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AN APPROACH TO MARKET-PENETRATION ANALYSIS FOR ADVANCED ELECTRIC-POWER-GENERATION TECHNOLOGIES

J. Lamontagne, P. Love, and A. Queirolo

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ABSTRACT

If commercialization of new technologies is the primary objective of the Department of Energy's Research, Development and Demonstration (RD&D) programs, the ultimate measure of benefit from RD&D programs is the extent of commercial acceptance of the developed technologies. Uncertainty about barriers to commercialization - government policy, fuel supply, etc. - make the task of estimating this acceptance very difficult. However, given that decisions must be made regarding allocation of RD&D funds, the best information available, with due regard for uncertainty, should serve as input to these decisions. This paper presents an approach for quantifying the range of market potential for new technologies (specifically in the utility sector) based on historical information and known plans for the future.

ACKNOWLEDGMENTS

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Thanks are due also to Mr. John Facey of the Department of Energy and Dr. Paul Bauer of Argonne National Laboratory for their support and encouragement.

The Electric Utility Stochastic Model, the central feature of the methodology outlined in this paper, is the creation of Peter Love of the Commission of the European Communities, DG XII. His development of this innovative methodology, as well as his authorship of Section III and Appendix A of this report, are gratefully acknowledged.

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I. INTRODUCTION

Market Penetration Estimates and RD&D Allocation

Central to calculating the benefits associated with the development and introduction of new technologies are estimates of of their rate of acceptance (market penetration) and ultimate market potential. Since quantification of the benefits of technology development depends directly on the market penetration of these technologies, this area deserves special attention. As stated in an earlier paper on this subject, "no single, completely satisfactory means of estimating market penetration of a new technology has ever been developed."[1] Nor is it likely that a single method will be evolved. The inherent differences in market sectors, changes in consumer habits, and unforeseen innovations preclude development of a universally appropriate methodology.

In developing methods for dealing with questions of market penetration, factors such as the availability of data to support the methodology, the actual usefulness of the information derived, and the uncertainties in the "information" are too frequently ignored. Elaborate, expensive procedures requiring vast support activities generally produce results with a level of refinement totally unjustified by the verifiable confidence of the data inputs; in many cases, less costly methods would be adequate and can provide more useful information. The data inputs to elegant formulations and sophisticated methodologies may contain such a high degree of uncertainty that the model results are meaningless, or worse, misleading.

Normative and Exploratory Forecasting Approaches

Technology forecasting methods fall into two general classes, normative and exploratory. These categories are not entirely exclusive (e.g., a dominantly normative method may contain exploratory elements), but are broadly different philosophically. Normative forecasting assumes a desirable goal (e.g., a least-cost energy system) and identifies actions (resource allocations) necessary for goal realization. All linear programs, even when highly constrained for use in simulation modes, are normative models.

Normative models show what should happen in some optimal sense; they do not attempt to predict what will happen in the future. For a given set of input assumptions, they can establish the value of a new technology to a future energy system. However, model inputs and outputs are point data - uncertainty in major input assumptions is dealt with by the generation of alternative scenarios. Uncertainty in technology characterization data is often ignored. Energy system models of this class are widely used as aids to policy and budgetary decision making. Criticism of normative models generally focuses on the inconsistency of input data quality and the sophistication of the modeling approach. The meaningfulness of selected goals is also often suspect.

Exploratory forecasting starts from the current state of a system and attempts to predict the future state of that system based on aggregates of expert judgment and/or extrapolation of trends. Forecasts of probable system technological states are useful in aiding research and development resource allocation. The simple approaches used require a far lower commitment of resources than normative forecasting. The most complex area of exploratory forecasting involves the establishment of simple correlative models by statistical techniques.

It is possible to deal with uncertainty in a simple way through the use of exploratory techniques. In the approach outlined in this paper (the Electric Utility Stochastic Model), the mean and variance of the input data to the methodology may be used to set limits to the time horizon beyond which it would be impossible to draw intelligent conclusions about the technologies under study.

Criticism of the exploratory forecasting approach centers on its lack of attention to causal mechanisms. However, even the most sophisticated normative models use exploratory methods explicitly to limit the rate of diffusion of technological innovations and informally to determine the models' exogenous driving inputs (e.g., future energy demand).

Rationale for the Selection of the Electric Utility Stochastic Model

A review of available models for possible use in market penetration analysis for advanced power generation technologies was conducted as an earlier part of this program. This review revealed generic weaknesses in each of the two classes of models normally used in the evaluation of new utility sector technologies. Even the most appropriate energy/economy systems models suffer from their difficulty in dealing with uncertainty and lack of regional detail. Available utility capacity expansion models have insufficient time horizons to evaluate the technologies under consideration in this study, do not address uncertainty in technology characterizations, or are difficult to use in the assessment of new technologies. Both of the above classes of models require extensive data bases and have substantial computational requirements while the level of detail required is generally incompatible with the quality of the data available for characterizing emerging technologies.

The Electric Utility Stochastic Model (described in Section III of this report) is primarily an exploratory tool which avoids many of the problems of the models described above. The model deals explicitly with the uncertainty inherent in demand forecasts and the economic characteristics of immature technologies. Data and computational requirements are minimal, and operation at various levels of regional detail is easily accomplished. The model was developed by Peter Love of the Commission of the European Communities, DG XII, and is currently being revised by members of the The National Center for Analysis of Energy Systems at Brookhaven National Laboratory under his direction.

This approach does not take into account many of the considerations which utility capacity expansion models attempt to capture such as system reliability, load-following characteristics, etc. For the extended time frame required to introduce the technologies under consideration in this study, it is necessary to accept that many of the input parameters required to evaluate their performance in a utility system are very uncertain. For example, experience with any technology is necessary to determine such operating characteristics as downtime, overall efficiency, operating and maintenance costs, etc.

At this time it appears reasonable to consider all technologies in this study simply as being available for additions to base load power generation (capable of meeting base load demand growth or to replace existing base load units).

Technologies Selected for Analysis

The advanced technologies under study are coal-fired base/intermediate load power generation technologies:

- conventional coal combustion with advanced flue gas desulfurization (several processes);
- atmospheric fluidized-bed combustion;
- pressurized fluidized-bed combustion;
- coal gasification/combined cycle.

To allow these technologies time to achieve significant market penetration, the time horizon for the study will extend at least to 2000. It is assumed that renewable resources (e.g., wind, photovoltaics) are not a major factor in power generation by this time. "Until about A.D. 2000, the major choices are nuclear power, fossil fuels (of various sorts), or nothing, in varying proportions."[2] Oil and natural gas are assumed eliminated from competition by the Powerplant and Industrial Fuel Use Act of 1978. Synthetic fuel production for power generation (other than integrated coal gasification/combined cycle) will likely be too costly and limited in supply to have a major impact on base load generation in this time frame, although this option could easily be included for analysis at a later date. Although electricity from nuclear power is generally considered slightly cheaper than coal-based electricity,[3] the social controversy surrounding nuclear and the momentum of the political opposition to this alternative are assumed to limit its contribution by the turn of the century. Thus, the initial set of technologies considered to be in competition for the base/intermediate power generation are the four advanced coal utilization technologies listed above, along with lime/limestone (wet throwaway) scrubbing, the baseline technology.

II. BASIC CONSIDERATIONS AND APPROACH OVERVIEW

Overview

Although it is impossible to forecast with a high degree of confidence the eventual acceptance (market penetration) of a technology currently at the research and development stage, it is reasonable to assume that:

- Demonstration of a commercial-scale facility will be required before any general acceptance of the technology will be possible; and
- once demonstration has been achieved, it may be possible to estimate upper limits for growth based upon the historical behavior of other technologies (especially in the same industry).

The general approach proposed to quantify market penetration possibilities for new technologies in the utility sector consists of the following steps:

1. Estimate the completion date for construction of the first commercial-scale demonstration unit.
2. Estimate the time required for start-up, operation, and evaluation of this first unit (demonstration to commercial availability).
3. Estimate the time required for initial market penetration (commercial availability to threshold acceptance*).
4. Estimate economic, environmental, and performance characteristics of the new technology.
5. Estimate the growth rate of the new technology (market share).
6. Estimate market size by quantifying existing and planned capacity, anticipated retirements, and expected demand growth.
7. Quantify market capture by integrating the information established in steps 1 through 6.

Uncertainty considerations are involved in all these steps.

*Sufficient market capture to eliminate perception of technical risk and to adquately define process economics: taken as 4% of the total market in this report.

Commercial-Scale Demonstration - The Necessary Condition

The demonstration of commercial feasibility for a new technology, from both technical and economic perspectives, is a prerequisite for broader acceptance of that technology. Even if feasibility has been demonstrated, the upper limit of the technology's acceptance is difficult to ascertain because of economic and regulatory uncertainties, the behavior of other existing or emerging technologies, etc. However, it is possible to state definitely that acceptance (market penetration) will not start until commercial viability has been demonstrated. In making a case for the commercial-scale demonstration of a new technology for use by the electric utility industry (a 200 MW atmospheric fluidized-bed power plant), the General Accounting Office states[4]:

> "Utilities, like industry, also prefer to minimize risks of introducing new technology. Hence, a demonstration step is necessary to convince utilities of the attractiveness of fluidized-bed combustion as an alternative to conventional coal-fired plants with scrubbers. Utility companies will accept the technolgoy only if they are convinced that fluidized-bed combustion powerplants will (1) operate effectively and reliably in an interconnected electic power system; (2) meet all Federal, State, and local environmental regulations; and (3) require less capital and operating costs compared to conventional coal-fired steam plants with scrubbers.
>
> A July 1978 TRW Incorporated study performed for TVA states that the demonstration step is required to obtain scale-up information, environmental measurements control and other instrumentation requirements, design optimization data, and practical experience with the fluidized-bed combustion units. The manufacturers will need this information to be able to construct a commercial unit meeting the technical specifications of a utility. The study further states that demonstrating the reliability and economic attractiveness of the technology is required to convince the financial community that the fluidized-bed combustion technology is sound. This is necessary for the utilities to obtain reasonable financing rates for utility-size fluidized-bed combustion units."

For the technologies under consideration here, it is possible to estimate earliest commercial demonstration dates from the plans of DOE and others. These dates are listed in Table 1.

