Substituting Natural Gas Heating for Electric Heating: Assessment of the Energy and Environmental Effects in Ontario

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A technical and thermodynamic analysis is used to show that significant energy-utilization and environmental-emission reductions are possible in the province of Ontario, Canada by substituting natural-gas heating for electric heating. The greatest benefits from substitution are realized in the utility sector, where marked reductions occur in coal and uranium use and related emissions. The results suggest that consideration should be given to increasing the level of natural-gas substitution in the province. The results, which must be viewed in conjunction with economic, safety and other related studies, are most likely to be useful to the developers and designers of energy systems, and to decision makers on energy planning and policy.

À l'aide d'une analyse technique et thermodynamique, on démontre qu'il est possible de réduire de manière importante l'utilisation d'énergie et les émissions causées dans l'environnement dans la province canadienne de l'Ontario en remplaçant le chauffage électrique par le chauffage au gaz naturel. Les avantages les plus substantiels surviennent dans le secteur des services publics où l'on observe une baisse notable de l'utilisation du charbon et de l'uranium et des émissions liées à ces énergies. Les résultats suggèrent qu'on devrait envisager d'augmenter le niveau de substitution par le gaz naturel dans la province. Ces résultats qu'il faut considérer vis-à-vis de l'économie, de la sécurité et d'autres études analogues vont très probablement s'avérer utiles aux développeurs et concepteurs de systèmes d'énergie ainsi qu'aux décideurs dans les domaines de la planification et de la politique énergétique.

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1. Introduction

Currently, natural gas is used extensively as a heating fuel in the residential, commercial, institutional and industrial sectors, for such applications as space and water heating and industrial process heating (EMR, 1987, 1990; NEB, 1991, 1994a, b; Hedley, 1986; Brown *et al.*, 1996), and electricity generation (EMR, 1990; Blue Apple, 1987; Ontario Hydro, 1990b). Electricity is also used in many sectors for a variety of tasks, including space and water heating. The roles of natural gas and electricity are likely to be important in the future (NEB, 1994b; Ontario Ministry of Environment and Energy, 1994; Rogner, 1993; Robinson, 1987). Many propose that direct fuel heating, particularly using natural gas, should be substituted for electric heating (*e.g.*, Hay, 1992). A major advantage of such substitution is that much less fuel energy is required for direct heating, relative to the two-step process of electricity generation followed by electric heating.

This is not to say that natural gas should not be used for electricity generation; in fact natural gas has many advantages as an electricity supply option (Blue Apple, 1987). But if, after generation, the natural gas-based electricity is used for heating, the alternative option of direct natural-gas heating has many advantages.

The objective of this study is to perform a technical analysis for the province of Ontario of the effects of substituting electric heating with natural-gas heating. Energy and environmental factors are considered. The study is primarily a technical and thermodynamic assessment; economic aspects of this substitution are taken to be outside the scope of this work. This paper refines and extends preliminary work reported elsewhere (Rosen *et al.*, 1995) (especially by considering environmental impacts), which was based in part on an earlier study (Sy, 1995).

This paper forms part of a larger study involving the authors directed at practical ways of reducing Ontario's energy consumption and environmental emissions. A major portion of this activity has focussed on the benefits achievable through cogeneration (*i.e.*, the simultaneous production of electricity and useful heat) in appropriate regions and sectors of the province (Rosen, 1994; Rosen and Le, 1994; Hart and Rosen, 1995). In line with this broader research program, studies are presently ongoing into the effects of implementing some degree of cogeneration along with the natural-gas substitution possibilities considered in the present paper.

2. Natural Gas and Its Use in Ontario

Natural gas is a mixture of hydrocarbon gases consisting mainly of methane (usually 85% to 95% on a volume basis), and varying amounts of such other constituents as ethane, propane and butane (Hedley, 1986). Before natural gas from underground gas reservoirs is used for commercial or industrial processes, it is processed to remove impurities, yielding "marketable" natural gas (EMR, 1990).

Canada's established reserves of marketable natural gas were estimated to be 2.4 trillion cubic meters in 1988. About 80% of these were within the province of Alberta. Ontario's natural gas reserves were estimated to be 17 billion cubic meters (Ontario Ministry of Energy, 1990b). Since then, the size of the known natural gas resource base has steadily increased due to exploration and other developments (NEB, 1994b).

