change incorporated" (Brooks et al.,1983,16).

Table 6.1 and Figures 6.1 and 6.2 indicate that should the conditions governing Scenario F be realized, Canada's total energy demand in 2005 may rise to 8224 PJ, while the consequent emission of carbon as carbon dioxide would fall to 74.2 Tg. The latter values represent an increase of 14.0% (0.66% p.a.) in total energy demand and a decrease of -27.54% (-1.60% p.a.) in total carbon dioxide emissions over 1985 levels (Table 6.4). Scenario F is the only case in which total energy demand increases and carbon dioxide emissions decrease in comparison with 1985 levels.

Of the 8224 PJ of total energy demand, only 48.9% is met by fossil fuels, 48.8% by hydro and renewables and 2.3% by nuclear (Table 6.2 and Figure 6.3). This represents a dramatic departure from our present-day conventional energy balance in which fossil fuels play such an overwhelmingly dominant role. In Scenario F, demand for fossil fuels (4024 PJ) decreases by -26.9% over 1985 demand (5505 PJ), while demand for renewable energy (2778 PJ) increases by 437.3% over 1985 demand (517 PJ).

The projected emission of 74.2 Tg of carbon for a total energy demand of 8224 PJ is equivalent to an emission rate of 0.00902 Tg of C as CO2 per PJ of total energy demand (Table 6.2 and Figure 6.4). This emission rate is second lowest among the scenarios analysed in this thesis, the result of a significant movement away from fossil fuels and towards renewable energy.

Of the projected 74.2 Tg of total carbon dioxide emission, 31.7% is attributed to natural gas, 32.9% to coal and 35.4% to refined petroleum products (Table 6.3 and Figure 6.6). This is the most even distribution of carbon dioxide emissions among the three categories of fossil fuels, of any scenario analyzed in this thesis. Natural gas, coal and refined petroleum products account for 42.3%, 23.9% and 33.8% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5). In no other scenario does natural gas represent such a large share and refined petroleum products such a small share of total fossil fuel demand (Table 6.3 and Figure 6.5).

6.2.7 Scenario G

Scenario G represents Friends of the Earth Canada's vision of what Canada's total energy demand and consequent carbon dioxide emissions might be should we follow a more vigorous soft energy future. Scenario G is based on Brooks et al.'s (1983) Consumer Saturation (CS) scenario. In terms of their energy analysis, "in the Consumer Saturation scenario somewhat less than fully cost-effective scenarios were incorporated and modest lifestyle changes allowed at the discretion of provincial analysts" (Brooks et al.,1983,16).

Table 6.1 and Figures 6.1 and 6.2 indicate that should the conditions governing Scenario G be realized, Canada's total energy demand in 2005 may fall to 6430 PJ and the consequent emission of carbon as carbon dioxide to 49.9 Tg. The latter values represent a decrease of -10.8% (-0.57% p.a.) in total energy demand and a decrease of -51.27% (-3.53% p.a.) in total carbon emissions over 1985 levels (Table 6.4). It is interesting to note that the decrease in total energy demand of -10.8% over 1985 levels shown for Scenario G is less than the decreases in total energy demand calculated for Scenario E (Table 6.4).

Remember that Scenario E incorporates potential reductions in energy demand from the adoption of improved energy technology alone and not from fuel substitution combined with efficiency improvements, as with Scenarios F and G.

Of the 6430 PJ of total energy demand, only 41.6% is met by fossil fuels, 56.2% by hydro and renewables and 2.2% by nuclear (Table 6.2 and Figure 6.3). As with Scenario F, the total energy balance is markedly different from today's conventional distribution. The 56.2% share of the total energy balance met by hydro and renewables is the highest for that category among the scenarios, while the 41.6% share met by fossil fuels is the lowest value calculated for that category. In Scenario G, demand for fossil fuels (2673 PJ) decreases by -51.4% over 1985 demand (5505 PJ), while demand for renewable energy (2415 PJ) increases by 367.1% over 1985 demand (517 PJ).

The projected emission of 49.9 Tg of carbon for a total energy demand of 6430 PJ is equivalent to an emission rate of 0.00776 Tg of C as CO2 per PJ of total energy demand (Table 6.2 and Figure 6.4). This emission rate is the lowest among the scenarios analyzed in this thesis and is almost half the rate calculated for 1985 (Table 6.2 and Figure 6.4).

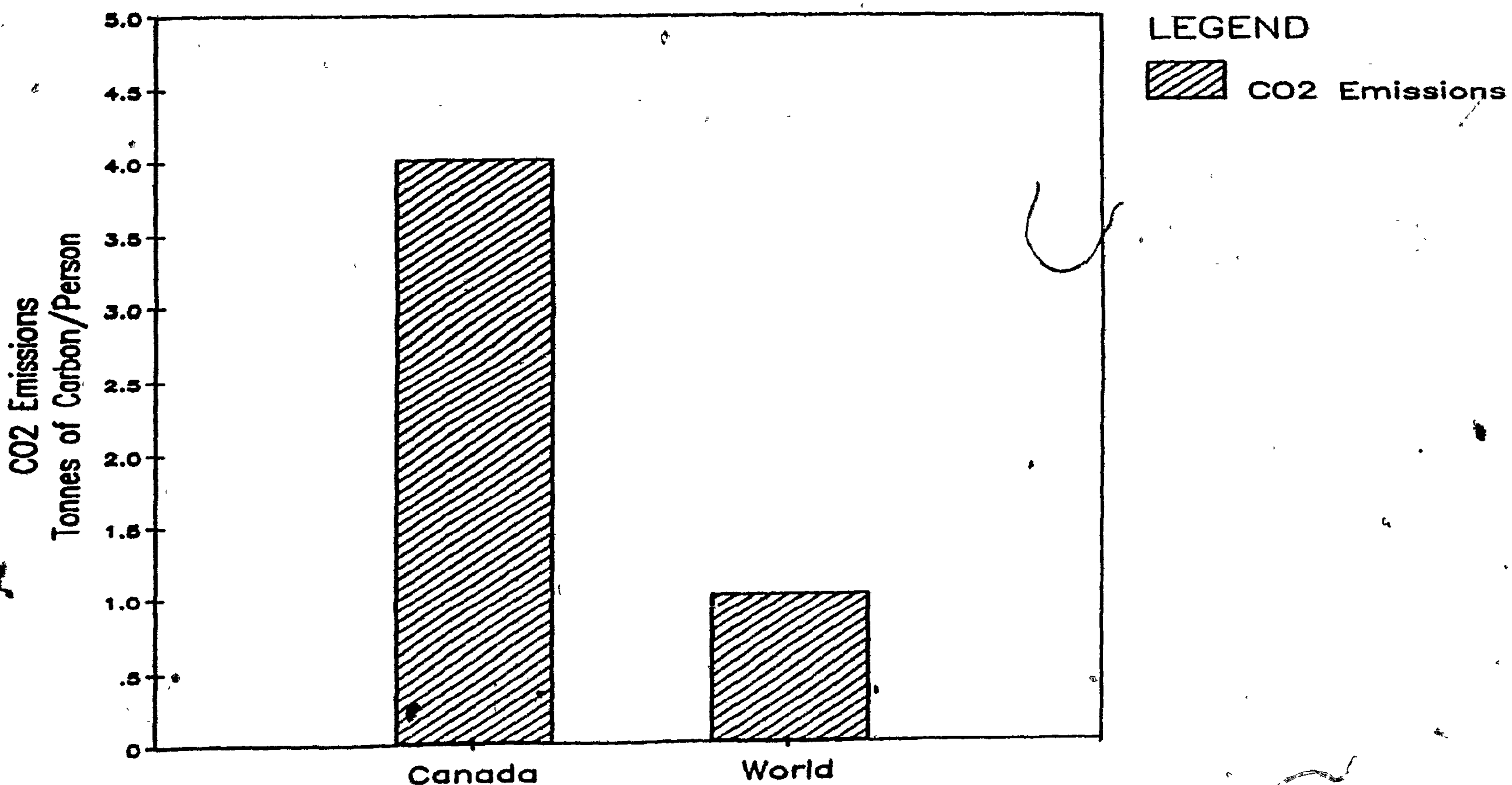
Of the projected 49.9 Tg of total carbon emission, 29.0% is attributed to natural gas, 34.7% to coal and 36.3% to refined petroleum products (Table 6.3 and Figure 6.6). Natural gas, coal and refined petroleum products account for 39.5%, 25.3% and 35.2% of total fossil fuel demand respectively (Table 6.3 and Figure 6.5).

