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ENERGY ~ODELLING IN SERF:
THE SOCIO-ECONOMIC-RESOURCE FRAMEWORK

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The Structural Analysis Division of Statistics Canada is engaged in the development of a Socio-Economic-Resource Framework (SERF) which permits the analysis of the flows of materials and energy from the natural resource base that are required to meet domestic and international needs.

1. INTRODUCTION

The Socio-Economic-Resource Framework (SERF) is a consistent, disaggregated set of models which, taken together with their associated data bases, can be used to simulate possible evolution paths of the Canadian economy over the long term. Emphasis is placed on modeling the physical flows of materials and energy that are required to meet human needs, and the processes that transform raw materials into finished goods. Short-term or cyclical phenomena are not captured, and the behavioral responses of economic agents are left to the model user to specify in the course of constructing a simulation.

SERF builds on the framework of the Statistics Canada Long Term Simulation Model. This earlier model was employed in studies examining Canadian energy growth possibilities [lJ and the development of soft energy paths [2J.

The Socio-Economic-Resource Framework is designed to meet several objectives: it is an analytical tool which may be used to develop scenarios or alternative views of the future; it is an information framework containing integrated sets of data pertaining to the socio-economic-resource system and information about relationships among components of the system; it is an interactive educational tool for the needs of policy makers; and finally it provides the means for establishing priorities for data collection and analysis.

At a very high level SERF may be viewed as a systems model of the economy with three main components. A demographic model provides the driving variables: population, households, and labor supply. The demand model measures the flows of goods and services required by the simulated population. The production model represents the material transformation processes required to convert resources into consumer goods. The details of these calculations are spread through some 24 sub-models, all linked within a common modeling framework. Constructing a simulation with SERF is typically a process of generating scenarios for simulation variables, then iteratively adjusting these scenarios in order to balance supply and demand of resources and labor, and external trade.

The bulk of this paper is concerned with the sub-models having an important bearing on energy supply and demand. We document the structural relationships in SERF using diagrams with precise meaning: boxes represent procedures, triangles stocks, circles flow variables, and hexagons ratios and other parameter types.

2. ENERGY SUPPLY AND DEMAND IN SERF

One of the prime motivations in the development of the Socio-Economic-Resource Framework is the desire to model the interaction of human populations and their needs with the resource base. The resource chosen for elaboration in this first version of SERF is energy. Because of its diversity of forms, intrinsic importance, pervasive nature, and because of the realization of the finiteness of the traditional forms of energy available in Canada, energy serves as an important and useful example of resource analysis using SERF.

The explicit modeling of the Canadian population, their stocks of goods, and the services which flow from these goods, imposes an important discipline of the exercise of examining supply and demand of energy over the next fifty years. The assumptions made about household formation, the size and type housing, the stock of heating equipment and insulation standards of this housing, the stock of appliances using energy and their efficiencies, and the number, usage, and efficiency of automobiles per household are all critical to this analysis. In a broader context,-the energy-using characteristics of the industrial processes producing goods for consumers and the transportation systems required for this production also have bearing, in an essential way, on the level of energy demand.

It is equally important to measure some of the physical constraints and ramifications of the process of investing in energy supply facilities. Old facilities have finite lifetimes and declining capability. Bringing new facilities online requires significant construction lead times and a flow of goods and services associated with this construction. The process of investment itself has an impact on the resource base.

The real power of the SERF model structure lies in its imposition of consistency on the user. All components of a scenario interact to produce disequilibria of energy supply and demand. Equilibration requires explicit assumptions on the part of the user for its achievement. What is produced in this process is a consistent world view of the technological possibilities over time and the type of society employing this technology. Consistency constraints comprise a powerful test of our intuition about the future.

The remaining sections of this chapter layout in some detail the individual components of energy consumption and supply in SERF. The elements of consumption include the residential energy demand block, the appliance model, the transportation block, and the industrial energy and use model. The design of the energy supply model is detailed. And finally there is a discussion of the modes of use of the combined energy supply/demand portions of the model in order to achieve an energy balance.

2.1 The Residential Energy Demand Model

The household model is a micro-simulation framework and related data base of the evolution of the Canadian housing stock, residential construction, and the uses of energy for space heating and hot water. It is designed to provide an analytical tool for examining a variety of energy consuming strategies involving thermal characteristics, building performance standards, fuel substitutions, and new space conditioning technologies. In common with other modules of SERF it is a simulation model, leaving the assumptions about behavior to the user. An example of the use of this model was an examination of alternative "off-oil" programs for the province of Ontario [3].

This model is distinguished from other parts of SERF in having a significant degree of regional disaggregation. This is necessitated of course by the wide