Almost 98% of Canadian natural gas production occurs in Alberta and the other western provinces. Marketable natural gas is transported to Ontario and the rest of the country primarily via pipelines. Compressors are located at regular intervals to drive the gas through the pipelines to local distribution companies, which in turn supply the natural gas to consumers. In Ontario, there are three major distribution companies: Consumers Gas, Centra Gas Ontario and Union Gas (Ontario Ministry of Energy, 1990a). In October 1985, the Canadian government ended the regulation of wholesale natural gas prices, in part to create a more competitive natural gas industry, and with the hope of increasing exports and local use of natural gas.

Natural gas is utilized in many sectors in Ontario (Ontario Ministry of Energy, 1990b; Robinson, 1987). The largest portion of Ontario's natural gas consumption (45%) occurs in the industrial sector. Natural gas use is particularly prevalent in the petrochemical industry, since hydrocarbons are the chemical feedstocks for may petrochemical products (Brown *et al.*, 1996). Natural gas consumption is also significant in the residential and commercial sectors, which are responsible for 29% and 18% of total provincial natural gas consumption, respectively. The utility sector accounts for most of the remaining natural gas use.

3. Rationale for Substituting Natural Gas Heating for Electric Heating

Several benefits can accrue from the substitution of electric heating with natural-gas heating. These are discussed in this section in a general sense, and with a focus on how they pertain to the paper's focus on Ontario.

3.1 Increased Energy Efficiency and Reduced Energy Use

Through substitution, the same heating services can normally be provided using less energy (in the form of natural gas) than would be required to generate electricity from fuel energy and heat electrically. Consequently, the overall energy efficiency of the heating process is increased. This point can be illustrated through the following simple hypothetical example. First, consider the case of a direct natural-gas heating process. If the device has an energy efficiency of 90%, then the overall fuel-to-heat efficiency for this direct heating process is also 90%. Next, consider the case of a two-stage heating process, using a fuel-to-electricity conversion device of 35% efficiency, followed by an electric heater of 100% efficiency. The fuel-to-heat energy efficiency for this case is 35% (0.35 x 1.00), a value less than one-half that of the efficiency for the previous case. This illustration clearly demonstrates that the provision of the same heating services with the direct natural-gas heating process, in place of the two-stage process involving electric heating, requires much less fuel and is more efficient. It should be noted that this general trend is approximately valid for direct heating processes using any hydrocarbon fuels.

3.2 Reduced Environmental Impact

Environmental emissions are normally reduced with natural-gas substitution for two main reasons. First, emissions are reduced via substitution because, for the same total heating services delivered, fuel use is reduced. The reasoning behind this fuel-use decrease is discussed in the previous subsection. The second main reason why environmental emissions are reduced via substitution is that natural gas, which has relatively low emissions per unit energy, often replaces fuels such as coal and oil, both of which have greater emissions (Ontario Ministry of Energy, 1990b).

The above point is particularly significant for carbon dioxide (CO_2) emissions. For example, when considering fossil fuel-based electricity generation in Ontario, the CO_2 emission factors (in tonnes of CO_2/terajoule of electricity generated) are approximately 87 for coal, 74 for heavy fuel oil and 50 for natural gas. That is, the amount of CO_2 emitted during the generation of a fixed quantity of electricity is 48% higher when heavy fuel oil is used instead of natural gas, and 74% higher when coal is used instead of natural gas.

In Ontario, the amounts and types of electricity-generation fuels displaced through substituting natural-gas heating for electric heating depend in large part on the mix of fuels used in electricity generation in the province. Of course, costs and other factors would also affect which fuels would be displaced via such substitution. The main fuels/resources used for electricity generation in the recent past in Ontario can be broken down as follows:

- 31.3% (in 1990) and 25.2% (in 1995) from hydro resources;
- 45.7% (in 1990) and 55.9% (in 1995) from nuclear fuel;
- 20.4% (in 1990) and 10.9% (in 1995) from coal;
- 1.3% (in 1990) and 6.9% (in 1995) from natural gas; and
- 0.9% (in 1990) and 0.8% (in 1995) from heavy fuel oil.

It is noted that overall electricity generation increased by 18.9% during this period, from 129,700 gigawatt-hours (GWh) in 1990 to 154,200 GWh in 1995. For utility-based electricity generation in Ontario, hydro and nuclear electricity are used mainly to meet base-load demand. Coal and heavy fuel oil are mainly used for peak-load purposes.

3.3 Improved Economics

Often, the achievement of heating via natural gas is less expensive than generating electricity from fuels and then heating electrically. For a consumer requiring heating services, the economic attractiveness of substituting natural-gas heating for electric heating often depends on: (i) the cost differential between natural gas and electricity that exists at present and is expected to exist over the next several years; and (ii) the initial capital cost of converting to a natural-gas heating system from an electric heating system (or the cost difference between the two systems for a new installation). Usually, the natural gas-based system has a higher initial capital cost but lower operating (including fuel) costs, resulting in a period of time (the payback period) before the natural gas system becomes economically advantageous. The details of such a calculation for any application are specific to the case considered.