6.3 An Analysis of Canadian Fossil Fuel Based Carbon Dioxide Emissions from a Global Perspective

The 1985 global emission of carbon as carbon dioxide from the combustion of fossil fuels has been estimated to be about 5 gigatonnes (1 GT = 10EXP9 T)(Canadian Climate Centre,1986,4). Therefore, Canada's contribution of 102.4 Tg (1 Tg = 10EXP12 g) of carbon as carbon dioxide from fossil fuel combustion in 1985 represents about 2% of global emissions.

Statistics Canada (1986b,39) estimates that Canada's population in mid-1985 was 25,359,800. Kent and Haub (1985,1) of the Population Reference Bureau estimate that the world population in mid-1985 was 4,845,000,000. Using the latter population estimates, one can calculate the average per capita emission of carbon for Canada and the world. Dividing total carbon emission by population one obtains a per capita emission rate of 4.04 tonnes of C per person for Canada alone and 1.03 tonnes of C per person for the world (including Canada) as a whole (Figure 6.7). Based on these calculations it would appear that on average Canada's per capita emission of carbon as carbon dioxide is almost four times that of the world as a whole.

Figure 6.7
1985 Average Per Capita Emission of Carbon Dioxide — Canada and the World



7.0 SUMMARY AND CONCLUSIONS

The very nature of Canada's energy demand and its resource options provide an excellent topic for study. Canada, by any measure, is a conspicuous consumer of fossil fuels. In 1983, Canada had the highest per capita energy consumption of any country in the world, consuming close to 9,000 kilograms of oil equivalent per person (Statistics Canada,1986a,158). At present, the annual global anthropogenic contribution of carbon dioxide from the combustion of fossil fuels is approximately 5 gigatonnes, of which Canada contributes 102.4 teragrams, or about 2 per cent. If the atmospheric concentration of carbon dioxide is allowed to increase to double that of its pre-industrial level, then a warming of the global average surface air temperature of between 1.5 and 4.5 degrees Celsius is expected. Even at the lower end of this range, the impact on climate, and hence the environment, is expected to be significant.

When faced with the prospect of such a significant change in Earth's climate one can approach the problem in one of two ways. Firstly, one may try to adapt to the expected changes or, secondly, one may take steps to decrease the output of the substances that are causing the problem. In view of the severity and nature of the carbon dioxide problem this thesis has advocated the reduction of anthropogenic carbon dioxide emissions through better use of the types and quantities of fuels Canada chooses to meet its energy demands.

Two important observations with respect to energy demand and carbon dioxide emissions are evident from the results of this thesis. Firstly, if Canada continues to consume the same types of energy resources, in the same proportions and at a similar rate of growth in demand as we do today, our output of carbon dioxide will continue to increase significantly. The results of the analysis of Scenarios B, C and D, the National Energy Board scenarios, indicate that our output of carbon dioxide in the year 2005 may be between 24.51% and 52.54% greater than that of 1985 (see Table 6.4). Recall that these scenarios emphasize a conservative outlook with respect to the types of fuels we may choose to meet our future energy demand. In other words, while we use more energy in Scenarios B,C and D than we did in 1985, the types and proportion of fuels remains essentially the same, as does the technological efficiency with which the fuels are consumed. Clearly, by following our present path with respect to energy demand and consumption, Canada will continue to significantly contribute to the accumulation of atmospheric carbon dioxide.

The second observation one can make is that with respect to energy demand and consumption, Canada does have viable options, and these options appear to offer the potential for significant reductions in our current output of carbon dioxide. If we simply apply the best available energy consuming technology as outlined by Cheng et al. (1986) in Scenario E, by the year 2005 our output of carbon dioxide would be 21.78% less than that of 1985 (see Table 6.4). This reduction is achievable using the same types and proportion of fuels we use today, but using them as efficiently as possible. If we take these efforts a step further, by not only using energy more efficiently, but also by beginning the movement towards adopting different and more environmentally benign fuels accompanied by some minor lifestyle changes, Canada may be able to reduce its current output of carbon dioxide by 27.54% to 51.27% by the year 2005 (see Table 6.4). The latter values were derived from the analysis of Scenarios F and G. Recall that these scenarios encourage the adoption of what have become known as 'soft' energy paths (see Section 4.4.3), and hence represent a significant departure from current trends in Canadian energy demand and consumption.

Although Scenarios E through G represent significant changes over current energy demand and consumption in Canada, they are by no means unrealistic options. These scenarios were chosen because of the credibility and expertise of the individuals and organizations that developed them. It is this very credibility that challenges us to seriously examine these alternatives. They question the very nature and desirability of our conventional wisdom and offer viable alternatives to the current path. The alternative scenarios analyzed in this thesis are by no means the only solutions to limiting our carbon dioxide output, but they are an indication of the potential range of options available in Canada. They also indicate that Canadians have the resource diversity and technology to decide what types of fuels we may choose to meet our future energy demand.

In <u>Perspectives on Resource Management</u>, T. O'Riordan (1971) describes the process of choice as being a central theme in resource management. If we consider the atmosphere to be a resource, and the accumulation of carbon dioxide in the atmosphere as being a threat to that resource, than the question of choice becomes critical if we are to solve this resource management problem. Clearly, the results presented in this thesis indicate that Canada has both the resources and technology to limit its output of carbon dioxide without constraining its economic growth. What Canada now requires is the leadership and the policy to implement such a program. As Peter G. Brewer (1983,189) notes in Changing Climate:

> The CO2 content of the future atmosphere will largely reflect how much CO2 we choose to put in. The key word is choose, for however hard those decisions may be, they represent choices distinct from the natural laws that will inevitably be obeyed as the CO2 level rises.

As we have learned in this thesis, the atmospheric accumulation of carbon dioxide and its predicted impact on climate change is a global issue. The results of this thesis indicate that while the population of Canada is only approximately 0.5% of the world population, we presently contribute 2% of all carbon dioxide emitted from the combustion of fossil fuels. Expressed in terms of per capita emissions, Canadians emit approximately four times more carbon dioxide per person than does the average inhabitant of this planet. Given the fact that Canada's most likely current path of energy demand and consumption will inevitably lead to even greater emissions of carbon dioxide, and given the fact that we do have viable energy options available that would reduce our output of carbon dioxide, one might suggest that not only should we move to reduce our emissions, we must. The carbon dioxide issue elegantly demonstrates the dramatic imbalance between the developed and developing world with respect to resource consumption and environmental impact. It can be strongly argued that countries such as Canada have a moral obligation to take leadership in demonstrating that "non-conventional energy paths" are viable and ecologically sound.

The results of this thesis by no means suggest that the adoption of alternative technologies will be easy; what they do indicate is that it can be done. The very geography of Canada, its spatial extent, its population, economic, climatic, social and political characteristics, have conspired to make Canada dependent on fossil fuels to meet its energy "demand". Clearly, these very same characteristics will also influence the nature of whatever energy path Canada may choose to follow in the future.

I would like to conclude this thesis with some indication of the questions this research has raised. The principle limitation of this thesis is that it isolates and examines one single environmental issue. This was done because of constraints of time and space. While the increased loading of carbon dioxide in the atmosphere and its predicted impact on global climate change has emerged as one of the most significant atmospheric and environmental issues, it is by no means the only issue of concern.

Even more important than the realization that there are other atmospheric and environmental issues of concern is the growing awareness of how interdependent these issues are. Over the past decade there has been a movement among researchers to go beyond looking at a single issue by adopting a more holistic approach to the study of environmental problems. This approach attempts to define and measure the cause and effect linkages between known issues of environmental concern. One of the simplest observations from such an approach has been the realization that many of today's environmental issues have common sources. In particular, our consumption of fossil fuels is not only the principle cause of atmospheric carbon dioxide accumulation but it is also a major contributor to the problems of urban air pollution, arctic haze, ozone column alteration and, of course, acid precipitation.

On a more complex level, there is a growing awareness that the individual chemical constituents that contribute to these environmental problems can interact physically and chemically with each other and thus enhance or hinder the processes associated with these issues. With some understanding of the interdependence of these issues, one must ask what the impact of future energy consumption might be, not just with respect to carbon dioxide accumulation, but to all the issues of concern. Even though this thesis concentrates on the reduction in emission of carbon dioxide, in general, one can suggest that any of the scenarios that demonstrate a reduction in the demand for energy, and in particular fossil fuels, would also lead to the reduction of other emissions associated with the variety of atmospheric and environmental issues of concern.

