A Technique for Multi-Attribute Utility Expansion Planning under Uncertainty: with Focus on Incorporating Environmental Factors into the Planning Process

by

Arnulfo de Castro

APPROVED:

Saifur Rahman

Saifur Rahman, Chair

Robert P. Broadwater

Robert P. Broadwater

Yilu Liu

Yilu Liu

Ben S Blanchard

Benjamin S. Blanchard

Jeffrey R. Alwang

Jeffrey R. Alwang

A Technique for Multi-Attribute Utility Expansion Planning under Uncertainty: with Focus on Incorporating Environmental Factors into the Planning Process

by

Arnulfo de Castro

Saifur Rahman, Chair

Electrical Engineering

(ABSTRACT)

Within the past two decades, the planning arena has changed considerably and increasing awareness of the impacts of utility generation, intensifying pressure from the public and regulators, and growing competition from other energy and electricity suppliers have made the utility planning process rather complex. The *variety of players* in utility planning has introduced new priorities and a new set of *competing objectives*. Increased resource scarcity, the requirement for economic efficiency and the need to view the electricity production and utilization process in its entirety also necessitate an integrated resource planning approach, resulting in a wider *array of expansion alternatives* that must be evaluated. Another characteristic that makes planning so complicated is the *uncertainty* in the factors that influence the cost of the power system plan.

Public concern for the environment has resulted in a series of legislations for controlling emissions of acid rain precursors (SO_2 and NO_x) and other pollutants. More and more regulators are also requiring electric utilities to internalize environmental externalities in their planning processes. The potential for new legislation on currently uncontrolled effluents like CO_2 likewise remains. There is thus a need to examine the modeling of emissions that would reflect not only the cost of control but the environmental impacts of these emissions as well.

This thesis combines the features of the trade-off and decision analysis techniques to address the multiplicity of objectives and the uncertainties of planning. It draws on Saaty's analytic hierarchy process (AHP) and the interdependent data analysis (IDA) technique developed at Virginia Tech to develop priority weights among objectives and probability distributions of uncertainties. It elucidates the relationship between the competing techniques of trade-off analysis and the method of weights in terms of the economic theory of the firm. The confidence intervals determined with the IDA technique are then used to obtain a range of

alternatives that satisfy the requirements of both approaches for evaluation by the decision maker (DM).

Special attention is given to the environmental impacts of the generation plan and the model accounts for these issues as attributes in the planning process as well as being legislation uncertainties.

Acknowledgments

I am thankful to my advisor, Dr. Saifur Rahman, who gave me support and guidance throughout my doctoral studies and my dissertation research. His insights on the planning of electric utilities and on the environmental impacts of electricity generation have directed this work. I would also like to thank my committee members, Dean Benjamin Blanchard, Dr. Jeffrey Alwang, Dr. Robert Broadwater and Dr. Yilu Liu, for serving in my committee, for their comments and suggestions, and for all their help.

During the course of my studies, I have developed close associations with my co-workers at the Center for Energy and the Global Environment and with my fellow Filipino students. I deeply appreciate the physical and emotional support that they and other friends, too many to mention here, have provided to my family and to myself during these trying times. I am specially thankful to Mr. Yonael Teklu, who has been a constant companion and co-researcher at the Energy Laboratory, and who has been a very dear friend.

I am very grateful to my family and to my wife's family, without whose help and support my doctoral studies would not have been possible.

My wife, Laami, and my daughters, Catherine and Eloisa, have sacrificed much during this period. It is to them that I dedicate this work.

Table of Contents

List of Figures

List of Tables

Chapter 1

Planning the Electric Utility: an Introduction

This chapter briefly discusses current issues and concerns in utility planning and then gives an exposition of the actual industry response to the problem of generation planning in a complex decision-making environment. It then identifies opportunities for enhancement in the current application of decision techniques to utility planning and introduces a planning framework for addressing these issues.

1.1 Generation Planning Concerns

Generation planning has previously been the realm of utility engineers concerned with supply availability, and of planners focused on profitability. Within the past two decades, however, the planning arena has changed considerably and increasing awareness of the impacts of utility generation, intensifying pressure from the public and regulators, and growing competition from other energy and electricity suppliers have made the utility planning process more complex. As a result, decision-making in the utility can no longer be so narrowly viewed as

a management prerogative with the object of profit maximization and with inputs from engineers concerned with reliability and supply availability. It is the result of the interaction between the utility (management and engineers), its customers and the general public, and the government regulatory bodies. One need only look at the current state of development of nuclear power generation to see the influence of public perceptions on utility decision-making.

The variety of players in utility planning has introduced new priorities and a new set of competing objectives. In addition to the objective of profitability, and the constraints of reliability and safety, the utility must now look at social and geopolitical issues and the requirement for resource diversity, environmental acceptability and flexibility, to name but a few.

Increased resource scarcity, the requirement for economic efficiency and the need to view the electricity production and utilization process in its entirety also necessitate an *integrated resource planning* approach, resulting in a wider array of expansion alternatives that must be evaluated. Demand-side management, power purchases, fuel switching and repowering are some of the utility options being considered.

Another characteristic that makes planning so complicated is the *uncertainty* in the factors that influence the cost of the power system plan. Among these are the availability and cost of fuels, technological development, economic and load growth rates, environmental regulations and public attitudes. These uncertainties can seriously impact the economy and viability of a generation expansion plan.

Chapter 2 gives a discussion of the attributes, uncertainties and choices considered in generation planning.

1.2   Approaches to the Utility Planning Problem

Utilities have explored a number of approaches, including sensitivity analysis, scenario analysis and Monte Carlo simulation, in accounting for the multiplicity of objectives and the uncertainties of planning. The most used techniques, however, have been the trade-off methods

and decision analysis techniques based on probability theory. These methods have proven to be very powerful planning tools. There are, however, remaining issues that need to be addressed, i.e.,

1. The need to assist the expert in structuring the complex planning process;
2. The need to provide a structured procedure for generating probability estimates and extracting expert opinions; and,
3. The need to reduce the amount of computations needed to account for the uncertainties and the different attributes.

Chapter 3 reviews techniques for multi-attribute planning under uncertainty. It gives a background on decision making and then investigates applications of the theory to the planning of electric utilities.