FIGURE B.1.1
HOUSING STOCK

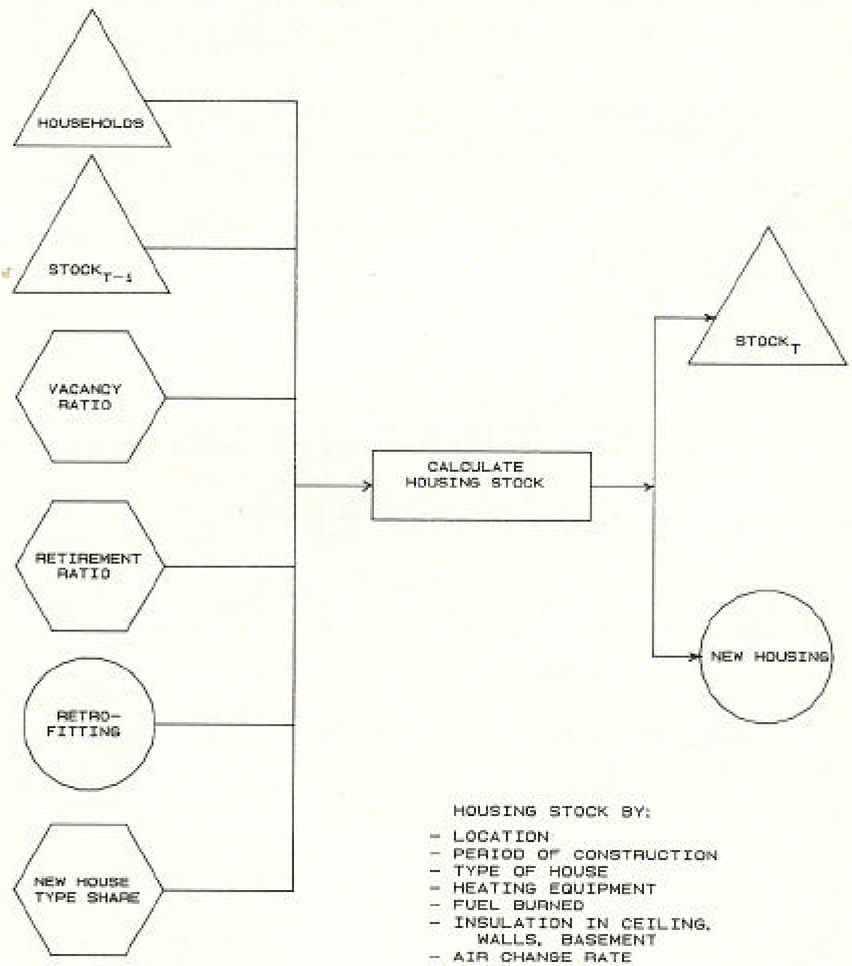
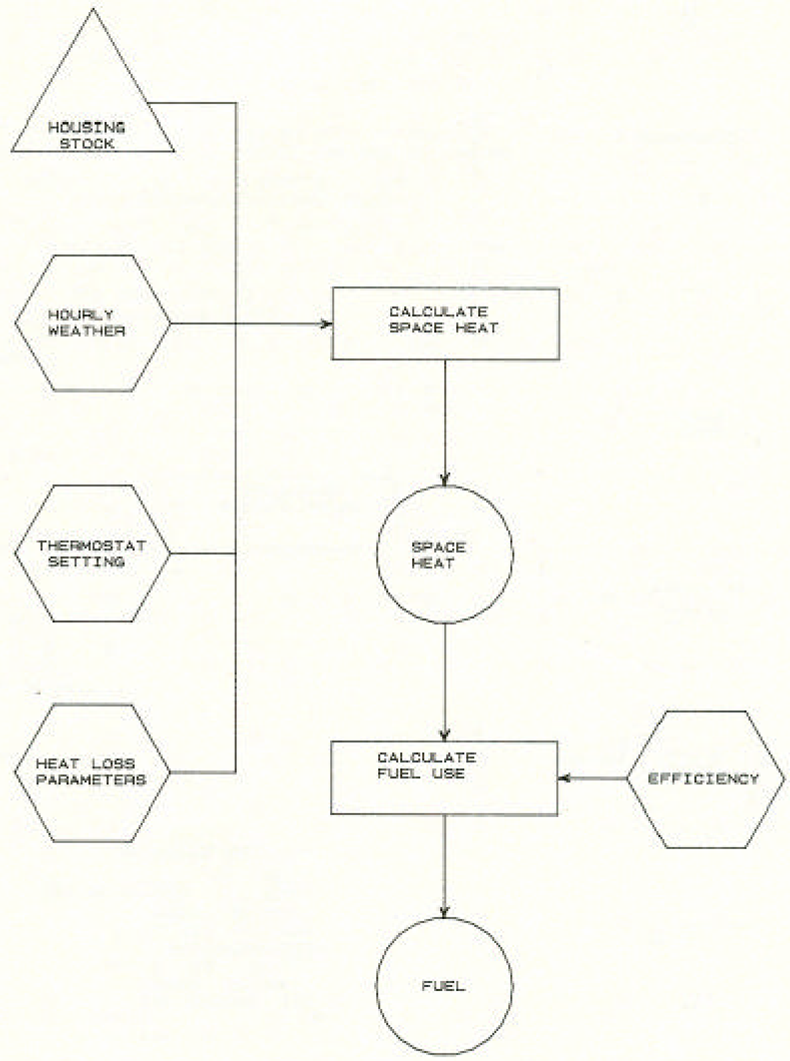


FIGURE B.1.2
HOUSEHOLD SPACE HEAT



variation in weather and therefore space conditioning demands experienced from coast to coast in Canada.

Figures B.1.1 and B.1.2 give a very high level view of the housing and household energy calculations respectively. The model consists of six major blocks: the historical housing stock, demolitions, thermal retro-fitting, heating equipment retro-fitting, new housing construction, and the energy requirements calculator. The following is a brief description of each of these.

Historical Housinq Stock - The starting distribution of housing stock is stratified by type, age, and heating equipment category. Housing types included are single detached, semi-detached and duplex, row housing and apartments. Heating equipment is divided into (1) water oil, (2) water gas, (3) water solid, (4) hot air oil, (5) hot air gas, (6) hot air solid, (7) electric, (8) space oil (i.e. point of use heaters), (9) space gas, and (10) space solid. Hybrid heating technologies are also permitted, such as the so-called "Saskatchewan House", heat pump-oil, heat pump-gas, heat pump-electric, heat pump-solar, gas-solar, and electric-solar. Housing of each age category and type is given a thermal archetype relating to insulation of ceilings, walls, and basement walls, and physical characteristics relating to average areas of wall, ceiling, basement wall, window, doors, and average living area.

In addition, weather data is available on a 4-hour1y basis for the major geographical regions giving ambient temperatures and solar heat gain factors. Heating equipment is stratified by seasonal heating efficiences by type and fuel used.

Demolitions - The rates of demolition of existing housing are specific to the type of house and period of construction.

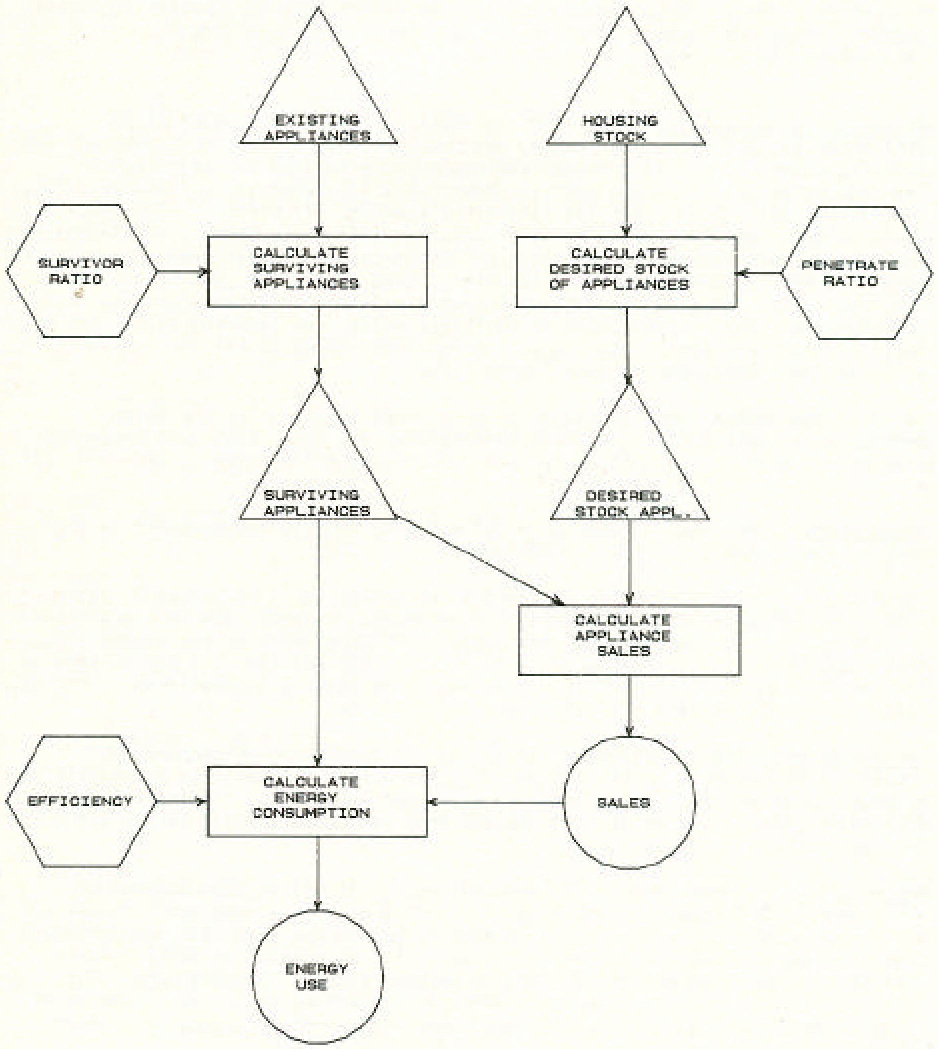
Thermal Retro-fit - The degree of thermal retro-fitting is simulated by using time dependent and thermal characteristic dependent propensities to upgrade the housing stock. For example, we simulate by estimating what is the probability that a particular house having R20 insulation in its ceiling will be upgraded to R28 insulation in a given period. Four heat loss areas are considered: ceiling, walls, basement, and air infiltration.