As our understanding of the physical and chemical workings of the atmospheric environment increases, it would be desirable to study future energy paths from a 'total emissions perspective'. Only when this level of understanding has been reached can one truly make a rational decision as to what the most environmentally benign energy path would be. Until then, it is hoped that studies such as this thesis can make some small contribution to this growing body of knowledge.

In summary, this thesis has attempted to demonstrate the following:

That the carbon dioxide issue is real and its anticipated effects are potentially devastating;

That a variety of solutions to this problem exist, the most desirable and feasible being better management of our energy consumption;

That energy demand scenarios can be used to delineate future carbon dioxide emissions and thus can be used as decision making tools in choosing the most desirable energy path. Also, that the research methodology outlined in this thesis can be easily adapted to other energy demand scenarios and also to the study of fossil fuel related carbon dioxide emissions from other countries;

That Canada is a significant contributor to the world's carbon dioxide problem;

That Canada does have viable options with respect to energy policy that would significantly reduce our output of carbon dioxide in comparison with current levels;

That as a developed country with diverse energy resources and technological capabilities, Canada has an obligation to be a world leader in reducing carbon dioxide and other emissions associated with energy consumption; and

That further research of a 'holistic' nature would be desirable in the general area of energy and environment.

In conclusion, this thesis has determined that Canada has the ways and means to significantly reduce its current output of carbon dioxide over the next twenty years. By doing so Canada could lead the way in demonstrating that the global problem of atmospheric carbon dioxide accumulation can be dealt with by managing the types and quantities of fuels chosen to meet its energy demand. Considering the serious nature of this global environmental problem, the adoption of a more environmentally benign energy path such as those proposed under Scenarios E through G is strongly advocated. The degree to which Canada departs from its current energy path is only limited by political and social will.

APPENDIX A

Detailed Calculations of Carbon Dioxide Emission Factors

i) Natural Gas

The national average gross energy content of natural gas is 38.03 MJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of natural gas contains 38.03 MJ of energy.

Note that: 1 megajoule (MJ) = 10^6 Joules

1 exajoule (EJ) = 10^{18} Joules

Therefore, 1 m^3 of natural gas has an energy content of 0.000,000,000,038,03 EJ.

Dividing each term by 0.000,000,000,038,03 we find that, 26,295,030,000.0 m^3 of natural gas contains 1 EJ of energy.

The carbon content of natural gas is 524g of carbon (C) oxidized to carbon dioxide (CO_2) per m^3 (Keeling,1973,191). Therefore, the amount of CO_2 released from the combustion of an amount of natural gas producing 1 EJ of energy is,

26,295,030,000.0 m^3 of natural gas X 524g of C

= 13.78 X 10^{12}g of C as CO_2/EJ

= 13.78 Tg of C as CO_2/EJ

= 0.01378 Tg of C as CO_2/PJ

Note that: 1 teragram (Tg) = 10^{12} grams

1 petajoule (PJ) = 10^{15} Joules.

ii) <u>Bituminous Coal</u>

The national average gross energy content of bituminous coal is 29.30 GJ/tonne (NEB,1986,130). That is to say, 1 tonne of bituminous coal contains 29.30 GJ of energy.

Note that: 1 tonne = 10^6 g

1 gigajoule (GJ) = 10^9 Joules

Therefore, 1 tonne of bituminous coal has an energy content of 0.000,000,029,3 EJ.

Dividing each term by 0.000,000,029,3 we find that, 34,129,692.83 tonnes of bituminous coal contains 1 EJ of energy.

The carbon content of bituminous coal is approximately 70% (0.7) by mass (Campbell,1986,55).

Therefore, the amount of CO_2 released from the combustion of an amount of bituminous coal producing 1 EJ of energy is,

34,129,692.83 tonnes of bituminous coal X 0.7

= 34.129,692,83 Tg X 0.7

= 23.89 Tg of C as CO_2/EJ

= 0.02389 Tg of C as CO_2/PJ.

iii) <u>Lignite</u>

The national average gross energy content of lignite is 15.35 GJ/tonne (NEB,1986,130). That is to say, 1 tonne of lignite contains 15.35 GJ of energy.

Therefore, 1 tonne of lignite has an energy content of 0.000,000,015,35 EJ.

Dividing each term by 0.000,000,015,35 we find that,
65,146,579.81 tonnes of lignite contains 1 EJ of energy.

The carbon content of lignite is approximately 43% (0.43) by mass (Campbell,1986,55).

Therefore, for every tonne of lignite consumed, 43% by mass will be released as carbon dioxide.

Therefore, the amount of CO_2 released from the combustion of an amount of lignite producing 1 EJ of energy is,

65,146,579.81 tonnes of lignite X 0.43

= 65.146,579,81 Tg X 0.43

= 28.013 Tg of C as CO_2/EJ

= 0.028013 Tg of C as CO_2/PJ.

iv) Subbituminous Coal

The national average gross energy content of subbituminous coal is 19.76 GJ/tonne (NEB,1986,130). That is to say, 1 tonne of subbituminous coal contains 19.76 GJ of energy.

Therefore, 1 tonne of subbituminous coal has an energy content of 0.000,000,019,76 EJ.

Dividing each term by 0.000,000,019,76 we find that, 50,607,287.45 tonnes of subbituminous coal contains 1 EJ of energy.

Since subbituminous coal is an intermediate grade of coal whose energy quality lies somewhere between bituminous coal and lignite, let the carbon content of subbituminous coal be estimated from the average of the carbon emission factors of bituminous coal and lignite as follows,

The carbon emission factor of bituminous coal = 23.89 Tg of C as CO_2

The carbon emission factor of lignite = 28.013 Tg of C as CO_2/EJ

The average of these two emission factors = 25.9515 Tg of C as CO_2/EJ

= 0.0259515 Tg of C as CO_2/PJ

Note that: 25.9515 divided by 50.607,287,45 Tg of subbituminous coal is equivalent to a carbon content of approximately 51% (0.513) by mass.

v) Motor Gasoline

The national average gross energy content of motor gasoline is 34.66 GJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of motor gasoline contains 34.66 GJ of energy.

Therefore, 1 m^3 of motor gasoline has an energy content of 0.000,000,034,66 EJ.

Dividing each term by 0.000,000,034,66 we find that, 28,851,702.25 m^3 of motor gasoline contains 1 EJ of energy.

There are 8.50 barrels of motor gasoline in a tonne of gasoline (Keeling,1973,184).

1 tonne divided by 8.50 barrels = 117,647.06g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 117,647.06 = 740,000g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 740,000g X 0.869 = 643,060g

Therefore, 1 cubic metre of motor gasoline contains 643,060g of carbon.

Or, 643,060g of C as CO_2/34.66 GJ

= 18.55 Tg of C as CO_2/EJ

= 0.01855 Tg of C as CO_2/PJ.

vi) Kerosene

The national average gross energy content of kerosene is 37.68 GJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of kerosene contains 37.68 GJ of energy.

Therefore, 1 m^3 of kerosene has an energy content of 0.000,000,037,68 EJ.

Dividing each term by 0.000,000,037,68 we find that, 26,539,278.13 m^3 of kerosene contains 1 EJ of energy.

There are 7.76 barrels of kerosene in a tonne of kerosene (Keeling,1973,184).

1 tonne divided by 7.76 barrels = 128,865.98g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 128,865.98g = 810,567.01g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 810,567.01g X 0.869 = 704,382.73g

Therefore, 1 cubic metre of kerosene contains 704,382.73g of carbon.

Or, 704,382.73g of C as CO_2/37.68 GJ

= 18.69 Tg of C as CO_2/EJ

= 0.01869 Tg of C as CO_2/PJ.

vii) Aviation Gasoline

The national average gross energy content of aviation gasoline is 33.52 GJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of aviation gasoline contains 33.52 GJ of energy. Therefore, 1 m^3 of aviation gasoline has an energy content of 0.000,000,033,52 EJ.

Dividing each term by 0.000,000,033,52 we find that, 29,832,935.56 m^3 of aviation gasoline contains 1 EJ of energy.

There are 8.50 barrels of aviation gasoline in a tonne of aviation gasoline (Keeling,1973,184).

1 tonne divided by 8.50 barrels = 117,647.06g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 117,647.06 = 740,000g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 740,000g X 0.869 = 643,060g

Therefore, 1 cubic metre of aviation gasoline contains 643,060g of carbon.