1.3   An Enhanced Technique for Utility Expansion Planning

The proposed technique is designed to facilitate the strategic planning of power systems under uncertainty by generating probability estimates from expert opinions using the interdependent data analysis (IDA) technique developed at Virginia Tech (Rahman and Shrestha, 1990). This enables the decision maker to model opinions which are still forming. Applied with the decision analysis, this results in a robust methodology to evaluate the effect of new regulations and public perceptions on utility planning decisions.

This method combines the features of the trade-off and decision analysis techniques to address the multiplicity of objectives and the uncertainties of planning. Figure 1.1 shows a simplified chart of this process. The steps in the process are described below:

1.3.1   Identify Attributes, Uncertainties and Alternatives.

This step defines the value, chance and decision nodes for influence diagram or decision tree analysis. The resulting influence diagram, however, would be very large and while it may not take very long to evaluate this influence diagram, each scenario will entail an EGEAS optimization or production costing run.
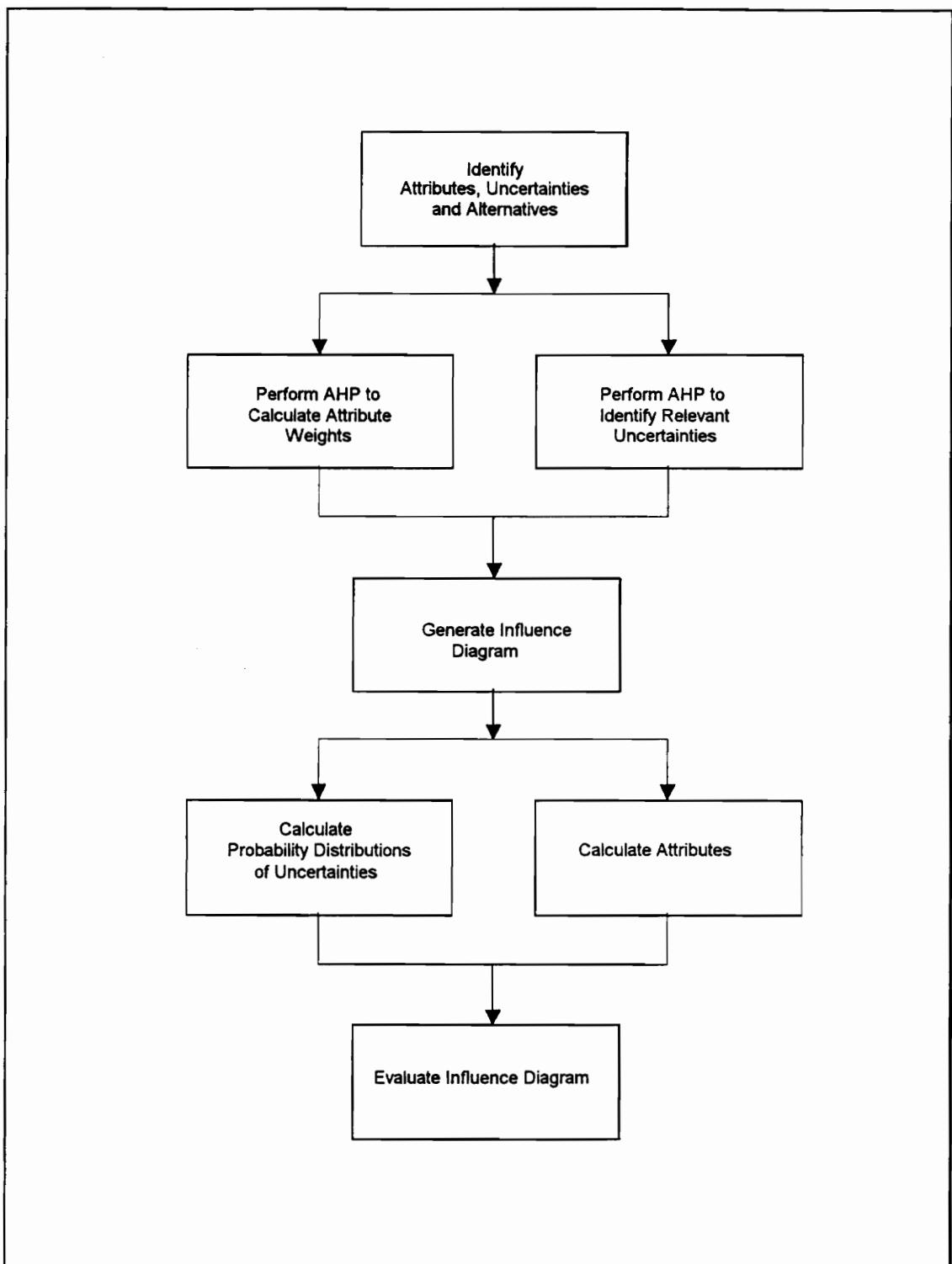
Figure 1.1. Chart of Planning Process

1.3.2 Perform AHP to Calculate Preference Weights.

This step uses the analytic hierarchy process to determine the preference ranking that the DM attaches to the different attributes of the power system plan. It also allows elimination of attributes of low priority.

1.3.3 Perform AHP to Identify Relevant Uncertainties.

This step also uses the analytic hierarchy process, this time as a screening technique to determine which uncertainties have a considerable impact on the solution. The decision maker (DM) does pair-wise comparisons of the impacts of the different uncertainties, forming a judgment matrix. Evaluation of the eigenvector of the judgment matrix provides weight rankings. Those uncertainties that score low will be eliminated. We distinguish between the importance of a factor and the importance of its uncertainty, i.e., the DM will decide whether the expected variations of the factor will affect the plan.

1.3.4 Generate Influence Diagram.

This step involves generating a smaller, more manageable influence diagram. This diagram will include only those attributes and uncertainties selected in the previous sections.

1.3.5 Calculation of Probability Distributions of Uncertainties.

This step involves determining the discrete probability distributions of the different uncertainties based on the expert judgment of the planner.

1.3.6 Calculation of Attribute Values.

Simulations for each scenario involve production costing runs. These calculations determine the values of the attributes of the scenario. These simulations use EGEAS (Stone & Webster, 1989).

1.3.7   Influence Diagram Simulation.

Out of the list of possible alternatives, Influence Diagram analysis gives the optimal solution that accounts for the preferences/weights generated in the previous step.

