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DEPARTMENT OF ENERGY AND ENVIRONMENT

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NATIONAL CENTER FOR ANALYSIS OF ENERGY SYSTEMS
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ABSTRACT

Market penetration estimates for new technologies at various federal funding levels are required by DOE's Office of Coal Utilization (OCU) to aid in the allocation of research and development funds. This report reviews analytic methods for estimating the market penetration of new technologies in the electric utility sector. Included in the review are integrated energy/economy modeling systems (with focus on electric sector representations), utility capacity expansion models, and technology substitution models. The applicability of generic model classes and individual models within each class to OCU's needs is addressed.

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I. INTRODUCTION

The ultimate benefits of federal expenditures in research and development for new technologies are dependent upon the degree of acceptance of these technologies. Market penetration considerations are central to the problem of quantifying the potential benefits of research and development expenditures. These benefits are inputs to the selection process of projects competing for finite R&D funds.

Market penetration is the gradual acceptance of a new commodity or technology. The Office of Coal Utilization (OCU) is concerned with the specialized area of market penetration (also called technological diffusion) of new electric power generation technologies for both replacement and new capacity. The common measure of market penetration is the fraction of the market serviced by the challenging technology for each time point considered.

The factors influencing the market penetration of new technologies are not well understood, and their relative importance differs across markets and time. Numerous methodologies have been developed and used in attempts to predict the market acceptance of new technologies, but no single method for estimating market penetration has been widely adopted. Individual methods that may be appropriate to specific technologies will generally be inappropriate to others. The intent of this document is to provide overviews of different models and methodologies that have been or could be used to estimate market penetration, and to relate these methodologies to the needs of OCU, U.S. Department of Energy (DOE). At present, the OCU mission is to assess the market potential for several coal utilization technologies being developed by DOE for power generation by electric utilities.

The appropriate methods for estimating market penetration for new electric generating technologies must be capable of dealing with the factors influencing their acceptance within the time frame that the technologies become available for commercial use. The methods should also be capable of incorporating uncertainty in the factors affecting market penetration and incorporating information which relates various funding levels to the probability of market acceptance. The evolution of a "best" methodology for appraising the candidate technologies will involve a synthesis of desirable features of several of the models considered. This synthesis will be discussed in a subsequent paper. The purpose of this paper is to review currently available methodologies in terms of their strengths and weaknesses.

In order to provide a basis for comparison among the methodologies, the factors perceived as influencing market penetration of new technologies in the utility sector are first defined and examined. These factors include the characteristics of the technologies and the systems into which they are to be introduced, the characteristics of competing technologies, the need for new power generation capacity, the regulatory and financial environment, and the behavior of suppliers (vendors) and purchasers (utilities). These factors are interrelated, and thus must be dealt with in an integrated framework.

The methodologies for estimating market penetration are divided into three generic classes:

- integrated energy/economy modeling systems,
- utility capacity expansion models, and
- technology substitution models.

In general, the integrated energy/economy modeling systems have three advantages: they provide internally consistent macro, energy-economy scenarios, they account for the effect of prices on demand by fuel form, and they explicitly capture the effects of population growth and the level and structure of economic activity on energy demand. A variety of deficiencies appear in most energy-economy systems models. These include a failure to account for regional factors, inability to handle detailed differences among technologies, lack of electric sector detail, inability to specifically account for uncertainty, large data requirements, costly model operation and maintenance, and difficulty in interpretation of results. The models are useful in estimating electricity demand in a given energy/economy scenario and can be of some use in estimating market penetration for generic technologies without regard for regional variations and uncertainty. Their results can be very misleading when attempting to quantify market penetration of new technologies, especially the "normative" models which suggest what should happen in some optimal sense, but which have difficulty in dealing with actual system behavior. They can be of use in assessing the impact of various R&D policies on the "optimal" penetration of technologies. The relative abilities of several prominent energy/economy models to estimate market penetration of generic new technologies in the electric sector vary considerably.

Utility capacity expansion models usually contain a high level of detail on utility operations, and consequently handle differences among technologies with more success than energy/economy systems models. Several of the utility models considered are designed explicitly for the analysis of technologies by utilities. However, these models are not readily applicable to the issue of market penetration of new technologies. The models require exogenous input of demand, and their sophistication in dealing with such factors as system reliability and load following characteristics may be irrelevant given uncertainties in demand growth and changing system characteristics over the extended time frame necessary for studying technologies currently under development. Also, the models' least-cost optimization of investments may not correlate well with utility behavior; there is evidence that decisions by firms subject to rate-of-return regulation tend towards alternatives that are excessively capital intensive.[1]

Technology substitution models attempt to represent the process by which a technological innovation with economic or other advantages replaces an existing technology. Market penetration is measured by market share, and the market share calculation is based on the characteristics of the competing technologies. Different models focus on different characteristics, but all manage to show a close fit of model results to historical data. This implies that the models can be used as forecasting tools, but their ability to replicate historical data is no guarantee that they can be used successfully in a predictive mode.[2] Another weakness is that they assume a competitive market and therefore may not properly model a regulated industry.

All of the methodologies discussed may be applied at some level to questions of market penetration of new technologies in the utility sector; choice of methods for a particular analysis must be conditioned by the scope of the analysis, data availability, and the relative cost of alternative analysis.

II. FACTORS AFFECTING THE MARKET PENETRATION OF NEW TECHNOLOGIES IN THE ELECTRIC UTILITY SECTOR

The projection of market penetration for new energy technologies requires consideration of numerous interrelated factors, each having associated uncertainties. These factors include:

- electricity demand
  - demographics,
  - level and structure of economic activity,
  - consumer responses to changing electricity and other fuel prices,
  - load pattern;

- government actions
  - allowed rates of return,
  - environmental regulations,
  - taxes,
  - fuel use constraints,
  - required reserve margins;

- fuel cost and availability;

- financial conditions
  - interest rates,
  - inflation rates;

- technology performance
  - investment, operation, and maintenance costs,
  - efficiency,
  - utilization factors,
  - system reliability,
  - environmental residuals,
  - economies of scale,
  - first date of commercial availability,
  - vendor supply behavior.

How utilities respond to these factors and their perceived uncertainties will determine the timing, rate of penetration and ultimate level of acceptance of new technologies in the industry. Because of the degree of uncertainty in each of these factors, and uncertain consumer and producer responses to these uncertainties, it is, at best, only possible to assign probabilities to potential futures for each technology on the basis of current knowledge.

In recent years studies of energy policy have generally used models which incorporate the assessment of new technologies in an integrated energy/economy framework. This captures the impacts of federal policies and resource prices on the demand for electricity and other fuels, and insures consistency between the energy/economy system and the demand for electricity. In planning utility capacity expansion, a diverse set of techniques have been used which range from "rules of thumb" to more detailed optimization techniques involving linear and nonlinear programming, dynamic programming, and decomposition. These models are most useful in dealing with the factors relating to technology performance. Technology substitution models have been developed to capture and anticipate the penetration characteristics of new technologies.

The above techniques and their uses are discussed in following sections of this report: energy/economy systems models (Section III), utility capacity expansion models (Section IV), and technology substitution models (Section V).

III. ENERGY/ECONOMY SYSTEMS MODELS

This chapter focuses on the prominent energy/economy systems models which might be used to insure consistent energy-economy scenarios at the macro level. Some of these approaches model only the energy system, while others incorporate energy-economy linkages. All of them are time dynamic. The models selected for discussion meet several criteria: the time horizon for analysis extends to at least 2010; the methodologies are "state-of-the-art"; they are capable of capturing energy-economy interactions; and they are actively used for policy analysis by DOE.