Other economic advantages can also develop via substitution. For example, the need to expand electricity-generation capacity, when demand nears supply capability, can be eliminated or deferred through substituting natural-gas heating for electric heating.

4. Methodology

To model and analyze the effects of substituting natural-gas heating for electric heating, a computer simulation model, Cogeneration and Fuel Substitution V.2 (CFS V.2) is used. The original version of the simulation model, CFS, was developed by P. Gharghouri and M.A. Rosen; CFS was enhanced by E. Sy and M.A. Rosen to create this second version. The simulation model can analyze the effects on a system of implementing:

- electric utility-based cogeneration (of electricity and heat) to satisfy a portion of the heating requirements of the system;
- substitution of natural-gas heating for a portion of the electric heating occurring within the system; and
- both of these actions simultaneously.

The portion of the simulation model relating to the second function is of primary interest in the present study, and is discussed below. Details concerning the logic used in the portions of the simulation model related to the first function above are discussed extensively elsewhere (Rosen, 1994; Rosen and Le, 1994; Hart and Rosen, 1995), and are in many parts common to the logic related to the second function.

The simulation model considers energy use and environmental emissions in: (i) the electric-utility sector in the province of Ontario (which is represented by Ontario Hydro); (ii) the non-utility sector; and (iii) the total province. The energy resources considered are: coal, petroleum products, natural gas, nuclear energy, and hydraulic energy. Renewable energy resources (*e.g.*, wind, solar, wave, tidal) are neglected since the quantity used in Ontario is minor relative to other resources (Statistics Canada, 1991). The electric-utility sector includes processes for electricity generation from coal, petroleum products, natural gas, and nuclear and hydraulic energy sources. The non-utility sector consists of the residential, commercial, institutional, industrial and transportation sectors. The residential, commercial and institutional (including public administration) sectors are driven mainly by fossil fuels and electricity, and involve as principal devices space heaters, water heaters, cooking appliances and clothes dryers. The transportation sector is primarily driven by fossil fuels and includes rail, marine, air, road and urban transport, pipelines, and retail pump sales. The industrial sector has as its main tasks work production and heating, and is diverse, including, for example, the following industries: mining, smelting and refining, pulp and paper, cement, iron and steel, chemical and petrochemical, petroleum refining, manufacturing and agriculture (Brown *et al.*, 1996).

In the assessments, heat production and consumption, by fuel type and user application, are input from published data and statistics.

The main logic related to energy calculations applied in the substitution calculations is as follows:

- For the percentage of electric heating specified by the user to be substituted with natural-gas heating, the corresponding reduction in electricity consumption and increase in natural gas consumption is determined for the province, using the appropriate electric heating efficiencies.
- Assuming that this reduction in electricity consumption leads to an equivalent reduction in electricity production in the province, the corresponding reductions in electric-utility fuel use, are determined for each fuel type, using the appropriate electricity generation efficiencies and the appropriate breakdown of fuels used by the provincial electric utility.

The assumption made in the latter point regarding the consumption of each utility-sector fuel that will be avoided through natural-gas substitution is made for simplicity and straightforwardness; in reality, considerable uncertainty exists in Ontario Hydro regarding the actual utility-sector fuel consumption that is avoided at any instant in time through a reduction in electricity demand. The actual avoided fuel consumption is a complex function of the actual fuels used for electricity generation (see the discussion in Section 3.2 above) and many other factors.

A similar calculation scheme is used for environmental emissions evaluations. Based on the changes in energy-resource use, corresponding changes in environmental emissions are evaluated for each energy resource.

The model employed simplifies the Ontario space-heating market by not addressing directly such details as space-heating load characteristics, base- and peak-load demands, and regional and seasonal variations. Rather, the model considers such factors indirectly by assessing overall levels of natural-gas substitution. Clearly, the attainment of any given level of substitution would be affected by specific values and/or characteristics for the factors listed above and others.

In using the computer simulation model, the user inputs details on energy consumption (fuel type and amount) for the base year, for the overall region under consideration (here, Ontario), broken down by sector. The user also specifies the natural-gas substitution level to be considered. The simulation model uses the logic described earlier in this section to generate relevant results.

