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Self-Consistency in Estimating Future Electrical Energy Consumption

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SELF-CONSISTENCY IN ESTIMATING FUTURE ELECTRICAL ENERGY CONSUMPTION*

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Abstract

A socio economic computer simulation model for the State of Oregon is described. The Oregon State Simulation Model (OSSIM) includes a thirty-seven sector model of electrical energy consumption. Coupling between this model and the OSSIM ensures self-consistent scenarios of socio economic phenomena which underlie energy consumption. One of the purposes of this effort is to help state-level decision makers understand the determinants of electricity consumption within a context of changing economic conditions.

1. INTRODUCTION

Until recently, examples of personal inconvenience or attenuation of economic growth caused by increasing prices or local shortages of electricity have been rare. Now, however, the local environmental, economic, and social impacts of electrical energy production and consumption are major concerns. To deal with these concerns, various policies--both exogenous and endogenous to individual states--have been developed or are proposed and many of them carry serious implications for electricity costs and availability. Possible implementation of such policies, combined with definite changes in energy prices and even shortages of some energy forms, makes the estimation of future electrical energy consumption for individual states a challenging problem.

Techniques which have been used in the past to attack this problem have been remarkably accurate. This does not necessarily mean, however, that comparable techniques employed today will yield equally good results. Until recent years, energy demand projections have been performed in the context of: seemingly endless, steady growth in

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population and economic activity; surplus or at least adequate energy supplies; and real energy prices which were low and in many cases steadily declining. Few and perhaps none of these conditions exist today, nor are they likely to exist in the forseeable future.

The present authors contend that future electrical energy consumption should be viewed as arising from elements of a complex socioeconomic system and that these elements can only be correctly addressed in concert with one another. It is vital that this viewpoint be appreciated by state level decision makers, whose actions can influence not only the electricity supply system but the general economic condition of the state. For example, in the latter half of 1974 the United States electric utility industry cancelled or postponed the construction of large numbers of generating stations, particularly nuclear power plants. Analysis by L. J. Perl* indicates that these cancellations are principally a result of capital shortages, and places the blame on state regulatory agencies for failure to grant required rate increases. Thus the regulatory commission, having the capability of directly influencing both electricity prices and supplies, is itself an important element in a state's energy system. Clearly, it is imperative that key inputs to the complex, dynamic energy system be manipulated with maximum understanding of the potential consequences, both direct and indirect, and short-term and long-term.

The methodology presented in this paper is casual in structure and relies only to a limited extent upon correlation and extrapolation. Electrical energy consumption is determined, in concert with economic and demographic activity, in the Energy Component of a socioeconomic simulation model of the State of Oregon (described in Section 2). A major strength of this approach is that self consistent scenarios of underlying economic and demographic activity are ensured. That is, most variables that are exogenous to econometric models, and thus whose self-consistency cannot be demonstrated mathematically are endogenous to this model. M.F. Searl**, in a recent review of contemporary energy modeling efforts lends support to the importance of this feature:

> "Historically, most energy models have not been coupled to comprehensive economic models. Instead, the economic input to the energy model was in terms of individual demographic and economic projections presumed to be consistent but rarely derived from a comprehensive economic model."

Self-consistency is particularly important when models are used to assess possible impacts on future energy consumption of proposed policies which are not at first perceived to be directly related to energy.

2. OREGON STATE SIMULATION MODEL (OSSIM)

In late 1972, the Rockefeller Foundation awarded a grant to Oregon State University with the goal of enhancing the University's capability to address the complex problems of economic growth and environmental quality in Oregon. One specific objective of the project has been the development of the Oregon State Simulation Model (OSSIM). A brief description of the model is contained in the latter part of this section. However, because some confusion can arise concerning the objectives, the capabilities and the limitations of computer

* Perl, L.J. "The Future of Nuclear Power in the Electric Utility Industry." Nuclear News, 17, No. 15 (1974), pp. 60-63.

**Searl, M.F. "Introduction." Energy Modeling. Ed. by M.F. Searl. Washington, DC: Resources for the Future, Inc., March 1973.

simulation models such as OSSIM, the following summary is provided.

The principal objective of the OSSIM is to provide a mechanism for making research results available to state level decision makers that hopefully will:

(1) Heighten their appreciation for the complexity and dynamic interrelatedness of economic growth, energy consumption, land use, and environmental quality, and

(2) Provide them with one more means of estimating the likely consequences or outcomes associated with various policies and/or scenarios.