The Energy Information Administration (EIA) Mid-range Energy Forecasting System (MEFS), formerly known as PIES, fails to meet the above criteria in that it has an inadequate time horizon (1995). Other models, such as those used by Data Resources Inc. (DRI) and the Wharton School, have also been excluded because they do not contain sufficient detail on the energy side or because their time horizons are too short.

The five major models selected for review are:

- FOSSIL79 - used by Dr. Naill, Policy and Evaluation (PE), DOE;
- PILOT/Welfare Equilibrium Model (PILOT/WEM) - developed by Professor Dantzig and S. Parikh of Stanford University;

- Energy Technology Assessment/Macroeconomic model(ETA-MACRO) - developed by Professor Manne at Stanford University;

- Time-stepped Energy Systems Optimization Model/Long-term Interindustry Transaction Model (TESOM/LITM) - developed at Brookhaven National Laboratory (BNL) and Dale W. Jorgenson Associates, Incorporated (DJA);

- Long-term Energy Analysis Package (LEAP) - developed by E. Cazalet of Decision Focus, Incorporated (DFI) and modified by DOE and BNL staff for the DOE's EIA.

A close cousin of the LEAP model, the GULF-SRI model, now resident at Standford Research Institute (SRI) International, differs from LEAP primarily in that LEAP is currently a single-region (U.S.A.) model while the GULF-SRI model is regionalized to the nine-census-region level. The data and computational requirements of the model are considerably more extensive than those of LEAP. Other differences are minor, and the SRI model is discussed only briefly in the text.

Table 1 summarizes the major characteristics of the models. More detailed descriptions are available in Reference 3 and in the references for the models given in Table 1.

The FOSSIL79 Modeling System

FOSSIL79,[4] a systems dynamics simulation model, was developed to serve as a simulation tool for evaluating the potential magnitude of the U.S. energy problem and for assessing the impacts of various energy policy options on the U.S. energy system.

Systems dynamics models integrate three distinct disciplines to analyze social systems:

- feedback control theory,
- organizational behavior, and
- computer simulation technology.

The focus of the systems dynamics methodology as applied to energy modeling is the representation of energy flows and decision making as a feedback control system. The idea that social systems (involving human decision-making processes) can be modeled with the same techniques as physical systems is the foundation of systems dynamics.[5] Computer simulation techniques provide the means to analyze complex nonlinear systems.

Table 1
Comparison of Model Features:
Energy/Economy System Models

	FOSSIL79	PILOT/WEM	ETA-MACRO	TESOM/LITM	LEAP	SRI
Objective:	Find prices, demand and production in energy sector in "disequilibrium transitions".	Determine internally consistent energy-economy solution.	Determine consistent energy-economy growth path which balances demand and supply.	Determine consistent energy-economy equilibrium which balances demand prices and quantities with supply prices and quantities.	Find energy prices that balance supply and demand.	Find energy prices that balance supply and demand.
Modeling technique:	Systems Dynamics (simulation) finite difference equations, behavioral responses.	Linear programming formulation for both PILOT and WEM; PILOT minimizes discounted cost, WEM maximizes "welfare".	This model; couples two models ETA; (Energy Technology Assessment) with a macroeconomic growth model (MACRO). This framework is that of a non-linear objective function to be minimized with linear constraints.	Linear programming for the energy component (TESOM). Econometric for the macroeconomic component (LITM)	Network flows with non-linear resource production and market share behavior.	Network flows with non-linear resource production and market share behavior.
Time domain:	Dynamic, 1950-2020	Dynamic, 1975-2010 for the combined system.	Dynamic, 1975-2050 in five year increments.	Dynamic, 1975-2025 in five year increments.	Dynamic, 1975-2025 in five year increments.	Dynamic, 1975-2025 in five year increments.
Inputs:	GNP through time, initial conditions of the energy system for the simulation, energy prices and gas and oil depletion rates, behavioral response relations, technology characterization, demand elasticities, demographics.	Demographic information, projected input-output coefficients, resource supply curves, energy import prices, technology characterization of energy conversion and delivery systems.	Macroeconomic parameters, potential GNP growth at constant prices, elasticity of aggregate energy demand, substitution possibilities.	For the energy components (TESOM): Technology characterization, first dates of commercial availability, optimistic technology penetration rates, long-term resource price curves, short-term resource production constraints.	Long-term supply and demand curves, specification of network with all conversion processes, GNP track through time, demand elasticities, demographics.	Long-term supply and demand curves, specification of energy network with all conversion processes, GNP track through time, demand elasticities, demographics.

Table 1 (Cont'd)

	FOSSIL79	PILOT/WEM	ETA-MACRO	TESOM/LTIM	LEAP	GULF-SRI
Inputs:				For the macroeconomic growth model (LTIM); Demographics, energy prices and quantities, depreciation rates, tax rates, production coefficients, capital stock.		
Outputs:	Adjusted GNP, energy prices, flows in the energy systems through time.	Macro-economic aggregates, resource production and energy use on supply and demand sides.	Domestic energy consumption, petroleum and gas imports, electric generation by source, production capacity levels for all technologies, actual GNP, shadow prices, present value of consumption, annual investment rate for electric utilities.	Macroeconomic aggregates of activity, equilibrium prices and activities across the entire economy. Special detail on energy side. Utilization of technologies in the energy system.	Energy equilibrium prices, demand and network flows.	Energy equilibrium prices, demand and network flows.
Level of regionalization:	National	National	National	National, regionalization can be approximated for supply side.	National	9 census regions
Level of detail for energy system:	Generic technologies on the supply side, fuel flows to aggregate demand sectors. Little inter-fuel substitution is considered on the demand side.	All technologies on the supply and demand side are modeled generically.	This is basically a limited supply side model with little detail on the demand side.	All technoloigies on both the supply and demand side modeled generically; regionalization can be approximated for the supply side.	All generic technologies; regionalization can be approximated for the supply side.	Generic definition of technologies at regional level.

Table 1 (Cont'd)

	FOSSIL79	PILOT/WEM	ETA-MACRO	TESOM/LITM	LEAP	GULF-SRI
Specification of the Electricity sector:						
. Utility dec. making	No	No	No	No	No	No
. Regulatory agencies	No	No	No	No	No	No
. Financing of energy production	Yes	Yes (for resources)	No	No	Yes	Yes
. Peak/intermediate/base loading	No	Yes	No	Yes	Yes	Yes
. seasonal/time-of-day loading	No	No	No	Yes	No	No
. Env. impacts	No	No	Yes	Yes	No	No
. Nuclear energy	Yes	Yes	Yes	Yes	Yes	Yes
. Regionality	No	No	No	No	No	Yes
Energy-economy	Limited	Yes	Yes	Yes	Limited	Limited
Market penetration representation	Endogenous	Upper bounds; no dynamic adjustments.	Upper bound constraints.	Optimistic path set exogenously but dynamically adjusted endogenously.	Endogenous	Endogenous
Reference:	3,4	3,6,7,8,9,10	3,11,12	3,13,14,15	3,16	3,16

FOSSIL79 is a dynamic disequilibrium model of the United States energy system which does not assume that markets always function in an optimal cost-minimizing manner. Instead, the model incorporates exogenous decision rules governing the flow of investment, resources, and energy-consuming goods. The model structure represents a causal theory of energy use behavior and is designed to function as a policy tool for analyzing potential energy problems. The model concept is appropriate for policy analysis because, in addition to the accounting rules required to track energy flows, the model directly represents the response of corporate, financial, and social institutions to the effects of the evolving energy situations. However, the basis for supporting the specific behavioral characteristics of institutions is not firmly grounded.