1.4   Features of the Technique

The features of the proposed method include the following:

1. It shows the planner how the changes in his preferences impact on the alternatives in the trade-off curve;

2. It gives an optimal solution while at the same time providing the DM with a range of choices;

3. It uses a structured procedure for generating probability estimates and extracting expert opinions;

4. It provides a model of the complex planning process; and,

5. It reduces the amount of computations needed to account for the uncertainties and the different attributes.

Chapter 4 describes the proposed technique for expansion planning addressing multiple attributes and uncertainties.

1.5   Focus on Environmental Issues

The quality of the environment is fast becoming an attribute of concern in utility planning. This attribute is unique for two reasons. Firstly, the uncertainties attendant to the issue of environmental impact of electricity generation, while not new, are quite complex. Emissions, being an externality, and more importantly because they are a public "bad", are less determinable and manageable than other uncertainties that the utility industry is facing. Secondly, it is not known how recent legislation and the market for emissions that it creates will perform. Uncertainties in the price of emission allowances need to be addressed, and the possible impact of additional legislation and implementing regulations must be considered.

The modeling of the environmental impact of the generation expansion plan must be considered. Indeed, it is tempting to rely on valuation of emissions based on market prices which are expected to be closely linked to the cost of control, since it is both convenient and very practical from the utility point of view. Such valuation, however, does not reflect the social cost of emissions that do not exceed the cap stipulated in the CAAA, or of those emissions for which the CAAA imposes no limits at all. Using cost of control assumes such costs to be zero. This assumption may not be realistic in situations where different players are involved in the decision process. Thus, there is a need to provide a model of emissions that is more representative of the preferences of the different players in the utility expansion planning process.

Chapter 5 deals with the modeling of environmental uncertainty in the context of this new focus. It discusses the particular role played by electricity in the production and control of emissions, the impacts that these emissions have on the environment and on those that rely on such environment for their survival, approaches to the control of emissions at the policy level and at the utility level and how these measures are implemented in the U.S., and the impacts of these activities on the operation of electric utilities and their modeling in utility planning.

1.6   Case Study and Conclusions

Chapter 6 presents the application of the technique to an actual electric utility. It involves the representation of the attributes and the uncertainties in the planning process in a hierarchy to identify significant entities, the simulation of the different scenarios of alternatives and possible futures, the formulation and solution of the influence diagram and subsequent analysis directed at identifying other plans that satisfy the priorities of the decision maker to a certain level of confidence.

The last chapter concludes with some recommendations on further development and applications of the proposed method.

Chapter 2

Attributes, Uncertainties and Choices
Involved in the Planning of Electric Utilities

This chapter discusses the attributes, uncertainties and choices considered in generation planning. The number of factors involved illustrates the complexity of the generation planning process. It must be realized, however, that each electric utility is unique and would emphasize a different subset of the group in its decision-making. For the same reason, it is not possible to exhaust all the possible considerations that utility planners may have. This diversity of electric utilities underscores the need for structured techniques to evaluate the different objectives, probabilities of uncertain events and planning alternatives.

2.1 Uncertainties in Planning

The load growth, the performance of the generating system, capital and operating costs, environmental regulations and social and political attitudes introduce uncertainties in utility planning. The following paragraphs describe these factors:

2.1.1 Load

High load growth rates increase the need for power and, thus, for additional resources. The utility's future demand and energy consumptions, however, are dependent on a variety of economic, social and political factors that dynamically change with time. The model coefficients, the future values of the exogenous factors and the model structure itself that is used to predict the load are all uncertain (Hirst and Schweitzer, 1988). Among the factors that affect the load are population growth, economic variables, technological changes, consumer behavior and DSM impacts.

2.1.1.1 Population growth

Individual consumption patterns need not change in order to effect load growth, since the population continues to increase.

2.1.1.2 Economic factors

External factors that affect energy and demand growth include residential appliance saturations, electricity prices, prices of substitute fuels and disposable income (Virginia Power, 1992).

2.1.1.3 Technological changes

Increased appliance efficiencies and better insulation practices can result in slower load growth (Stoll, 1989).

2.1.1.4 Consumer behavior

Aside from economic factors and technological advances, changes in end-use patterns which may not be captured by existing models also affect the load. Improved insulation, for example, may result in higher temperature settings in winter and lower settings in summer and prevent the realization of expected impacts. Customers may also respond differently to competing energy and electricity sources.

2.1.1.5 DSM impacts

These refer to the effect of demand-side management policies on the peak load and on energy consumption. Uncertainties associated with these impacts are the participation of customers in the programs, customer adoption of recommended DSM actions, effects of the programs on the load curve and public attitudes toward these programs (Hirst and Schweitzer, 1988).

2.1.2 Reliability

2.1.2.1 Existing utility attrition

This refers to the possible retirement of utility capacity due to age, CAAA requirements, regulatory uncertainty specially with respect to nuclear and hydro unit relicensing.

2.1.2.2 Future availability of utility generation

This is the expected loss of MW capacity due to economic reasons, licensing delays and construction risk.

2.1.2.3 Existing non-utility attrition

This is the expected loss of NUG capacity due to economic conditions, lack of fuel and the lifetime of the technology.

2.1.2.4 Future availability of non-utility generation

This refers to the non-utility capacity that will be available considering licensing complications, construction schedules and financing availability.

2.1.2.5 Life and performance of plants

There is uncertainty in the expected life of repowered plants, as well as in the forced outage rates of generating units.

2.1.2.6 Required reserve

Reserve requirements can vary with future load shapes, future energy limited resources, unit availabilities and tie capabilities.

2.1.3 Cost

2.1.3.1 Fuel prices

Fuel prices vary, some more than others. The Clean Air Act Amendments are expected to add to this uncertainty.

2.1.3.2 Construction costs and time

Uncertainties in the construction time of large capacity plants can favor the use of some smaller plants which can cost more to operate but are more readily available. Aside from the revenue requirements, these also affect the utility's financial integrity.

2.1.3.3 Cost of resources/initial cost of options

This is one of the factors influencing the economic objective. While there are literature available on these values for conventional units, rapidly changing market conditions and technological development cause sufficient fluctuations in capital costs (MacGregor, 1993).

2.1.3.4 Operating and Maintenance Costs

Uncertainties in operating and maintenance (O&M) costs can result from emergency operation and unscheduled maintenance as well as from operational changes due to compliance decisions.

2.1.3.5 Capital escalation

Capital escalation and the discount rate affect the comparative decisions between high-investment, low-operating-cost and low-investment, high-operating-cost options.

2.1.3.6 Cost of replacing power lost due to emission abatement

Use of emission abatement equipment reduces the power output of generating plants and can affect the viability of borderline options.