It should be emphasized that the OSSIM is not intended to replace any of the sources of information already available to and used by decision makers. Simulation models do not yield decisions, but rather generate additional information that can facilitate decision making. (The specific role of the decision maker is indicated in Section 4.)

The computer simulation methodology is just one of a large and growing number of "systems approaches" which, though they differ considerably from one another in purpose, conceptual framework and technique, have one attribute in common; they all differ from classic analytical procedures in that:

(1) The interactions between the parts of a true "system" cannot always be neglected when describing the behavior of any isolated part, and,

(2) The sum of the behavior of the parts does not, in general, represent the behavior of the "system".

The system, the model, and the simulation are related to each other in the manner illustrated in Figure 1.

There are several important characteristics of the simulation process that should be kept in mind when evaluating the simulation results. First, simulation really consists of two translations "in series," and the degree to which the simulation replicates the observed behavior of the real world system depends on the validity and accuracy of both translations. The success of the first translation really depends on how much is known and understood about the system being modeled. The success of the second translation depends on the selection and correct application of appropriate computational techniques.

Second, it should be stressed that each translation is a "one-to-many" relationship. That is, for every real world system there are many models which could be devised, and the choice will (or should) depend on the objectives of the modeler. Once a model has been devised, there are then alternative ways of translating it into a simulation. There is usually less latitude in this choice, which will depend largely on the nature of the model and on the availability of computing equipment.

Finally, the broken arrow indicates the role the simulation plays (hopefully) in the real world. Studying the behavior of the model improves our understanding of how the real world functions, and this knowledge is "translated" into better real world decisions. In other words, the simulation model is simply a way of structuring one's thinking which forces methodical, meticulous, and simultaneous consideration of all important factors and interrelationships in the real world. The simulation output is one more piece of information that can be available to decision makers, and information plus judgment yields decisions.

OSSIM is a dynamic, nonlinear continuous

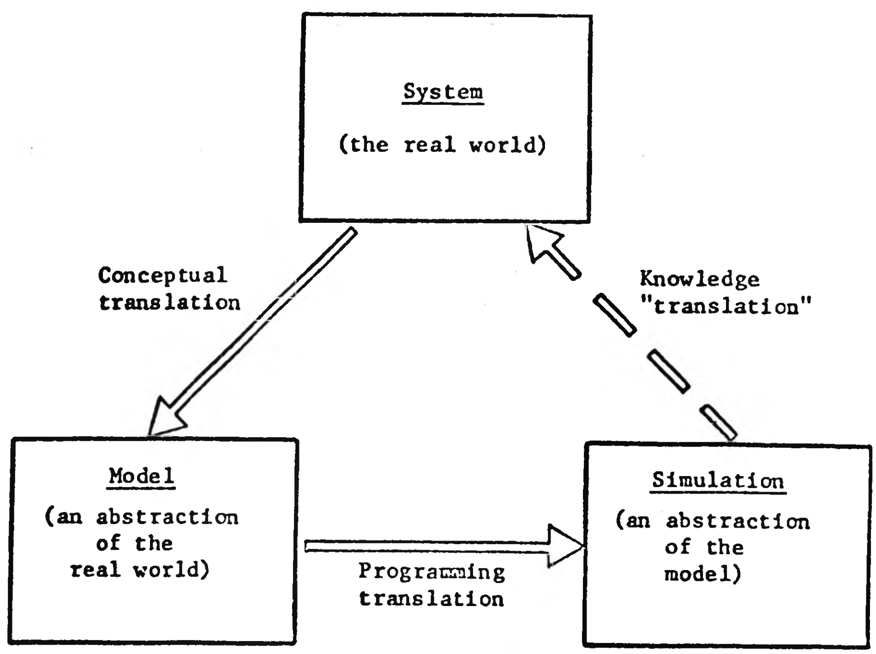

Figure 1. RELATIONSHIP BETWEEN THE SYSTEM, MODEL AND SIMULATION

simulation model of man's activities in the State of Oregon. It was built utilizing the well-known systems approach alluded to earlier--with the general procedure being an iterative process of problem definition, mathematical modeling and simulation, model refinement and testing and model application.

As many of the questions raised in the problem formulation stage centered on differences between the Willamette Valley and the rest of Oregon, the state was divided into three geographic regions as illustrated in Figure 2. While the general boundaries of these regions are primarily related to the physical geography of the state, it was clear that they also differed from one another in many other respects (e.g. climate, economic base, population density, etc.). Hence, the OSSIM consists of three interdependent "parallel" models which are structurally identical but numerically different.