Or, 643,060g of C as CO_2/33.52 GJ

= 19.18 Tg of C as CO_2/EJ

= 0.01918 Tg of C as CO_2/PJ.

viii) Natural Gas Liquids (Propane, Butane and Ethane)

The national average gross energy content of natural gas liquids (NGLs) is 24.17 GJ/m^3 (Propane = 25.53 GJ/m^3; Butane = 28.62 GJ/m^3 and Ethane = 18.36 GJ/m^3)(NEB,1986, 130). That is to say, 1 m^3 of NGLs contains 24.17 GJ of energy.

Therefore, 1 m^3 of NGLs has an energy content of 0.000,000,024,17 EJ.

Dividing each term by 0.000,000,024,17 we find that, 41,666,666,67 m^3 of NGLs contains 1 EJ of energy.

There are 11.64 barrels of NGLs in a tonne of NGLs (Keeling,1973,184).

1 tonne divided by 11.64 barrels = 89,910.65g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 89,910.65 = 540,378.01g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 540,378.01g X 0.869 = 469,588.49g

Therefore, 1 cubic metre of NGLs contains 469,588.49g of carbon.

Or, 469,588.49g of C as CO_2/24.17 GJ

= 19.43 Tg of C as CO_2/EJ

= 0.01943 Tg of C as CO_2/PJ.

ix) <u>Light Fuel Oil</u>

The national average gross energy content of light fuel oil is 38.68 GJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of light fuel oil contains 38.68 GJ of energy.

Therefore, 1 m^3 of light fuel oil has an energy content of 0.000,000,038,68 EJ.

Dividing each term by 0.000,000,038,68 we find that, 26,315,789.43 m^3 of light fuel oil contains 1 EJ of energy.

There are 7.23 barrels of light fuel oil in a tonne of light fuel oil (Keeling,1973,184).

1 tonne divided by 7.23 barrels = 138,312.59g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 138,312.59g = 869,986.17g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 869,986.17g X 0.869 = 756,017.98g

Therefore, 1 cubic metre of light fuel oil contains 756,017.98g of carbon.

Or, 756,017.98g of C as CO_2/38.68 GJ

= 19.55 Tg of C as CO_2/EJ

= 0.01955 Tg of C as CO_2/PJ.

x) Aviation Turbo (Kerosene and Naptha)

The national average gross energy content of aviation turbo is 35.93 GJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of aviation turbo contains 35.93 GJ of energy. Therefore, 1 m^3 of aviation turbo has an energy content of 0.000,000,035,93 EJ.

Dividing each term by 0.000,000,035,93 we find that, 28,571,428.57 m^3 of aviation turbo contains 1 EJ of energy.

There are 7.76 barrels of kerosene/jet fuel in a tonne of aviation turbo (Keeling,1973,184).

1 tonne divided by 7.76 barrels = 128,865.98g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 128,865.98g = 810,567.01g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 810,567.01g X 0.869 = 704,382.73g

Therefore, 1 cubic metre of aviation turbo contains 704,382.73g of carbon.

Or, 704,382.73g of C as CO_2/35.93 GJ

= 19.60 Tg of C as CO_2/EJ

= 0.01960 Tg of C as CO_2/PJ.

xi) Heavy Fuel Oil

The national average gross energy content of heavy fuel oil is 41.73 GJ/m^3 (NEB,1986,130). That is to say, 1 m^3 of heavy fuel oil contains 41.73 GJ of energy.

Therefore, 1 m^3 of heavy fuel oil has an energy content of 0.000,000,041,73 EJ.

Dividing each term by 0.000,000,041,73 we find that, 24,390,243.90 m^3 of heavy fuel oil contains 1 EJ of energy.

There are 6.62 barrels of heavy fuel oil in a tonne of heavy fuel oil (Keeling,1973,184).

1 tonne divided by 6.62 barrels = 151,057.40g/barrel.

1 m^3 of oil product = 6.29 barrels (NEB,1986,129).

Hence, 6.29 X 151,057.40g = 950,151.06g/m^3.

The carbon content of refined petroleum products is approximately 87% (0.869) by mass (Zimen et al.,1977,1545).

Hence, 950,151.06g X 0.869 = 825,681.27g

Therefore 1 cubic metre of heavy fuel oil contains 825,681.27g of carbon.

Or, 825,681.27g of C as CO_2/41.73 GJ

= 19.79 Tg of C as CO_2/EJ

= 0.01979 Tg of C as CO_2/PJ.

An average carbon dioxide emission factor for refined petroleum products can now be calculated from the values derived for the seven individual fuels:

Motor Gasoline	18.55 Tg of C as CO_2/EJ
Kerosene	18.69 Tg of C as CO_2/EJ
Aviation Gasoline	19.18 Tg of C as CO_2/EJ
Natural Gas Liquids	19.43 Tg of C as CO_2/EJ

Light Fuel Oil	19.55 Tg of C as CO_2/EJ
Aviation Turbo	19.60 Tg of C as CO_2/EJ
Heavy Fuel Oil	19.79 Tg of C as CO_2/EJ
Sum	134.79, n = 7

134.79 divided by 7 = 19.25571429

≈ 19.26, 1 standard deviation = 0.44

Therefore, on average, the combustion of refined petroleum products yields 19.26 Tg of C as CO_2/EJ

Or, 0.01926 Tg of C as CO_2/PJ.

Summary of Carbon Dioxide Emission Factors

Natural Gas	13.78 Tg of C as CO_2/EJ
Refined Petroleum Products	19.26 Tg of C as CO_2/EJ
Bituminous Coal	23.89 Tg of C as CO_2/EJ
Subbituminous Coal	25.95 Tg of C as CO_2/EJ
Lignite	28.01 Tg of C as CO_2/EJ

APPENDIX B

Details and Examples of Calculation of Percent Increase or Decrease in Total Energy Demand and Total Carbon Dioxide Emission

To calculate the percent increase or decrease in total energy demand (TED) for any scenario in the year 2005 over the historical value calculated for 1985 (Scenario A), the following formula is used:

$$\frac{\text{TED 2005} - \text{TED 1985}}{\text{TED 1985}} \times 100 = \text{Percent Increase or Decrease in TED}$$

Therefore,

$$\frac{\text{TED 2005} - \text{7212 PJ}}{\text{7212 PJ}} \times 100 = \text{Percent Increase or Decrease in TED}$$

For example,

i) Total Energy Demand in 2005 for Scenario B is calculated to be 10,864 PJ.

Therefore,

$$\frac{\text{10,864 PJ} - \text{7212 PJ}}{\text{7212 PJ}} \times 100 = \frac{3652}{7212} \times 100$$

$$= 0.506 \times 100$$

= 50.6% increase in TED for Scenario B in comparison with Scenario A.

ii) Total Energy Demand in 2005 for Scenario G is calculated to be 6430 PJ.

Therefore,

$$\frac{6430 \text{ PJ} - 7212 \text{ PJ}}{7212 \text{ PJ}} \times 100 = \frac{-782}{7212} \times 100$$

$$= -0.108 \times 100$$

= -10.8% decrease in TED for Scenario G in comparison with Scenario A.

To calculate the per annum percentage increase or decrease in total energy demand (TED) between the years 1985 and 2005, the following formula is used:

$$Xp(1 + r)^n = Xf$$

Where Xp = 1985 Historical Base Case value for TED
r = annual rate of change (+/-)
n = number of years = 20 (1985 - 2005)
Xf = 2005 TED

For example,

i) TED in 2005 for Scenario C is calculated to be 9784 PJ.

Therefore,

$$7212(1 + r)^{20} = 9784$$

$$(1 + r)^{20} = 9784/7212$$

$$1 + r = \sqrt[20]{1.3566}$$

$$r = 1.0154 - 1$$

$$= 0.0154$$

= 1.54% annual increase in TED.

ii) TED in 2005 for Scenario E is calculated to be 5890 PJ.