Equipment Retro-fit - Similar in concept to the simulation of thermal retrofitting, for each period and each housing type a set of transition probabilities between equipment types is employed to calculate retro-fits; for instance the probability that a duplex will be changed from water gas heating to hot air oil heating in a given period.

New Housinq - The requirement for new housing is calculated from provincial breakdowns of the Canadian population as calculated in the demographic block of SERF. Households are arrived at by applying age and sex specific probabilities that a per.son will be the head of a household to the population distribution. Housing is related to households through vacancy rates by housing type. The heating equipment type and thermal archetype of new housing is calculated using recent penetration rates of heating equipment and by making assumptions about "future building codes.

Energy Requirements - The actual computation of energy requirements proceeds by micro-simulation of ambient weather conditions in each region applied to the simulated housing stock by type, heating equipment, and thermal characteristic. Simulation time periods as small as four hours are required to correctly calculate energy requirements in hybrid systems where, for instance, heat pumps are only effective over certain temperature ranges, or solar collectors are

FIGURE B.2
APPLIANCE MODEL



usable only during daylight hours.

2.2 The Appliance Model

The appliance model is designed to allow simulation of the stocks of appliances accumulating in the households of the Canadian population over the long term, and their associated energy requirements.

There are ten bas i c types of app Ii ances tracked by the mode I: (1) elect ri c ranges, (2) gas ranges, (3) microwave ovens, (4) refrigerators, (5) automatic washers, (6) electric dryers, (7) gas dryers, (8) dishwashers, (9) freezers, and (10) air conditioners. Together these comprise much of the non-heat energy use in homes.

Because appliance sales are naturally associated with households and not with individuals, the model builds on much the same apparatus as the Residential Energy Dgmand Model. In particular, the two models share the treatment of household formation from the demographic block of SERF, the same underlying historical housing stock and the same calculation of housing construction by housing type, by relating households to structures through a vacancy rate. The parts of the model unique to appliances are shown in Figure B.2.

The basic driving force in determining appliance stocks is a penetration rate stratified by appliance type and housing type. This rate is based on aggregate historical ratios of the number of appliances of each type in each type of home. One of the basic simulation variables is the projection of these rates. The consequences for the ultimate stock of appliances in Canadian households are closely tied to whether the model user simulates, for instance, that in the future every home will have a microwave oven and a dishwasher, or whether these and other appliances will remain luxury items enjoyed by some subset of homes.

It should be clear that in specifying a set of penetration rates the model user is making a statement or assumption about lifestyles in the future.

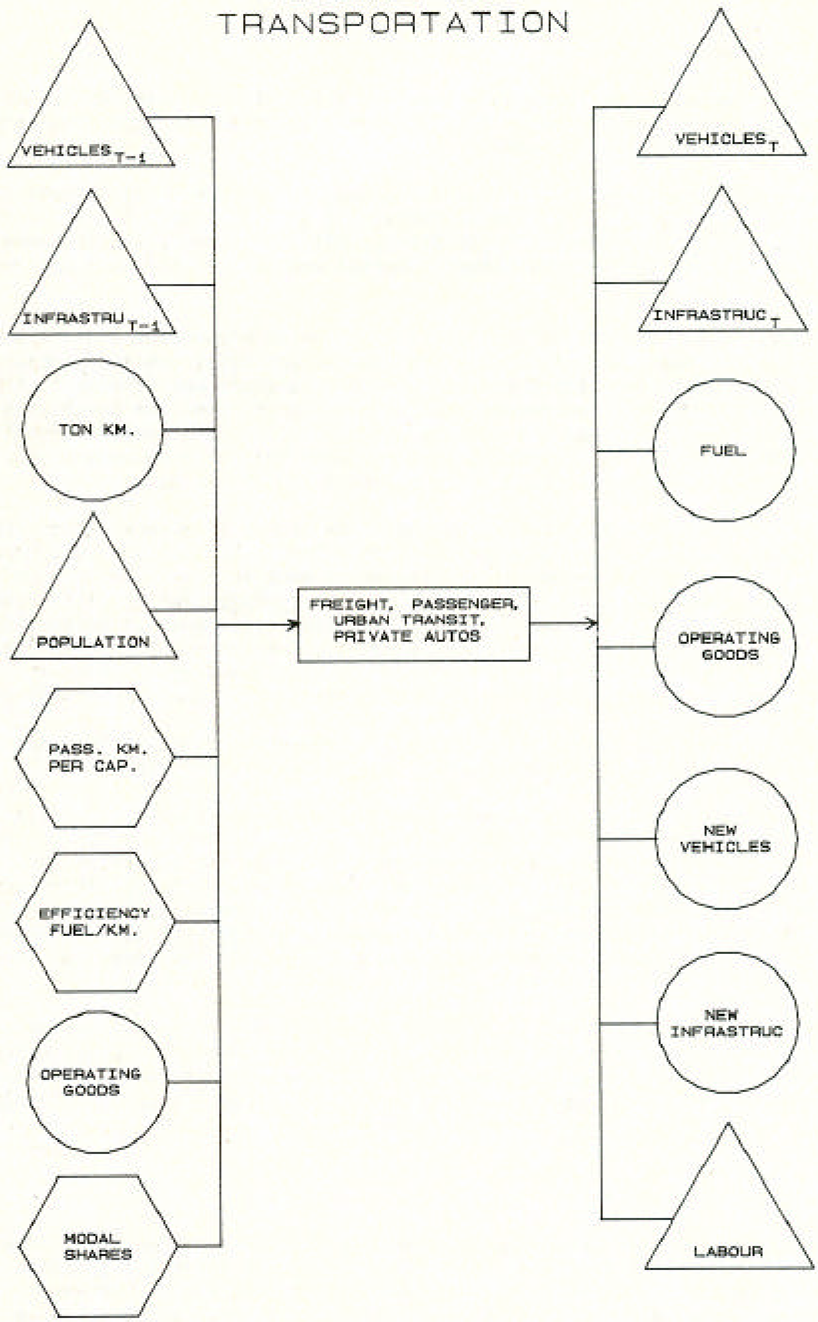
Sales of appliances will be related both to the change in stocks of appliances inherent in the other simulation variables and to the assumptions made about average lifetimes of these goods in service. Lifetimes are specified through survivorship curves by appliance type, i.e. the proportion of appliances of age T which will still be functioning, for T spanning some appropriately long time period. Appliance sales are passed to the production block of SERF as demands which must be met by the economic system, with their ultimate impact on the resource base.