The maximum time horizon for the model is fifty years (1970-2020). A much shorter time horizon (one to five years) was not considered appropriate since the questions raised in the problem definition phase involved long run projections. A time horizon in excess of fifty years was also considered inappropriate since the accumulation of technological and institutional changes occurring over that time span could make the model totally invalid.

There are seven components in the model structure: Demographic, Economic, Land Use, Transportation, Energy, Pollution and Government Revenue. These components are dynamically connected to one another in the manner illustrated in Figure 3. The "labels" on the arrows are representative samples of the nature of the interactions between components.

It should be noted that the internal structure of each component reflects the present modelers' conceptual views of the State of Oregon. While the methodology employed is general and could be used to model regions other than Oregon, the specific structure and dynamic behavior of

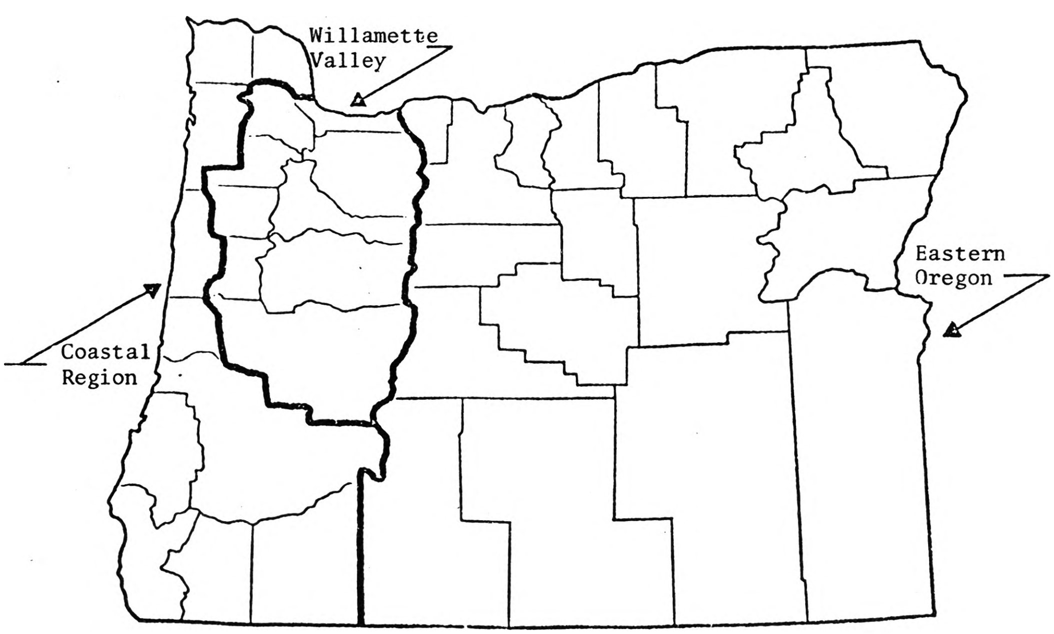

Figure 2. THE THREE REGIONS OF THE STATE OF OREGON

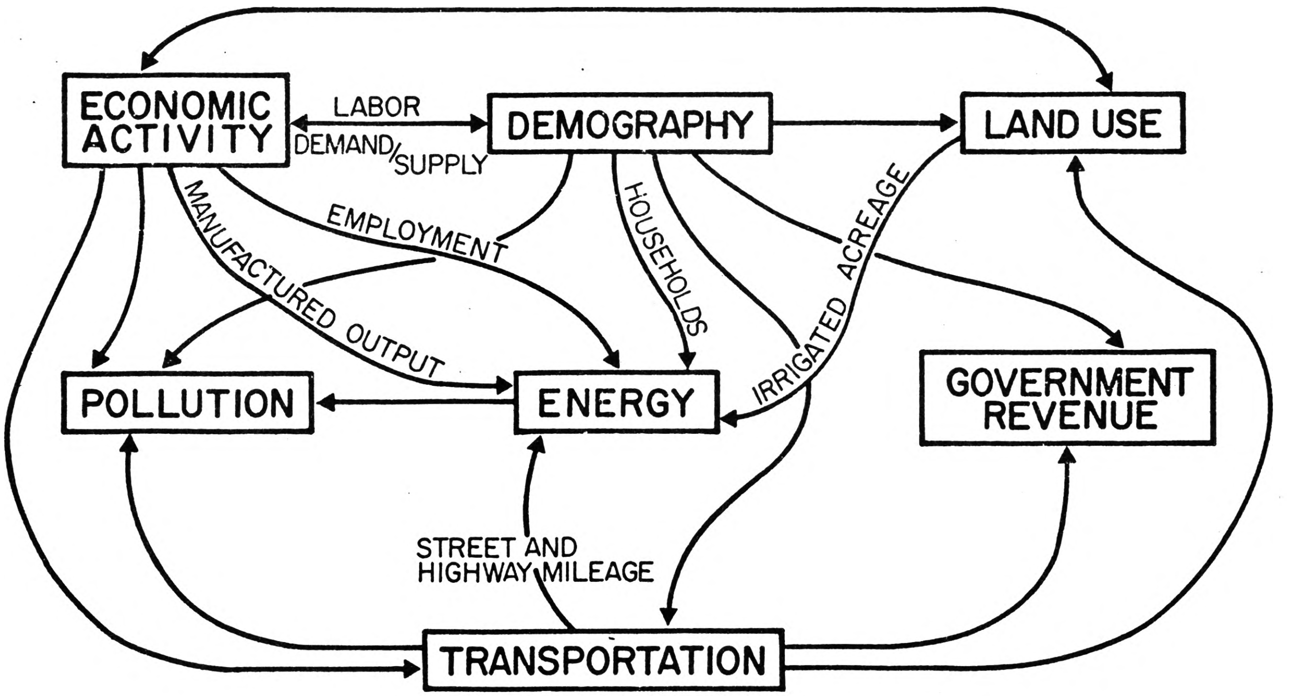

Figure 3. OREGON STATE SIMULATION MODEL (OSSIM)

any or all components could differ considerably from those presented here. Six of the seven components are discussed in the remainder of this section. The Energy Component is described in Section 3.

2.1 DEMOGRAPHIC COMPONENT

The Demographic Component contains a detailed accounting of the population of each region of Oregon, resolved into nine household size classes, two fertility classes, and two socio economic strata. The choice has been made to use numbers of households, rather than of individuals, as the principal variables since the household seems to be the more significant unit for economic and social considerations. This choice is a major departure from previous simulation models, which typically have used a standard age-cohort type of demographic analysis and projection.

In dynamic terms, the component traces the "life cycle" of households from formation to extinction. The major driving forces are the class-specific birth rates, which implicitly determine the age distributions within households and hence the fecundity and rates of maturation. These birth rates are modeled as being dependent on economic expectations through the regional unemployment rate, and on socio economic stratum as determining effectiveness of family planning. The dynamics of socio-economic stratification are modeled as processes of upward and downward diffusion between "marginal" and "mainstream" household classes, with spontaneous rates that are augmented on the upward side by subsidized job training as a typical "war-on poverty" policy variable.