Therefore,

$$7212(1 + r)^{20} = 5890$$

$$(1 + r)^{20} = 5890/7212$$

$$1 + r = \sqrt[20]{0.8167}$$

$$r = 0.9899 - 1$$

$$r = -0.0101$$

$$= -1.01\% \text{ annual decrease in TED}$$

To calculate the percent increase or decrease in total carbon dioxide emission the same formula is used with the following substitution:

$$\frac{\text{Total } CO_2 \text{ Emission 2005} - \text{Total } CO_2 \text{ Emission 1985}}{\text{Total } CO_2 \text{ Emission 1985}} \times 100$$

= Percent increase or decrease in total CO_2 emission

$$= \frac{\text{Total } CO_2 \text{ Emission 2005} - 102.4 \text{ Tg}}{102.4 \text{ Tg}}$$

To calculate the per annum percentage increase or decrease in total carbon dioxide emission between the years 1985 and 2005, the same formula as for TED is used with the following substitutions:

$$Xp(1 + r)^n = Xf$$

Where Xp = 1985 value for total CO_2 emission, 102.4 Tg

r = annual rate of change (+/-)

n = number of years = 20 (1985 - 2005)

Xf = total CO_2 emission calculated for 2005.

APPENDIX C

Raw Data for Scenarios A,B,C and D

Scenario A

Table A3-3 (Continued)
Total Energy Balance - Canada

(Petajoules) — 1985 — History

	Natural Gas (1)	NGL (2)	Coal, Coke, Coke Oven Gas (3)	Electricity (4)	Oil (5)	Steam (6)	Renewable (7)	Hydro [d] (8)	Nuclear [d] (9)	Total (10)
Sectoral Demand										
Residential	508	34	3	411	265	0	107	0	0	1329
Commercial	423	18	1	306	130	1	0	0	0	880
Petrochemical	305	100	0	0	132	0	0	0	0	537
Industrial [a]	618	12	264	611	274	40	378	0	0	2190
Transportation	1	14	0	3	1714	0	0	0	0	1732
Road	1	14	0	3	1389	0	0	0	0	1407
Rail	0	0	0	0	92	0	0	0	0	92
Air	0	0	0	0	160	0	0	0	0	160
Marine	0	0	0	0	73	0	0	0	0	73
Non-Energy Use [a]	0	0	0	0	211	0	0	0	0	211
Total End Use	1848	177	268	1334	2725	41	483	0	0	6866
Own Use and Conversions										
Own Use	133	17	4	125	221	0	0	0	0	500
Electricity Generation [d]	62	0	665	0	70	0	23	977	673	2530
Steam Production	0	0	3	0	7	0	0	0	41	51
Other Conversions	13	36	221	0	-38	0	0	0	0	234
Total Own Use and Conversions	208	53	923	125	288	0	23	977	715	3265
Less Non-Primary Demand [b]	0	74	211	1460	-74	41	0	0	0	1710
Total Primary Demand [c]	2056	156	980	0	3081	0	517	977	715	9461
Fuels for Electricity Exports [d]	0	0	106	0	3	0	0	111	21	241
Sub-Total	2066	156	1087	0	3084	0	517	1088	735	8701
Exports of Primary Energy	981	163	802	0	1419	0	0	0	0	3376
Total Disposition [e]	3047	319	1890	0	4403	0	517	1088	735	12077
Energy Imports	0	0	437	0	796	0	0	0	0	1233
Energy Production	3047	319	1487	0	3607	0	517	1088	735	10808
Total Primary Supply [e]	3047	319	1924	0	4403	0	517	1088	735	12032

Notes: [a] Excludes Petrochemicals.
[b] Oil products include refinery LPG for the purpose of calculating primary energy demand.
[c] Butanes for blending in gasoline is excluded from oil and included in NGL at primary fuels level.
[d] Hydro and Nuclear are converted at 3.6 GJ/MWh and 12.1 GJ/MWh respectively.
[e] Disposition and supply may not balance due to inventory changes.

Source: NEB (1986,160).

Scenario B

Table A3-3 (Continued)
Total Energy Balance - Canada

(Petajoules)

2005

Low Price Case

	Natural Gas (f) (1)	NGL (2)	Coal, Coke Coke Oven Gas (3)	Electricity (4)	Oil (e) (5)	Steam (6)	Renewable (7)	Hydro (d) (8)	Nuclear (d) (9)	Total (10)
Sectoral Demand										
Residential	648	41	2	618	184	0	142	0	0	1648
Commercial	693	27	2	552	110	1	35	0	0	1420
Petrochemical	400	168	0	0	100	0	0	0	0	668
Industrial (a)	1283	21	446	1007	347	31	446	0	0	3829
Transportation	11	20	0	5	2243	0	0	0	0	2279
Road	11	20	0	5	1754	0	0	0	0	1790
Rail	0	0	0	0	128	0	0	0	0	128
Air	0	0	0	0	231	0	0	0	0	231
Marine	0	0	0	0	130	0	0	0	0	130
Non-Energy Use (a)	0	0	0	0	318	0	0	0	0	318
Total End Use	3034	288	450	2213	3334	32	621	0	0	9983
Own Use and Conversions										
Own Use	182	28	10	184	278	0	0	0	0	681
Electricity Generation (d)	71	0	1488	0	118	0	48	1422	1495	4641
Steam Production	0	0	1	0	2	0	0	0	37	40
Other Conversions	14	38	368	0	-38	0	0	0	0	383
Total Own Use and Conversions	287	67	1868	184	355	0	48	1422	1532	5755
Less Non-Primary Demand (b)	0	98	351	2408	-49	32	0	0	0	2791
Total Primary Demand (c)	3308	287	1966	0	3787	0	670	1422	1532	12946
Fuels for Electricity Exports (d)	0	0	157	0	0	0	0	128	23	307
Sub-Total	3308	287	2123	0	3787	0	670	1550	1555	13253
Exports of Primary Energy	0	0	938	0	637	0	0	0	0	1576
Total Disposition	3308	287	3061	0	4424	0	670	1550	1555	14829
Energy Imports	0	106	658	0	2768	0	0	0	0	3531
Energy Production	1751	182	2404	0	1726	0	670	1550	1555	6818
Total Primary Supply	1751	287	3061	0	4495	-0	670	1550	1555	13349

Notes: (a) Excludes Petrochemicals.
(b) Oil products exclude refinery LPG for the purpose of calculating primary energy demand.
(c) Butanes for blending in gasoline is excluded from oil and included in NGL at primary fuels level.
(d) Hydro and Nuclear are converted at 3.6 GJ/MWh and 12.1 GJ/MWh respectively.
(e) Differences in oil supply and disposition result from differences in conversion factors and treatment of gas plant butanes.
(f) Differences between natural gas supply and disposition reflect the cross-over of supply and demand in the later years of the projection.

Source: NEB (1986,175).

Scenario C

Table A3-3 (Continued)
Total Energy Balance - Canada

(Petajoules) — 2005 — High Price Case

	Natural Gas (f) (1)	NGL Coke (2)	Coal, Coke Oven Gas (3)	Electricity (4)	Oil (e) (5)	Steam (6)	Renewable (7)	Hydro (d) (8)	Nuclear (d) (9)	Total (10)
Sectoral Demand										
Residential	578	30	2	[illegible]	124	0	140	0	0	1523
Commercial	566	25	1	525	80	1	31	0	0	[illegible]
Petrochemical	400	188	0	0	100	0	0	0	0	688
Industrial (a)	1081	20	400	[illegible]	313	28	441	0	0	3277
Transportation	20	30	0	13	1831	0	0	0	0	1894
Road	20	30	0	13	1514	0	0	0	0	1578
Rail	[illegible]	0	0	0	118	0	0	0	0	118
Air	0	0	0	0	186	0	0	0	0	185
Marine	0	0	0	0	113	0	0	0	0	113
Non-Energy Use (a)	0	0	0	0	305	0	0	0	0	305
Total End Use	[illegible]	303	404	2180	[illegible]	27	618	0	0	9057
Own Use and Conversions										
Own Use	156	28	9	190	231	0	0	0	0	615
Electricity Generation (d)	68	0	1405	0	65	0	49	1388	1572	4547
Steam Production	0	0	1	0	2	0	0	0	31	34
Other Conversions	12	38	330	0	-38	0	0	0	0	342
Total Own Use and Conversions	236	64	1745	190	283	0	49	1388	1603	5538
Less Non-Primary Demand (b)	0	88	315	2380	-48	27	0	0	0	2692
Total Primary Demand (c)	3018	279	1834	0	3214	0	667	1388	1603	11903
Fuels for Electricity Exports (d)	0	0	180	0	0	0	0	124	28	333
Sub-Total	3018	279	2014	0	3214	0	667	1512	1632	12235
Exports of Primary Energy	0	8	[illegible]	0	[illegible]	0	0	0	0	[illegible]
Total Disposition	3018	287	[illegible]	0	[illegible]	0	667	1512	1632	[illegible]
Energy Imports	0	0	540	0	1486	0	0	0	0	2035
Energy Production	[illegible]	287	2413	0	[illegible]	0	667	1512	1632	[illegible]
Total Primary Supply	[illegible]	287	[illegible]	0	[illegible]	0	667	1512	1632	14844

Notes: (a) Excludes Petrochemicals.
(b) Oil products include refinery LPG for the purpose of calculating primary energy demand.
(c) Butanes for blending in gasoline is excluded from oil and included in NGL at primary fuels level.
(d) Hydro and Nuclear are converted at 3.6 GJ/MWh and 12.1 GJ/MWh respectively.
(e) Differences in oil supply and disposition result from differences in conversion factors and treatment of gas plant butanes.
(f) Differences between natural gas supply and disposition reflect the cross-over of supply and demand in the later years of the projection.