Finally, starting from historical figures on appliance energy consumption per year by year of production, the user may project these figures for appliances produced in the future, creating vintage-specific energy efficiencies. The model simply sums up the energy consumption of the stocks of appliances by vintage to arrive at annual energy consumption.

2.3 The Transportation Model

In a country as large as Canada, with so widely dispersed a population, the importance of transport in the economy and its importance for energy demand, in particular, is clear. We have distinguished four categories of transport, each with its particular driving variables and characteristics. In addition, a submodule of the transportation model calculates the required investment in infrastructure t~ support the transport system. A high level view of the model

FIGURE B.6
TRANSPORTATION



is given in Figure B.6.

The freight transport module is essentially driven by required ton-kilometers of transport of goods by mode. This variable is decoupled from industrial production to allow maximum flexibility in simulating changing industrial structure. Coefficients of total stock of transport equipment per ton-kilometers by mode are used to calculate the required freight stock. Using variables for the average distance travelled per unit of stock, the energy efficiency by vintage (in units of energy per kilometer) and a fuel distribution, the total energy requirements are derived.

Inter-city passenger travel is calculated using the population from the demographic block, coefficients of trips per capita, and figures for average trip length. From the passenger miles so calculated, we derive passenger miles by mode (aircraft, trains, and buses) using a distribution of trip length by mode. The required stock of passenger transport equipment is calculated using coefficients of stock per passenger mile by mode. Energy requirements are derived from average distance travelled per unit of transport stock, a vintagespecific energy efficiency and the distribution of fuel types.

The stock of private automobiles is obtained by applying ownership rates to the number of households coming from the demographic block. Automobile usage is assembled from three components: commuting to work, other private auto travel, and fleet usage. By taking the labor force figures from the labor demand calculation in SERF, applying a proportion of employees commuting in autos and using figures for the average number of passengers per commuting vehicle, the number of automobiles used each working day in commuting is calculated. Total commuting kilometers comes from variables representing the average distance to work and the total number of working days per year. Total kilometers of other private automobile travel is a separate simulation variable, as is the number of autos used in fleet operations; total fleet kilometers per year is simply derived from a coefficient of average kilometers travelled in a year per fleet auto. Having arrived at total automobile kilometers travelled per year, energy usage is calculated from the usual vintage-specific vehicle efficiencies and fuel distributions. Distributions of fuels used in autos can be affected both by the characteristics of new vehicles and by retro-fitting existing ones.

Urban transit is also divided into commuting and other travel. Commuters are calculated using a simple proportion of the labor force which commutes on public transit. Other travel is derived from rates of. use of public transit by the general population for purposes other than commuting. The stock of urban transit vehicles comes from ratios of stock by mode per fare population. The ~nergy requirements for urban transit are then based on fuel usage rates per unit of stock by vintage, and split using a distribution of fuels.

Figure B.2 shows the other outputs of the transportation modules such as vehicle sales, labour required for the operation of transit systems, and the infrastructure which must be developed to support transportation. Infrastructure construction and production of new vehicles both feed demands for goods and services to the SERF production block, adding to the indirect energy requirements of transportation.

2.4 The Industrial Energy End Use Model

The philosophical basis for modeling the demand for energy in the industrial (goods producing) sector is our belief that energy is not desired per se in economic processes, but rather what are desired are the services or end uses which it provides. Thus industrial processes require heating of a particular is given in Figure B.6.

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So rather than representing industrial energy use in the traditional Input-Output manner of employing coefficients of fuel use per unit (constant dollar) of production. SERF is based on coefficients of energy use in Joules per unit of production. The elaboration of the relationship between energy and use, energy efficiency, and specific fuel types in the industrial sector appears in Figure C.3.

For the roughly ISO industrial sectors identified in SERF, we employ historical coefficients of the requirements for five end uses (motive power. electricity as heat, process heat < 2I2F, process heat between 2I2F and 500F. and process heat> 500F) per constant dollar of production. For many sectors these involve estimates based on aggregates; for some sectors such as farming and construction there are not even estimates. The key variables for simulating changes in energy efficiency are just these coefficients - the user's scenario for the technical possibilities for decreasing high temperature heat requirements' in"stee1-making, for instance, is represented in changes in the end use coefficients over time, with the consequent decrease in the energy intensiveness of the industrial sector.

The relationship between end uses and fuel types is captured in a set of fuel share coefficients for each end use and industry. User scenarios for the rate of substitution of one fuel for another in, for example, the provision of high temperature process heat in the cement industry, taken together across all sectors, end uses, and fuels determine the overall extent of fuel substitution in the industrial sector. A refinement of this procedure, which we hope to introduce as data become available. will reflect the technologies transforming fuel types into end uses explicitly - this is important because the amount of natural gas which can substitute for a given amount of oil, for instance, in a particular application is technologically constrained and should be represented direct1y.

The product of the simulated coefficients of end use by industry and the fuel shares by end use, when multiplied by the sectoral production as calculated in SERF's Input-Output model, gives the requirements for fuels in the industrial sector over time. The essential link between technology and industrial structure on the one hand, and the resource" base on the other, is therefore maintained.