The effects of substituting natural-gas heating for a part of electricity heating in each sector are calculated by the simulation model and then compared to the base case (*i.e.*, the situation before the substitution is implemented). CFS V.2 allows a percentage (specified by the user) of the provincial heat requirement met by electric heating to be converted so as to be met with natural-gas heating. The results generated by the simulation model present the change in fuel energy use due to substitution, and a comparison between the new energy use situation and the original base case. The simulation model does not assess the economic impacts of such substitution.

4.1 The Base Case

The base-case year is a typical recent year, which is used for comparative purposes. The base-case annual energy consumption is taken to be that for Ontario for the year 1990. It is presented in the two sections of Table 1, in energy units and physical units, respectively. The information is obtained from Statistics Canada (1991) and Ontario Hydro (1989a, 1990a), and is the same as the base case used by the authors in previous studies on related topics (Rosen, 1994; Rosen and Le, 1994; Hart and Rosen, 1995). Corresponding base-case environmental emissions data are presented in Table 2, based on information in Ontario Hydro (1989b, c, d, 1991), the Ontario Ministry of Environment (1989, 1991), and others (SENES, 1990; DPA Group *et al.*, 1989).

Based on recent data for Ontario (Statistics Canada, 1991), the base-case annual heat demand is taken to be 514.5 petajoules (PJ) for the residential, commercial and institutional sectors, and 414 PJ for the industrial sector. The residential, commercial and institutional heat demands are almost exclusively for low-temperature heat for space and water heating, while the industrial heat demand is for various tasks at various temperatures.

4.2 Assumptions and Approximations

The following assumptions and approximations are made:

- Excluding hydro, 33% of electricity generation by the provincial electric utility is from coal, and 67% from uranium (Statistics Canada, 1991).
- The electricity-generation efficiency is assumed to be 37% for coal-fired plants, and 30% for nuclear plants (Rosen, 1990).
- The energy-conversion efficiency is assumed to be 90% for electric space heating (a conservative estimate since the actual value is probably closer to 100% for electric heaters and over 100% for electric heat pumps), and 80% for fuel space heating (Rosen, 1992). All energy-conversion efficiencies for hot-water heating are assumed to be 100% (Rosen, 1992).

Table 1: Annual Base-Case Energy Use in Ontario

	PetaJoules						
	Electricity	Natural Gas & NGLs	Oil & Petroleum Products	Coal	Other	Uranium	Total
Utilities	-	-	14	286	-	640	940
Others	477	824	782	21	158	-	2260
Total	477	824	796	307	158	640	3200

	Physical Units					
	Electricity (terawatt-hours)	Natural Gas & NGLs (teralitres)	Oil & Petroleum Products (gigalitres)	Coal (megatonnes)	Other (kilotonnes)	Uranium (tonnes)
Utilities	-	-	0.33	10.4	-	1040
Others	132	21.0	21.5	0.71	5340	-
Total	132	21.0	21.8	11.1	5340	1040

Table 2: Annual Base-Case Emissions to the Environment in Ontario

	Material Emissions (kilotonnes)							Thermal Pollution (PJ)	Radiation (10^{15} Bq)
	SO_2	NO_X	CO_2	CO	Particulates	VOC	Spent Uranium		
Utilities	321	92	32,000	4	11	0.5	1.04	591	11
Others	1060	526	132,000	3500	837	775	-	-	-
Total	1380	618	164,000	3504	849	775	1.04	591	11

- Substitution is assumed to be implemented across all the sectors which utilize electric heating, in proportion to the amount of electric heating occurring. It is noted that the results presented subsequently (Section 5) are not strongly dependent on this assumption, and do not vary significantly if the distribution of the substitution effort is adjusted across the different sectors.

5. Energy-Related Results and Discussion

The effects on energy utilization were examined for various degrees of substitution, by applying the simulation model to the full range of possible substitution levels (*i.e.*, 0% to 100%). Provincial energy use for the full range of substitution possibilities is presented in Figure 1, broken down by energy type, and in Figure 2, broken down by sector. Also illustrated are the reductions in provincial energy use with substitution, broken down by energy type (Figure 3) and by sector (Figure 4). In Figure 3, the reductions are presented in energy units (top half of figure) and on a percentage basis (bottom half), and the percentage reductions are relative to the energy-use values, for each fuel/energy form, for the no-substitution case (shown in Figure 1). Similarly, in Figure 4, the reductions are presented in energy units (top half of figure) and on a percentage basis (bottom half), and the percentage reductions are relative to the energy-use values, for each fuel/energy form, for the no-substitution case (shown in Figure 2).

Environment-related results are presented in the next section. It is noted that the "appropriate" or optimal levels of substitution are not indicated in these energy and environmental results, as economic and other factors must be considered in making such determinations.