FOSSIL79 uses difference equations to represent the state-determined dynamics of the system, and this has an important implication relating to the theory of general economic equilibrium: the value of a level variable in a given time period can depend only upon values of level variables from previous and current time periods.

The FOSSIL79 model dynamically simulates the behavior of the energy system from 1950 through 2020, projecting gross and net production, fuel-specific demands, and prices. In FOSSIL79 the energy system is divided into five sectors: a demand sector and four production sectors (oil, gas, coal, and electricity). Each of the production sectors is further subdivided into supply/demand balance, financing, and production subsectors.

The current version of FOSSIL79 treats energy demand in a highly aggregated manner. The demand sector calculates the total end-use demand for energy in the U.S. on the basis of the movement of the gross national product (GNP) and the average energy price. This is the model's only linkage to the economic system. End-use demand is then broken down into demand for several specific forms of energy--gas, oil, coal, electricity, and decentralized energy.

The energy production sectors demand energy from each other. Since electricity converts gas, oil, and coal (as well as other energy sources) to electrical energy, the electricity sector must demand feedstocks from those three production sectors. Similarly, synthetic gas and oil are produced from coal, and, therefore, the oil and gas sectors will demand coal once synthetic conversion plants have been constructed in the model.

The electric utility system in FOSSIL79 is modeled much like the other production sectors described above. Electric load demand is highly aggregated. The required installed capacity is approximated by what amounts to a simple set of multipliers which transform the demand for electricity to required installed capacity requirements. Since the demand for electricity is aggregated, the required installed capacity will probably not be accurately reflected in that built by the model. Further, the effect of changing reserve margin requirements cannot be assessed within the system context by FOSSIL79.

The PILOT Modeling System

The PILOT energy modeling system currently houses several energy models. Demographic and economic scenario assumptions are fed to the welfare equilibrium model (WEM),an economic growth model containing a process submodel of energy supply and a variable coefficient input/output industrial system submodel, which is driven by a household welfare function of consumption and leisure time. WEM produces a dynamic economic equilibrium solution. The labor, capital, energy input/output coefficients of the nonconsumer sectors, and the workweek hours, all in time profile indices form, together with the scenario assumptions, are next fed to the PILOT Process Integrated Model (PPIM).[6-9] PPIM is an economic growth model, with a fixed coefficient input/output industrial system. However, it contains a more detailed process submodel of energy supply than WEM and yields a detailed physical flow solution. The shadow prices of WEM, the energy supply/demand balances, and the macroeconomic variables of PPIM are reported as the model solution.

PPIM is a time-phased (dynamic), linear programming model of a single region which optimizes over planning horizons of up to 100 years, beginning in 1973 in five-year increments. Given population, workforce, and labor productivity projections, the model calculates the projected economic growth which maximizes a linear objective function, usually the discounted sum of personal consumption over the time horizon of the scenario run. The PPIM model is a fixed-coefficient, input-output model integrated with an energy conversion process model. The integrated system is cast in an optimization framework for which the discounted present value of personal consumption (goods and services in dollar values) is maximized for the entire time horizon. The energy conversion devices are generically represented with associated capital costs, operation and maintenance costs, availability factors, conversion efficiencies, inputs and outputs. PPIM contains unidentified "back stop" electric and non-electric technologies which act to moderate the cost of energy. Other technology inputs to PPIM include first dates of commercial availability and upper bound capacity constraints which act to limit the potential capacity built for any new technology.

Economic activity is represented by twelve producing sectors: seven non-energy, and five energy. The energy sectors are modeled through a detailed description of raw energy extraction and conversion processes including exhaustible and renewable resources and existing and new technologies. The inputs for producing the non-energy sectors are characterized by fixed input-output coefficients, including labor and noncompetitive imports. These coefficients for each of the time periods must be provided exogenously. The GNP of each period is divided endogenously between capital formation, for replacing retired capacity and capacity expansion, and consumption that provides the nation's current standard of living. Imports cannot exceed the available revenue from exports in any five-year period. Consumer demands for goods and services, including energy services, are described by linear functions of population and personal income. The ability of consumers to select residential end-use energy systems of different types and efficiencies, to insulate homes, and to select different automobile prototypes is modeled through the process-type, consumer end-use submodel.

WEM[10] is a time-phased single-region linear programming model for developing internally consistent, long-run projections of energy supply, demand, and economic growth within an economic framework of aggregate consumer welfare maximization. Economic welfare is assumed to be a function of per capita consumption, average workweek, and population. Substitution across labor, capital, and energy permit the economic system to adjust to energy scarcities.

Demands for electricity are generated by the individual sectoral models in the equilibrium solution and these are mapped into base load, intermediate, and peak electric demand requirements. Each of these is then scaled up by a multiplier which attempts to capture the contribution of this demand type to capacity. The total capacity requirements are the sum of these capacity contributions by the three components. This capacity is then tempered by any additional required reserve margins and availability constraints (planned shutdowns). The capacity installed is based on an annual load curve with no seasonal or time-of-day consideration. The selection of capacity installed is based on the minimization of total discounted cost to the energy system.

The ETA-MACRO Modeling System

The ETA-MACRO[11,12] modeling system was developed to study the interrelationships between U.S. economic growth, conservation, and energy technologies in a normative optimization model. Constraints regarding energy demand, supplies from existing and new technologies, and factors associated with development of supply technologies are incorporated.

ETA-MACRO represents a merger of a process analysis model, Energy Technology Assessment (ETA), with a macroeconomic growth model, MACRO, which captures substitution possibilities between capital, labor, and energy inputs. The ETA model is linked to the MACRO model through the equilibrium price and quantity of energy in the domestic economy.

In order to account for the eventual exhaustion of today's fuels, the time horizon is divided into 16 five-year time intervals extending from 1975 through 2050. ETA-MACRO simulates a market clearing economy over time assuming consumers and producers can anticipate future scarcities. Supplies, demands and prices between the energy producing and energy consuming sectors are matched through a dynamic, nonlinear programming model (linear constraints) where the objective function may be viewed as maximizing the sum of consumer's plus producer's surplus in year 1975 discounted present value terms. The supply side of ETA characterizes a few generic technologies. Electric energy can be produced by coal fired power plants, light water reactors, fast breeders and an advanced electric technology which is characteristically defined as a black box with associated capital, operating and maintenance and resource costs. The number of conversion processes need to be kept to a relatively small number because of the nonlinear objective formulation. Non-electric energy may be supplied by oil, natural gas, coal, coal or shale synthetics or hydrogen via electrolysis. Technology penetration limits can be included as upper bounds and the selection level is based on the optimization criteria defined above.

The demand for energy in ETA-MACRO is derived through an aggregate production function. This production function is in nested form to minimize the number of parameters that need to be estimated from time series or cross-section data.

The economy uses energy in two basic forms: electric and nonelectric. The gross output of the economy, expressed in GNP terms, depends upon the inputs of energy, labor, and capital. In turn, the output is allocated between current consumption, investment in building the stock of capital, and current payments for energy costs. The macroeconomic production function in MACRO permits substitution among the factor inputs--capital, labor, and energy. The initial response of the economy to energy price increases and supply shortages is to substitute labor and capital for energy. The allocation of demand between the two forms of energy, electric and nonelectric, is accomplished by using individual price elasticities.

The demand for electricity is not modeled in detail in the ETA-MACRO model. (There is no load specificity.) The demand for electricity is one aggregate generated endogenously and a simple multiplier transforms total electric demand to total required capacity.