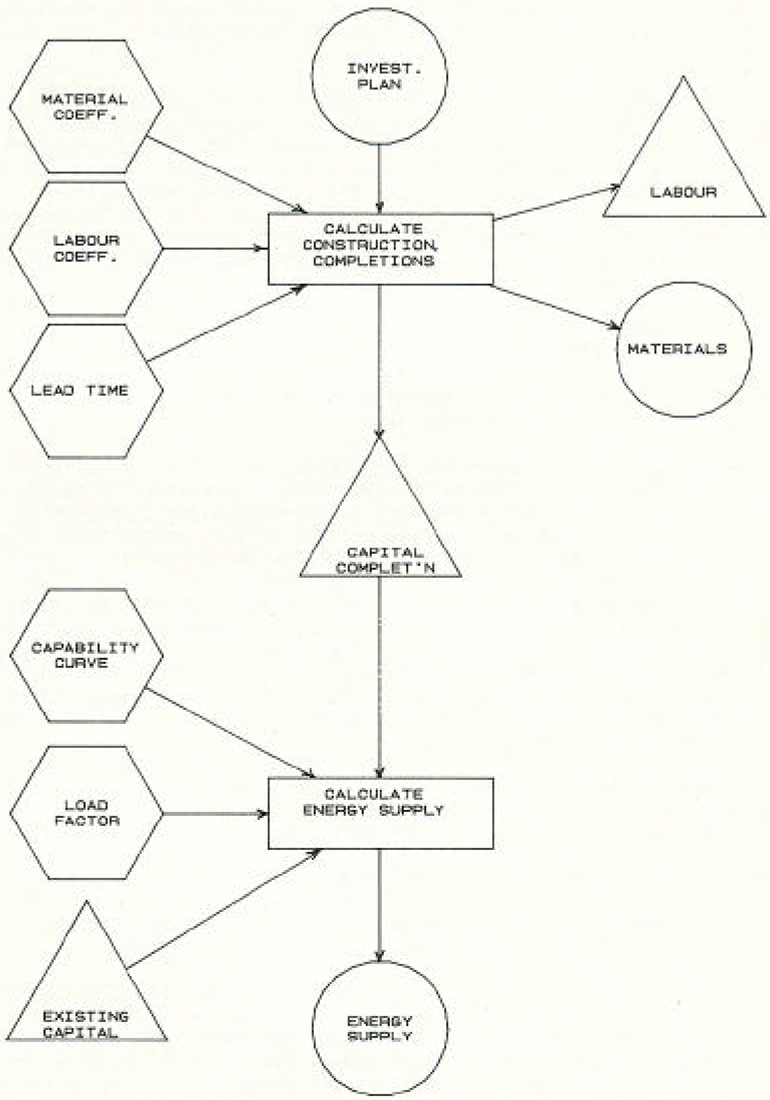
2.5 Other Energy Demand

Although the bulk of demand for energy is captured in the modules described so far, there remain significant areas in which SERF does not attempt a detailed treatment. One such area is household demand for electricity used in lighting. home entertainment, and so on. Energy for lighting space conditioning and equipment operation in the government, health, education, and service sectors is calculated using coefficients relating to the stock of structures measured in constant dollars. There are major data problems preventing any progress in developing this part of the model. It is clear that we should treat these sectors on the basis of the physical infrastructure of buildings and equipment which are employed in the course of their activities. but it is precisely these data which are the most difficult to obtain or estimate.

2.6 Energy Supply

Most energy analysts and prognosticators have their own scenarios for energy supply in the future, based on their own estimates, guesstimates, or hopes for

FIGURE C.1.1
ENERGY SUPPLY - NON OIL OR GAS



the supply possibilities which we face. What has been lacking is a tool for rigorously examining the consequences for the rest of the economy of choosing a particular energy supply development path. It was with this goal in mind that the energy supply model of SERF was designed and implemented. And, as pointed out earlier, by explicitly modeling supply and demand separately the analyst is forced to construct a consistent picture of the energy system in the context of the economy as a whole.

To date, SERF models the following energy supply technologies: conventional onshore oil, secondary oil recovery, enhanced oil recovery, offshore oil, and Arctic oil; oil sands mining and upgrading; conventional onshore gas, enhanced gas recovery, offshore gas, and Arctic gas; underground coal mining and surface mines; thermal, nuclear, and hydro-electricity; and petroleum refinery capacity. The framework wi11 be more complete when several "soft" technologies are added, including a variety of solar and biomass options. Also lacking at present is the representation of energy transport technologies such as oil and gas pipelines, tank cars, and ice-breaking oil and LNG tankers.

The models of energy supply can in general be described as being plan driven. The major inputs are simulated additions to production capacity. Oil and gas facilities present a challenge to the modeller attempting their representation which is distinct from the other technologies. We will discuss the methodological issues for oil and gas separately.

First, though, Figure C.l.l shows the model structure for oil sands and all other non-oil and gas facilities. The driving variable in a simulation is planned additions to production capacity measured in terms of numbers of nominal facilities representing typical facility sizes - in this manner the "lumpy" nature of capital investment is captured. Completions of energy projects are lagged by a facility-specific construction lead time. As facilities are completed their capacity is added to surviving energy capital, calculated from capability curves (a capability curve for a typical energy supply technology would start at 1.0 representing the ability to operate at rated capacity when the plant is new, then decline as the plant ages until the rated technological life is reached, when the curve drops to 0.0). Mediating between energy production capacity and actual production in any simulation time period is a load factor, which itself is a major simulation variable.

The supply model is linked to the rest of SERF in three ways. The calculated energy production is a tension variable going to one of the major reports of SERF (this will be discussed in the next section). During the reconstruction of facilities the stream of material and energy requirements is passed to the production model as a demand for goods. And finally, the labor required for construction is added into the overall model's calculation of labor demand. It should be noted that the materials, energy, and labor required for the operation of energy supply facilities is modelled in the production block.

One fundamental distinction of oil and gas production, as shown in Figure C.l.2, is in the behavior of the existing capital stock. Rather than having a capability curve and fixed technological life, individual hydrocarbon reservoirs when fully developed exhibit exponentially declining production curves as a consequence of inevitable declines in reservoir pressure and loss of continguity of the hydrocarbon structures. The rate of decline is typically related to the rate of extraction. Rather than employing a detailed model of hydrocarbon reservoirs, we have used estimates of the aggregate rate of decline of developed reservoirs and functionally related this to the load factor for oil and gas. To capture the fact that most conventional oil wells eventually employ secondary recovery (drilling peripheral holes and pumping water into the reservoir), a lagged investment in secondary production facilities is built into the model.