The full range of substitution from 0 to 100% is presented for completeness and illustration, and is not intended to imply that the full range of substitution is realistic or practi-

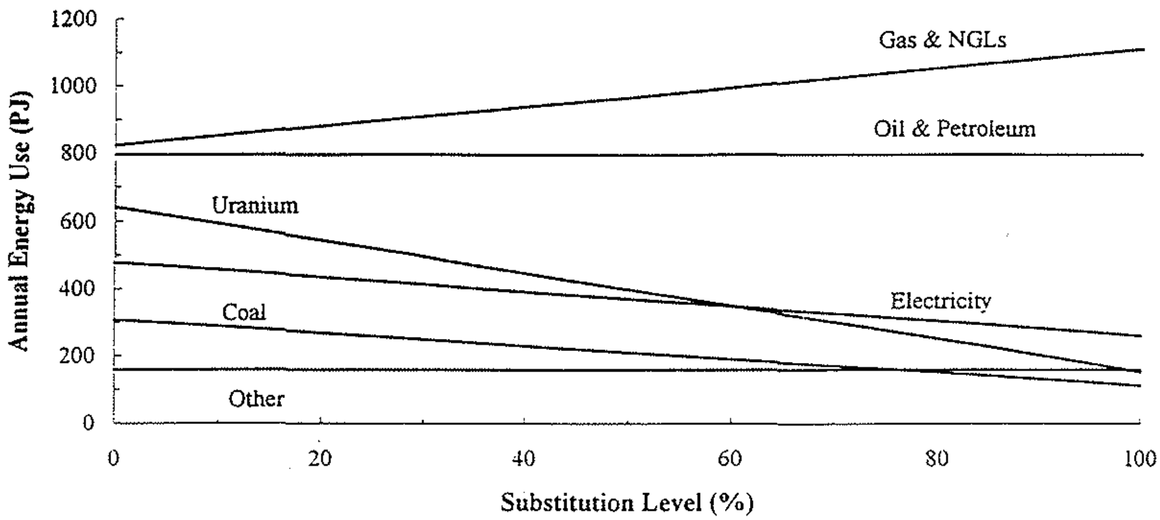

Figure 1: Annual Energy Use in Ontario, by fuel/energy form (as a function of the substitution level of natural-gas for electric heating)

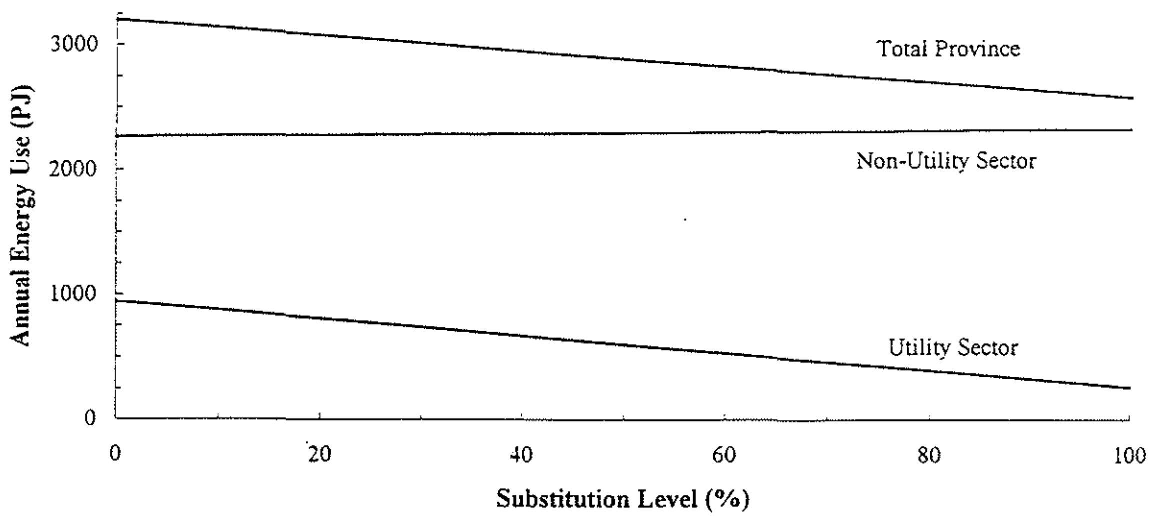

Figure 2: Annual Energy Use in Ontario, by sector (as a function of the substitution level of natural-gas for electric heating)

cally achievable. For example, throughout the sectors that use electricity, the conversion from electric to natural-gas heating would in many instances be prohibitively expensive, or impractical for technical or other reasons (*e.g.*, natural gas cannot straightforwardly displace electricity for heating in regions of the province where natural gas is not available). The realistic level of substitution achievable, depending on the criteria imposed, is likely well under 50%.