The TESOM/LITM Modeling System

The combined Brookhaven National Laboratory/Dale W. Jorgenson associates (BNL/DJA) energy-economy model system, TESOM/LITM, consists of a coupling of BNL's energy model, TESOM[13] with DJA's economic growth model, LITM.[14] The coupling is accomplished through an integrative interface which is essentially a "reduced-form" version of the Brookhaven/University of Illinois Input-Output Model.[15]

LITM is a simulation model of the structure and growth of the U.S. economy. It combines a two-sector (consumption, investment) and two-factor (capital, labor) neoclassical model of macroeconomic growth with a multisector, input- output model using flexible coefficients. For each year, it analyzes economic activity on a sectoral basis and integrates these sectors into a consistent whole. There are ten producing sectors, four non-energy and six energy, consisting of energy extraction and processing activities. There are three other sources of inputs into production (capital, labor, and competitive imports) and four categories of final demand for goods and services (personal consumption expenditures, investment, government purchases, and exports). These activities are organized into a matrix of interindustry transactions with 13 supply sectors and 14 purchasing sectors. Within this interindustry framework, balance or consistency is required to hold.

TESOM is a national energy system model based on Brookhaven's Reference Energy System (RES). The RES provides a complete and consistent accounting system, in physical units, for energy flows through energy technologies (stocks). With appropriate conversion efficiencies, the RES proceeds from the extraction or importation of primary energy resources and products, through refining and the various stages of energy conversion, transportation, distribution, and storage, to the consumption of fuels and electricity by end-use technologies corresponding to a particular energy service demand. Within the RES, emphasis is placed on a comprehensive technological structure relating energy flows which enter the system (oil, gas, coal, uranium, solar, etc.) to the relatively nonsubstitutable, functional, energy services that are the final product of the flow (space conditioning, motive power, process heat, lighting, etc.). Thus, the RES framework reflects the full, feasible range of interfuel and technological substitutability. Technologies in TESOM are generically defined by investment costs, operation and maintenance costs, efficiencies, availability factors, inputs, outputs; dates of commercial availability and optimistic capacity levels for new technologies are also required.

For each year the model optimally allocates energy resources and products and selects the optimal mix of supply, conversion, and demand technologies according to least-cost economic criteria to satisfy a specified set of energy service demands. Resource supply representations are specified as long- or short-term supply curves or fixed prices and availabilities by year. The TESOM model provides a "vintage" representation of the nation's energy system in that the optimal levels of the decision variables for any time-period are determined from:

- the optimal levels established for previous periods;
- the retirement and deterioration rates, the lifetimes, and the associated costs of vintage capital stocks;
- the economic and technological factors affecting the feasible levels of the decision variables for the period under investigation (e.g., decline rates, supply elasticities, cumulative resource availabilities, market penetration considerations, etc.).

TESOM provides a detailed representation of the electric sector. A set of **demand types** (e.g., base and intermediate loads, off-peak, heating, cooling, etc.) are defined. Each demand type has its own set of characteristics regarding its stochastic behavior and its seasonal (winter, summer, spring-fall) and daily (day, night) loading. Required capacity is governed by the highest total peak demand which occurs during some time of the year and day. By appropriately loading the electric energy service demands onto the various (or, in some cases, corresponding) demand types and, subsequently, loading these demand types onto the various season/day combinations, the height of the total peak for each season-day is determined. Required capacity is simply the maximum of the individual season-day peaks with allowances for transmission and distribution losses and reserve margins. This feature permits the introduction of load management considerations into the problem formulation as the load duration curve is, in part, exogenously determined from the detailed demand characteristics and their implications for the electric system.

As utilized, the two models are naturally complementary: the DJA system models energy demand and economic effects; TESOM models energy supply and conversion but not energy demand. The two models, therefore, interface at energy demand with the DJA model covering from aggregate energy demand through the general economy and with TESOM covering from resources through energy demand. The linked system extends the coverage and applicability of either model. Further, the linked system provides a framework for the consistent analysis of the role of energy technologies, energy supply and conversion, energy use, and energy-economy interactions.

The LEAP Modeling System

The LEAP model is a single-region, dynamic model of the supply and demand for energy in the United States. The methodology of the model was developed in 1973 to analyze synthetic fuel strategy for Gulf Oil Corporation and has since been extended and modified for use in DOE's long-range energy analysis.[16] Refinements to the model are on-going both in-house and through subcontracts. A detailed description of the current version of the Gulf-SRI model is not available. A brief description of the current version of LEAP, known as ARC-78, is available in Reference 3.

Categorized as a general energy equilibrium model, LEAP uses a methodology for the coordinated decomposition of complex time-dependent optimization problems. The energy system is divided into a number of simpler submodels which are coordinated within the model structure. LEAP does not impose one universal goal where the allocation of resources and demand is determined by explicit optimization of a single objective function. Rather, the models in LEAP represent the solutions to the decentralized optimization problem. A successive solution algorithm is used to coordinate the decentralized solution into an equilibrium solution. In LEAP, technologies are generically characterized through their investment costs, operation and maintenance costs, inputs, outputs and efficiencies. Market penetration in LEAP is price determined through a market share formulation. Price-superior technologies do not capture the entire market but capture a fraction which is determined by a price sensitive input parameter (γ), in a logistic formulation. The market shares have been shown to be very sensitive to values of γ and the appropriate values have not yet been empirically estimated.

The ten major sectors in LEAP contain activities (or processes) connected by links that pass information through a network. Each process is characterized by a set of mathematical relations, both economic (based on historic and projected data) and subjective (based on expert judgment). These relations may be physical, describing how physical flows interact over time, or behavioral, describing human choices. The basic network describes the links among the processes. These links are expressed as flows of prices and quantities of energy products. Some links can also represent environmental controls, the relationship of the energy sector to the economy, and constraints on prices or quantities.

The LEAP model identifies three annual electric demand load categories (base, intermediate and peaking). Each generation type is a "conversion node" in LEAP and as such is defined exactly as any other technology by its technical, economic, and financial characteristics. A scalar multiplier is used to compute the required capacity of each type. The mix of plants is also required to satisfy minimum reserve and availability requirements. Since LEAP is modular, the precise rule for selection of the mix of plants is variable and can be made as sensitive or as insensitive to competing prices for delivery of each type of electricity as desired.

Summary of Energy/Economy System Models

The systems models just described can be broadly categorized for OCU's needs by three criteria:

- their ability to capture energy/economy interactions,
- the level of detail at which the electric utility sector is modeled, and
- the regional structure of the model.

FOSSIL79, LEAP, and the GULF-SRI model do not currently capture energy-economy interactions. Projections of economic growth drive these models, but no feedbacks (resulting, for example, from capital and labor requirements) from the energy system are captured. PILOT/WEM, ETA-MACRO, and TESOM/LITM all capture energy-economy interactions in both directions at different levels of detail; ETA-MACRO provides the least detail, PILOT/WEM and TESOM/LITM provide the most.

TESOM/LITM provides the most detail of the electric generation sector. PILOT/WEM, LEAP, and GULF-SRI provide somewhat less detail, and FOSSIL79 and ETA-MACRO have the least electric system detail.

While the GULF-SRI model is the only methodology which explicitly models by region, the model is difficult (and expensive) to use. LEAP and TESOM/LITM have the capability to model regional supply availability and costs.

Overall, the energy-economy model system which seems to best meet the three criteria mentioned above is the TESOM/LITM system.