Table 1
Earliest Planned Installation Dates for Power Generation Technologies
(Demonstration Size Plants)

	Planned Installation				
Technology	Planned Year of Operation	Unit Location	Unit Size	Company	References
Atmospheric Fludized-Bed Combustion	1990		200MW	Tennessee Valley Authority	9
Pressurized Fluidized-Bed Combustion	1986	New York	170MW	American Electric Power Service Corp.	5
Coal Gasification/ Combined Cycle	1983	Edison Cool Water Power Plant, San Bernadino, CA	100MW	Southern California Edison Co.	6,8,10,17
Advanced Flue Gas Desulfurization					12,13,14, 15
1. Dual Alkalai	1979	A.B. Brown No. 1, West Franklin, IN	265MW	Southern Indiana Gas & Electric Co.	
		Cane Run No. 6, Louisville, KY	288MW	Louisville Gas & Electric Co.	
		Newton No.1, Newton, IL	575MW	Central Illinois Public Service	
2. Magnesia Scrubbing	1975	Eddystone No. 1A, Eddystone, Pa	120MW	Philadelphia Electric	
3. Wellman-Lord Sulfite Scrubbing	1976	Dean H. Mitchell No. 11, Gary, IN	115MW	Northern Indiana Public Service Co.	
4. Dry Injection/ Baghouse Filter	1980	Riverside Station No. 6 & 7, Minneapolis, MN	100MW (each)	Northern States Power Co.	7,16
5. Spray Dryer/ Baghouse Filter	1981	North Dakota Coyote Station No. 1, Beulah, ND	440MW	Otter Tail Power Co.	
		Antelope Valley No. 1, Beulah, ND	440MW	Basin Electric Power Cooperative	
6. Aqueous Carbonate	1974	Reid Garder No. 1 & 2, Moapa, NV	125MW (each)	Nevada Power	

Demonstration to Commercial Availability

Once a commercial-scale demonstration facility has been constructed, additional time is required for start-up, operation, and evaluation. In addition, vendors must have time to make adjustments in their operations to produce the new technology. For the electric utility industry, this period has historically ranged from three to eight years.[18-21]

Initial Market Penetration - Commercial Availability to Threshold Acceptance

After a technology has been demonstrated as viable and been made available for commercial selection, the time period required to achieve a significant portion of the market, say, 4% of total capacity in place, can be estimated from the recent performance of the industry. The minimum time required to achieve threshold acceptance would be the sum of times required for planning, design, permitting, and construction of new units after commercial demonstration has been successful.

Nuclear power required 15 years to achieve 4% of electric power generating capacity, and flue gas desulfurization captured this market share after 11 years (see Figures 1 and 2).

The increased regulatory and licensing requirements for new power plants are expected to slow the rate of introduction of even the most attractive new technologies. "No future electric power option is likely to exceed the nuclear power speed record."[22]

Once a technology has achieved threshold acceptance, it can be assumed that the major uncertainties about its performance have been overcome, and that the risk aversion associated with these uncertainties will play a minor role in the selection process from this point on. Several technology substitution models assume that once this degree of market acceptance (2 to 4%) has been attained, further market penetration of the technology can be forecast on the basis of its economic characteristics and those of its competitors.

Economic, Environmental, and Performance Characteristics of New Technologies

Consistent estimates of economic, environmental, and performance characteristics for the various coal-fired technologies are important in the development of market penetration forecasts. Overall consistency is essential for an equitable evaluation of technologies. To achieve this consistency, it is important that identical methods and assumptions be used for each technology.

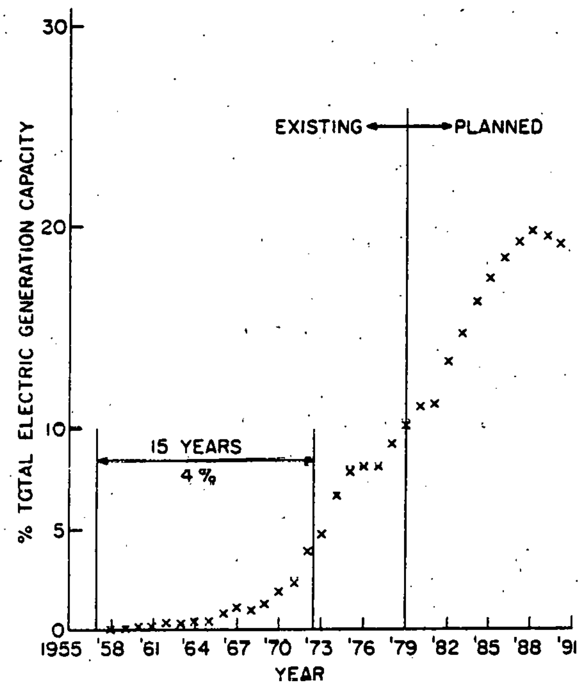


Figure 1
Percent Generating Capacity - Nuclear Power

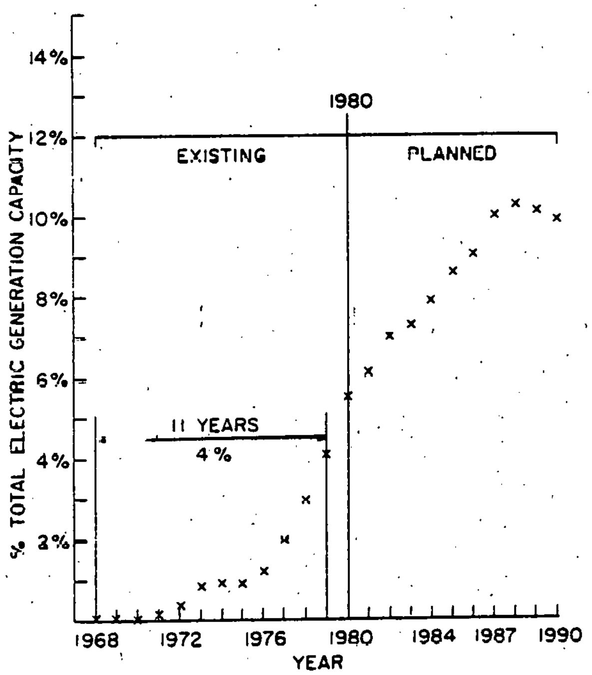


Figure 2
Commercial Operation of New and Retrofit FGD Systems

In estimating these characteristics we must deal with the fact that future events and the available data contain some degree of uncertainty. Understandably, the degree of uncertainty for conventional technologies is less than for those technologies not yet commercialized. In addition, characteristic uncertainties that are common to any one technology should not vary between these technologies (e.g., cost uncertainty involving identical equipment should not vary for different technologies).

The analysis of uncertainty in the estimates of economic, environmental, and performance characteristics of new generating technologies is being performed by Argonne National Laboratory (ANL).

Market Penetration Rates for New Technologies

<u>General Considerations</u> - Once a new technology has achieved threshold acceptance, its rate of market capture (degree of substitution) is limited by many factors, including the inherent inertia of the potential customers, uncertainty over potential regulations,[23] uncertainty over anticipated improvements or remaining anxieties concerning technology performance, and the ability and/or willingness of equipment suppliers to provide the new units.[24] These and other factors lead to the market penetration behavior observed by Fisher and Pry,[25] Peterka,[26] and others: that of the familiar S-shaped growth curve (logistic curve). Numerous attempts have been made to explain this widely observed historical behavior of new technologies displacing existing technologies. Generally it is believed that the shape of the curve reflects the penetration process as proceeding slowly at first as the market overcomes its uncertainties about the new technology's benefits and costs. With time, these uncertainties and risks are overcome by an increased acceptance of the reality of the benefits of the newcomer. Also, utilities whose existing capital stock is relatively old will be prompt to accept the new technologies, while other utilities might anticipate an improvement in performance or a reduction in cost of the new technology and delay acceptance.

Mathematically, parameters (generally costs) characterize the existing technology which are used to obtain the data set with which new competing technologies are then compared in order to establish their rate of market penetration. One element of our approach will be to develop a curve or set of curves which capture the behavioral and other factors which limit the substitution rates for new technologies. These curves will be based on historical data sets from the electic utility industry's evolution (e.g., the substitution of nuclear for fossil steam for power generation). In addition, the Peterka technology substitution model will be used, with appropriate modification, to calculate market penetration based on the economic assessments of the new technologies. Since this method does not capture behavioral aspects, it will serve to provide an optimistic penetration rate based solely on economic criteria; this rate will not be allowed to exceed the best historical substitution rate. (EPRI scientists estimate a ceiling market share of about 8% by 2000 for a new power generation technology achieving commercial-scale demonstration in 1985.)[27]

History of the Adoption of New Technologies by the Utility Industry.

> "Our task of forecasting and assessing technology is difficult. Yet we, ourselves, discount all but the most recent past. (Trend extrapolation does use recent past data.) We talk in texts bravely about historical analogies but when do we use them? In fact, technology forecasters and assessors are shockingly ignorant about the history of technology. Yet history provides the only laboratory or models we have for studying complex interactions between technology, the individual, and society -- after all the essence of TA."[28]

Scenario building - forecasting - requires professional judgment of what constitutes a reasonable future. "Models don't forecast, model builders do," and often the use of a model is simply an elaborate justification for a model builder's preconceptions. Rates of change relative to a base year are central to defining reasonable futures, yet these rates are often specified without adequate justification. In an attempt to better provide indications of reasonable limits for rates of technology acceptance in the electric utility industry, research into the evolution of technology in this sector is currently being conducted, and will be published as a separate paper. It is to be hoped that this work will result in a better understanding of the dynamics of technological change in this sector and provide empirically grounded estimates of likely and maximum rates of change. These estimates will be used in the definition of parameters for use in a technology substitution (rate limiting) model to be used as part of this study. In actual application, this model will be used as a guide, not a rule.

> "It should be emphasized that while historical data provide indications of likely acceptance rates, forecasts must be supplemented by professional judgment of recent (and possibly incipient) trends."[29]

Technology Substitution Models: Strengths and Weaknesses. Central to most technology substitution models are the basic Fisher-Pry hypotheses:

- If a substitute captures a few percent of the market, it will proceed to dominate the market (if no subsequent superior technology is introduced), and
- the rate of substitution is proportional to the remaining market to be captured.

This behavior has been identified in many industries, including segments of the utility industry, and in the absence of "facts about the future" we will assume that it holds for this study.

An important aspect of this method is that it sets limits on the capture of fractional market share, not on the absolute amount of the market taken. This decomposes the substitution process into the calculation of market shares and the estimation of market growth. Thus, total market size is separated from the market share calculation, and scenarios based on different growth rates, retirement rates, etc. can be used to estimate the magnitude of the market potential.