Source: NEB (1986,176).

Scenario D

Table A10-3
Total Energy Balance – Canada 2005

(Petajoules)

	Electricity	Oil	Natural Gas	Ethane	Propane and Butanes	Coal Coke CK Oven Gas	Steam	Wood	Other Renewable	Hydro	Nuclear	Total
Sector Demand												
Residential	589	133	548	0	36	2	0	120	32	0	0	[illegible]
Commercial	518	59	703	0	40	2	1	0	10	0	0	1303
Petrochemical	0	76	372	115	40	0	0	0	0	0	0	[illegible]
Other Industrial	1081	291	1192	0	16	171	21	445	8	0	0	3454
Transportation	13	1877	41	0	30	0	0	0	0	0	0	[illegible]
Road	13	1377	41	0	30	0	0	0	0	0	0	1461
Rail	0	109	0	0	0	0	0	0	0	0	0	109
Air	0	217	0	0	0	0	0	0	0	0	0	217
Marine	0	174	0	0	0	0	0	0	0	0	0	174
Non Energy Use	0	314	0	0	0	0	0	0	0	0	0	314
Total End Use	2211	2750	2857	115	173	376	22	565	39	0	0	9168
Own Use & Conversions												
Energy Supply Industry	220	201	149	0	24	1	0	0	0	0	0	594
Electricity Generation	0	48	32	0	0	1063	0	27	13	4503	1538	7225
Steam Production	0	2	1	0	0	5	0	0	0	0	20	28
Other Conversions	0	0	20	0	0	22	0	0	0	0	0	42
Total Own Use & Conversions	220	250	202	0	24	1081	0	27	13	4503	1558	7888
Less Non Primary Demand	2431	0	0	0	0	0	22	0	0	0	0	2453
Total Primary Demand	0	3001	3058	115	197	1457	0	592	112	4503	1558	14603
Firm Exp Electricity Exports	0	0	0	0	0	91	0	0	0	78	65	234
Sub Total	0	3001	3058	115	197	1558		704		4580	1623	14837
Exports of Primary Energy	0	558	0	0	82	837		0		0	3	[illegible]
Total Disposition	0	3560	3070	115	279	2395		704		4580	1623	[illegible]
Energy Imports	0	576	0	0	0	348		0		0	0	[illegible]
Energy Production	0	3044	2986	115	280	2045		704		4580	1623	[illegible]
Total Primary Supply	0	3620	2986	115	280	2393		704		4580	1623	[illegible]

Source: NEB (1984,A-205).

APPENDIX D

Calculations Used to Develop Scenario E

Cheng et al. (1986,32) estimate that with foreseeable technological improvement in energy consumption, by the year 2050 Canada can reduce its mid-1970s energy consumption by the following amounts:

55% for refined petroleum products,
61% for natural gas,
70% for coal, and
43% for electricity.

These values represent a net improvement in efficiency over a seventy-five year period (1975 - 2050).

The values were adapted to the format of this thesis in the following manner:

> For example, assume that in 1975 Canada consumed 1000 units of refined petroleum products (RPPs). By the year 2050 Cheng et al. (1986,32) estimate that we can improve our consumption 55%. In other words, at the end of this 75 year period Canada would only require 450 units of RPPs to meet the same energy requirements as in 1975.

To determine the annual rate of improvement in efficiency we use the following compound interest formula:

$$Xp(1 + r)^n = Xf$$

Where Xp = 1000 units, hypothetical demand for RPPs in 1975

n = 75 years (1975 - 2050)

Xf = 450 units, demand for RPPs at efficiency improvement of 55% over 1975 demand

r = unknown annual improvement in efficiency.

Therefore,

$$1000(1 + r)^{75} = 450$$

$$(1 + r)^{75} = 0.45$$

$$1 + r = \sqrt[75]{0.45}$$

$$r = 0.9894 - 1$$

$$= -0.0106$$

$= -1.059\%$ annual decrease in demand for RPPs.

Now that an annual rate of improvement in efficiency has been calculated, this value can be applied to the 1985 historical data to determine demand for RPPs in the year 2005.

Once again, we make use of the compound interest formula:

$$Xp(1 + r) = Xf$$

Where Xp = 2774 PJ, the 1985 historical demand for refined petroleum products.

n = 20 years (1985 - 2005)

Xf = unknown demand for RPPs in 2005

r = annual rate of improvement in efficiency in use of RPPs of -0.0106.

Therefore,

$$2774(1 + (-0.0106))^{20} = Xf$$

$$2774(0.9894)^{20} = Xf$$

$$2774(0.8080) = Xf$$

$$2241 \text{ PJ} = Xf$$

With appropriate substitutions, the same formulas were used to calculate the efficiency improvements expected for the other fuels, natural gas, coal and electricity.

APPENDIX E

Raw Data for Scenarios F and G

Scenario F

TABLE C6-12

PRODUCTION OF PRIMARY SOURCES AND SECONDARY FORMS
IN CANADA IN 2000
BUSINESS AS USUAL SCENARIO
(PJ)

PRIMARY SOURCES					SECONDARY FORMS					
SOURCE	Production	Net Imports	Availability	Energy Supply Sector	Production	Net Imports	Energy Supply Sector	Non-Energy Use	End Use	FORM
COAL & PEAT	901.57	235.77	125.40	2.73	122.75	--	--	--	122.75	COAL & PEAT
			304.03	25.15	278.88	--	--	145.30	133.50	COKE
			106.26	12.01	94.25	--	--	--	94.25	COKE OVEN GAS
			502.57	370.01	204.56	*	*	*	*	ELECTRICITY
			22.00	9.00	13.00	--	--	--	13.00	METHANOL
NATURAL GAS	2027.20	(47.00)	2264.30	101.36	1906.20	--	225.22	291.00	1389.76	NATURAL GAS
					216.00	--	--	--	216.00	METHANOL
			76.06	50.20	25.86	*	*	*	*	ELECTRICITY
CRUDE	2356.70	(39.21)	2356.05	--	2356.05	--	220.06	724.90	1411.09	RPP's
			0.64	0.42	0.22	*	*	*	*	ELECTRICITY
URANIUM	766.30	--	766.30	536.07	229.91	*	*	*	*	ELECTRICITY
HYDRO	1203.29	--	1203.29	--	1203.29	*	*	*	*	ELECTRICITY
ACTIVE SOLAR	130.12	--	127.02	--	127.02	--	--	--	127.02	ACTIVE SOLAR
			3.10	--	3.10	*	*	*	*	ELECTRICITY
WIND	7.16	--	7.16	--	7.16	*	*	*	*	ELECTRICITY
BIOMASS	2170.09	--	887.05	8.01	879.04	--	41.40	--	838.26	BIOMASS SOLIDS
			1129.22	433.68	695.54	--	108.55	--	586.99	METHANOL
			14.30	0.70	13.60	--	--	--	13.60	VEGETABLE OIL
			103.13	48.83	54.30	--	11.20	--	43.10	BIOGAS
			35.59	24.46	11.13	*	*	*	*	ELECTRICITY
					(1685.23)	(157.63)	198.25	--	1329.35	TOTAL ELECTRICITY
TOTAL	10045.51	109.56	10315.07	1671.03	8644.04	(157.63)	804.00	1162.00	6239.45	TOTAL
			10,15 07							

* All flows of secondary electricity are shown on the Total Electricity line.

Source: Brooks et al. (1983,193).