IV. UTILITY CAPACITY EXPANSION

This chapter addresses the potential of utility capacity expansion models for use in market penetration analysis. The acceptance of new technologies by utilities is determined not so much by their analytical methods as by their behavior in response to their tools' output and the other uncertainties they face. What is needed for market penetration analysis is a model of utility behavior and not simply a model which optimizes some discounted function which a particular utility may use. Utility behavior is the key determinant and those desiring to understand utility behavior in order to influence it must infer it from historical trends. Only a brief comparative summary of utility planning optimization models is provided.

A good review of selected capacity expansion models with possible application to market penetration in the electric utility industry is provided by Buehring, Cavallo, Dux, Hub, and Van Kuiken, Recommended Methods for Analysis of Competition Among New and Existing Technologies for the Electric Generation Market,[17] and our review draws heavily on this report for information on various utility planning models. In the above report, the treatment of the models analyzed is thorough and representative of the state-of-the-art for utility capacity expansion modeling through 1977. Since then two notable developments have taken place. The first is the completion, verification and validation of the Baughman-Joskow model[18] which is essentially a generic utility planning model. The second is the work currently underway for Electric Power Research Institute (EPRI) at the Massachusetts Institute of Technology (MIT) Energy Systems Laboratory to develop a user-oriented utility planning methodology.[19] Table 2 identifies the features of the Regionalized Electricity Model (REM) by Baughman and Joskow and other models (see Ref. 17).

SLICK: A Stochastic Least-Cost Market-Penetration Model

SLICK, developed by MITRE, computes the probability that a given technology with uncertain costs will have lower busbar costs than those of other technologies which also have uncertain costs. It is an optimization model and the competition is simulated for several new technologies simultaneously. The model is regional and resource and vendor constraints are imposed to limit market penetration. Resource constraints, demand, fuel prices, capital cost, and operation and maintenance costs are all defined by region, and the results are computed for 10 regions. The study period is 45 years with five year increments.

Among the input data to SLICK are triangular cost distributions, consisting of low, most likely, and high estimates of leveled life-cycle costs for each technology, by region and time period. The data are output from another MITRE model, the full Life-cycle Costing Program (FLICK). Other input data to SLICK include the data on each technology (e.g., capacity factor profiles),

Table 2
Comparison of Model Features:
Utility Planning Models

	SLICK	TRW	SURGE	OGP	SYSREL	WASP	GULF-SRI
Primary objective:	Monte Carlo simulation of the commercial introduction of new technologies	To assess generating and transmission technologies	To estimate market penetration by new technologies under uncertain conditions.	To determine optimum expansion of capacity	To assess reliability and cost performance of expansion alternatives.	To find an expansion policy.	To analyze the effects of national energy policy proposals on the electric utility industry and consumers.
Decision criterion:	Minimum leveled life-cycle cost.	Minimum leveled life-cycle cost.	Minimum operation and investment costs; employs generation expansion logic.	Minimum present value of revenue requirements each year in study period.	Does not optimize, but calculates performance for comparison with others.	Minimum discounted expenditures over study period.	Minimum annualized costs; deals with supply, demand, and regulatory aspects simultaneously.
Key input:	Leveled life-cycle costs, region and time period, technology characteristics, resource and vendor limits on implementation and electricity demand.	Technological and economic parameters, fuel and transportation price projections, and electricity demand.	Technological and economic parameters, generating capacity required, load data, and future fuel prices.	Technological and economic parameters, demand and load duration, and future fuel prices.	Technological characteristics, demand and load duration, and expansion plan.	Technological and economic parameters, demand and load duration data, and constraints on expansion possibilities.	Initial value parameters, technology characteristics, financial and regulatory conditions, historical trends for demand, and load characteristics of demand.
Key output:	Market share of each technology, mean busbar costs, and likelihood of commercial success.	Range of life-cycle busbar cost, revenue saved by a new technology and associated probability, and pollution indicators.	Number of units of each technology installed, production costs, and investment costs.	Optimum expansion plan year by year, expected generation by all units, system costs, and environmental factors.	Mean time between failures, LOLP, LOE with and without interties, reserve requirments, energy allocation among units and energy cost.	Optimum expansion policy over entire study period, expected generation by all units, and system costs.	Expansion and generation mix decisions, prices and demands.

Table 2 (Cont'd)

	SLICK	TRW	SURGE	OGP	SYSREL	WASP	REM
Time step:	3 year increment, 45 year study period.	Annual calculation, continuous curves over time.	One year, 45 year study period.	One year, 20 year study period.	Results output year by year; reliability and energy calculated bi-weekly.	Annual, with seasonal analysis.	Half year, 1947-1997.
Regionality:	10 regions	Several regions	Single reliability council.	One at a time.	Separate regions, one at a time.	Separate regions, one at a time.	9 census regions.
No. of technologies handled simultaneously	Several	One	One	Six	One	Several	One
Treatment of base, intermediate and peaking sectors:	Baseload Sector only	Separate analysis for each sector	Intermediate and base load not separated	All sectors integrated.	All sectors integrated.	All sectors integrated.	All sectors integrated.
Load following characteristics are calculated endogenously.	No	No	Yes	Not clear	Yes	Yes	Yes

THE FOLLOWING ARE EXPLICITLY ADDRESSED IN THE MODEL:

	SLICK	TRW	SURGE	OGP	SYSREL	WASP	REM
Uncertainty in costs and characteristics	Yes	Yes	Yes	No	No	No	No

Table 2 (Cont'd)

	SLICK	TRW	SURGE	OGP	SYSREL	WASP	REM
Generating system reability	No	No	Yes	Yes	Yes	Yes	No
Momentum of early decisions and learning curves	Yes	No	Yes	Yes	Yes	Yes	Yes
Transmission and Distribution	No	Yes	No	No	Yes	No	Yes
Limits on Technology Implementation are comptuere endogen-eously	Yes	Yes	No limits	Not clear	Not clear	No User imposed	Yes
Recognition of scale factors	No	No	Yes	Yes	Yes	Yes	No
References:	34,35,36	35	37	37,38,39	40	41	18,19

electricity demand for each period and constraints on implementation. These constraints include vendor constraints, resource constraints (e.g., availability of uranium), and locational constraints (e.g., for hydrothermal technologies). The primary outputs of SLICK are the fraction of the time that each technology was selected, the average busbar costs when the technology was selected, and the total cost to the nation of baseload electricity at the busbar.

The SLICK model uses cost uncertainties and fixed capacity factors in computing the probability that a given baseload technology would provide the lowest busbar cost. Use of the Monte Carlo method prevents one technology from capturing the entire market. The principal strengths of SLICK include the explicit incorporation of uncertainty in cost and performance, the simultaneous treatment of several new technologies for baseload sector demand and its relative simplicity. Some of its limitations include (a) the use of fixed-capacity factors, (b) absence of system reliability, (c) nonuniform treatment of costs across technologies for the same fuel or component equipment, (d) limited capability to analyze intermittent supply systems or unit sizes, and (e) absence of risk in the computation of market share.

TRW'S Analysis of Costs and Benefits of New Technologies

The TRW Energy Systems Planning Division published an assessment of new technologies from a utility perspective. This approach employs an optimization methodology where competition is simulated for one new technology at a time. Leveled busbar costs are computed for each technology and the present value of potential revenue saved for each technology in comparison with the conventional system is calculated. Resource constraints, demand and fuel prices are defined by region and expected savings are computed for each region. Annual calculations are presented as continuous curves over time.