2.1.4 Environment

2.1.4.1 Environmental Impacts

While the technology for measuring emissions is available, there is much uncertainty on the results of models predicting their impacts.

2.1.4.2 Environmental regulation

Although some emission limits are already in place, e.g. SO_2, there are still uncertainties on the cost of future emission allowances. There is also the possibility of more stringent requirements imposed by state regulatory bodies. In addition, other pollutant gases such as CO_2 might be regulated in the future. The implementation of these types of regulations result in uncertainties on what the requirements will be, what will be their impacts, say on allowance prices and on fuel costs, and how the industry will react.

2.1.5 Social and Political

2.1.5.1 Attitudes

Public attitudes toward the facility vary according to prevailing conditions, their needs and their perceptions and may not necessarily result from its technical merits.

2.1.5.2 Regulation

In addition to environmental compliance, regulatory approvals on facility siting and power needs are another source of uncertainty.

2.2 Attributes of Concern

A list of the attributes concerning the utility is given below. Some of the items in the list overlap but are sufficiently distinct to be cited separately. These attributes provide the gauge by which the attainment of objectives is measured. Note that many of these objectives, such as minimization of costs and reduction of emissions, are conflicting. In addition, attributes such as the balance of payments and effects on employment rank differently between different types of utilities and decision-makers.

2.2.1 Costs and Rates

2.2.1.1 Costs

These include capital investment and operating costs often quantified in terms of the revenue requirements (Megdal, 1991).

2.2.1.2 Rates

These include items such as the average price to customers, and the smoothness of rate increases over time (Megdal, 1991).

2.2.1.3 Other ratepayer costs (Merrill and Wood, 1990)

Some options, such as DSM, result in other costs to the consumer.

2.2.2 Financial Integrity (Megdal, 1991; Ko, 1983; Mulligan, 1981)

Increased construction costs, long lead times, high interest rates and regulatory lag can seriously compromise a utility's cash position and debt-service or interest-coverage ratio, and limit its capability to generate funds internally.

2.2.3 Robustness

This is defined as the strength of the power system to withstand external impacts. Robustness is ensured by planning for all reasonable contingencies (Hirst and Schweitzer, 1988; Merrill and Wood, 1990).

2.2.4 Exposure to Risk

Among the risks considered are trading complications, joint ownership conflicts, reliance on the allowance market, construction lead time and site disruption, vulnerability to sabotage, coal price risks (Metzler, 1992), risks associated with plant operation and risks to health and of exposure of populations to pollution (Kavrakoglu, 1983; Siskos, 1983). Measures used to reduce exposure to risk include diversifying the plant mix, reducing reliance on the allowance market, reducing dependence on external sources of power and adoption of environmentally benign technologies.

2.2.5 Flexibility

Flexibility is the adaptability to changes in conditions prevailing at the time of planning so as to reduce the effect of uncertainty (Brancart, 1991).

2.2.6 Quality

2.2.6.1 Reliability

Reliability is concerned with the successful operation of a system throughout its planned mission (Blanchard, 1990). Power system reliability is usually measured in terms of the loss-of-

load-probability (LOLP), expected unserved energy (EUSE) or loss of energy probability (LOEP), expected loss of load (XLOL) and the frequency and duration of outages (FAD) (IAEA, 1984).

2.2.6.2 *Maintainability* (Buttorff, 1991)

Maintainability refers to the ease, economy, safety and accuracy with which the resulting system can be maintained (Blanchard, 1990).

2.2.6.3 *Producibility (Constructibility)* (Buttorff, 1991)

This refers to the effectiveness and efficiency with which the system can be produced (Blanchard, 1990).

2.2.6.4 *Supportability, Viability, Technical Feasibility*

Supportability is concerned with the capability for effective and efficient supply of materials and energy, and of maintenance and repair facilities (Blanchard, 1990). For a new system, this requirement includes the availability of the technology to sustain it.

2.2.7 Environmental Impacts

The environmental effects of the generation of electricity range from the use of natural resources (e.g., right-of-way and fuels) to damaging the natural environment. There is focus on fossil-fuel generation because of impacts ranging from the localized thermal and particulate emissions through the regional effects of acid precipitation to the predicted climatological alterations resulting from global warming. Emissions are known to damage materials, destroy forests, reduce animal populations and affect human health.

In view of the wide-ranging impact and uncertainties attendant to electricity production and the environment, this thesis will focus on the modeling of this linkage.

2.2.8 Socio-Political

The socio-political objectives factor directly into the planning of government owned utilities (Siskos, 1983; de Castro, 1989) or, in investor-owned companies, through federal and state regulations and public pressure. Among the attributes used to measure these objectives are the following:

2.2.8.1 Macroeconomic effects

Balance of payments (Siskos, 1983)

A primary consideration in national power development projects is the preservation of foreign exchange through the development of indigenous resources. This translates to the balanced development of fuel sources for electricity generation.

Effect on employment (Siskos, 1983)

While the number of jobs required for the different types of plants per se may not differ considerably, job creation becomes significant when considering the whole energy chain beginning from plant construction to fuel sourcing to electricity production and utilization.

2.2.8.2 Effects on local economy

This refers to the level of local industrial and business activity that would be generated by each expansion option. Decisions, for example, between plant construction and power purchases or transmission line upgrades might consider the effects on any local industry development and job creation opportunities.

2.2.8.3 National independence

Some conditions warrant increasing generation capacity in spite of the availability of cheaper external supply sources to ensure the continuity of the supply of electricity.

2.2.8.4 Effects on policy goals

This involves impacts of generation plans on policies and objectives set by government-owned utilities and regulators, and are closely related to items 2.2.8.1 to 2.2.8.3. One such goal may be an electrification program that can have precedence over purely profit considerations.

2.3 Integrated Resource Planning

The increased involvement of government regulatory bodies, private power producers and an environmentally aware public have resulted in a reassessment of the traditional practice of utility planning and given rise to the concept of least-cost planning and integrated resource planning (IRP) (Buttorff, 1991; MacGregor, 1993). Used interchangeably, these terms refer to the evaluation of combined demand and supply options in the planning process with a view to minimizing overall "costs" which encompass a wide scope of attributes.

Options which may be considered in IRP are the conventional technologies plus a host of supply and demand options including repowering with new technologies, power purchases, distributed generation, life extension, non-utility generation (NUG), environmental compliance alternatives and demand-side management.