Peterka[30] extends the Fisher-Pry method to a model that considers more than two competing technologies, 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. His assumptions seem basically defensible. These include that no technology can be permanently supported by external capital[31] and that the rate of substitution is positively correlated with profitability of the new technology and negatively influenced by the relative capital investment required to introduce the new technology.[32,33]

The use of these equations as predictive tools is open to criticism. The central weakness is that while the equations can achieve excellent fits to some past observed behavior, their performance in anticipating future developments cannot be verified.

> "Instead of evaluating the past performance of technological forecasting, forecasting theorists generally analyzed past growth trends in the technologies themselves, which usually implied that a given technology would have been forecasted accurately because it is now known that its growth trend followed some identifiable curve or formula. This conclusion makes sense, of course, only if that specific curve or formula (i.e., the appropriate forecasting method) definitely was used by the hypothetical earlier forecasters. It does not provide any real justification for optimism."[34]

In addition, the factors used by such models to explain the past behavior of technologies may not be the important determinants in the future market penetration of other new technologies. "All the precise models of technological substitution considered above can serve as valuable tools in estimating market penetration, but they cannot hope to be all inclusive in considering influences on the market and a product's development."[35] The dominance of social and political factors in the case of nuclear energy, for example, have led to a different market behavior (illustrated by Figure 1) from that predicted by Blackman's technology substitution models (Figure 3). Blackman's model anticipated the market increase for nuclear generating capacity (at the expense of fossil steam) to exhibit the familiar logistic curve behavior; this prediction, while reasonably correct for early years, has been invalidated by the vigorous and effective opposition to nuclear power by various special interest groups.

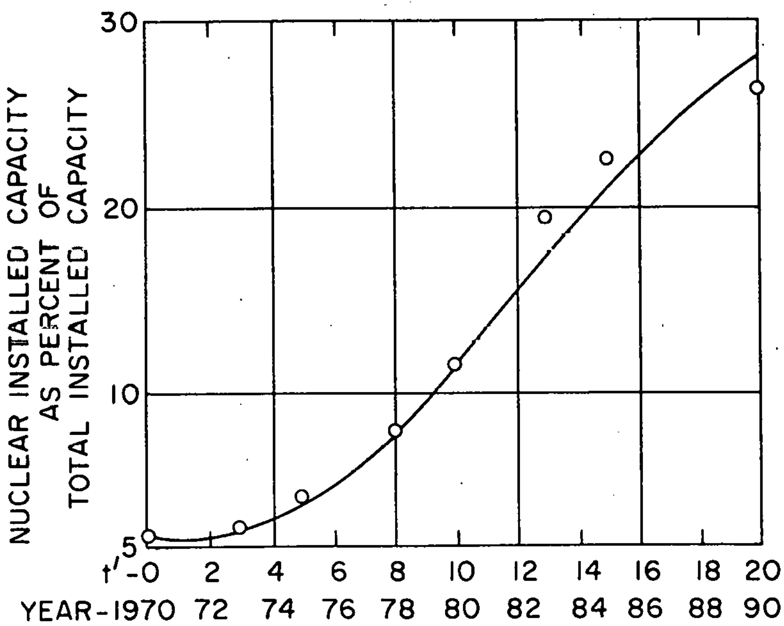


Figure 3
Market Behavior Predicted by Technology Substitution Models

Dynamics of the displacement of steam base/intermediate load generating capacity by nuclear non-breeder-type reactor systems:

°forecast data, ln m/0.28-m = -3.892 + 0.354t', m = market share of nuclear systems, t' = year - 1970, and correlation coefficient = 0.948 -- model production.

Source: Blackman, A.W. Jr., "A Mathematical Model for Trend Forecasts," Technological Forecasting and Social Change, 3, 449, Fig. 9, 1972.

The use of empirically derived technology substitution models as forecasting tools provides a convenient means for defining historically consistent limits on substitution rates for new technologies. They incorporate the diverse behavioral and dynamic aspects of technological evolution in a usable form, thus supplying an historical basis for projecting future changes. When model parameters are derived from historical data (especially for the same industry and for similar prior technological substitutions), they can be used to place reasonable limits on the range of possible futures.

> "... maximum historical rates of change will most probably not be exceeded and rates of change during "normal" times and during the substitution of one technology for another will be quite helpful in scenario building. The economic rationale for a given rate of change need not be well understood to allow application of that rate to an analogous future situation and a new technology with some reasonable confidence in the predicted results."[36]

Market Size: Retirements, Planned Additions to Capacity, and Demand Growth

General Considerations - The utility market for new technologies can be conceptualized as being a function of the retirement of existing capital stock and the total requirement for power generation.

Not all new capacity will be included in the potential market for the new technologies considered in this study. Time frame constraints (technology availability), current utility plans for expansion (Figure 4), appropriateness of new technologies to utility load curves, environmental restrictions, and other considerations will limit the market availability. These considerations can be conveniently incorporated in an energy systems modeling framework.

Total capacity required is a function of demand and reserve margin. Nationally, a reserve margin of 20% is generally considered adequate.[37] Forecasting demand has become a difficult task. From 1954 until 1973, demand rose steadily by 7 to 8% annually.[38] Following the 1973-1974 oil embargo, the growth rate slowed to less than 5% annually, and is likely to be held down by reduced GNP growth, conservation, increased efficiency of use (e.g., heat pumps), and other factors. However, the industrial rate of purchases of electricity could increase as the Powerplant and Industrial Fuel Use Act of 1978 forces out industrial use of oil and gas. Projection has become a new and risky game; even short-term demand growth is now difficult to predict. The National Electric Reliability council predicted that the 1979 summer peak load would grow by 7%, the Edison Electric Institute (EEI) predicted 4%, and the EEI official survey found actual growth to be 0.5%.[39]

An extended time frame must be considered to allow the technologies in this study to achieve significant market share. This introduces a large degree of uncertainty into the demand estimates for electric power, which in turn makes market size highly uncertain.

"In essence, a forecast must account for the characteristics of a trend from the date the forecast is made to the target date. The longer the forecast period (i.e., the more remote the target date from the forecast date), the greater the chances any of the conditions affecting the trend may change. In other words, the certainty of prevailing conditions declines as the length of the forecast period increases. It is plausible, therefore, that more remote forecasts are intrinsically more difficult, and in general will be made with less accuracy."[40]

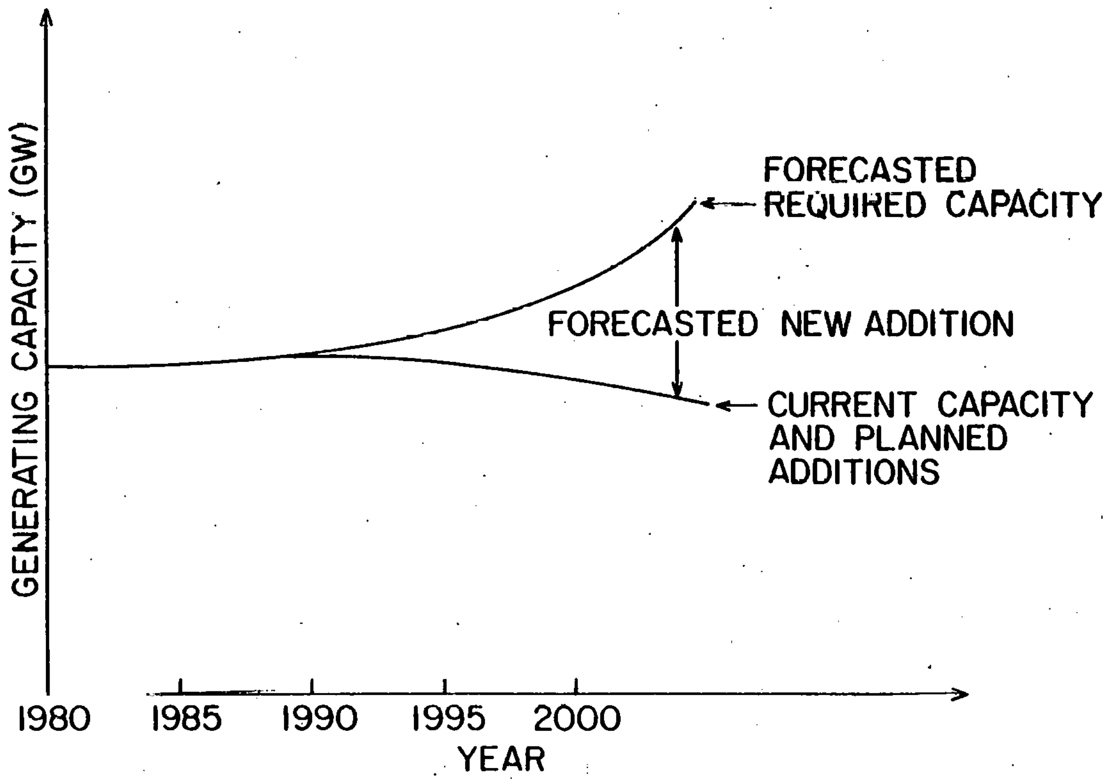


Figure 4
Illustrated Market Size

This point is illustrated in Figure 5.

These forecasts were made in a period of relative energy security. In more volatile periods, with the energy system undergoing traumatic change, greater errors are to be expected. There can be little doubt that we are entering an era of such volatility.

Existing Capital Stock, Planned Additions, and Retirements. Existing capital stock, its vintages, and planned additions to capacity will be defined on the basis of data contained in the Energy Information Administration's Generating Unit Reference File (GURF). Retirement rates by equipment type, size, fuel, and region will be estimated using distributions to be derived from time series data contained in GURF, the latest Economic Regulatory Administration's Additions to Generating Capacity for the Contiguous United States, and other data bases identified in Survey of Electric Utility Data Sources with Application to R&D Planning. Relevant data will be extracted from several data bases and organized into a convenient, manageable format for statistical analysis of retirement rates and technology acceptance. Data on current capital stock and planned additions and retirements will also be made readily available to provide suitable foundations for scenario building at various levels of geographic disaggregation. It is anticipated that this data base will be updated annually as new information becomes available.