A second driving force which affects Oregon's demographic characteristics is migration, which is modeled with two different types of relationships for three different age groups (age of head of household). Net migration in the age groups 15-29 and 30-44 is assumed to be sensitive to employment opportunity in the region, as measured by the unemployment rate, and to the social size of the region, as measured by its population. Only the parameters are different for these two age groups. The age group 45+ is assumed to continue a net inmigration to Oregon at a rate which depends on the number of such households already in Oregon. In addition, a joint distribution of households by income and family size is generated using wage income information supplied by the economic component.

The principal output from the Demography Component to the Energy Component is the number of residential utility customers, which is computed as a function of the household size and income distribution.

2.2 ECONOMIC COMPONENT

The Economic Component is viewed as having four basic sectors which operate in each of the three subregions: logging and wood products, agriculture and food products, manufacturing, and services. These have been modeled and programmed as subroutines which are called in sequence by a calling program. This calling program is itself a subroutine of the overall model, and also performs the "bookkeeping" tasks of summing up total labor demands by occupational category, comparing this demand with the labor force supplied from the Demographic Component, and computing unemployment rates and resulting wage rates. The Economic Component avoids reliance on exogenous variables by incorporating the assumption that there are fundamental natural and human resource bases that both support and limit regional production. The four sectors are discussed below, in order of their importance to Oregon's economy as a whole.

2.2.1 Logging and Wood Products Sector

The level of logging activity is viewed as depending, over the long run, entirely on the resource base of mature and growing timber and its management. Projections of the annual sawtimber yields over the next one hundred years have been made by the U.S. Forest Service, and these projections are provided as exogenous information.