2.3.1 Supply-Side Options

2.3.1.1 Conventional Technologies

When supply-side technologies are used, particularly fossil generation, the utility must deal directly with the problems of greenhouse gas and acid rain emissions. A plan that complies with the acid rain provisions of CAAA 90 may involve one or a combination of several options including the following (Desai, 1991; Zmuda, 1992; McManus, 1993; Metzler, 1992; Buttorff, 1991; Molburg, 1992):

- Flue gas desulfurization retrofit
- Fluidized bed combustion

- Use of lower-sulfur fuels
- Use of environmental instead of economic dispatch
- Replacement or expansion of capacity with low-emitting technologies
- Allowance trading
- Retirement of high-SO_2 emitters.

Flue Gas Desulfurization Retrofit

FGD systems can remove more than 95% of SO_2 emissions. These systems are normally classified into wet FGD and dry FGD systems. In wet FGD systems, the flue gas is sprayed with a slurry such as calcium, lime, limestone or sodium carbonate which cools it to the saturation temperature. An alkali reagent in the slurry removes more than 95% of the SO_2 regardless of the sulfur content. FGD system retrofits typically cost $175 to $200/kW (Stallard and Ferguson, 1991) but can range from less than $25/kW to more than $1000/kW (Zmuda, 1992).

Dry and semi-dry FGD systems do not cool the flue gas to saturation temperatures. An electrostatic precipitator or fabric filter then captures the reaction products and unused reagent. Spray dryers cost about $175/kW and can remove around 90% SO_2.

Repowering

Utilities also have the option to repower their plants. The most promising technologies for this are fluidized bed combustion (FBC) and integrated gasification combined cycle (IGCC) plants. While coal is burned with air in FBC, a sorbent in the bed captures SO_2 and limits NOx formation. SO_2 removal in FBC ranges between 70 and 90%. IGCC converts coal and air to fuel gas, removes the sulfur and burns the gas in a combustion turbine. The waste heat is then used to produce steam. Electricity is generated by both combustion and steam turbines. IGCC conversion removes between 95 and 99% of SO_2.

Lower Sulfur Fuels

Low-sulfur coal contains about 0.6% sulfur, versus 2 to 3% for ordinary coal. A fuel switch to low-sulfur coal can impact the performance of existing electrostatic precipitators, possibly requiring ESP modifications. Coal purchases across state boundaries might be limited by state legislatures in order to protect local coal industries. The increased demand for low-sulfur coal is expected to raise its price by about $4 to $5 per ton of coal (Desai, 1991).

Environmental Dispatch

Environmental dispatch involves the scheduling of plant generations to account for the cost of emissions. It takes the rate of emissions and the cost of allowances into account in the economic dispatch (Stojka, 1993; Hobbs, 1992).

Replacing Existing Technology with Low Emitting Technologies

This option can be capital intensive unless the unit in question is up for retirement in the near future. It involves trade-offs between the cost of an emission abatement technology that might not be able to serve its life cycle on the one hand and the cost of advancing construction of new generation on the other.

Allowance Trading

The CAAA provides for allowance trading as an efficient means for industry to control emissions. It is intended to allow utilities that cannot feasibly control their emissions to participate in emission reduction by providing incentives to those that can do so economically. Because of the higher allowances allowed in Phase I of CAAA and because it involves a limited number of plants, prices for these allowances are expected to be lower. Due to uncertainties, however, and the more stringent requirements of Phase II, utilities are expected to hold or bank their allowances, thereby limiting supply and raising prices.

2.3.1.2 Power Purchases

A popular peak-shaving practice, the profile of power purchases is expected to change with CAAA. Allowance prices can add between 0.6 and 1.2 cents per kilowatt-hour to the cost of electricity in Phase I and up to 2.4 cents per kiloWatt-hour in Phase II.

2.3.1.3 Non-Utility Generation

The last decade saw a surge in the privatization of electric utilities all over the world. In the U.S., the Public Utility Regulatory Policies Act of 1978 (PURPA) exempted cogenerators and small power producers from federal regulations. It also required investor-owned utilities (IOUs) to provide them with back-up power at reasonable cost and to purchase their generation at the avoided cost. This created an independent power industry that now accounts for half of the new annual electric generating capacity in the U.S. (Greenberger, 1992).

2.3.1.4 Alternative Energy Systems

Utilities are looking into applications of alternative energy technologies such as photovoltaic generation, solar thermal power systems and wind turbine energy systems (Rahman, 1992). While these options are not yet attractive for large-scale use, they are increasingly becoming competitive for small-scale distributed generation. These facilities ease the load on the system and reduce investment requirements for long transmission lines.

2.3.2 Demand-Side Options

Aside from the increase of production capacity, the utility can avail of demand-side alternatives which delay the requirement for additional investments. These include demand-side management and conservation options.

2.3.2.1 Demand-Side Management

Electric Power Research Institute (EPRI) studies show the benefits of load shifting, peak shaving and valley filling not only in the reduction of the load and in improving operating efficiencies but in emission reduction as well (EPRI Customer Systems Division, 1991). American utilities plan to meet up to one-third of new capacity needs with DSM (Levine, 1993). Demand-side management requires careful study because base generation is usually done using high-emission coal plants having lower operating costs and peak generation with low-emission gas turbines having high operating costs. Coal plants, even with FGD, emit 1000 times more SO_2 than natural gas combustion turbines.

2.3.2.2 Energy Conservation

Studies show that considerable improvements can also be achieved in the efficiencies of residential appliances such as lighting, refrigerators, air conditioners and heaters (use of heat pump). Better energy management control systems and variable-speed motors can also be used to reduce the total electric energy consumption (Levine, 1993).

Table 2.1 lists some of these options and their estimated costs.

Table 2.1

Capacity Options

Capacity Option			Cost (c/kWh)
Supply Side	Conventional (Hubbard, 1991)	Coal with compliance	5-7
		Hydro	2-3
		Gas	3-4
		Cogeneration	3
	Alternative (Yeager, 1992)	Photovoltaics	30-40
		Wind	7-9
		Biofuels	5
		Solar Thermal	10
		Geothermal	5-7
Demand Side	Valley Filling (EPRI CSD, 1991)		2-3
	Efficiency Improvement (Levine, 1993)	Refrigerator	3
		Water Heater	1-3
		HVAC	1-2
		Lighting	1-3
		High-Effy Motors	1-3

Chapter 3

Multi-Attribute Planning Under Uncertainty

This chapter reviews the techniques available for the multi-attribute planning of utilities under uncertainty. It comprises two major sections. The first section provides a background on the science of decision making, while the second investigates the applications of the theory in the planning of electric utilities.