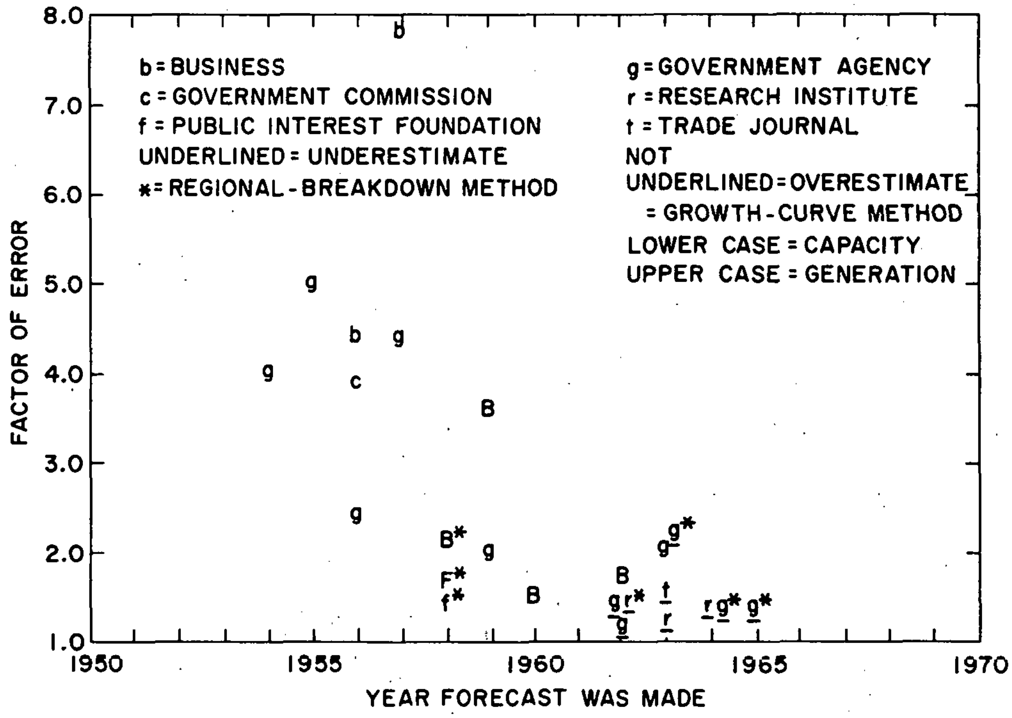


Figure 5
Range of Forecast Due to Extended Timeframe
(Errors of Ten-Year Nuclear Energy Forecasts)

Source: Ascher, W. Forecating, An appraisal for Policy-Makers and Planners, John Hopkins University Press, Baltimore, MD, 1978, p. 173, Fig. 7.2.

Demand Growth. Estimation of the probability distribution for future electrical energy demand is an integral part of the Electrical Utility Stochastic Model. Demand estimation is discussed in detail in Section III of this report.

III. THE ELECTRIC UTILITY STOCHASTIC MODEL

Introduction

This section outlines the principles of a simple overall methodology for market forecasting with the objective of providing guidance in the allocation of RD&D resources. Although it specifically discusses the electrical utility sector the reasoning may be applied generally.

In the last seven years literally hundreds of analyses have been conducted in the energy field and much of the interest has centered upon techno-economic models. These have tended to become increasingly complex, commonly involving econometric, input/output and linear programming models in a closed-loop system, often with the interconnections being made manually. The considerable detail involved has required a large data base for the deterministic evaluation of energy interests across a range of scenarios.

It has gradually become apparent that the considerable uncertainties associated with much of the data, e.g., oil price projections, elasticities, social concerns, environmental impacts, etc., lead to a wide range of outcomes and a continual updating of any set of likely future projections.

Given this very valuable hindsight, it is therefore pertinent to examine the adequacy of employing simple stochastic models to address problems which do not require a detailed perception of the energy system. This has the advantage of greatly reducing the data acquisition load, while at the same time simplifying the problem of selection by the straightforward acceptance of a range of expert opinion as a data set, inclusive of its variance, for any given parameter.

It is therefore proposed that an approach be adopted which explicitly reveals the range of uncertainty that exists and allows the policy maker to interject his own preference for risk taking into the analytical outcome. This is most readily accomplished by accepting the probabilistic state of energy affairs and utilizing it to provide the results through stochastic inference and analysis. It is implicit in such an approach that the variance of the data will set limits to the time horizon beyond which it will not be possible to draw any intelligible conclusions.

Uncertainty and Risk in the Assessment of New Technologies

The overall objective of many system analysis programs is to provide an analytical basis for the assessment of technologies in support of the formulation of a strategy for research and development budgeting.

In order to assess any number of new technologies, it is first necessary to decide upon some common unit of measure of their quality. If such qualities can be quantified, it is then possible to rank the technologies in order of preference and to make choices among alternatives as required.

The qualities of RD&D projects cannot be ascertained with complete confidence. Estimates of future qualities often become more difficult as the time horizon recedes. Any appraisal of new technologies should, therefore, take this into account in a logical and consistent way. The analyst also needs to convey the magnitude of these uncertainties to the decision maker so that the latter can apply his own preferences with regard to his propensity for risk taking in the evaluation of projects.

Uncertainty and Risk - The provision of information as single-figure estimates, while attractive in its simplicity, can be very misleading. The advantage of discussing technological evaluations in terms of uncertainty and risk is the increased information which usually carries with it an implied reduction of risk - in this case, a reduction of the risk of the policy maker making the wrong decision. Alternatively, he can evaluate various outcomes against the odds of failing to meet the objective and can, therefore, include his own conception of the project's likelihood of success in the decision making process.

For example, it is one thing for a decision maker to have to choose between two policies, given single figure estimates that 'A' will provide a higher return that 'B'. It is quite another thing if additional information indicates that there is a real possibility of 'A' failing to provide any return at all, while such an outcome for 'B' is very unlikely indeed.

It is often forgotten that utilizing data obtained from a deterministic assessment implies that decisions may be taken which are based upon outcomes having odds against their being achieved. For example, many models are largely multiplicative by nature and a stochastic analysis of the associated distributions will reveal an approximately log-normally distributed solution. Because of its inherent skewness the mean, or expected outcome, may well have less than a 50% probability of being bettered.

This is not in accord with the normally observed risk preferences of most institutionalized policy makers who prefer to work with a 3 or 4 to 1 odd-on chance of success in decision making.

Quantifying Uncertainty and Risk - If we are to make comparative evaluations on an intertechnology basis, it is essential that they be carried out in a consistent manner. The literary terms used above, such as 'real possibility' and 'very unlikely,' are too vague. To assess uncertainty and risk in quantitative terms, data must be provided and processed in a manner which more clearly defines the methods and assumptions that may have been employed. This is done by introducing the concept of probability.

Probability assessments ratings may be either objective or subjective, or a mixture of the two. If objective, they usually refer to the frequency of occurrence of an event. When subjective, they express the degree of belief that one feels that some particular event will occur. When we are concerned with the probability of future events occurring, these ratings must be subjective, because we are unable to carry out experiments to determine any sort of frequency pattern. This does not preclude subjective probability ratings being based upon hard evidence, however, but analytical judgment is always essential to making any estimate of possible future outcomes based upon past occurrences.

The techniques of obtaining such assessments are in the domain of the practicing psychologist, and a wide range of literature is available for reference. The conclusions of L. Phillip's[41] presentation to the 1979 International Energy Systems Analysis Conference in Dublin summarizes basic practice:

> "As said previously, our concern should be on getting right the circumstances so that it will be possible to make precise, reliable, accurate assessments of probability. Getting these right should at least include the following items (for practical procedures, see Spetzler and Stael von Holstein, 1975):[42]
>
> 1. If the assessor is unfamiliar with probabilistic thinking, some brief familiarization using reference gambles should be given. If the assessor continues to experience great difficulty in making probability judgments, the assessment should be abandoned and another assessor sought.
>
> 2. Only experts in the substantive area should be asked for assessments. This is particularly important where probabilities for complex events are needed.
>
> 3. Whenever possible, complex events should be broken down into simple events, and assessments given only for the latter. This includes using Bayes' theorem, not unaided judgment, to aggregate data.
>
> 4. Assessment procedures should always exploit coherence. More assessments should be obtained than are needed so that coherence can be checked. It may even be necessary to introduce extra events, to "extend the conversation," thus ensuring that at least some of the probabilities will be redundant.
>
> 5. The assessment process should be iterative, not "once-off." Incoherence should be brought to the attention of the assessor, who can then work toward providing a coherent set of probabilities.

6. Difficulties in obtaining a probability assessment are frequently a sign that the problem is structured differently from the assessor's internal view of the problem. Restructuring so as to provide more direct access to the assessor's experience may solve the problem."

Model Structure and Operation

A Market Substitution Model - The substitution of a new technology for an old one is an evolutionary process. Techniques which have been in use for decades are unlikely to have room for further refinement. On the other hand, with new innovations there are many opportunities for major improvements which can lead to higher productivity, greater uniformity, and the production of devices which are not possible with current means.

If strong commercial reasons exist for the introduction and development of a new technique, a substitution process is suggested, wherein the new technology allows the user to perform an existing function and to meet an ongoing need more efficiently than before. The new product has, in effect, a greater perceived value to the consumer than the old one.

Examples abound; from the introduction of stoneware (1400 B.C.) to the introduction of the handheld calculator of today. Despite such a long history of technological innovation, it was only in 1971 that J.C. Fisher and R.H. Pry[43] proposed a substitution model to describe the phenomena. Their paper provided considerable empirical evidence to substantiate their hypotheses, which have also been widely verified.

This model is limited to substitution between two technologies, the new replacing the old. In 1975 C. Marchetti[44] proposed an enhancement to Fisher and Pry's work to account for substitution between any number of technologies, although his main interest lay in the field of energy analysis. This was, again, a primarily empirical dissertation.

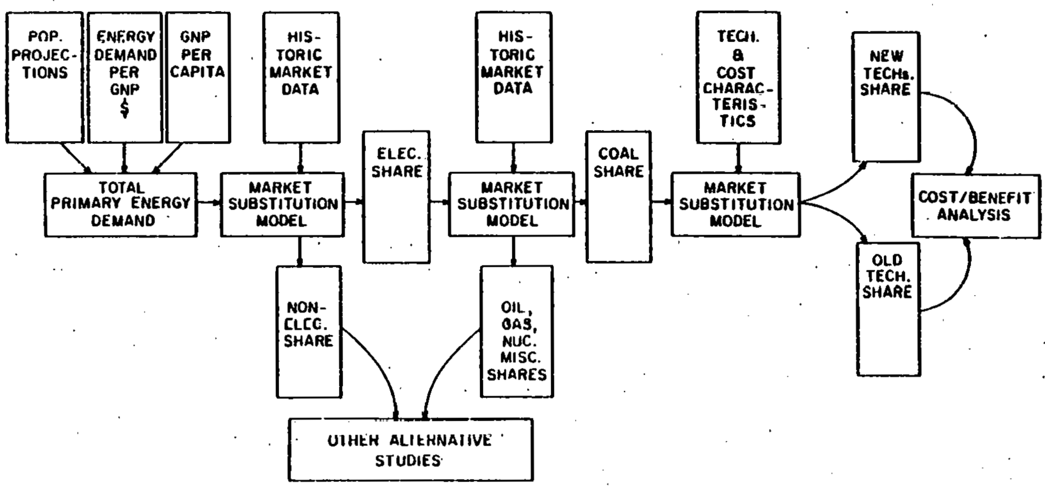
Most recently V. Peterka[45] has sought to provide a mathematical underpinning to this developing methodology by an in-depth and detailed paper published by the International Institute for Applied Systems Analysis (IIASA) in November 1977. Although the driving forces involved are open to interpretation, as evidenced by the parameters and assumptions given, they do provide a very convenient tool for market analysis.