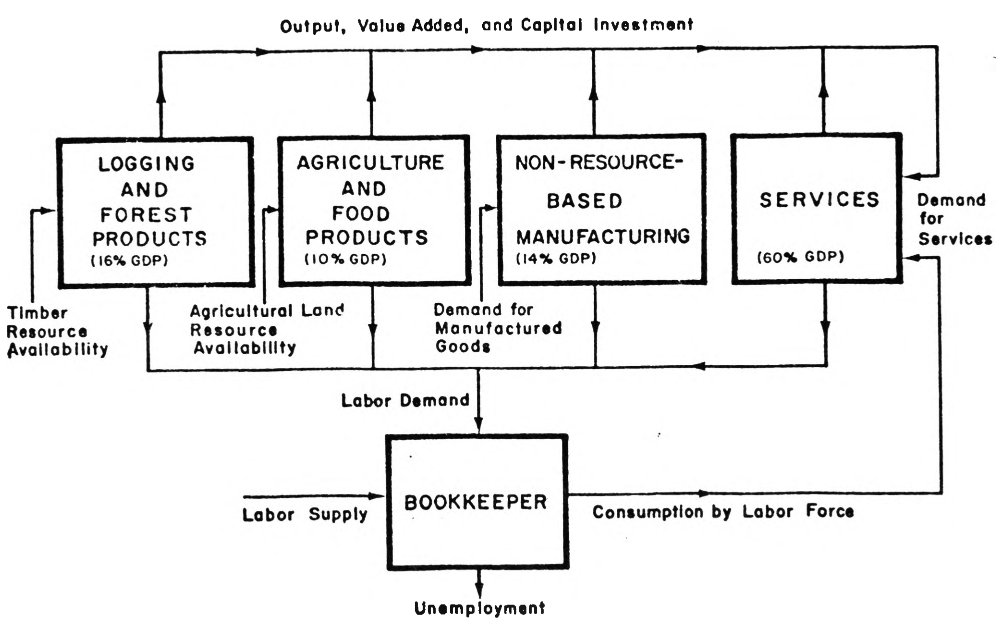

Figure 4. STRUCTURE OF THE ECONOMIC COMPONENT

Different projections can be supplied for each subregion, depending on the policy choices of rotation period and management intensity. While the actual annual cuts will vary from the projected yield because of the short-run cyclical nature of the sector, these variances are thought to have little long-run effect.

The annual sawtimber yield is then distributed among three wood products industry activities: production of lumber, plywood, and pulp and paper. The raw material inputs to each of these are calculated from the annual sawtimber projection by applying factors which apportion the board feet of sawtimber to lumber and veneer, and which give the volume of residues and small roundwood available for pulp and paper.

Value added by each wood product industry is then calculated, and supplied to the Energy Component as a dynamic input.

2.2.2 Agriculture and Food Products Sector

The agriculture and food products sector, like the logging and wood products sector, is viewed as depending on a natural resource base. Agricultural land and the capital stock associated with that land are assumed to be the key factors of agricultural production. Operating expenses, labor costs, taxes and interest are deducted from the calculated value of gross production to determine net returns. A deferred annual capital gain, based on the increase in speculative value of agricultural land, is added to net returns and the sum forms the basis for capital formation in agriculture.

Value added by primary processing of farm products is also calculated and supplied to the Energy Component as a dynamic input.

2.2.3 Manufacturing Sector

The manufacturing sector sums the demand for durable and non-durable goods from the other sectors, including exports. Required inputs of these goods are taken as being equal to current output minus total current demand (the excess demand). Required investment in new capital is determined by the smoothed excess demand and a subsequent delay called the excess demand closure time. Environmental standards and availability of labor influence the length of the excess demand closure time. A capital installation delay allows for the time delay between ordering and installing capital.

Value added by the manufacturing sector, which is determined by the level of installed capital, is then supplied to the Energy Component as another dynamic input.

2.2.4 Service Sector

The service sector accounts for all business and household services, including wholesale and retail trade, utilities, construction and financial, health care, educational and government services. The regional inter-industry demand is computed from the output of the other three sectors using technical input/output coefficients. Final demand is calculated as a function of household incomes, tourism, investment in the basic sectors, and government revenues. Inter-industry and final demands are summed to provide the total regional demand for services. A "regional shift matrix" is then employed to determine the regional breakdown of the supply of services, with some services being imported from outside Oregon.

Unlike the other sectors, regional employment in services is used as the surrogate for economic activity, which is supplied to the Energy Component as a dynamic input.

2.3 LAND USE COMPONENT

The Land Use Component maintains a current inventory of the land (by region) in each of eight use categories, and simulates the dynamic processes which results in transitions between categories.