FIGURE C.1.2
ENERGY SUPPLY - OIL AND GAS

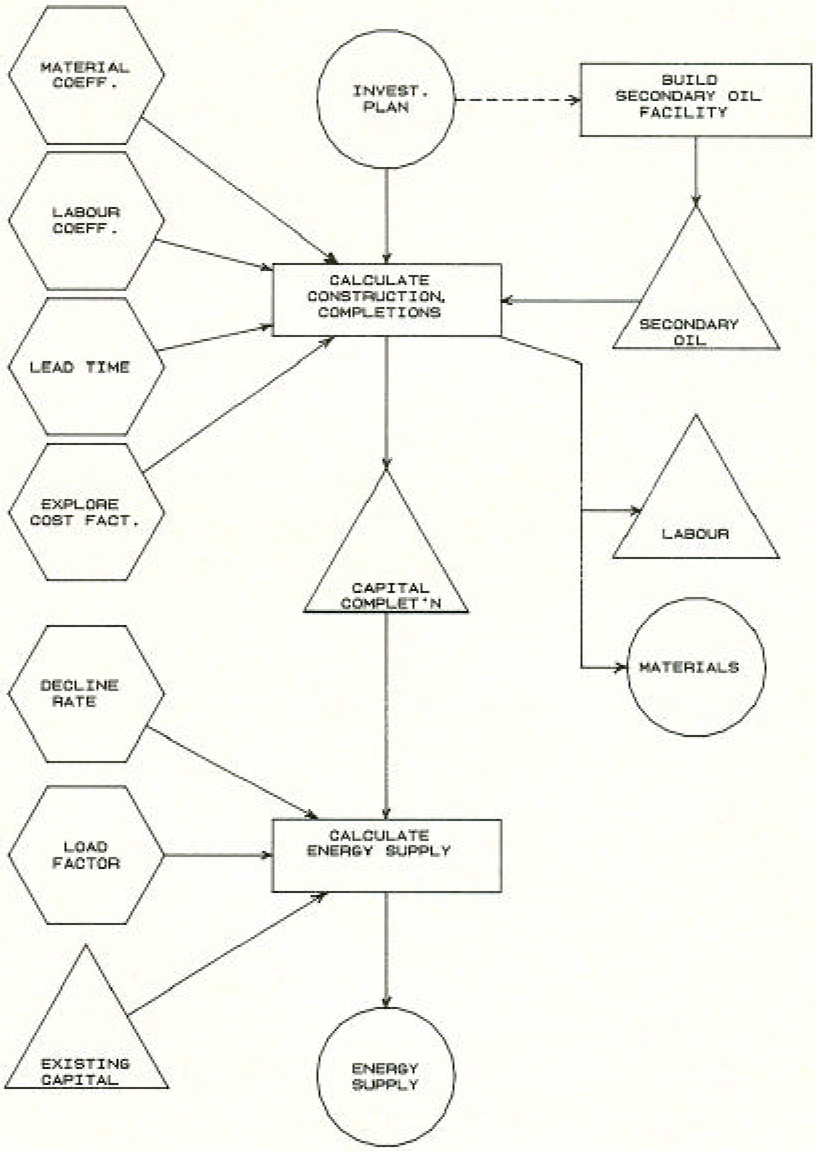


FIGURE C.3
INDUSTRIAL ENERGY END USE

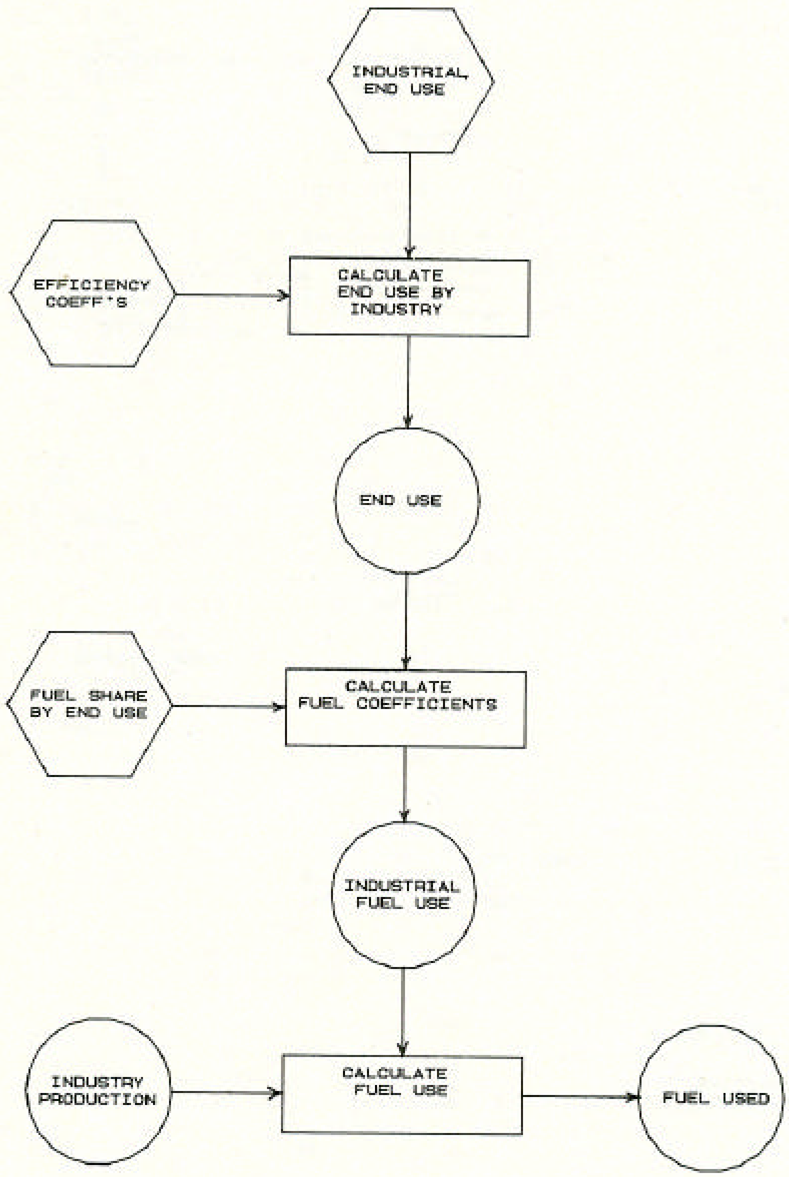
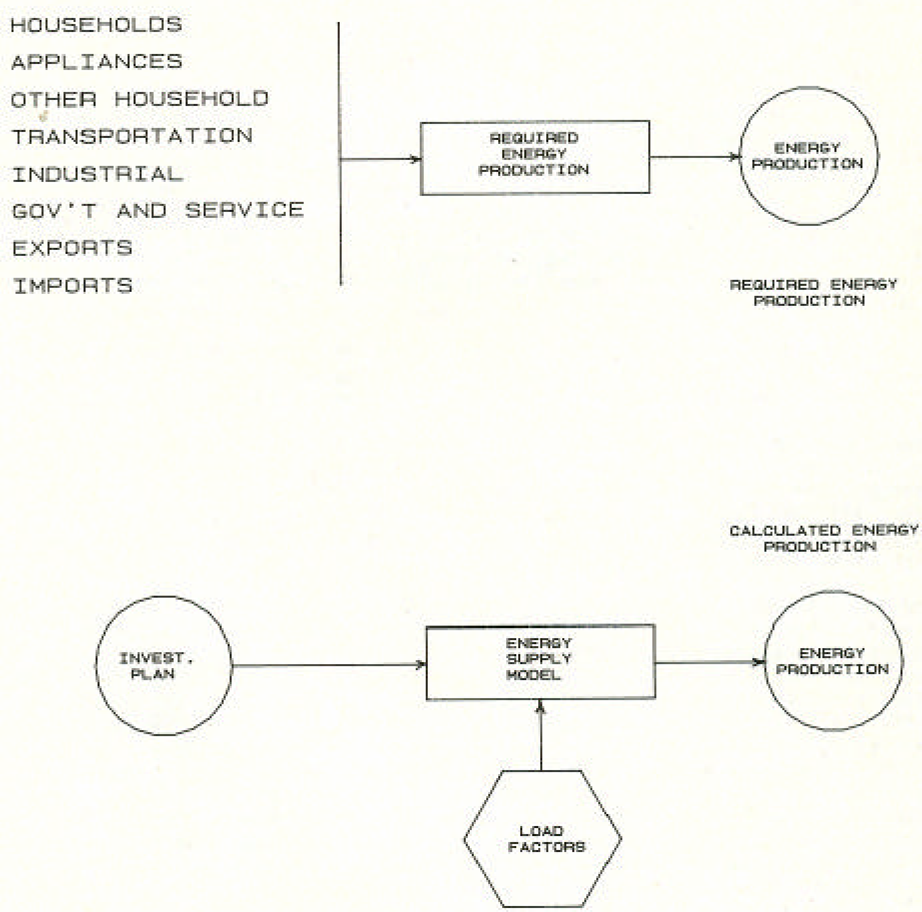