The Model Philosophy - Figure 6 shows a block-schematic diagram of the overall model which is primarily stochastic and exploratory in format wherein each parameter is described by an independent probability density function (PDF). There are two different aspects of its use in any assessment:

1. The absolute computation of the driving function which, in the version given, is the total primary energy demand; and

2. the proportional computation at decreasing levels of aggregation down to the point of specific interest.

For any quantitative analysis, the driving function will require definition in the form of a PDF. This may be most simply achieved by the deduction of an appropriate distribution through logical reasoning or by expert concensus. It has, however, been argued earlier in this paper that complex events should be broken down into simple events and assessments given only for the latter.



Note: All the parameters are probability distributions.

Figure 6
The Stochastic Model

It is therefore proposed that the total primary energy demand is decomposed into three time-dependent distributions: the population, the GNP per capita, and the primary energy required to generate each dollar of GNP.

The balance of the model, dealing with the market shares at various levels of disaggregation, may be dealt with by similar decomposition methods. For the sake of brevity in this initial discussion, these detailed comments will be reserved for a separate paper.

Corroboration of the Model's Projection of Energy Demand - The derived energy demand which results from the combination of the three projections of population etc. cannot, of course, be verified by any physical parallel. It is, however, possible to examine the likelihood of the result being a member of a set of professional estimates, arrived at by the use of other methodologies, and so corroborate the outcome by comparison with expert opinion.

There are a reasonable number of deterministic projections across a range of scenarios for the U.S. consumption of primary energy in 2000. These data have been examined in some depth and compared with the results obtained from the stochastic model. The detailed method of working and the conclusions of the tests used are given in Appendix A.

The objective outcome infers that the projected energy demand derived from the stochastic model is a similar distribution of expectation to that given by expert opinion, and that these data are log-normally distributed, as shown in Figure 7.

Corroboration of the Model's Projection of Electricity Generation - The case for substitution by electricity for other end-use energy forms cannot be simply accounted for on a cost comparison basis alone. Even when due allowance is made for the improved efficiencies of electrical end-use devices and the pervasiveness of the electrical grid system, it is not unusual to find that the unit energy cost of electricity is greater than its competitor's, even in situations where perfect substitution is applicable. Electricity also has the characteristic of being a substituting technology in allowing the user to meet the needs satisfied by all other energy forms.

In Peterka's original concept the basic market penetration coefficient of specific production costs was evaluated by using the first and last data points for a given technology in order to establish its slope to a logarithmic base. These points encompass a historical data set which was utilized to establish the parameters of the distribution for this slope in order to evaluate the market characteristics on a stochastic basis. As such it will include all the market forces, both economic and otherwise, which give rise to an increasing electrical demand. Based upon the historic data set, 1947-1976, Figure 8 displays both the historical match and the future projections generated by the market substitution model.

The output of this section of the model will be a proportional market share of electrical generation together with the non-electrical demand, both in primary energy terms. If the electrical probability distribution is applied to PDF's for primary energy demand and transformation efficiency, a composite distribution will be created in absolute terms of kilowatt hours generated.

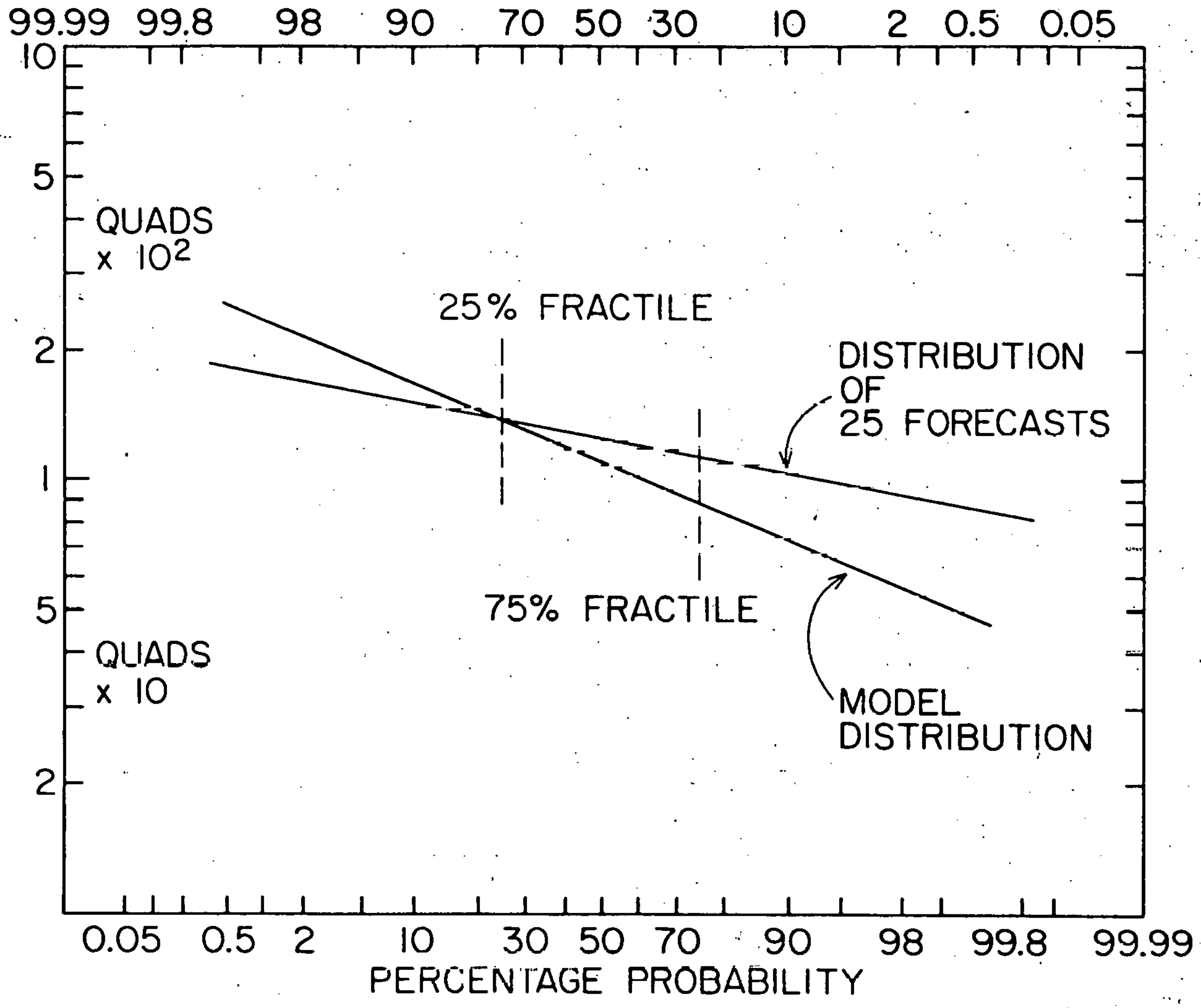


Figure 7
Comparison Between the Stochastic Model and 25 Other Forecasts
Year 2000 - Total Primary Energy Demand

This result was examined in a manner analogous to that employed in corroborating the energy demand using 32 expert projections for the year 2000. The list of sources for these data are included in Appendix A (Table A-6) and the reference section of this report.

The same objective outcome was arrived at which infers that the projected electrical generation derived from the stochastic model is a similar distribution of expectation to that given by expert opinion, and that those data are log-normally distributed, as shown in Figure 9.