The busbar cost uncertainties are represented by a normal distribution over four standard deviations. The cost distributions are calculated separately for base, intermediate, and peaking sectors. Market penetration is treated as an independent variable from the first year the new technology is commercially available; thus, no gradual implementation or vendor and user limits are imposed on these calculations.

The key inputs are data on each technology, fuel and transportation price projections, economic parameters, electricity demand projections, and capacity factors for each load sector. The key outputs are range of life-cycle busbar cost of electricity from each technology by region and time period, present value of revenue saved by a new technology showing a cost advantage over existing ones, the probability that the present value of saved revenue is positive, and pollution indicators.

The primary strengths of the TRW approach are the treatment of uncertain costs by a normal probability distribution, relative simplicity, and the inclusion of transportation and distribution cost adjustment in the comparison of peaking units. However, the approach has the following weaknesses:

- It tends to overestimate the net savings of any one technology since it can analyze only one technology at a time;
- There is no cross-technology correspondence in costs of identical equipment and fuel;
- It has no vendor and user limits on implementation; and
- Capacity factors need to be input exogenously.

SURGE: Stochastic Utility Regional Generation Expansion Model

The SURGE model, developed by Control Analysis Corporation, estimates market penetration for new technologies using a capacity expansion approach that explicitly incorporates uncertainties over future demands, prices and technological characteristics. SURGE is an optimization model and the optimal capacity expansion profile is determined on an annual basis, for a 45 year study period. Hydroelectric capacity and energy are fixed for the whole period. The model applies to a single electricity reliability council (SERC). The model uses a normal distribution over two standard deviations to set high, nominal, and low costs for each technology. The intermediate and base load sectors are not separated in the model.

The key inputs are data on each technology including unit size and costs, generating capacity required and load data, reserve margin required, economic parameters, future fuel prices, and data on existing system. The key outputs are the mean and standard deviation of number of units of each technology installed each year and cumulatively over study period, mean and standard deviation of production costs each year and cumulatively, and mean and standard deviation of investment costs each year and cumulatively. Cumulative production and investment costs are discounted.

Strengths of the SURGE model include the determination of optimal capacity factors, the timing and size of specific plant implementations, the use of load duration curves to determine the optimal expansion path and technology usage, and quantification of uncertainty ranges for market shares based on the uncertainties of the cost and performance characteristics.

Some of the limitations include the essentially deterministic approach to uncertainty with only three states possible for each uncertain parameter, the absence of peak electric demand requirements (which biases the results toward excess base or cycling capacity), and the restriction that only one capacity type may be added each year. The model logic also appears to indicate an optimization over one year, instead of the longer planning horizons (8 to 15 years) of electric utilities. This may not give optimal solutions in the long run.

OGP: Optimum Generation Planning Program

The OGP is a detailed power generation planning model developed by General Electric and used by EPRI and several electric utilities. It is an optimization model and is applied to one region at a time. The approach used in OGP starts with evaluation of the reliability of the existing system plus the postulated addition for a particular year. Those possible configurations that meet the specified standard are evaluated in terms of production and investment cost. Leveled fuel and maintenance costs are included, and it is possible to include some environmental impacts and constraints. After all configurations that meet the specified constraints are examined, the one with minimum revenue requirements is selected and the program moves on to the next year. The results are presented for each year in a typical 20 year study period, with hydroelectric and storage capacity fixed for the whole period. To study the effects of uncertainty in costs and characteristics a deterministic sensitivity study is necessary, with a separate run for each set of parameters. Only six technologies can be compared in one run.

The key inputs are data on each technology including unit size, cost, forced outage rates and scheduled maintenance, demand and load duration over study period, future fuel prices, data on existing system, and economic parameters. The key outputs are optimum expansion year by year, expected generation by all units, system costs, and environmental factors.

The primay strengths of OGP are its consistent approach to system reliability, calculation of expected capacity factors, integrated treatment of the generating system, and sensitivity to load duration and unit sizes. Its major limitation is its overall complexity which makes it difficult to incorporate many technologies with uncertain costs and characteristics.

SYSREL: Electric Utility Generating System Reliability Code

SYSREL is a descriptive model (not optimization) of the electric utility system for an exogenously specified expansion plan. The model is designed to assess the reliability and economic performance of alternative expansion patterns of electric utility generation systems. From a utility perspective, SYSREL is ideal because it imposes no criteria for choice of configuration. It produces, for a particular system configuration, estimates of the mean time between system failures, required reserve capacity to meet a prespecified criterion for system failure frequency, and expected electric generation from each unit and system cost. It provides no insights into utility behavior. The model also appears suitable for study of decentralized systems with nonintermittent supply.

SYSREL is a regional model and the results are output on an annual basis. Reliability and energy are calculated biweekly. The limits on implementation are user-imposed in the input expansion plan. A deterministic sensitivity study with a separate run for each set of parameters is necessary to study the effects of uncertainty in costs and characteristics.

The key inputs to the model are technological data (e.g., capacity forced outage rate, maintenance) for each unit in the existing system and in the expanded configuration to be evaluated, demand and load duration data over study period, and the expansion plan. The key outputs are estimates of the meantime between system failures required reserve capacity to meet a specified criterion for system failure frequency, expected energy generation from each unit, and system energy cost.

Among the principal strengths of SYSREL are its consistent treatment of reliability in comparing alternatives, its output of outage frequency and duration, and its ability to calculate unit capacity factors while accounting for forced outage, maintenance, and differences in variable costs. The model, however, is not suitable for analyzing systems with uncertain cost and performance characteristics.

Recently, some improvements and additions to the SYSREL model were made by Argonne National Laboratory and this has resulted in a new model - "Reliability and Cost Model for Electrical Generation Planning" (RELCOMP), with greatly expanded capabilities. Documentation on this model is not yet available. RELCOMP is a non-optimizing computer program that determines the expected reliability and cost of electrical utility generating system configurations. The typical time period for analysis is 1 to 20 years and the calculations are performed on a biweekly basis.

The key inputs to the RELCOMP model include expected electricity demand over time, the generating system configuration over time, technology characteristics of each generating unit, fuel prices, firm purchases or sales, emergency interties and spinning reserve goals (if any). The key outputs are a maintenance schedule for the system, reliability performance of the generating system (mean time between failures, lost-of-load probability (LOLP) etc.), reserves required to meet specified reliability criterion, the expected generation from each generating unit, the quantity of fuel used, and the generating system costs.

WASP: Wien Automatic System Planning Package

The WASP model is a single region dynamic optimization methodology for finding the optimal generation expansion policy over an entire planning horizon. A probabilistic simulation model is used to derive operating costs. Resource Planning Associates (RPA) has extracted SIMUL (Probabilistic SIMULATION model) from WASP and embellished it for use in utility capacity expansion planning. The WASP model is well-suited for the calculation of the optimal expansion pattern when costs and performance characteristics are known for a limited set of technologies. Uncertainty in prices requires new runs for each point of the parametric analysis.

The model calculates total discounted cost for all possible configurations over a planning period of up to 30 years. The model applies to separate regions and the calculations are done on an annual basis.

The key inputs to the model are data on technologies (including unit size, cost, forced outage rates, and scheduled maintenance), demand and load duration data, data on existing system, economic parameters, constraints on expansion possibilities to be considered. The key outputs are the optimum expansion policy over the entire study period, expected generation by all units, and system energy costs.

The principal strengths of the WASP are its ability to calculate capacity factors on the basis of variable costs, its consistent treatment of reliability, its recognition of specific unit sizes, its ability to take into account future costs and expansion possibilities, and its sensitivity to load duration. As with any optimization framework, small changes in cost can lead to substantially different choices of expansion paths and this, together with the limitations on the number of technologies which can be dealt with simultaneously, are the principal limitations of the model.