Scenario F

TABLE C4-13

PRODUCTION OF PRIMARY SOURCES AND SECONDARY FORMS
IN CANADA IN 2025
BUSINESS AS USUAL SCENARIO
(PJ)

	PRIMARY SOURCES				SECONDARY FORMS					
SOURCE	Production	Net Imports	Availability	Energy Supply Sector	Production	Net Imports	Energy Supply Sector	Non-Energy Use	Energy Use	FORM
COAL & PEAT	781.46	289.52	139.43	2.73	136.70	--	--	--	136.70	COAL & PEAT
			348.10	28.00	319.38	--	--	177.00	142.22	COKE
			123.46	13.91	109.75	--	--	--	109.75	COKE OVEN GAS
			323.74	211.71	112.03	*	*	*	*	ELECTRICITY
			66.00	23.00	43.00	--	9.00	--	34.00	METHANOL
NATURAL GAS	1164.29	(31.00)	1132.84	5.37	1127.47	--	182.32	508.10	537.05	NATURAL GAS
			0.45	0.30	0.15	*	*	*	*	ELECTRICITY
CRUDE	1054.43	--	1054.24	--	1054.24	--	97.47	785.22	171.55	RPP's
			0.19	0.13	0.06	*	*	*	*	ELECTRICITY
URANIUM	--	--	--	--	--	*	*	*	*	ELECTRICITY
HYDRO	1376.03	*	1376.03	*	1376.03	*	*	*	*	ELECTRICITY
ACTIVE SOLAR	334.48	--	306.44	--	306.44	--	--	--	306.44	ACTIVE SOLAR
			28.04	--	28.04	*	*	*	*	ELECTRICITY
WIND	30.90	--	30.90	--	30.90	*	*	*	*	ELECTRICITY
BIOMASS	4256.69	--	983.72	10.81	972.91	--	45.30	--	927.61	BIOMASS SOLIDS
			2878.36	956.21	1930.15	--	391.67	--	1528.48	METHANOL
			93.30	4.60	88.70	--	--	--	88.70	VEGETABLE OIL
			236.07	101.20	135.67	--	18.00	--	117.67	BIOGAS
			104.39	71.00	33.39	*	*	*	*	ELECTRICITY
					(1580.60)	(178.52)	392.07	--	1209.21	TOTAL ELECTRICITY
TOTAL	9848.10	178.52	9224.74	1431.37	7754.93	(178.52)	656.63	1470.40	5209.10	TOTAL

* All flows of secondary electricity are shown on the Total Electricity line.

Source: Brooks et al. (1983,194).

Scenario G

TABLE CA-16

PRODUCTION OF PRIMARY SOURCES AND SECONDARY FORMS
IN CANADA IN 2000
CONSUMER SATURATION SCENARIO
(PJ)

PRIMARY SOURCES					SECONDARY FORMS					
Source	Production	Net Inflow	Availability	Energy Supply Sector	Production	Net Inflow	Energy Supply Sector	Non-Energy Use	Energy Use	Form
COAL & PEAT	681.70	121.12	78.14	3.00	78.26	--	--	--	78.26	COAL & PEAT
			217.00	10.14	198.06	--	--	103.38	95.68	COKE
			74.91	8.42	66.49	--	--	--	66.49	COKE OVEN GAS
			412.77	267.70	144.99	*	*	*	*	ELECTRICITY
			20.00	7.00	13.00	--	3.00	--	10.00	METHANOL
NATURAL GAS	1521.12	(87.00)	1010.91	7.19	1411.72	--	135.00	203.10	1073.62	NATURAL GAS
			45.21	16.64	8.57	*	*	*	*	ELECTRICITY
CRUDE	1655.07	--	1654.69	--	1654.69	--	165.21	518.55	970.93	RPP's
			0.38	0.25	0.13	*	*	*	*	ELECTRICITY
URANIUM	403.00	--	403.00	422.17	100.91	*	*	*	*	ELECTRICITY
HYDRO	1162.19	--	1162.19	--	1162.19	*	*	*	*	ELECTRICITY
ACTIVE SOLAR	126.64	--	123.39	--	123.39	--	--	--	123.39	ACTIVE SOLAR
			3.25	--	3.25	*	*	*	*	ELECTRICITY
WIND	6.70	--	6.70	--	6.70	*	*	*	*	ELECTRICITY
BIOMASS	1060.54	--	752.12	6.03	744.09	--	37.70	--	706.39	BIOMASS SOLIDS
			1050.59	413.72	645.07	--	174.14	--	470.73	METHANOL
			12.20	0.60	11.60	--	--	--	11.60	VEGETABLE OIL
			103.05	48.73	54.30	--	11.20	--	43.10	BIOGAS
			33.62	23.67	9.95	*	*	*	*	ELECTRICITY
					(1516.77)	(380.50)	169.00	--	1046.41	TOTAL ELECTRICITY
TOTAL	7727.10	34.12	7761.26	1244.32	6515.00	(380.50)	696.05	825.03	4693.40	TOTAL

* All flows of secondary electricity are shown on the Total Electricity line.

Source: Brooks et al. (1983,195).

Scenario G

TABLE CA-15

PRODUCTION OF PRIMARY SOURCES AND SECONDARY FORMS
IN CANADA IN 2025
CONSUMER SATURATION SCENARIO
(PJ)

	PRIMARY SOURCES				SECONDARY FORMS					
SOURCE	PRODUCTION	NET IMPORTS	AVAIL-ABILITY	ENERGY SUPPLY SECTOR	PRODUCTION	NET IMPORTS	ENERGY SUPPLY SECTOR	NON-ENERGY USE	ENERGY USE	FORM
COAL & PEAT	577.07	156.10	96.56	3.88	92.66	--	--	--	92.66	COAL & PEAT
			263.11	21.77	241.30	--	--	133.98	107.36	COKE
			93.06	10.52	82.56	--	--	--	82.56	COKE OVEN GAS
			228.56	150.19	78.35	*	*	*	*	ELECTRICITY
			50.00	17.00	33.00	--	7.00	--	26.00	METHANOL
NATURAL GAS	785.00	(20.00)	681.25	3.14	678.11	--	65.64	369.40	243.07	NATURAL GAS
			0.15	0.10	0.05	*	*	*	*	ELECTRICITY
CRUDE	732.65	--	732.65	--	732.65	--	60.01	502.14	81.60	RPP's
			--	--	--	*	*	*	*	ELECTRICITY
URANIUM	--	--	--	--	--	*	*	*	*	ELECTRICITY
HYDRO	1335.50	--	1335.50	--	1335.50	*	*	*	*	ELECTRICITY
ACTIVE SOLAR	295.29	--	279.64	--	279.64	--	--	--	279.64	ACTIVE SOLAR
			15.65	--	15.65	*	*	*	*	ELECTRICITY
WIND	20.02	--	20.02	--	20.02	*	*	*	*	ELECTRICITY
BIOMASS	3373.37	--	823.08	6.52	816.56	--	44.20	--	770.36	BIOMASS SOLIDS
			2132.27	719.27	1413.00	--	309.61	--	1103.39	METHANOL
			78.20	3.00	74.40	--	--	--	74.40	VEGETABLE OIL
			242.78	103.33	139.45	--	18.00	--	121.45	BIOGAS
			97.04	68.31	28.73	*	*	*	*	ELECTRICITY
					(1486.38)	(363.01)	177.94	--	945.41	TOTAL ELECTRICITY
TOTAL	7047.70	129.78	7177.56	1109.43	6667.73	(363.01)	691.23	1085.52	3927.90	TOTAL

* All flows of secondary electricity are shown on the Total Electricity line.

Source: Brooks et al. (1983,196).