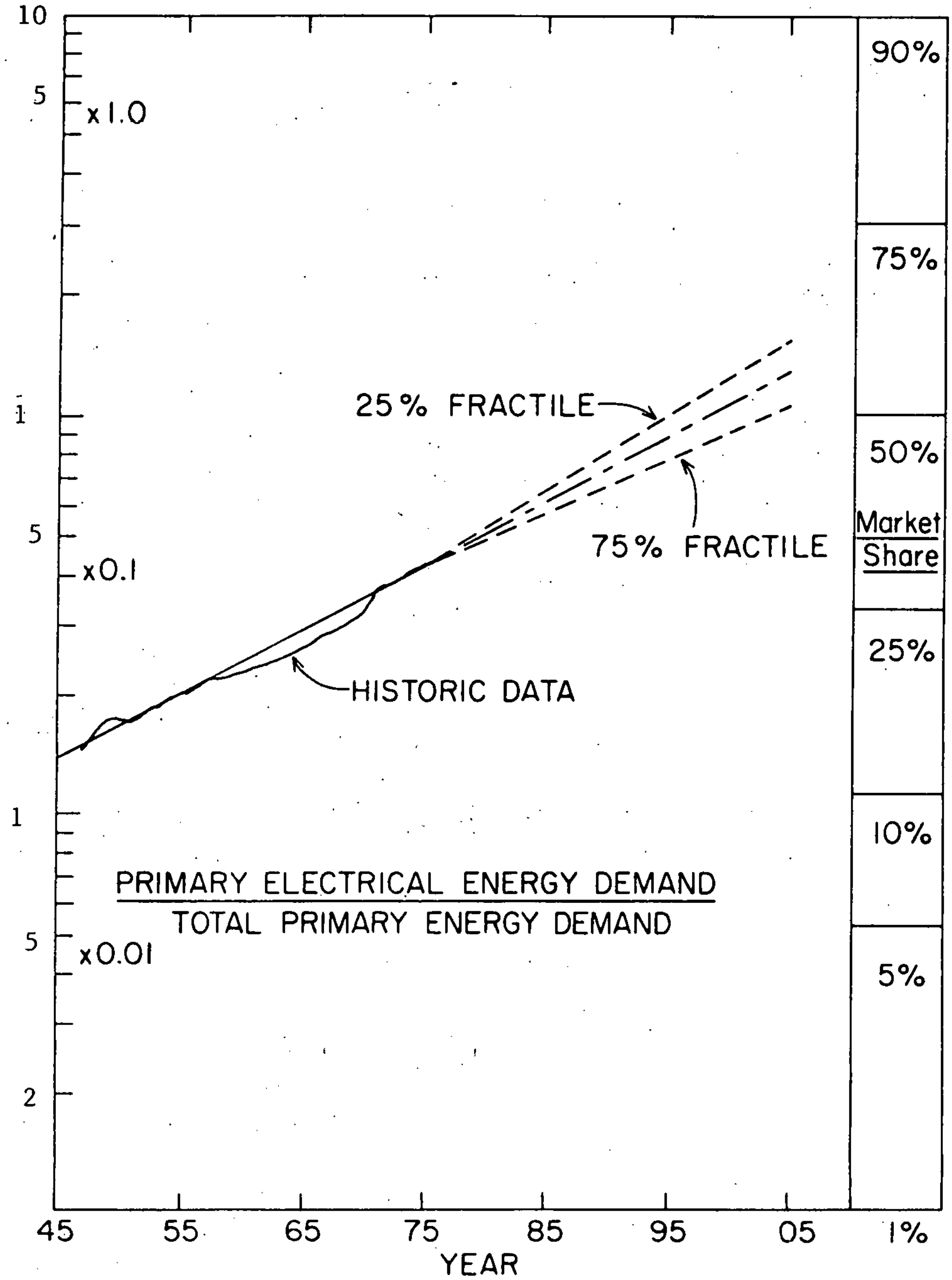


Figure 8
Percent of Total Energy Consumed by Electrical Utilities
from the Market Substitution Model

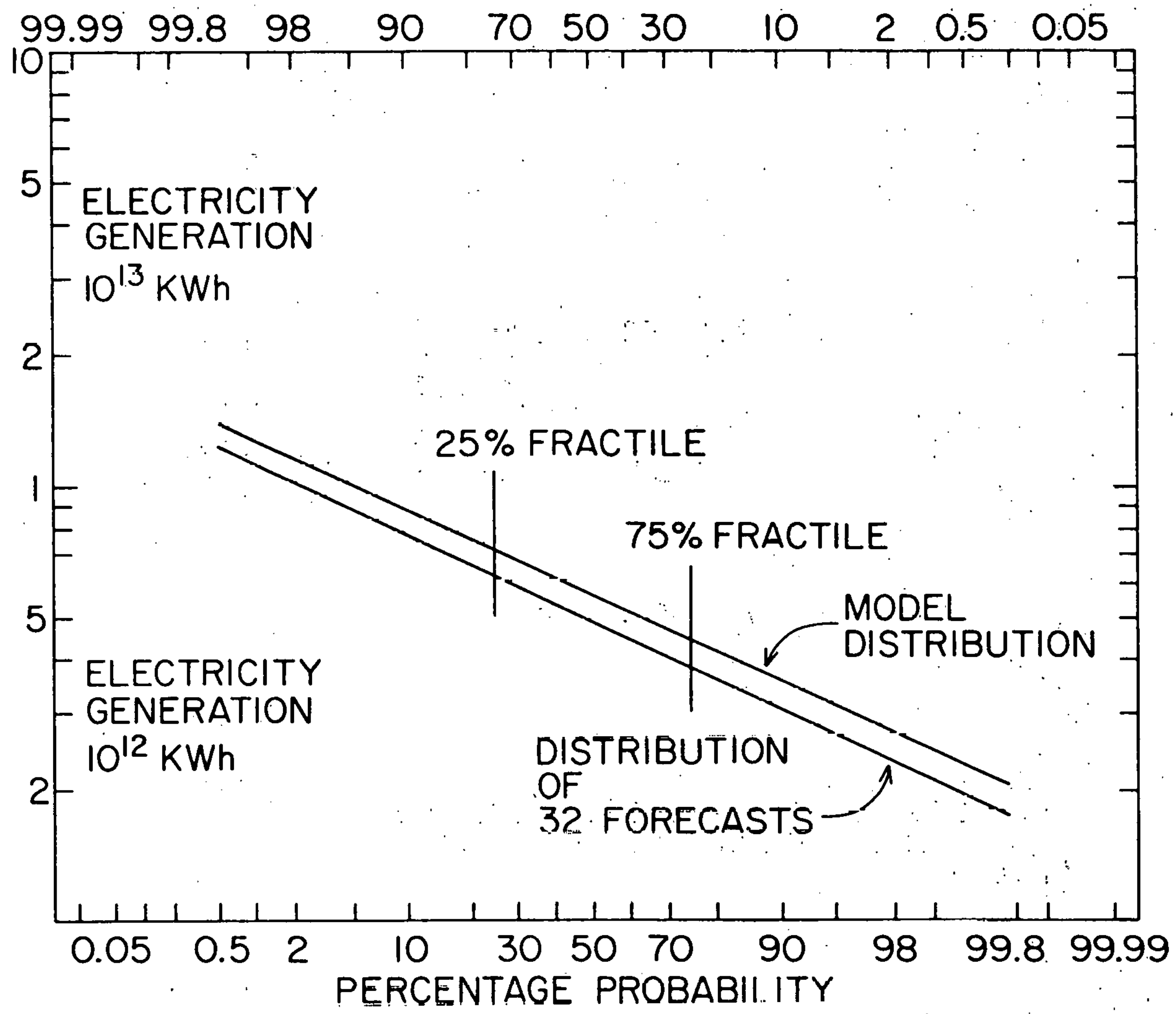


Figure 9
Comparison Between the Stochastic Model and 32 Other Forecasts
Year 2000 - Electrical Generation

Market Penetration of New Technologies

Generation by Fuel Type and by Specific Technologies - For a more detailed examination of the electrical conversion industry, the technologies are classified through a two-step process:

1. electrical generation by fuel type, and
2. electrical generation by specific fuel technologies.

From the same market substitution model previously discussed in developing the electrical share, the stochastic market for a specific electrical generating technology (E) is given at time 't':

$$\hat{E}_{ij} = \hat{E} \times \hat{F}_i \times \hat{P}_j \qquad \text{if } \sum_{i=1}^{m} F_i = 1; \ \sum_{j=1}^{n} P_j = 1,$$

where

$$F_i = f(M_{1i}, M_{2i}, M_{3i}); \ P_j = f(M_{1j}, M_{2j}, M_{3j})$$

and

E = electricity generation as previously described,
F_i = fraction of total electrical generation produced from the i^{th} fuel,
P_j = fraction of electrical generation derived from the i^{th} fuel by the application of the j^{th} process,
m = number of fuels generating electricity,
n = number of processes utilizing a specific fuel,
$M_{1j}-M_{3j}$ = the first three moments of the probability distribution for the fractional share of electricity generated by the i^{th} fuel,
$M_{1j}-M_{3j}$ = the first three moments of the probability distribution for the fractional share of electricity generated by the j^{th} process using the i^{th} fuel,
E_{ij} = the electricity generated by the i^{th} fuel and the j^{th} process,
$\wedge$ = denotes a probability distribution.

The series of quantities describing a frequency or probability distribution are known as 'moments,' of which the first three are the expected or mean value, the variance, and the coefficient of skewness.

Assessing the Distributions of Market Penetration - The market penetration model based upon the Fisher-Pry - Peterka reasoning will, a priori, generate the moments of the appropriate distributions of future market shares from the historical data set. An interim step in this process is the evaluation of the slopes, to a log-base, of these shares, any one of which may be used as the reference technology to which the remainder are compared.

If, however, there is good reason to believe that these products of past events cannot be projected into the future, then it becomes necessary to evaluate them from an alternative standpoint. An obvious example of extrapolation failure is a new technology without historical precedent. Other causes might be legislative changes which prohibit the expansion of an existing technology, or force its decline; social or environmental concerns which can only be met by significant cost increases; and so on.

In many cases there will be considerable uncertainty regarding the impact of change and, in this sense, the stochastic aspects of this modeling approach can be helpful. Since the historically dependent slopes of each existing technology will be available, a stable technology may be selected as the reference case for comparison purposes with other technologies whose future slopes are estimated on the basis of their technological, economic, and social characteristics. Since this judgment will be in the form of establishing a distribution of possible values, any uncertainty, however great, may be readily included.

The input data will be gathered in a form which will be based upon the assumption that the given values are drawn from a binormal distribution. This is a pragmatic simplification because of the inherent difficulty in obtaining detailed distributions of subjective beliefs. In practice, however, the exact shape of the input distributions is of second-order importance, although sensitivity tests will be carried out to demonstrate this.

The model will not provide any insights with regard to operation of the national energy system. For example, no definitive equations are employed to determine the link between the productivity of the nation and its energy demand. It is simply an observed relationship which has associated with it some mean, variance, and coefficient of skewness based upon the historical data available. The projection of these data into the future, with or without modification, is a matter of analytical judgment.

The technological substitution methodology requires that the parameters of new and largely unknown technologies be evaluated through the use of expert opinion. Experience has shown that human judgment regarding beliefs concerning uncertain events can suffer from severe and systematic errors. It is therefore necessary to collate the data through a process of decomposition and consistency checks to reduce such sources of error as far as possible.

IV. SUMMARY

The approach to market penetration estimation presented in this paper has numerous attractive features lacking in available alernative methodologies, chiefly:

- Explicit consideration of the uncertainty inherent in projections of energy demand and technology characterizations.
- Limited data and computational requirements.
- Extreme flexibility and ease of use.

It is hoped that these positive features will enable this method to make a strong contribution to the assessment of the potential role of technologies currently under development and to the identification of the most promising areas for further research.

Market penetration estimation is, in essence, a prediction of the future based on what is known, or thought to be known, today. Precise estimates, especially for extended time frames, are virtually certain to be wrong. The method presented in this paper is an attempt to define and integrate, in an intelligible manner, the information currently available about the possible future of new technologies and to set ranges of confidence to the resulting market penetration estimates. The flexibility of the method allows adjustments to be easily made for alternative assumptions and as more knowledge is gained in the evolution of the energy system.

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APPENDIX A

Introduction

Energy analysis of some future event involves data which exhibit scatter introduced by subjective judgment. To deal with this situation in a way which incorporates this variability within the analysis requires that the uncertainty is dealt with in explicitly probabilistic terms. According to Benjamin and Cornell[6]:

> "When the element of uncertainty, owing to natural variation or incomplete professional knowledge is to be considered explicitly, the models derived are probabilistic and subject to analysis by the rule of probability theory."