The demand for residential land in three density classes is driven by the Demographic Component. The housing demand is a function of household size and income, the price of land and housing, the cost of providing services to the land, and the residential density. Changes in the housing stock required to meet the changing demand are calculated, with appropriate adjustments for replacement and vacancies.

Agricultural land is the principal source of land entering the residental use category. Transfers of land to or from the forest land, "open space," or unused categories is permitted as a user-supplied scenario. The number of acres of land available for agricultural production is supplied to the agricultural sector of the Economic Component, where it is a factor of production. In addition, the number of acres currently undergoing irrigation is supplied to the Energy Component as a dynamic input.

The forest land use category accounts for all land upon which commercially harvestable timber is growing. The industrial/commercial land use category responds to demands generated by the level of activity in the industrial and service sectors of the Economic Component, with agricultural and high density residential land acting as the sources. The Open Space/Wilderness use category enables the model user to set aside agricultural/forest land in a preservation status. Unused land is that area of each region which does not qualify for one of the other seven use categories (a residual).

2.4 TRANSPORTATION COMPONENT

The Transportation Component analyzes transport demand, provides measures of effectiveness of Oregon's transport service and determines the consequences of providing that service. Transportation demand between and within fifteen urban areas, the five largest in each region, is analyzed.

The Transportation Component allocates to each of the urban areas increments of regional population growth provided by the Demography Component. Models of urban travel, intercity passenger travel, and intercity cargo transport estimate the total passenger vehicle miles and cargo ton miles of transport by significant modes. One output of the Transportation Component is the number of illuminated highway miles, which is supplied to the Energy Component as a dynamic input.

2.5 POLLUTION COMPONENT

The Pollution Component translates levels of polluting activities (e.g. transportation, manufacturing, space heating) furnished by other components of the model into rate of discharge of air pollutants (presently fine particulates and SO_x).

The level and emission intensity of various polluting activities in conjunction with the control strategy for that category of sources (as reflected in the emissions intensity ratio) determine rate of pollutant emissions in that source category. When the emissions by each source category are added together, the impact of a particular emission control strategy on the aggregate emissions can be assessed.

2.6 GOVERNMENT REVENUE COMPONENT

The function of the Government Revenue Component is to translate certain output variables of the Demographic, Economic, and Transportation Components into the common language of tax dollars, with reference to three important taxes collected at the state level in Oregon. The joint distribution of households by size and family income, generated in the Demographic Component, provides the basis for the state personal income tax revenue calculation. Corporate income tax revenue is projected on the basis of value added in each sector of the Economic Component. Finally, the level of transportation activity, determined in the Transportation Component, is utilized to project motor vehicle tax revenue.

3. ENERGY COMPONENT

The Energy Component provides estimates of electrical energy consumption by means of a detailed consideration of energy use in thirty-seven consumer categories. Appropriate groups of these categories compose the four traditional sectors of industrial, commercial, transportation, and residential users. The Industrial Sector consists of three resource-based manufacturing industries, sixteen non-resource-based manufacturing industries, and three irrigation regions. These nineteen industries constitute the Commercial Sector, which is highly aggregated due to data limitations, while the Residential Sector is based upon far more extensive data which allows consideration of thirteen specific household appliances.

The consumption of electrical energy in each consumer category is written as the product of two time-dependent functions, here designated Ue and Y.

$$DE = Ue(p,t) \cdot Y(p,t)$$

Ue represents the intensiveness of electricity use in each category or subsector and is called "electrical energy intensiveness." Y is a surrogate for the level of economic or demographic activity of that subsector. Since Ue and Y are simulated separately, it can be readily determined whether changes in the rate of economic growth, or to both and in what proportion. Note that, in general prices (represented by p) of electricity, gas and petroleum products may affect both intensiveness and economic activity.

It is further asserted that electrical energy intensiveness functions can be unfolded into two additional functions, one of which is independent of energy prices:

$$Ue + Ue_o(t) \cdot Fe(p)$$

The utility of this effort lies in the isolation of two components which will, in all probability, behave quite differently from one another in the future. That is, Ue_o (which is called "base energy intensiveness") depends upon fundamental phenomena such as technical progress and can reasonably be expected to follow past trends. Fe(p), on the other hand, depends upon the history of energy price changes and will most likely deviate considerably from pre-1970 patterns.