Some details in Tables 1 and 2 and in Figures 1 to 4 require clarification if the results are to be properly understood and interpreted. In Table 1 (top portion) and Figures 1 and 3: (i) hydraulic energy use is not shown since it is not considered affected in the analyses performed; (ii) the "Other" category includes coke and coke oven gases, which are originally produced from coal; (iii) the energy value of uranium is taken to be the heat from fission delivered from the nuclear reactor to the power cy-

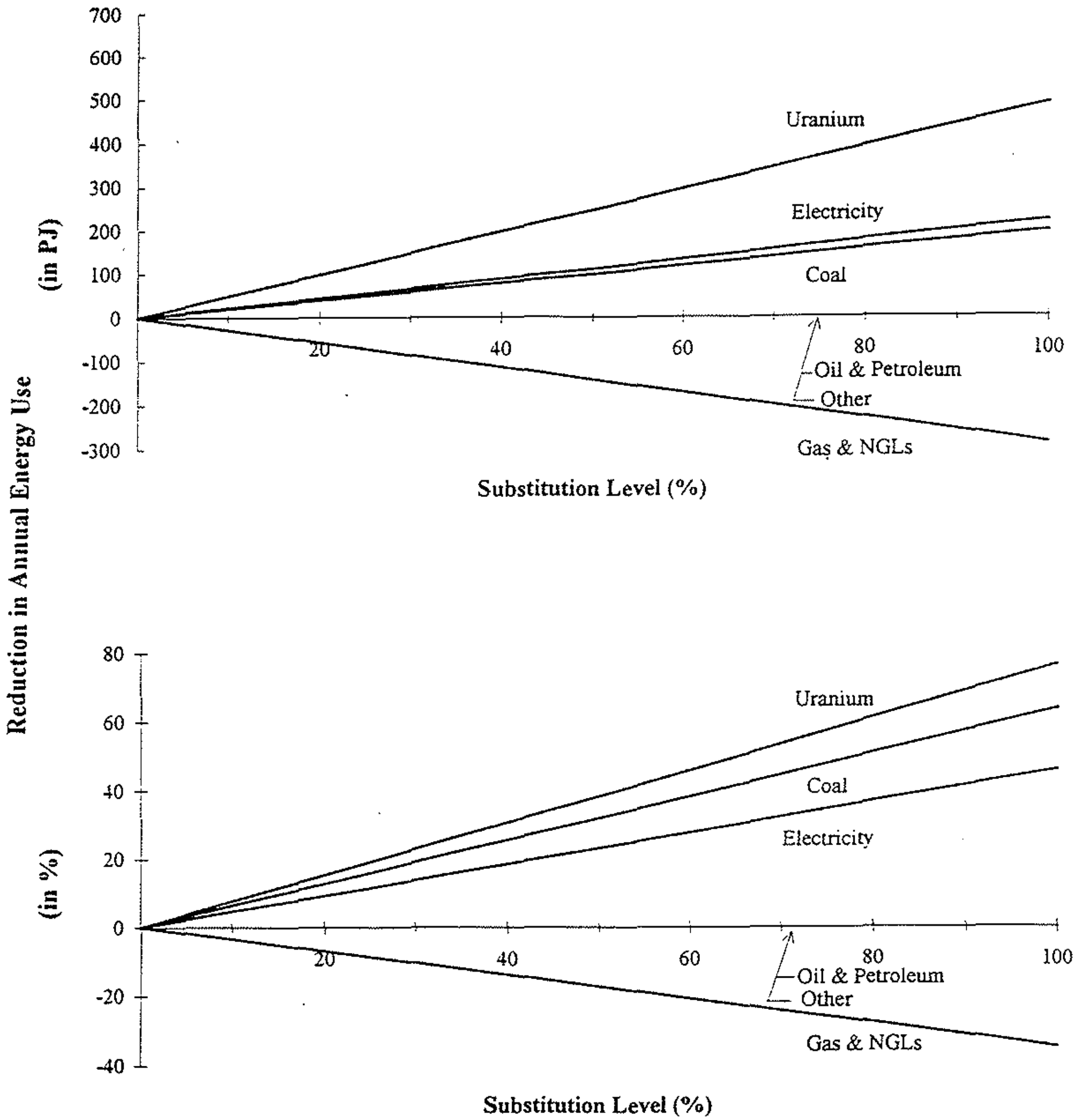

Figure 3: Reductions in Annual Energy use in Ontario, by fuel/energy form (as a function of the substitution level of natural-gas for electric heating)

cle; and (iv) NGLs denotes natural gas liquids and VOC denotes volatile organic compounds. In Figures 2 and 4, total base-case annual energy use for the overall province includes the shown primary energy forms, as well as the secondary from – electricity.