FIGURE D.4
ENERGY SUPPLY/DEMAND TENSION



The second fundamental distinction of oil and gas production is the fact that a great deal of effort is put into exploration and development activity before a well is brought into production. In the current version of SERF we are handling this by using average numbers of holes drilled per producing well for each type of facility - the construction materials and labor for bringing new facilities online is related to this number. The user may simulate the declining drilling success rates which would be expected in a mature basin by specifying an exploration cost factor which escalates over time, proportionately increasing material and labor demand per unit of new capacity. While this is a serviceable treatment of exploration, we plan to put this portion of the model on sounder methodological grounds by developing an oil and gas exploration model based on the probabilistic methods and geological data employed by earth scientists in representing this problem.

2.7 Balancing Energy Supply and Demand

fhe process of constructing a complete scenario in SERF is, as the foregoing indicates, a major task. We have simplified this process where possible by producing conservative extrapolations of model variables to serve as a baseline scenario. However, the user must still make many decisions between alternate paths as they home in on a scenario which fits their expectations of the development of the Canadian economy. At the end of this process of judicious selection of simulation variables, the overall consistency of the user's scenario is tested. Nowhere is this more clearly exemplified than in the comparison of energy supply and demand.

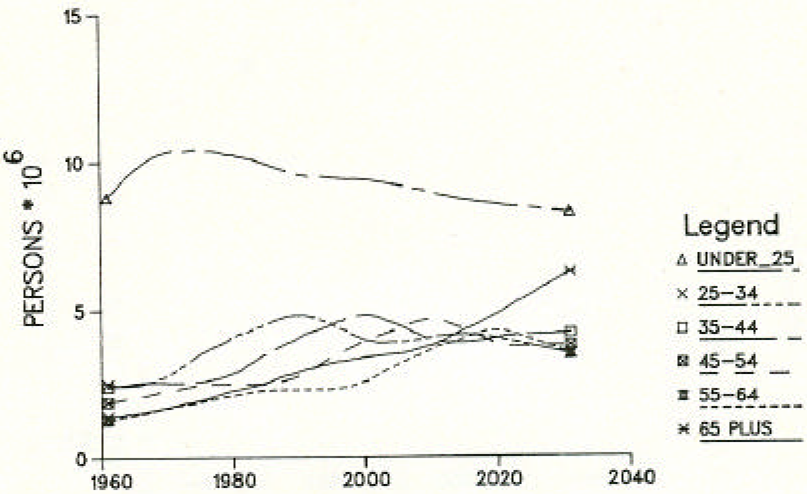
As Figure D.4 shows, there are a great many components to energy supply and demand. In order to arrive at what the model calculates .as the required energy production, scenarios must be constructed for household heating and hot water possibilities, appliance penetration, other household energy, transportation energy consumption, industrial energy consumption coefficients, energy required in government and the service sector, and finally exports and imports of energy. The calculated energy supply is, to simplify, the product of investment plans and load factors for energy facilities. Bringing the required and calculated energy production into line is an essential facet of producing a consistent scenario.

One mode of model use will likely be "demand oriented". The user would construct scenarios for the various intensity variables for energy demand, based on expectations about changing efficiencies of energy use and the mix of fuels required to meet this demand. The supply model would then be run with investment plans consistent with the required production. Because putting new energy facilities in place requires energy in turn, the model solution process would have to be iterated a couple of times in order to produce a balance. Another basic mode of use may be "supply oriented". Here, expectations about discoveries and development of energy supplies would be the chief variables of interest. After solution of the demand portions of the model, the specified supply scenario can be examined for its adequacy to meet the required energy production. Gross shortfalls or over-supplies would force a re-examination of the assumptions going into the scenario.

In practice we expect that model users will combine elements of these strategies in constructing a consistent scenario. They will quickly discover the highly interdependent nature of the model (and the economy which it represents). Choices in one part of the model will have consequences for other parts. For instance, energy supply and demand can always be brought into line through imports and exports - but the consequences of arbitrarily high levels of imports of oil, for example, will be felt in our export industries and perhaps ultimately