REM: Regionalized Electricity Model

As previously mentioned, the REM model is a noteworthy recent advance. One feature distinguishing REM from the other models is that it combines a behaviorial model of the demand for electricity and competing fuels with a supply model that incorporates a process engineering approach, all conditioned by the fact that the industry is regulated. It is the only model that combines these three components in an integrated fashion. REM is a dynamic model of the electricity market and it was developed to analyze the effects of national energy policy proposals on the electric utility industry and consumers. It has a time horizon of 50 years (1947-1997) with half year increments, and applies to nine census regions.

REM has three submodels - demand, supply, and financial/regulatory. The demand submodel projects electricity and competing fuel demand by state separately for the residential and commercial sector, and for the industrial sector. Important independent variables include population, gross national product, personal income, and industrial value-added and fuel prices. The supply submodel projects the capacity expansion, generation mix, transmission and distribution costs and investments for each of the nine census regions. Generation mix decisions are based upon minimizing variable costs subject to the constraint of the load duration curve. The financial/regulatory submodel projects the capacity financing schedule and the price of electricity based on the plant capacity and the T&D structure of the industry, the interest rate, an allowed rate of return, and a set of accounting rules as to what is included in the rate base.

The key inputs to REM are the initial value parameters, technology characteristics, financial and regulatory conditions, historical trends for demand, and load characteristics of demand. The key outputs are the expansion and generation mix decisions, prices and demands.

However, it is not well suited to technology assessment in its present form:

> "REM as presently configured is not well suited for technology assessment. First, the model planning horizon (to 1997) is too short to consider the potential for most emerging technologies. Second, it is very difficult to specify new plant types in the model, either for a conventional technology (e.g., baseload versus cycling coal) or new generating type (central station solar). Extending the model for use in this type of application is likely to require a major redesign of the model implementation." (Ref. 19, pp. S-7.)

Summary of Utility Planning Models

The six models (other than REM) summarized in Table 2 can be broken down into two groups. The first three models (SLICK, TRW's analytical model and SURGE) were designed for long-range assessment of economic competition among new technologies with uncertain performance characteristics, and the models in the second group (OGP, SYSREL, and WASP) are not market penetration models in the strict sense but technology assessment tools. None of the models in the table includes noneconomic factors in the decision process.

The Futures Group Decision Logic and METREK models are two other models which take into consideration noneconomic factors of decision making (see Ref. 17). These models take into consideration the value judgments of the decision makers in the utility industry and their perceptions of relative merits of competing technologies. However, they both have some problems in assigning relative merits to different technologies.

None of the existing models is sufficiently complete or comprehensive to serve alone in projecting the market acceptance of advanced power generating technologies. Our review reiterates the need for modifying suitable existing models (drawing on their strengths and rectifying their weaknesses) and/or building submodels to supplement them.

V. TECHNOLOGY SUBSTITUTION MODELS

This chapter addresses the potential of technology substitution models for use in market penetration analysis in the electric power generation sector. Since the acceptance of any technology is not always based solely on cost but also on other behavioral factors, the technology substitution models represent another attempt to capture the dynamics of technological substitution. Unlike the systems or utility models discussed in Chapters III and IV, technology substitution models are basically regression analysis approaches. These approaches are characterized by the attempt to use historical trends and a small number of driving variables to project the potential market for the future. It is, however, a reasonably well-known fact that regression approaches cannot always be counted on to provide good projections (extrapolations) from historical trends and this is perhaps the single most important criticism of this generic approach. The problem is further compounded by the institutional framework in which electric utilities must operate.

Mansfield

The seminal contribution to this approach to market penetration analysis was made by Mansfield in 1961.[20] He investigated the question of technological diffusion which might be stated as: Once an innovation is successfully introduced in one firm, what are the factors which cause the innovation to spread through the industry? This question is similar to the one that OCU is addressing except that in the OCU's case, the initial introduction may not be voluntary but may result from a government-sponsored demonstration. It is open to investigation as to whether the difference in the mechanism by which the technology penetrates invalidates the approach.

Mansfield examines the rate of substitution between time t and time t+1 and hypothesizes that "the proportion of 'hold-outs' at time t that introduce the innovation by time t+1 is a function of

(1) the proportion of firms $n(t)/N$ that have already introduced it at time t, where N is the total number of firms which may adopt the innovation and $n(t)$ is the total which have adopted by time t;

(2) the profitability of installing it (relative to other investments), π;

(3) the size of the investment required to install it (defined as fraction of firm's capital), S; and

(4) other unspecified variables (see Ref. 20).

He develops both a deterministic and stochastic model and fits and tests them against data for twelve innovations in four industries.

In functional notation, his assumptions are equivalent to

$$\frac{n(t+1) - n(t)}{N - n(t)} = [f(\pi, S, n(t)/N, \ldots)].$$

Mansfield then takes the first nonconstant term of the Taylor's expansion for f to rewrite the hypotheses as a differential equation.

$$\frac{dn}{dt} = \dot{n}(t) = \phi \frac{n(t)}{N} [N - n(t)],$$

where the constant, ϕ, consists of the terms

$$\phi = \alpha_1 + \alpha_2 \pi + \alpha_3 S .$$

The solution is given by

$$n(t) = \frac{N}{1 + \exp(-k - \phi t)},$$

where k is the constant of integration.

This can be rewritten as

$$\ln \frac{n(t)}{N - n(t)} = k + \phi t,$$

and it permits a least squares estimation for k and ϕ for each innovation.

Mansfield is forced to assume, owing to a limited number of innovations, that the coefficients of profitability and investment size are constant over industries. Using the ratio of the average acceptable payout period of the industry to expected payout period for each innovation as a surrogate for π, and the percent of total assets of the firm represented by investment in each innovation as the surrogate for S, he statistically derived ϕ as

$$\phi = Z + 0.530 - 0.027\ S$$
$$(r = 0.997),$$

where the constant for each industry Z was

coal mining:	-0.57
iron and steel:	-0.52
railroads:	-0.59
brewing:	-0.29.

Note the strong positive dependence (0.53) on profitability (π) and the negative weaker dependence on the size of the investment (-0.027) and the significant contribution from the constant term. Little additional variance appears to need explanation for these industries from other considerations such as industry growth, national business conditions, time since first adoption, and remaining service life of equipment replaced. Notice that Mansfield modeled a single technology. Other competitors are indirectly accounted for through the profitability variable. The explicit replacement and substitution of one technology for another are not explicitly considered here. The significance of Mansfield's work is that it recognizes interindustry differences and plausible intraindustry factors for the rate of technical innovation. His method seems most appropriate for estimating the growth, in absolute terms, of an economically attractive energy conversion process.

Blackman

Blackman has applied a version of the Mansfield model to two electric utility innovations and four consumer durable market penetrations,[21] turbofans and commercial jet engines in aircraft,[22] eight consumer durable, and eight commercial and recreational marine applications.[23] As in the case of the other investigations, the empirical data show a good agreement with the model. He attempts to provide a methodology for forecasting both with and without historical data. He suggests using the historical data available immediately after a technology is introduced and form the function to fit it. When no historical data exist, he suggests that an innovation index be used. He has developed innovation indicies for 12 industries based upon a calculated representative industry constant, a profitability index, and an investment index. Finally, he has incorporated forecasting with substitution analysis into a broader venture analysis framework.