It can be seen in Figures 2 and 4 that total energy consumption for the province decreases markedly with substitution, from approximately 3200 PJ to as low as 2580 PJ (where the extreme limit is represented by the 100% substitution case). Also, the utility sector experiences a significant reduction in total energy use with substitution, from 940 PJ to as low as 257 PJ, while non-utility sector energy consumption increases slightly, from about

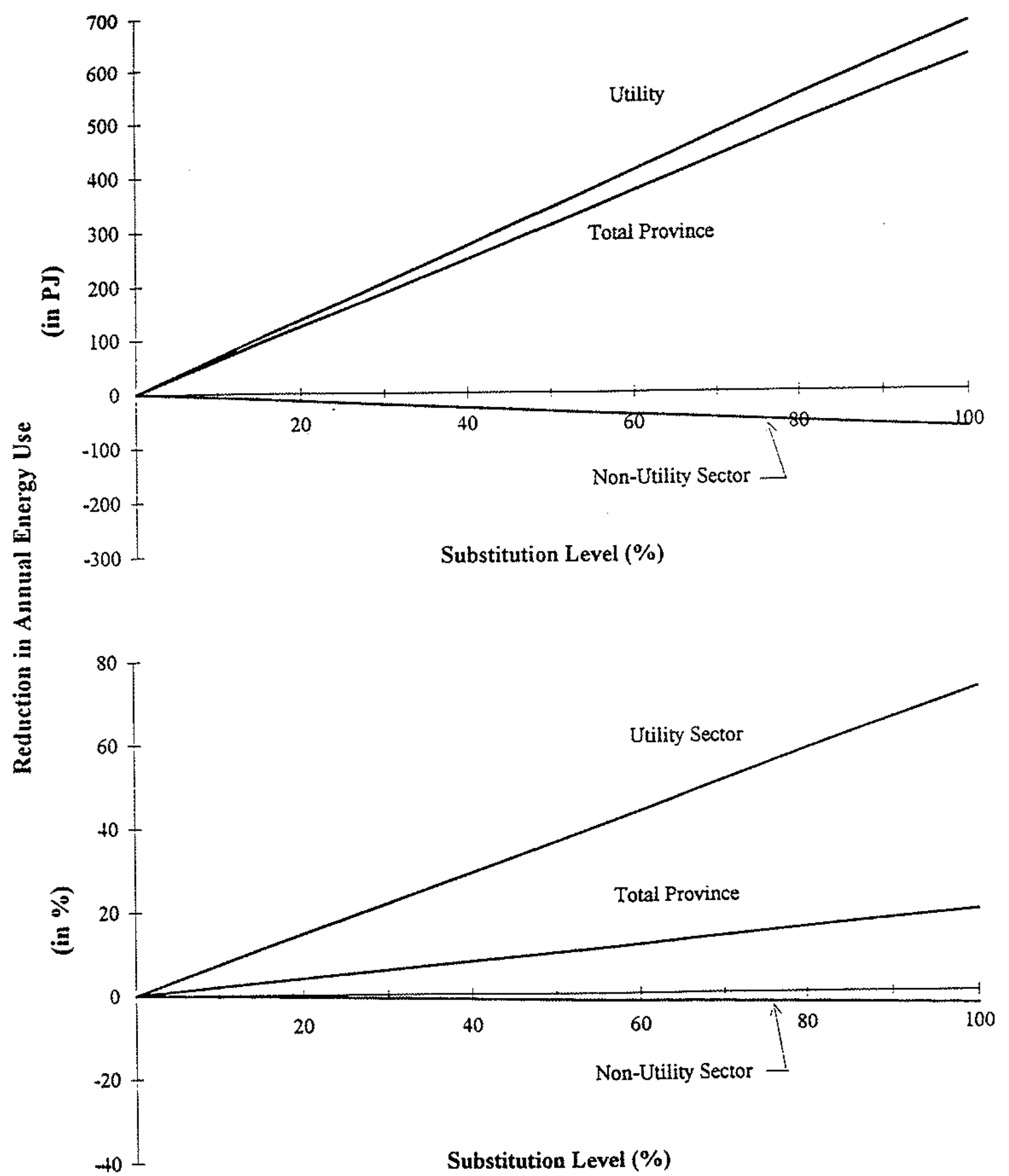

Figure 4: Reductions in Annual Energy use in Ontario, by sector (as a function of the substitution level of natural-gas for electric heating)

2260 PJ to as high as 2330 PJ. The net reduction in total provincial energy consumption, which is the net sum of the energy-consumption reductions for both sectors, is mainly attributable to the reduced fuel use in the utility sector.