3.1   The Science of Decision Making

Power system planning involves decisions among alternatives and therefore can be solved using decision analysis techniques. Although many earlier approaches to planning have involved deterministic models, the probabilistic analysis and other types of representation of uncertainty are not uncommon. The power system planning problem is getting to be more complex, however, necessitating the more structured approach offered by decision analysis

techniques. This section reviews these techniques, drawing from the work of Szidarovsky (1986), Raiffa (1968), Keeney and Raiffa (1976), and the summary done by Shrestha (1990).

3.1.1 Decision Theory

Decision theory is the branch of statistical theory that attempts to quantify the process of choosing between alternatives. It involves the concepts of value and probability, and attempts to provide a structured approach to decision making based on the decision-maker's preferences and the probabilities of the decisions resulting in some desired outcomes. Valuation is based on the axioms of orderability and transitivity which concern preferences for outcomes under certainty:

> *Orderability* asserts that all outcomes are comparable, even if described by many attributes, such that given the outcomes x_1 and x_2, one either prefers x_1 to x_2 or x_2 to x_1 or is indifferent between them; and,
>
> *Transitivity* asserts that the orderings are consistent, i.e., if one prefers x_1 to x_2 and x_2 to x_3, he should also prefer x_1 to x_3.

The following relationships are defined in the preference structure:

Strict preference ($\succ$): $x \succ y$ is interpreted to mean that the decision maker strictly prefers the outcome x to the outcome y. This is also read as x is preferred to y.

Indifference ($\sim$): $x \sim y$ means the decision maker is indifferent between outcome x and outcome y. This is also read as x is indifferent to y.

Weak preference ($\succsim$): $x \succsim y$ means the decision maker weakly prefers x to y. This is also read as x is weakly preferred to y.

The axiom of transitivity can then be written as:

$$x_1 \succ x_2 \text{ and } x_2 \succ x_3 \Rightarrow x_1 \succ x_3. \tag{3.1}$$

A second set of axioms -- monotonicity, decomposability, substitutability and continuity -- describe preferences under uncertainty:

Monotonicity states that when comparing two lotteries having the same outcomes but different probabilities, a decision maker should prefer the one with the higher probability of the preferred outcome.

Decomposability says that a DM should be indifferent between any two lotteries having the same eventual outcomes with the same probabilities.

Substitutability asserts that in a complex lottery, substitution between a lottery and a certain outcome (certainty equivalent) between which a DM is indifferent should not affect the preference for the lottery.

Continuity says that if one prefers outcome x_1 to x_2, and x_2 to x_3, then there exists some probability α such that the DM is indifferent to getting x_2 for certain and the lottery with an α chance of getting the best outcome x_1 and a $(1-\alpha)$ chance of getting the worst outcome x_0.

These permit the definition of the utility function u(x) such that:

$$x_1 \prec x_2 \Leftrightarrow u(x_1) < u(x_2) \tag{3.2a}$$

$$u\big(\alpha x_1 + (1-\alpha)x_2\big) \geq \alpha u(x_1) + (1-\alpha)u(x_2) \quad \forall \quad x_1, x_2 \in \rho \tag{3.2b}$$

$\alpha \in (0,1)$, where ρ is a weakly-ordered mixture set.

They also allow the definition of a scalar utility function which attaches a value or a cardinal scale indicating the utility difference between the outcomes.

The utility function for a two-variable (or good) system can be expressed as follows:

$$u(x_1, x_2) = c \tag{3.3}$$

Figure 3.1 illustrates this preference structure on a two-dimensional space. The axes represent two attributes of the different outcomes which are being compared. Lines known as indifference curves are drawn such that all points on the curve represent the same level of satisfaction for a given DM.

At the point (x_1^0, x_2^0), it would be possible to define a marginal rate of substitution:
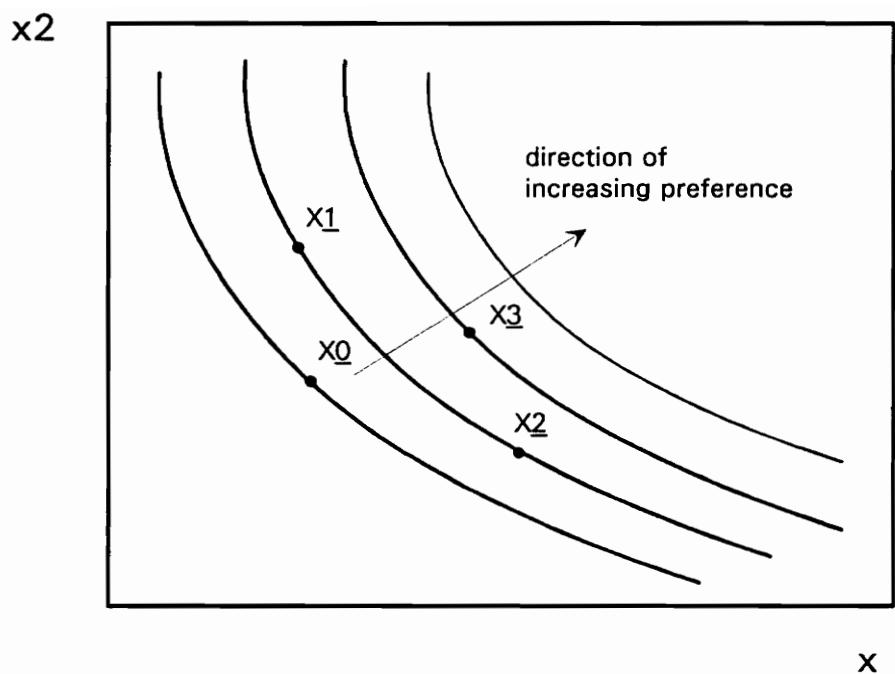
Figure 3.1   Indifference curves.

$$\lambda = -\left.\frac{dx_1}{dx_2}\right|_{x_1^0, x_2^0} = \frac{u'_{x_2}\left(x_1^0, x_2^0\right)}{u'_{x_1}\left(x_1^0, x_2^0\right)} \tag{3.4}$$

This means that at x^0, the DM is willing to give up $\lambda\Delta$ units of x_2 for Δ units of x_1.