In principle there exists an economic demand function for each subsector, which indicates the degree to which demand for electrical energy is elastic.* However energy is an intermediate good, and adjustment of patterns of energy consumption to changing energy prices cannot occur instantaneously. Studies have also shown that the response of energy demand to a change in price can be approximated by the response of a first-order, linear system with some characteristic time constant. Figure 5 illustrates an economic demand curve for electrical energy with demand as a function of time shown in Figure 6.

We have written demand as the product of intensiveness and activity; however, we

*Note that the word "demand" is used in the sense of the economist rather than in that of the electrical engineer.

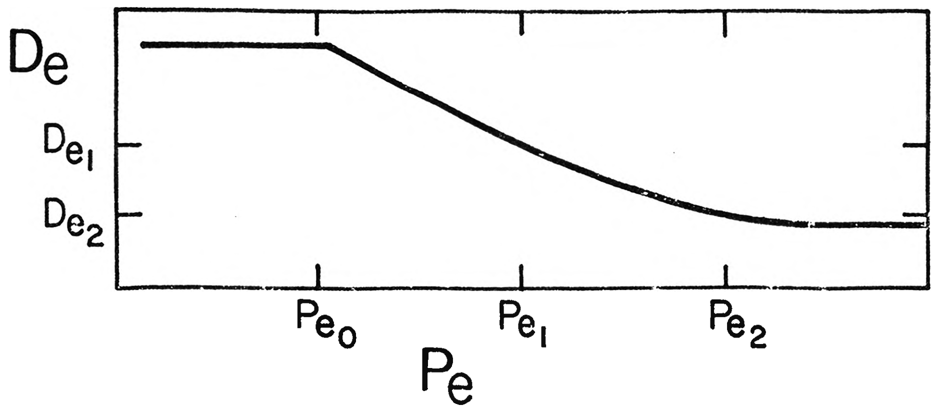

Figure 5. HYPOTHETICAL ECONOMIC DEMAND CURVE FOR ELECTRICAL ENERGY

are really interested in the individual response of each of these factors. We thus define a new quantity--price elasticity of intensiveness--which is completely analogous to price elasticity of demand. We also recognize that the own-elasticity of intensiveness ξ_e, can have three components: one pertaining to electricity conservation; one which accounts for interfuel substitution; and one reflecting locational decisions of industries. Interfuel substitution, of course, can occur from electricity to gas or to petroleum products (ξ_{e_s}), and also from each of the fossil fuels to electricity (represented by ξ_g and ξ_p).

$\frac{\partial Ue}{\partial Pe} \frac{Pe}{Ue} = \xi_e$, the own-elasticity of intensiveness of electricity;

$\frac{\partial Ue}{\partial Pg} \frac{Pg}{Ue} = \xi_g$, the elasticity of substitution to electricity for gas;

$\frac{\partial Ue}{\partial Pp} \frac{Pp}{Ue} = \xi_p$, the elasticity of substitution of electricity for petroleum.

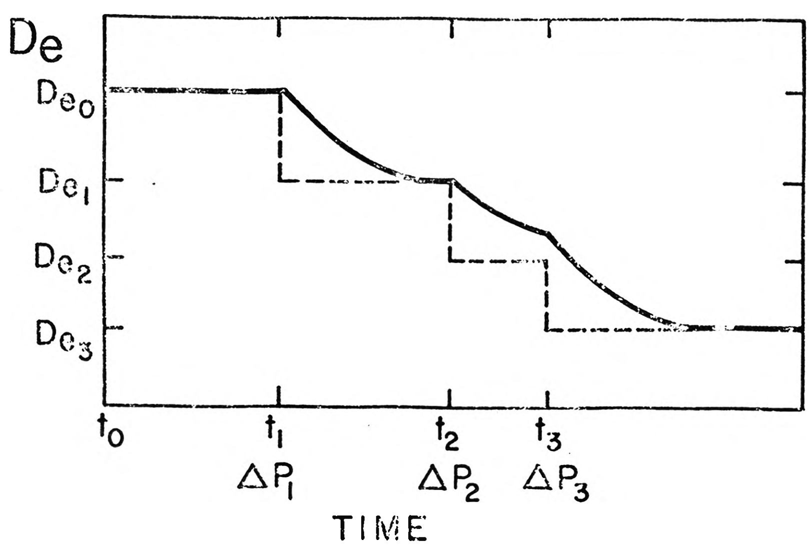

Figure 6. DEMAND IN TIME DOMAIN

$\xi_e = \xi_{e_c}$ (conservation) + ξ_{e_s} (substitution) + ξ_{e_ℓ} (location)

$$\xi_{e_s} = \xi_{e_{e \longrightarrow q}} + \xi_{e_{e \longrightarrow p}}$$

Finally, we associate time constants with these various kinds of consumer responses. These time constants are related to the time required for a given subsector to alter its average pattern of energy use--or energy intensiveness--in response to energy price changes. For example, in the Industrial Sector conservation would be the initial response to a significant increase in electricity price, perhaps being felt in 1-3 years. On the other hand, interfuel substitution is a longer-run effect, due to the relatively long lifetime of much process equipment.