When substitution occurs, energy use is affected for only some energy forms and some sectors. Specifically, substitution affects the consumption of coal and uranium in the utility sector, and natural gas and electricity in the non-utility sector. The reductions in energy use in Figures 1 and 3 emphasize the changes for the energy forms affected by substitution.

It can be shown, using the data in Figure 3, that the reductions in consumption of these energy forms vary in direct proportion to the degree of gas substitution. For every 100 energy units that natural-gas use increases through substitution of natural-gas heating for electric heating, coal use is reduced by 72 units and uranium use by 170 units. This proportional relationship is not necessarily valid in general, but exists here due to the assumptions applied (*i.e.*, that electricity demand reductions are met by coal and nuclear fuel only, in fixed proportions, and that energy-conversion efficiencies are fixed).

In summary, substitution leads to net reductions in overall energy consumption for the province as a whole, compared to the original base case. The utility sector benefits the most from substitution, with significant reductions accruing in coal and uranium use, and electricity production. The non-utility sector experiences relatively minor increases in net energy use as a result of substitution. This increase occurs because, in the non-utility sector, electric heating (at high efficiencies) is replaced with natural-gas heating (at high, but relatively lower, efficiencies).

6. Environment-Related Results and Discussion

Several environmental effects are expected to result from natural-gas substitution. The changes in fuel consumption caused by substituting natural-gas heating for electric heating lead to: (i) marked reductions in the emissions and wastes associated with coal and uranium use in the utility sector, but (ii) slight increases in the emissions and wastes associated with natural-gas use in the non-utility sector.

The above paragraph implies that, through substitution: (i) some of the emissions and wastes from consuming coal and uranium are eliminated; and (ii) some of the coal- and uranium-related emissions and wastes are replaced by natural gas-related emissions and wastes. The first of these effects is beneficial, as is the portion of the second effect involving the replacement of coal-related with natural gas-related emissions and wastes. The environmental impacts of natural-gas use are generally considered to be more benign than those from coal use, per unit fuel energy. The portion of the second effect involving the replacement of uranium-related with natural gas-related emissions and wastes could be argued to be positive or negative environmentally, depending on the perspective one has on the impacts of uranium use on the environment (an issue that is still the subject of debate).

As a first-order approximation, the percentage changes in all emissions and wastes associated with using each of these fuels is predicted here to be the same as the percentage changes in the consumption of each fuel. Hence the percentage reductions in energy use broken down by energy type (shown in the top portion of Figure 3) also represent the approximate percentage reductions in the environmental emissions associated with the fuel type (relative to the base-case emissions in Table 2).

The changes in specific emissions are not evaluated in detail here. Further environmental effects associated with the full life cycle of energy resource extraction through to final use are also excluded from the present discussions, although details on the types of emission changes anticipated, and the environmental, health and financial implications of such changes, are discussed elsewhere (Hart and Rosen, 1995).

7. Concluding Remarks

Based on the results of the technical and thermodynamic assessments carried out in this study, it is concluded that substitution of natural-gas heating for electric heating would be beneficial for the province in terms of reductions in energy use and environmental impact, with the greatest energy and environmental benefits from substitution being realized in the utility sector. The complete theoretical range of possible substitution levels is considered in this paper, and the benefits of substitution are observed to exist for all levels of substitution.

Consequently, the authors feel that consideration should be given to increasing appropriately the level of natural-gas substitution in the province. The level of substitution which is "appropriate" is not determined in this paper, and requires a detailed optimization operation considering one or more case-specific objective functions and a wide variety of case-specific constraints.

The results, which must be viewed in concert with assessments of economic and other factors, are most likely to be useful to the developers and designers of energy systems, and to decision makers on energy planning and policy. In the near term, the results could assist in determining the most appropriate level of substitution in Ontario.

Further work seems warranted to improve the accuracy of the results (which are dependent on simplifying assumptions and approximations, including several estimates of input energy data), and to expand the work to include assessments of the impact of substitution in other relevant dimensions (*e.g.*, economic aspects). In addition, studies into the benefits of implementing natural-gas substitution in conjunction with other measures for energy-use improvement (*e.g.*, cogeneration) would seem to be worthwhile.

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