3.1.2   Decision Analysis

Decision analysis addresses the applications of decision theory to real-world problems. It involves the eliciting of the utility function, representing uncertainty and generating probability distributions, modeling the decision problem and performing search procedures for utility maximizing decisions.

3.1.2.1 Methods for Utility Maximization

Decision making involves the evaluation of several alternatives based on their meeting a set of objectives measured using some attribute evaluators. Sometimes these evaluators can easily be translated to a common unit of measure. Many times, as in aesthetics and environmental responsiveness, they cannot, and must be valued in terms of the preferences of the decision maker (DM). In general, these preferences differ for the different attributes and change with the levels of attainment of these attributes in relation to each other. (One would be more willing, for example, to spend an additional cent per kWh of electricity produced by a cleaner generating source if it is determined that any further increase in the SO_2 emissions would severely damage the ecology of its affected region.)

Choices can be made with or without formalizing the preference structure for the attributes. Non-dominated solutions, aspiration levels and weights guide the planner in making decisions without the detailed modeling of the problem. Techniques using preference structures and the utility function provide the planner with a better understanding of his/her preferences but

involve more time and effort to develop and use. Details of these techniques can be found in (Keeney and Raiffa, 1976; and Szidarovsky, et al., 1986).

Non-Structured Techniques

Dominance and the Efficient Frontier

Given two choices A and B, we say that A dominates B when

$$A_i \geq B_i, \forall i \qquad (3.5a)$$

$A_i > B_i$ for some i where i is the attribute counter. $\qquad (3.5b)$

The efficient frontier gives the set of non-dominated solutions to a given decision problem. It is also known as the production possibilities frontier (PPF). The set of production possibilities comprises the economic solutions to the decision problem. Figure 3.2a illustrates this concept. Consider a utility that is looking into the levels of air quality and reliability resulting from its production of electricity. Each marker in the graph represents the states of reliability and air quality produced by a decision option (an electric generating plant by itself or a combination of these). Application of the dominance criterion (eqn. 3.5) gives the efficient frontier (circles). This frontier represents the maximum (efficient) amounts of output of air quality and reliability that can be achieved with a fixed level of resource production. According to the efficiency criterion, no combinations below the frontier are economically relevant. Because utility practice usually trades off cost of generation and level of emissions, the production possibilities curve takes an inverted form as shown in Figure 3.2b.
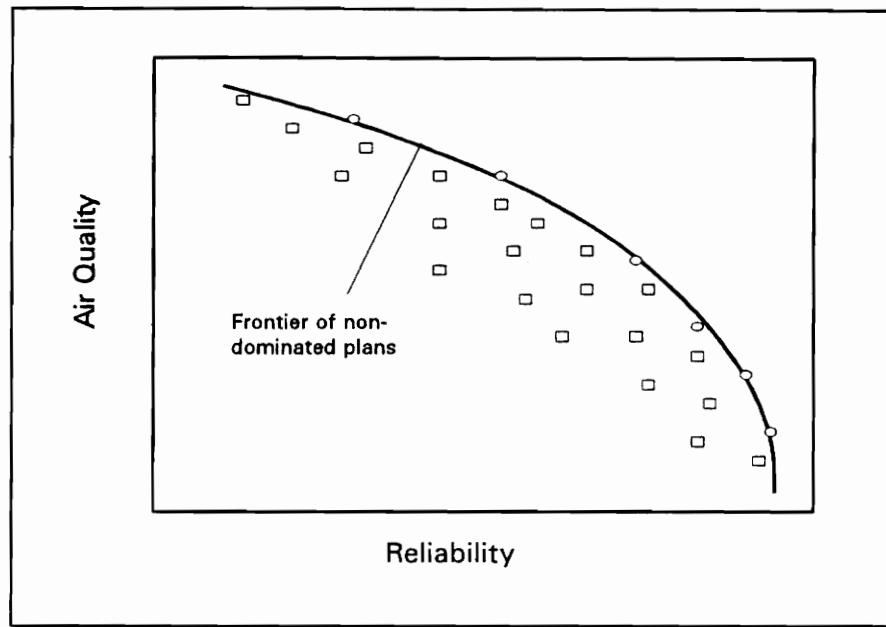
(a)
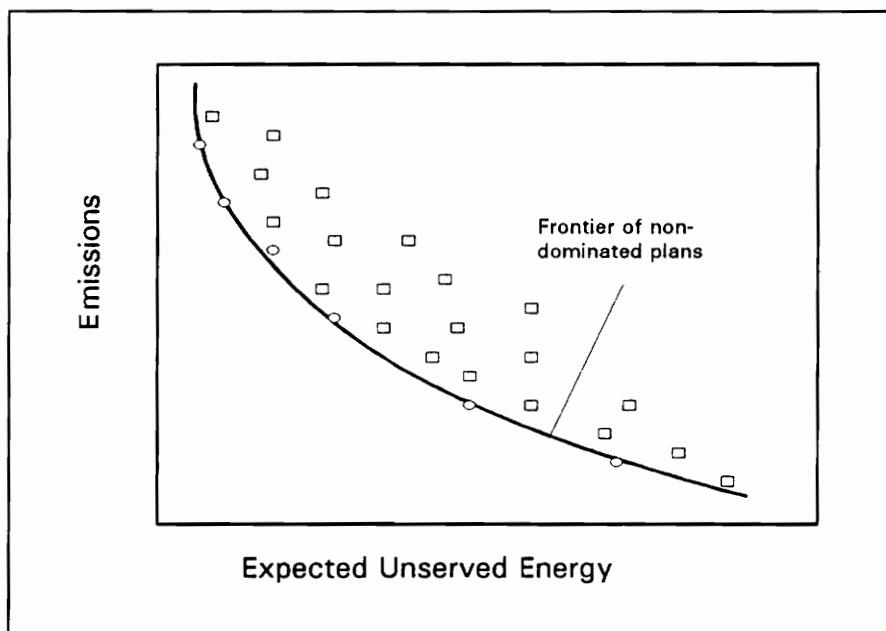
(b)

Figure 3.2.   Frontier of non-dominated plans.

The ε Constraint Method

This method involves the definition of aspiration levels that must be attained for the N attributes. The planner then performs an iterative procedure until the set of actions a ∈ A satisfy the constraint $X_i(a) \geq \varepsilon_i^o$. An optimal solution for the attribute with the highest preference can be obtained by setting an ε_i^o lower bound on the other objectives.