In summary, then, the following concepts are taken into account in the electrical energy demand model:

- consumers respond to energy price increases by conservation, interfuel substitution, and alteration of habits of appliance acquisition and industrial location.
- these responses may not occur until some threshold price is exceeded.
- changes in patterns of energy consumption take time.
- technical limits to conservation and interfuel substitution exist.

4. IMPLEMENTATION

For many years Oregon has been known as a leader in the area of environmental management. Recent legislation has asserted a similar leadership role in the area of land use planning and energy management. The creation of a Department of Energy, with broad energy planning responsibilities, has increased the potential for and actual interaction between modelers and decision-makers. With a statutory requirement to produce "independent" energy forecasts which "identify and account for all major components of demand and anticipated increase in demand, including but not limited to population, commercial, agricultural, and industrial growth," the need for employment of coupled socioeconomic models becomes more clear. The proper interpretation of model results requires a close working relationship between the modeler and the decision maker as illustrated in Figure 7.

Project personnel have been provided office space in the Department of Energy and are working on a regular basis with agency staff in the necessary interactive stages

CONSUMER RESPONSES TO ENERGY PRICE CHANGES

	Appliance Saturation	Appliance Consumption (Conservation)	Interfuel Substitution	Industrial Location
Response Time:	Quite Short	Short	Medium	Long
Sector of Importance:				
Industrial		X	X	X
Commercial	X	X	X	
Residential	X	X	X	

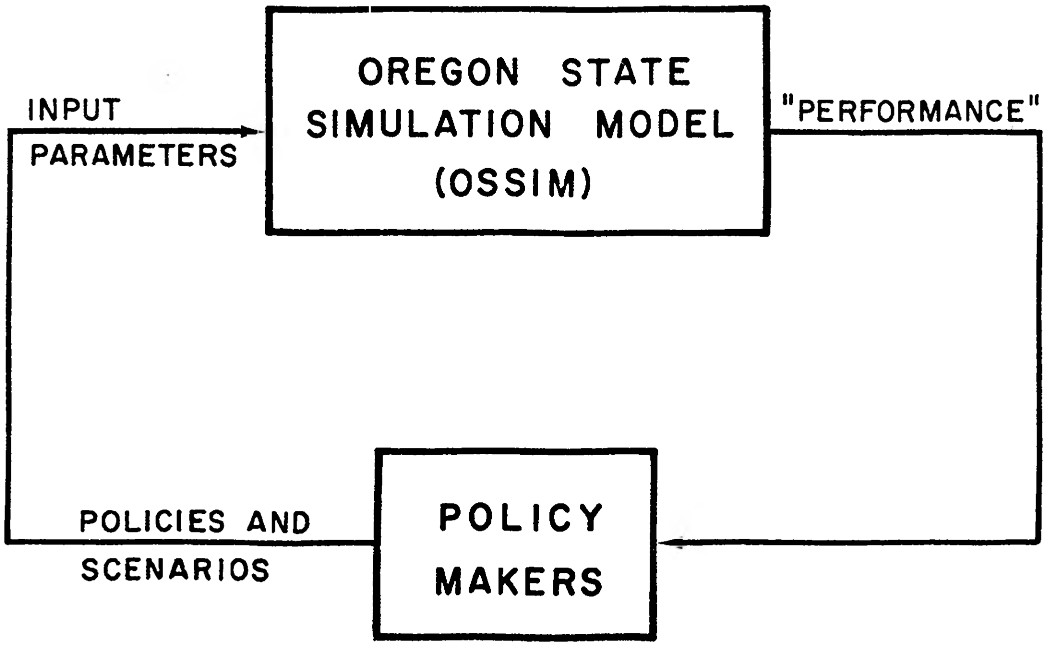

Figure 7. THE ROLE OF THE DECISION MAKER IN THE SIMULATION PROCESS

of problem identification, model refinement, and data analysis. Through this process the project is attempting to meet its objective of providing research results which will be useful to the people of Oregon as they make choices relative to environmental quality and economic growth.