APPENDIX F

Details and Examples of Calculations Used to Develop Scenarios F and G

Scenario F

The values for the year 2005 were extrapolated using a simple linear equation: $Y = mX + b$

Where m = the slope of the line

b = the y-intercept (i.e. the value of Y when $X = 0$)

Note: $$m = \frac{Y2 - Y1}{X2 - X1}$$

i) Coal

$X1 = 2000$ $Y1 = 994.96$ PJ

$X2 = 2025$ $Y2 = 823.85$ PJ

Therefore,

$$m = \frac{823.85 - 994.96}{2025 - 2000} = \frac{-171.11}{25} = -6.8444$$

Since $Y = mX + b$ then,

$$994.96 = (-6.8444)(2000) + b$$

$$994.96 = -13{,}688.8 + b$$

$$b = 14{,}683.76$$

For the year 2005,

$$Y = -6.8444(2005) + 14{,}683.76$$

$$= 960.738 \text{ PJ}$$

ii) Natural Gas

$X1 = 2000$ $Y1 = 1972.34$

$X2 = 2025$ $Y2 = 625.19$

Therefore,

$$m = \frac{625.19 - 1972.34}{2025 - 2000} = \frac{-1347.15}{25} = -53.886$$

Since Y = mX + b then,

$$1972.34 = -53.886(2000) + b$$

$$1972.34 = -107,772 + b$$

$$b = 109,744.34$$

For the year 2005,

$$Y = -53.886(2005) + 109,744.34$$

$$= 1702.91 \text{ PJ}$$

iii) Crude (RPPs)

X1 = 2000 Y1 = 1632.59

X2 = 2025 Y2 = 269.21

Therefore,

$$m = \frac{269.21 - 1632.59}{2025 - 2000} = \frac{-1363.68}{25} = -54.5352$$

Since Y = mX + b then,

$$1632.59 = -54.5352(2000) + b$$

$$1632.59 = -109,070.4 + b$$

$$b = 110,702.99$$

For the year 2005,

$$Y = -54.5352(2005) + 110,702.99$$

$$= 1359.914 \text{ PJ}$$

iv) Uranium

X1 = 2000 Y1 = 229.91

X2 = 2025 Y2 = 0.00

Therefore,

$$m = \frac{0.00 - 229.91}{2025 - 2000} = \frac{-229.91}{25} = -9.1964$$

Since Y = mX + b then,

229.91 = -9.1964(2000) + b

229.91 = -18,392.8 + b

b = 18,622.71

For the year 2005,

Y = -9.1964(2005) + 18,622.71

= 183.928 PJ

v) <u>Hydro</u>

X1 = 2000 Y1 = 1203.29

X2 = 2025 Y2 = 1376.03

Therefore,

$$m = \frac{1376.03 - 1203.29}{2025 - 2000} = \frac{172.74}{25} = 6.9096$$

Since Y = mX + b then,

1203.29 = 6.9096(2000) + b

1203.29 = 13,819.2 + b

b = -12,615.91

For the year 2005,

Y = 6.9096(2000) - 12,615.91

= 1237.838 PJ

vi) <u>Active Solar</u>

X1 = 2000 Y1 = 130.12

X2 = 2025 Y2 = 334.48

Therefore,

$$m = \frac{334.48 - 130.12}{2025 - 2000} = \frac{204.36}{25} = 8.1744$$

Since Y = mX + b then,

$$130.12 = 8.1744(2000) + b$$

$$130.12 = 16{,}348.8 + b$$

$$b = -16{,}218.68$$

For the year 2005,

$$Y = 8.1744(2005) - 16{,}218.68$$

$$= 170.992 \text{ PJ}$$

vii) <u>Wind</u>

$X1 = 2000$ $Y1 = 7.16$

$X2 = 2025$ $Y2 = 30.90$

Therefore,

$$m = \frac{30.90 - 7.16}{2025 - 2000} = \frac{23.74}{25} = 0.9496$$

Since Y = mX + b then,

$$7.16 = 0.9496(2000) + b$$

$$7.16 = 1899.2 + b$$

$$b = -1892.04$$

For the year 2005,

$$Y = 0.9496(2005) - 1892.04$$

$$= 11.908 \text{ PJ}$$

viii) <u>Biomass</u>

$X1 = 2000$ $Y1 = 2170.09$

$X2 = 2025$ $Y2 = 4296.64$

Therefore,

$$m = \frac{4296.64 - 2170.09}{2025 - 2000} = \frac{2126.55}{25} = 85.062$$

Since Y = mX + b then,

$$2170.09 = 85.062(2000) + b$$

$$2170.09 = 170,124 + b$$

$$b = -167,953.91$$

For the year 2005,

$$Y = 85.062(2005) - 167,953.91$$

$$= 2595.4 \text{ PJ}$$

<u>Scenario G</u>

i) <u>Coal</u>

X1 = 2000 Y1 = 699.44

X2 = 2025 Y2 = 597.27

Therefore,

$$m = \frac{597.27 - 699.44}{2025 - 2000} = \frac{-102.17}{25} = -4.0868$$

Since Y = mX + b then,

$$699.44 = -4.0868(2000) + b$$

$$699.44 = -8173.6 + b$$

$$b = 8873.04$$

For the year 2005,

$$Y = -4.0868(2005) + 8873.08$$

$$= 679.006 \text{ PJ}$$

ii) <u>Natural Gas</u>

X1 = 2000 Y1 = 1241.02

X2 = 2025 Y2 = 312.00

Therefore,

$$m = \frac{312.00 - 1241.02}{2025 - 2000} = \frac{-929.02}{25} = -37.1608$$

Since $Y = mX + b$ then,

$$1241.02 = -37.1608(2000) + b$$

$$1241.02 = -74,321.6 + b$$

$$b = 75,562.62$$

For the year 2005,

$$Y = -37.1608(2005) + 75,562.62$$

$$= 1055.216 \text{ PJ}$$

iii) <u>Crude</u> (RPPs)

$X1 = 2000 \qquad Y1 = 1136.52$

$X2 = 2025 \qquad Y2 = 150.51$

Therefore,

$$m = \frac{150.51 - 1136.52}{2025 - 2000} = \frac{-986.01}{25} = -39.4404$$

Since $Y = mX + b$ then,

$$1136.52 = -39.4404(2000) + b$$

$$1136.52 = -78,880.8 + b$$

$$b = 80,017.32$$

For the year 2005,

$$Y = -39.4404(2005) + 80,017.32$$

$$= 939.318 \text{ PJ}$$

iv) <u>Uranium</u>

$X1 = 2000 \qquad Y1 = 180.91$

$X2 = 2025 \qquad Y2 = 0.00$

Therefore,

$$m = \frac{0.00 - 180.91}{2025 - 2000} = \frac{-180.91}{25} = -7.2364$$

Since $Y = mX + b$ then,

$$180.91 = -7.2364(2000) + b$$

$$180.91 = -14,472.8 + b$$

$$b = 14,653.71$$

For the year 2005,

$$Y = -7.2364(2005) + 14,653.71$$

$$= 144.728 \text{ PJ}$$

v) <u>Hydro</u>

$X1 = 2000 \qquad Y1 = 1162.19$

$X2 = 2025 \qquad Y2 = 1335.58$

Therefore,

$$m = \frac{1335.58 - 1162.19}{2025 - 2000} = \frac{173.39}{25} = 6.9356$$

Since $Y = mX + b$ then,

$$1162.19 = 6.9356(2000) + b$$

$$1162.19 = 13,871.2 + b$$

$$b = -12,709.01$$

For the year 2005,

$$Y = 6.9356(2005) - 12,709.01$$

$$= 1196.868 \text{ PJ}$$

vi) <u>Active Solar</u>

$X1 = 2000 \qquad Y1 = 126.64$

$X2 = 2025 \qquad Y2 = 295.29$

Therefore,

$$m = \frac{295.29 - 126.64}{2025 - 2000} = \frac{168.65}{25} = 6.746$$

Since $Y = mX + b$ then,

$$126.64 = 6.746(2000) + b$$

$$126.64 = 13,492 + b$$

$$b = -13,365.36$$

For the year 2005,

$$Y = 6.746(2005) - 13,365.36$$

$$= 160.37 \text{ PJ}$$

vii) <u>Wind</u>

$X1 = 2000 \qquad Y1 = 6.78$

$X2 - 2025 \qquad Y2 = 28.02$

Therefore,

$$m = \frac{28.02 - 6.78}{2025 - 2000} = \frac{21.24}{25} = 0.8496$$

Since $Y = mX + b$ then,

$$6.78 = 0.8496(2000) + b$$

$$6.78 = 1699.2 + b$$

$$b = -1692.42$$

For the year 2005,

$$Y = 0.8496(2005) - 1692.42$$

$$= 11.028 \text{ PJ}$$

viii) <u>Biomass</u>

$X1 = 2000 \qquad Y1 = 1960.56$

$X2 = 2025 \qquad Y2 = 3373.37$

Therefore,

$$m = \frac{3373.37 - 1960.56}{2025 - 2000} = \frac{1412.81}{25} = 56.5124$$

Since $Y = mX + b$ then,

$$1960.56 = 56.5124(2000) + b$$

$$1960.56 = 113,024.8 + b$$

$$b = -111,064.24$$

For the year 2005,

$$Y = 56.5124(2005) - 111,064.24$$

$$= 2243.122 \text{ PJ}$$

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