This appendix examines an empirical data set of expert opinion regarding a specific future event. By the use of descriptive statistics it details comparisons with these data and the results obtained from a simple probabilistic model which was used to consider the same event.

Expert Opinion of a Future Event

Over the past few years a number of projections have been made regarding the possible primary energy demand for the U.S.A. in the year 2000. The application of any statistical inference procedures to these data would assume that they represent a random sample from some population, that is, that they are statistically independent and share a common distribution whose characteristics are of interest.

The assumption of independence seems questionable; anyone building a forecasting model has access to the earlier published results. That the predictions are drawn from a common population also is debatable. Each analyst constructs a different model, with different equations, constraints, and variables, adjusted during development to conform with his preconceptions. There are, however, some common elements. All models are based on approximately the same historical data. All models must include some projections about population growth and growth of GNP, for example, and these are based on regressions on the same data. So in some sense the projections represent a sample (albeit not random) of solutions of systems of equations chosen by experts, with coefficients based on common historical data, and constraints added, again, by experts.

It is, therefore, reasonable to examine this empirical distribution in order to test the validity of any hypothesis regarding its functional shape. On one hand this may be dealt with by comparing the higher sample moments with the corresponding moments of some given mathematical function. Alternatively their overall "shapes" may be compared graphically through the use of cumulative distribution functions (CDF).

Intuitively, the latter course of action appears preferable because it brings more of the information contained in the sample into the comparison. It also counters the criticism that many models may have nearly identical second- or third-order moments, but still have markedly different shapes.[46]

The Model Verification of Expert Opinion

Table A-1 details the 25 projections that were made for U.S. energy consumption in the year 2000. The datam sources are given at the end of the main body of the report.

An examination of the data leads to the following hypotheses and test procedure.

1. The null hypothesis, H_0, is that the empirical data of these expert opinions are log-normally distributed.

2. The alternative hypothesis, H_1, is that the distribution of these data are other than specified.

3. The statistical test selected is the Kolmogrov-Smirnov goodness-of-fit test at a significance level of $\alpha = 0.05$.

The choice of this test procedure was based upon the following:

1. The comparison is made on all the data in an unaltered form.

2. The test is an exact test for all sample sizes.

3. The model selected for comparison may be hypothesized wholly independently of the data.

4. The results may be graphically displayed.

Table A-1
Primary Energy Demand for the U.S. in 2000

Forecaster	Source*	Quads
Brookhaven National Laboratory/ Dale Jorgenson Associates (BNL/DJA)	1	117
Alan S. Manne's ETA-MACRO	1	121
FOSSIL2 (1978) - Department of Energy	1	119
LEAP (Long-range Energy Analysis Package) - Department of Energy	1	122
Stanford University's PILOT	1	129
Brookhaven National Laboratory: Report	2	107
Sourcebook for Energy Assessment (BNL)	3	137
Private Communication	4	114
Edison Electric Insitute	5	186
Edison Electric Institute	5	161
Edison Electric Institute	5	110
Exxon Company (1977)	6	141
Exxon Company (1978)	7	105
FOSSIL2 - BHS (Balance High Supply Scenario)	8	108
FOSSIL2 - BE (Best Estimate Scenario)	8	101
MARKAL PS-1	9	111
MARKAL SP-4/1.0	9	115
Resources for the Future	10	119
Resources for the Future	10	98
WAES (Workshop on Alternative Energy Strategies) C1	11	125
WAES (Workshop on Alternative Energy Strategies) C2	11	132
WAES (Workshop on Alternative Energy Strategies) D7	11	115
WAES (Workshop on Alternative Energy Strategies) D8	11	120
WEC (World Energy Conference)	12	110
WEC (World Energy Conference)	12	149

*See page 47.

The Calculation of the Test Statistic

The value of the second test statistic, D_2, may be more readily desk computed than D_1. It concentrates upon the deviations between the hypothesized CDF Fx(x) and the observed cumulative histogram:

$$F^*(x_i) = 1/n,$$

in which x_i is the i^{th} largest observed value in the random sample of size n. The D_2 statistic is given by:

$$D_2 = \max_{i}^{n} [\,|F^*(x_i) - Fx(x_i)|\,]$$

$$= \max_{i}^{n} [\,|i/n - Fx(x_i)|\,]$$

The resulting calculations are given in Table A-2 and this results in a D_2 statistic of 0.183. As a cross-check, the Kolmogorov-Smirnov special purpose routine NKS1, from the IMSL program suite,[47] was utilized and from the same set of data gave a D_2 statistic of 0.177.

Table A-2
Determination of the Test Statistic D_2

A	B	C^2	D	E^1	F^1	G
i	i/n	x_i^2	$\ln(x_i)$	$F_u\left(\frac{\lvert x_i - \bar{x}\rvert}{\sigma}\right)$	$\int f(x_i)$	$\lvert B-F\rvert$
14	0.56	119	4.779	0.168	0.433	0.127
15	0.60	120	4.787	0.109	0.453	0.147
16	0.64	121	4.796	0.051	0.480	0.160
17	0.68	122	4.804	0.007	0.497	**0.183**
18	0.72	125	4.828	0.177	0.570	0.150
19	0.76	129	4.860	0.398	0.655	0.105
20	0.80	132	4.883	0.560	0.712	0.088

Note: 1) After transformation by logs.
2) The empirical data arranged in an ascending order of magnitude.

Table A-3 provided the critical statistic for this test. Since D_2 is less than the critical value for a sample size of 25, it is concluded that the null hypothesis should be accepted.

A more robust test may be applied through the use of W statistic, as proposed by Shapiro and Wilk.[48] It has the drawback of not being so readily tabulated and is, therefore, not detailed in this appendix. It has, however, been applied to the null hypothesis and the results are above the 5% point of the null distribution.

Table A-3
Critical Statistic for the Kolmogorov-Smirnov Goodness-of-Fit Test (D2)

Sample Size	α = 0.10	α = 0.05	α = 0.01
5	0.51	0.56	0.67
10	0.37	0.41	0.49
15	0.30	0.34	0.40
20	0.26	0.29	0.35
25	0.24	0.26	0.32
30	0.22	0.24	0.29
40	0.19	0.21	0.25

The Graphical Presentation

This form of presentation is best carried out using probability paper which allows the reader to visualize the effects of the statistical uncertainty on the distribution as a whole. Figure A-1 shows the empirical data as a CDF, the boundary lines of the D2 test statistic (0.18), and the boundaries of the acceptance region for an alpha value of 0.05 (D2 = 0.256).

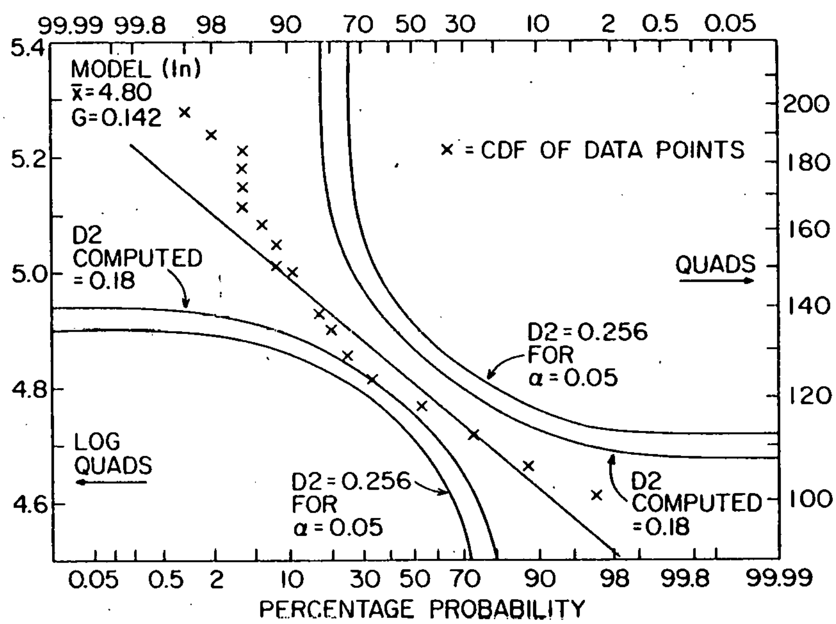

Figure A-1
Projection Data for U.S. Primary Energy Demand in 2000 and Model Kolmogorov-Smirnov Test
x = CDF of data points

The Stochastic Model

It is proposed that a simple stochastic model, based upon readily available data, be used to generate a set of probability distributions, at five-year intervals, which describe a projected range of total primary energy demands in the U.S.A. The outcome for the year 2000 will then be used as a benchmark for the purpose of comparison with the empirical data set of expert opinion already discussed.

The three basic data sets which are utilized by the model are:

1. The population projections for the period 1980-2005.
2. The historical data set for GNP per capita, 1900-1975.
3. The energy demand associated with GNP as a ratio for the period 1920-1975.

The derivation of probability distributions, from these data, is discussed under the appropriate subheadings as follows:

The Population Projections

The five-yearly projections of future U.S. population levels issued by the Bureau of the Census[49] gives three major projection series which form the basis of the estimating procedure given here.

In discussing the selection of any particular series, they say:

> "Population projections are "correct" by definition (except for computational errors) because they indicate the population that would result if the base date population is correct and if the underlying assumptions should turn out to be correct. Thus without an evaluation of the assumptions, there is no basis for choosing among alternative projections."

Although a desk study of these data reveals that it is impractical to evaluate these assumptions on a probability basis, the implied equality of occurrence is unsatisfactory for the following reasons:

1. The use of ignorance as a basis for selecting a rectangular distribution is unsound since it can lead to incompatible results (Bertrand's paradox).[50,51]

2. The sequential elements of any one series obviously violates the concept of a set of independent distributions.

In order to meet these objections, whilst still retaining a simplistic model, a set of population growth rates for each series was determined from the given population projections. These were then subjectively assumed to be members of some unspecified distribution whose shape was determined by computer analysis.[52] These results are as shown in Figure A-2 and the population (P) is given in time t:

$$P_t = P_{t=0} \times \prod_{i=0}^{n} (1 + \hat{g}_i)^5,$$

where g_i is the annual growth rate in the i^{th} five-year period, and ^ denotes a probability distribution.