Fisher and Pry

Fisher and Pry attempt to develop the Mansfield model into a forecasting tool.[24] The underlying assumptions are: (1) if a substitution has progressed as far as a few percent, it will proceed to completion, and (2) the fractional rate of fractional substitution of a new technology for an older one is proportional to the amount remaining of the old technology left to be substituted.

This may be written as

$$\dot{f}(t)/f(t) = [\ 1 - f(t)].$$

where f(t) is the challenger's share at time t and f(t) is the time <u>deriviation</u> of the market share of the challenger's derivative. If $t_{0.5}$ is the time of 50% substitution (f=1/2), then the solution to the differential equation is

$$f(t) = [1 + \exp - (t - t_{0.5})\ ]^{-1},$$

or equivalently

$$\ln \left[\frac{f(t)}{1 - f(t)} \right] = \phi (t - t^{0.5}).$$

If the "take-over time" Δt is the time required by the challenger to increase his share from 10 to 90% then t = 4.4/ϕ Lenz and Lanford[25] show how to fine tune this formulation based on only 2% market penetration.

Fisher and Pry present data and fit the model to 17 substitutions, ranging from consumer nondurable substitutions (margarine for butter) to consumer durable for other materials (fiberglass for wood in pleasure boats), to producer nondurables (T_iO_2 for P_bO-Z_nO paint pigments), to producer durables basic oxygen furnace (BOF) for Open-Hearth in steel production). The takeover times vary from 8 to 58 years. They conclude that the substitution once initiated flows to completion. They do not advance a mechanism to explain this phenomenon.

Peterka

Peterka[26] extends the observations of Fisher and Pry to a model that considers more than two competing technologies in the energy sector. Peterka's main assumption is the principle of no net capital transfer between competing energy supply sectors (i.e., a viable technology must grow on its own account - the mean value of external capital flow is zero).

Peterka expresses this mathematically as

$$\alpha_i(t)\ \dot{X}_i(t) = X_i(t)\ [p(t) - c_i(t)]$$

$$i = 1,2,\ldots,\ N$$

where

$X_i(t)$ = productive capacity at time t for industry i,

$X(t)$ = total production capacity at time t,

$\pi_i(t)$ = capital cost per unit of capacity for industry i at time t,

$p(t)$ = average market price of processed energy types at time t, and

$c_i(t)$ = total operating cost at time t for industry i.

By judicious rewriting of the above equation Peterka solves the problem, for smoothly varying operating costs relative to capital costs, with

$$f_i(t) = \left\{1 + \sum_{j \neq 1} (f_{jo}/f_{io}) \exp \left[-F_{ji}(t - t_o)\right]\right\}^{-1},$$

where

f_{jo} is $f_j(t_o)$, the market share when (at time equal to t_o) technology j is commercially available, and $-F_{ji}$ is the average of $-(c_i - c_j)/\alpha$ over the interval of interest.

Notice that $(p - c_i)$ can be identified as a profitability index from a unit expansion of production capacity and π_i as the size of the initial investment. Consequently Peterka's formulation generalizes both Mansfield's and Fisher and Pry's model.

Peterka finally shows how information about model parameters can be extracted from historical data, and demonstrates how a new technology can be incorporated in the model on the basis of its economic assessment.

Bass

Bass attempts to apply the Mansfield-Blackman framework to a forecasting model for consumer durables.[27] He explicitly attempts to isolate behavioral factors. His data set tests the accuracy of the model against eleven consumer durable products. The underlying behavioral assumption is that the timing of the initial purchase is related to the number of previous buyers. He also recognizes that at some point sales no longer represent initial purchases but begin to include replacements. His mathematical structure reflects this in that the probability that an initial purchase will be made at a specified time, given that no purchase has yet been made prior to that time, is a linear fraction of the number of previous buyers. The data provide a good fit to the model.

Summary of Technology Substitution Models

The substitution models described above, along with others,are reviewed by Hurter and Rubenstein[28] and by Condap and Kydes.[29] The additional papers all relate to similar models and differ primarily in suggesting varying interpretations of significant parameters or underlying behavioral forces. For example, one investigator provides a sociological rationale based on the interaction between adapters and nonadapters, while another suggests that the age of the capital stock or the distribution of firm size acts as a surrogate for industry resistance to some types of innovation.[30-33]

The technology substitution models are characterized as statistical models of market penetration. Virtually all investigators report excellent correlation with historical data; this is not surprising since statistical models would be expected to "predict" accurately the "historical data" used to calibrate them in the first place. Tests of several models assuming that knowledge is limited to that available in the first few years of a technology's market penetration provide some reassurance of the models' long-term predictive powers. Although these models "explain" the phenomena in a statistical sense, they do not explain the phenomena in a "micro" sense. We know very little about non-price factors which have a very strong influence on choice, viz., the public reaction to Three Mile Island. When the underlying determinants of choice are not well understood then statistical models for market penetration may be totally invalid for predicting acceptance in the longterm where the underlying factors may change.

VI. SUMMARY

This review has discussed several different models and methodologies which have been or could be used for the analysis of the market penetration potential of new electric generating technologies. No single methodology adequately captures all of the factors that might influence market penetration in the electric utility sector. However, from each class of models reviewed, certain methodologies emerge as being most appropriate for addressing the needs of OCU. The design of a "best" methodology for assessing the market potential of candidate technologies will involve a synthesis of several of the models discussed (**across** as well as **within** classes). This synthesis will be the subject of a subsequent paper.

In the class of energy/economy systems models, it appears that the TESOM/LITM best captures the bidirectionality of energy/economy interactions, although the PILOT/WEM and ETA-MACRO models also capture a significant portion of these interactions. However, the TESOM model provides the greatest detail of the electric utility sector in terms of capturing the load structure of demands as well as the factors affecting capacity requirements. The only system-wide model with complete regional detail is the GULF-SRI model, but this model lacks the energy/economy linkages and electric sector detail determined to be important for the analysis of market potential. However, the TESOM/LITM system (as well as LEAP) can capture regional differences in resource costs.

Electric utility expansion (or planning) models have several shortcomings in terms of meeting OCU's needs. These models are not models of utility behavior, but tools that provide only one of several inputs to the utility decision making process. These models may provide, as a first cut, the least cost solution to the utility expansion problem in a normative world. Given the regulated nature of the electric utility market, as well as its local monopoly nature, perhaps the government should be more concerned with such normative solutions as socially preferable to market solutions to utility expansion issues. In addition, these models require as an exogenous input the level of demand for electricity. For a single utility, this demand may in fact be exogenous (although uncertain) and may not be affected by a single utility's decision. However, for the system as a whole, the level and structure of the demands will be affected by decisions in the electric utility sector which impact the costs and availability of electricity.

The review of the planning models seems to indicate that the REM model developed by Baughman and Joskow best captures the interactions between electricity demand, engineering requirements, and the regulatory environment. However, its shortcomings in dealing with new technologies suggest the need for major modifications of the model before using it for the type of technology assessment being considered here.

Neither the system-wide models nor the utility expansion models adequately capture the competition among evolving technologies. Optimization utility capacity expansion models usually suffer from "all or nothing" behavior, i.e., the most attractive technology always enters the solution at the maximum permitted levels and some cost variations can cause substantial, unrealistic changes in the optimal capacity expansion path. Many substitution models have evolved from the early work of Mansfield. The most promising appears to be the Peterka framework in terms of sophistication and its ability to capture uncertainty with distributions around parameter values.

Overall, no single methodology known to the reviewers adequately addresses the factors relevant to the market penetration of new electric generating technologies. A synthesis of the approaches discussed here is necessary to adequately model the issues of importance to OCU.

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