Figure R.1

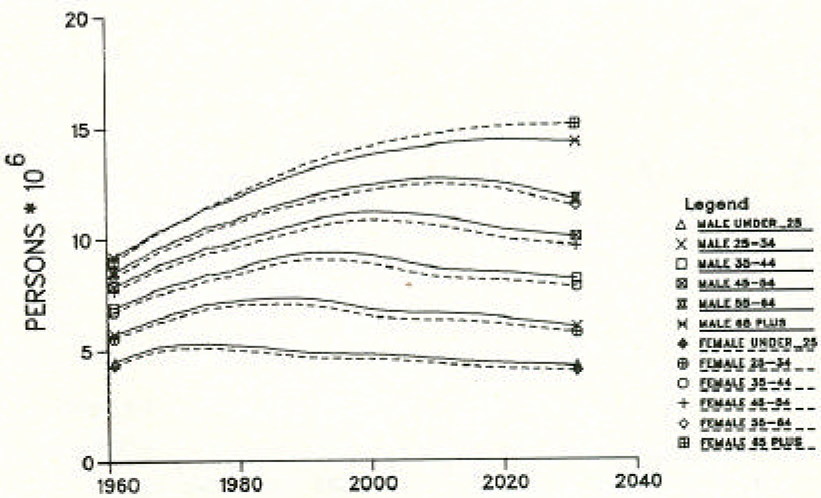
POPULATION*



* Separate age classes, both sexes

Figure R.2

POPULATION*



* Cumulative age classes, each sex

Figure R.3

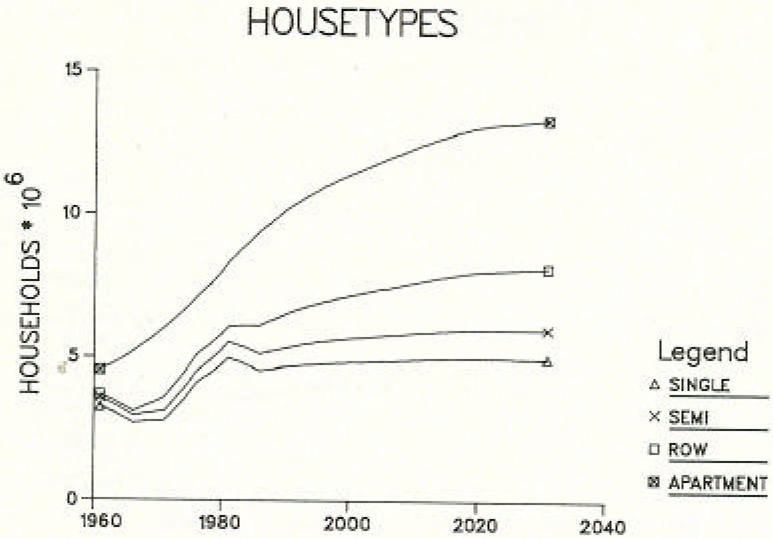


Figure R.4

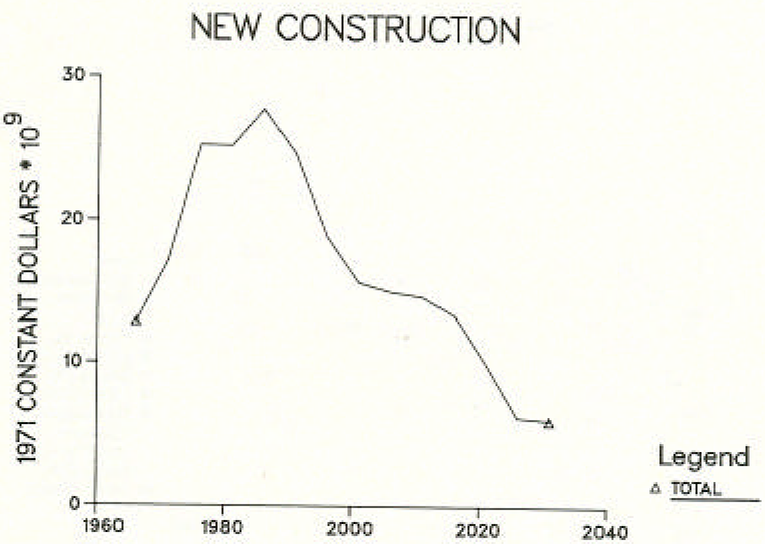


Figure R.5

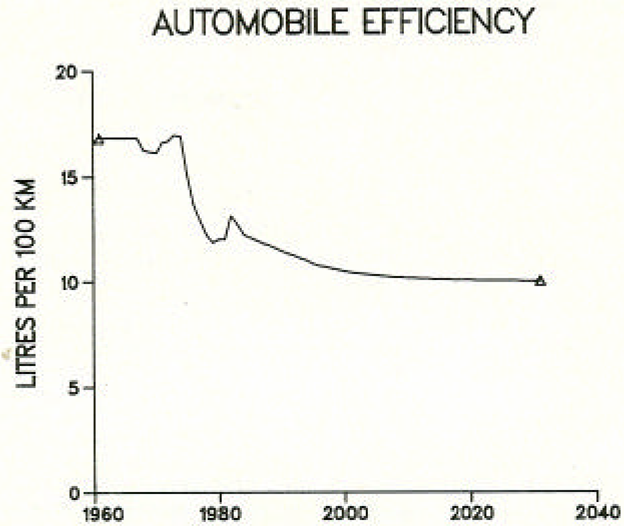
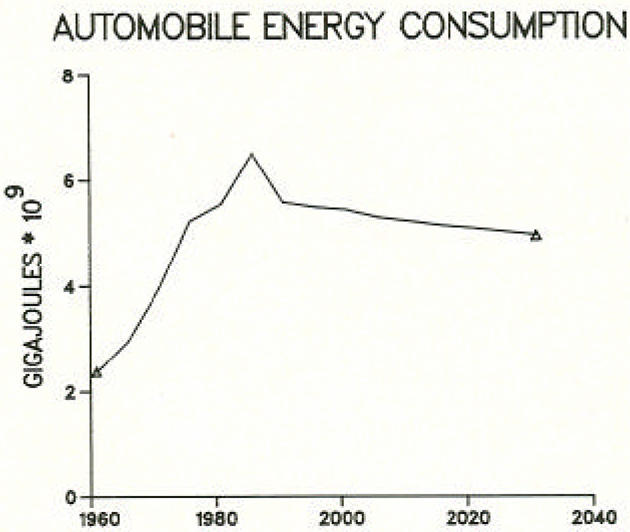


Figure R.6



in the terms of trade, with broad-based effects on the rest of the economy.

Decoupling so many portions of the model will make the user burden high in using SERF. It is our belief, however, that this will force people to be explicit about their assumptions in producing snapshots of the future. The model will, in an understandable manner, calculate the consequences of those assumptions. This in turn should foster rational discussion of our choices for the future.

3. SELECTED RESULTS

We may illustrate the power of the SERF model by following some of the internal variables over time. The first block of the model is the demographic block. The basic data is an age-sex structured population as provided by the Census of Population with projections provided by official forecasts released by the Demography Division of Statistics Canada. A base scenario is shown in the Figure R.l. The population is far from equilibrium as can be seen by the10cal maxima in the numbers of persons in the various age classes excepting the elderly. The display in Figure R.2 of the cumulative age classes by sex shows that the total population is increasing. The detailed population information is used in the labor supply portion of the demographic block as well as in the food, clothing, health care, education and other components of the domestic demand block. These individuals organize themselves into households with the model reflecting this behavior through a notion of headship with associated coefficients. The number of households for a base scenario is shown in Figure R.3 as the total number of households broken out by cumulative dwelling type. Alternate scenarios are available of various dwelling-type mixes that are achievable through alternative assignments of new construction. We may easily construct the required flow of dwellings, commonly called new construction, to meet the demand and to replace those dwellings destroyed through wear out and accident. The size of the housing stock is not increasing smoothly because of the non-equilibrium population and yields erratic requirements for new construction as shown in Figure R.4. The energy consumed by the housing stock stabilizes with the size of the stock and even declines under various retrofitting scenarios.

Another illustration of the use of an age-type structured stock is provided in the transportation component of domestic demand. Considerable change in automobile efficiency has been achieved by both market and regulatory influence on automobile manufacturers. We see a major improvement in efficiency in the years 1975-1985. Figure R.5 shows the change for standard-sized gasoline automobiles with corresponding changes for other sizes and fuel types. Alternative scenarios of projected efficiencies and market penetrations are available but are not illustrated. The energy use by automobiles for a base scenario is shown in Figure R.6. We see that the reversal and decline in energy use lags the improved efficiency by years as an increasing proportion of the automobile stock is replaced by the newer fuel efficient typed. After the stock renewal, the energy consumption shows small declines resulting from further efficiency gains and some shifting to compact cars.

4. CONCLUSION

This paper has outlined, at a very high level, the structure of the energy supply and demand components of SERF. We feel that the combination of the simulation approach, disaggregation of the sectors represented, a rich data structure capturing the age and energy-using characteristics of stocks, and adherence to the physical inter-relationships of the model components, provides a robust tool for energy modelling. The inherent understandability of each component and the requirement that user assumptions be made explicit should foster useful debate of

Canadi an energy policy.

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