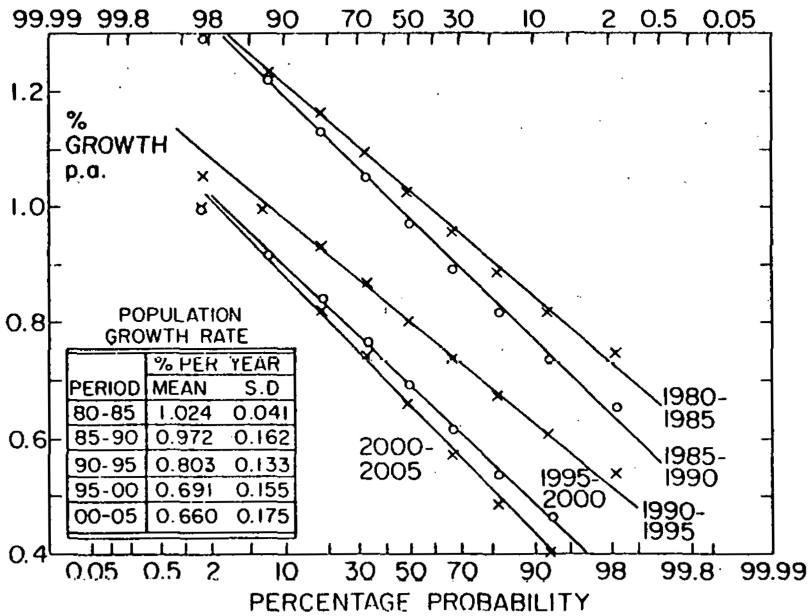

Figure A-2
Generated CDF's of U.S. Population Growth Rates
1980 - 2005 in Five-Year Steps

This is essentially a simple Markov chain process wherein the growth rates are independent samples at each time period applied to the entire history of the population trend.

The GNP/Capita Projections

These data were extracted from reference 53 and covered the period 1900–1975 in five-year steps. In a manner similar to the one above, a normal distribution of growth rates was derived from this historical data set and used, unchanged, for sampling future GNP/capita values. The rationale for this subjective judgment is based upon the fact that this period saw major economic booms and depressions, two world wars, and sundry lesser perturbations to the social system. It is, therefore, argued that the long-term mean and the variance of the growth rate will remain substantially unchanged by future events.

The values used in the stochastic model were:

Mean: 1.8% per year   Std. Dev.: 2.62%

and the GNP/capita (Y) is given at time t:

$$\hat{Y}_t = Y_{t=0} \times (1 + \hat{g}_i)^t,$$

where g_i is the annual growth rate in the i^{th} five-year period, and ^ denotes a probability distribution.

The Ratio of Primary Energy Demand to GNP

From the same source[53] and using methods similar to those above, the parameters derived from this historical data set for the annual rate of change are:

Mean: −0.5% per year   Std. Dev.: 1.5%

It was noted, however, that over the last two decades the mean growth rate was approximately zero, whilst at the same time it must be recognized that current conservation efforts will begin to be apparent from now on. The subjective judgment reflecting these effects are given in the following table.

Table A-4
Rate of Annual Change in
Primary Energy Demand/GNP $

Period	% Rate per Year	
	Mean	S.D.
80-85	-0.5	1.5
85-90	-0.75	1.5
90-95	-1.0	1.5
95-100	-0.5	1.5
00-05	0.0	1.5

These tabulated values are used in the stochastic model and the ratio (R) is given at time t:

$$\hat{R}_t = R_{t=0} \times \prod_{i=0}^{n} (1 + \hat{g}_i)^5$$

where g_i is the annual growth rate in the i^{th} period, and ^ denotes a probability distribution.

The Primary Energy Supply

On the assumption that the energy system will be in a state of long-term equilibrium, the final end-use demand will be matched by the total primary energy supply. This may be estimated at some future time from the knowledge of current values and the three growth rates already discussed. The total primary energy supply (E) is then given at time t by:

$$\hat{E}_t = E_{t=0} \times \prod_{i=0}^{t/5} [(1 + \hat{g}_{pi})(1 + \hat{g}_{ri})] \times (1 + \hat{g}_y)^t,$$

where

- t = the time horizon of the analysis,
- g_{pi} = the population growth rate for the i^{th} period,
- g_{ri} = the primary energy demand/GNP ratio for the i^{th} period,
- g_y = the GNP per capita growth rate, and
- ^ = denotes a probability distribution.

A Comparison of the Results

The stochastic simulation model was computed over the period 1975-2005, and the results were derived at five-yearly intervals.

From the foregoing description of the model, it will be apparent that the results are the outcome of a multiplicative process. If

$$Z = \prod_{i}^{n} Y_i ,$$

and the Y_i are independent random variables whose distributions have finite means and variances, then Z tends to be log-normally distributed. This fact may be observed in Figure A-3 which shows the model output for 2000.

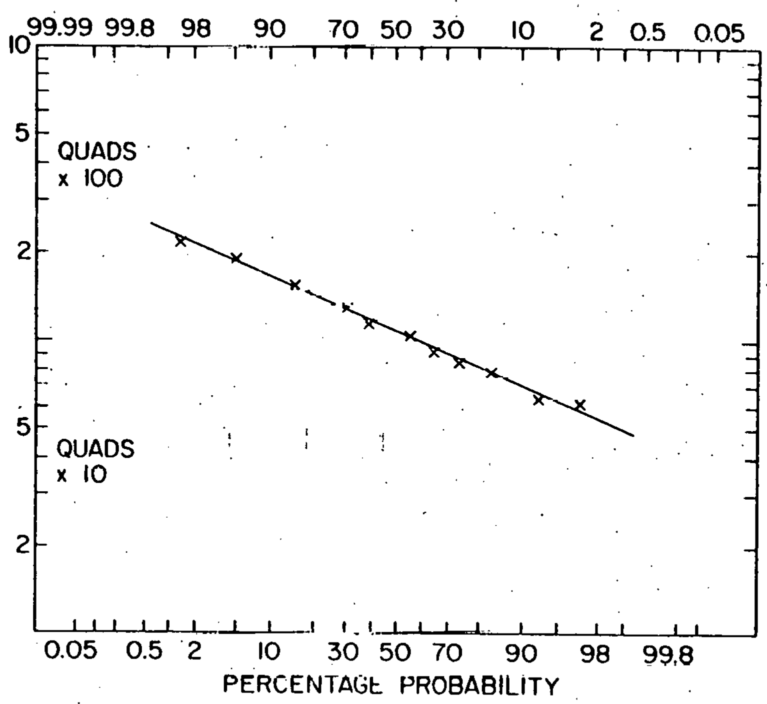

Figure A-3
Stochastic Model Projected U.S. Primary Energy Demand in 2000 as a CDF

The computed parameters of the empirical distribution of expert opinion and those of the model, both for 2000 and in natural log terms, are:

Table A-5
Parameters of the Comparative Distributions

	Number in Sample	Sample Mean	Sample Variance
Expert Opinion	25	4.803	0.02016
Stochastic Model	500	4.745	0.125

It is not surprising to find that the variance of expert opinion is less than that of the model. The former utilizes a considerably larger data base than the latter which leads to the expectancy of reduced uncertainty due to increased information.

The mathematical form of both distributions has been statistically demonstrated to be log-normal and the final comparative test is given:

H_o = The mean value of expert opinion could come from a distribution similar to that of the stochastic model.

H_1 = This mean value comes from a distribution other than specified.

Statistic: Students-t test where

$$t = \frac{(\bar{M} - \bar{E})\sqrt{n}}{\sqrt{\sigma^2}}$$

Here,

$\bar{M}$ = mean value from stochastic model,
$\bar{E}$ = mean value of expert opinion,
n = number of samples, and
σ^2 = variance of expert opinion.

significance criteria: $\alpha = 0.05$

Using the values given in Table A-5,

$$t = \frac{|(4.745 - 4.803)| \times \sqrt{25}}{\sqrt{0.02016}}$$

$$= 2.042$$

This result is less than the tabulated students-t statistic at the 5% significance level and the null hypothesis may therefore be accepted.

Conclusion

This Appendix has determined that the elements of the primary driving function of the U.S. energy system may be collated into a log-normal probability function, either through the use of expert opinion or by a simple stochastic model.

It is proposed that this model may be reasonably utilized as a surrogate for expert opinion in situations where the necessary body of professional analysis is not available, e.g., in regional and/or other country studies.

Table A-6
Year 2000 Forecasts of U.S. Electrical Utility Output

Forecaster	Source*	10^{12} kWh
D. Chapman, T. Tynell and T. Mount	1	3.5
D. Chapman, T. Tynell and T. Mount	1	2.0
D. Chapman, T. Tynell and T. Mount	1	3.3
D. Chapman, T. Tynell and T. Mount	1	1.9
D. Chapman, T. Tynell and T. Mount	1	4.6
D. Chapman, T. Tynell and T. Mount	1	9.9
Brookhaven National Laboratory/ Dale Jorgenson Associates (BNL/DJA)	2	4.8
Alan S. Manne's ETA-MACRO	2	4.3
FOSSIL2 (1978) - Dept. of Energy	2	4.6
LEAP (Long-range Energy Analysis Package) - DOE	2	5.2
Stanford University's PILOT	2	4.3
Bureau of Mines (1972)	3	9.1
Department of Commerce	4	5.8
Department of Interior	5	9.1
Edison Electric Institute	6	8.1
EPRI - Electric Power Research Institute	7	6.7
EPRI - Electric Power Research Institute	7	7.6
EPRI - Electric Power Research Institute	7	9.0
ETA - Energy Technology Assessment	8	4.3
ETA - Energy Technology Assessment	8	4.4
ETA - Energy Technology Assessment	8	4.5
ETA - Energy Technology Assessment	8	4.7
ETA - Energy Technology Assessment	8	8.0
Hudson-Jorgenson (1974)	3	7.1
Hudson-Jorgenson (1975)	9	7.0
Hudson-Jorgenson (1977)	3	6.0
Hudson-Jorgenson (1978)	3	5.5
Hudson-Jorgenson (1979)	3	6.8
National Energy Plan II (NEP-II)	3	4.6
Nordhaus	8	2.4
Nordhaus	8	3.0
Nordhaus	8	3.2
Nordhaus	8	3.6
Nordhaus	8	4.7
DESOM - Dynamic Energy System Optimization Model	8	4.2
DESOM - Dynamic Energy System Optimization Model	8	4.6
DESOM - Dynamic Energy System Optimization Model	8	4.8
ORNL - Oak Ridge National Laboratory	10	5.1

*See page 48.

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