The Method of Weights

The method of weights reduces the multi-objective problem to a single-objective problem using a set of non-negative numbers w_i, ..., w_N which are not all zero. These weights are considered to be the relative importance of the objectives based on the DM's preferences. The optimization problem can then be written as follows:

$$\max \sum_{i=1}^{N} w_i f_i(\underline{x}) \tag{3.6}$$

subject to $\underline{x} \in X$.

Distance-Based Methods

In distance-based methods, the planner specifies ideally good values f_i^* for all objectives. This gives the vector $\underline{f^*} = \left(f_i^*, ..., f_N^*\right)$ of "ideal" simultaneous pay-off values. This vector defines the ideal point. If the ideal point is feasible, the problem reduces to the solution of the set of equations

$$f_i(\underline{x}) = f_i^*, i = 1, 2, ..., N \tag{3.7}$$

Otherwise, the feasible region is searched for the solution that is closest to the ideal point, i.e.,

$$\max \rho\left(\underline{f(x)}, \underline{f^*}\right) \tag{3.8}$$

subject to $\underline{x} \in X$

where ρ is a distance of points in the N – dimensional space.

The distance used can be geometric or the distance function (Minkowski metric)

$$\rho_p(\underline{a}, \underline{b}) = \left\{ \sum_{i=1}^{N} C_i \left| a_i - b_i \right|^p \right\}^{\frac{1}{p}}, \quad p \geq 1 \tag{3.9}$$

Structured Techniques

Lexicographic Ordering (Method of Sequential Optimization)

This method involves ranking of the objective function according to the priority weights given by the DM. The optimization problem is then solved to maximize each objective function $f_k(\underline{x})$ in the order of priority.

Methods of Geoffrion and Dyer

This is a gradient-type iterative optimization method, except that it is used when the value function representing the preference order of the DM is not known. It reformulates the multi-objective problem:

$$\max \quad f_i(\underline{x}), \quad i = 1, \dots, I \tag{3.10}$$

as

$$\max \quad V\big(f_1(\underline{x}), \dots, f_N(\underline{x})\big) \tag{3.11}$$

subject to $\underline{x} \in X$

where V is an N-variate real valued function representation of the DM's preference order. The objective function V is further transformed to

$$\max \quad \sum_{i=1}^{N} w_i^{(k)} \nabla_{\underline{x}} f_i\big(\underline{x^{(k)}}\big) \underline{y} \tag{3.12}$$

subject to $\underline{y} \in X$,

where $w_i^{(k)} = \left(\dfrac{\partial V / \partial f_i}{\partial V / \partial f_1} \right)$

The Surrogate Worth Trade-off Method

The surrogate worth trade-off method consists of generating the non-dominated set and then generating a preferred solution from the non-dominated solutions. It recognizes the relative ease of comparing two objectives instead of directly assessing their values. It involves constructing the trade-off functions by generating the non-dominated set, and from these obtaining the desired solution.

The trade-off functions are obtained from the Lagrange multipliers. Given the objective function:

$$\max \quad f_{i_o}(\underline{x}) \tag{3.13}$$

$$\text{subject to} \quad \underline{x} \in X$$

$$f_i(\underline{x}) \geq \varepsilon_i \quad (i \neq i_0),$$

$$\text{where} \quad X = \left\{ \underline{x} \mid g_j(\underline{x}) \leq 0, j = 1, \ldots, M \right\}$$

The generalized Lagrangian can be written as follows:

$$\mathcal{L} = f_{i_o}(\underline{x}) + \sum_{j=1}^{M} \mu_j g_j(\underline{x}) + \sum_{i \neq i_o} \lambda_{i,i} \left(f_i(\underline{x}) - \varepsilon_i \right) \tag{3.14}$$

The solution can be written as:

$$\lambda_{i,i} \left(f_i(\underline{x}) - \varepsilon_i \right) = 0$$

$$\lambda_{i,i} \geq 0 \tag{3.15}$$

When the constraint is binding, $\lambda_{i,i}$ can be shown to be

$$\lambda_{i,i} = -\frac{\partial f_{i_o}(\underline{x})}{\partial f_i(\underline{x})}, \quad i \neq i_o \tag{3.16}$$

Varying the constant $\varepsilon_i \left(i \neq i_o \right)$ allows calculation of a large number of values of $\underline{X}$ and the trade-off rate functions $\lambda_{i,i}$ can be approximated.

The surrogate worth functions $w_{i,i}$ measure the preference of the DM to trade $\lambda_{i,i}$ marginal units of the $i_o\underline{th}$ objective for a marginal unit of $f_i(\underline{x})$, given that all other objectives do not change. Normally given on an ordinal scale, $w_{i,i}\left(\lambda_{i,i}\right)$ is positive when $\lambda_{i,i}$ marginal units of $f_{i_o}(\underline{x})$ are preferred to one marginal unit of $f_i(\underline{x})$, negative when the reverse is true, and zero when they are indifferent.

An iterative procedure solves for $\underline{f}^*$ for which $w_{i,i}\left(\lambda_{i,i}\right) = 0 \quad \forall \quad i \neq i_o$. This gives the trade-off function. The following optimization problem is then solved to obtain the optimal decision:

$$\begin{aligned}
\text{max} \quad & f_{i_o}(x) & (3.17)\\
\text{subject to} \quad & f_i(\underline{x}) \geq f_i^* \quad \left(i = i_o\right)\\
& \underline{x} \in X
\end{aligned}$$

The method of Zionts and Wallenius

In this method, the DM selects a set of positive weights and then generates a non-dominated solution using the weighting method. He then selects a subset of efficient variables from the set of non-basic variables. The DM then defines a set of trade-offs that increase some objectives and decrease some of the others, and identifies which ones are desirable. This produces a new set of weights for a repeat of the process. The procedure iterates until a satisfactory solution is reached.

The ELECTRE I and ELECTRE II methods

The ELECTRE methods allow the DM to rank alternatives based on qualitative criteria. ELECTRE I chooses alternatives preferred for most criteria but which do not result in an

unacceptable level in any other criterion. ELECTRE II attempts to outrank other alternatives completely.

Ranking is based on concordance C(k,l) and discordance D(k,l) indices as follows. The concordance index

$$C(k,l) = \frac{\sum_{i \in A(k,l)} w(i)}{\sum_i w(i)} \qquad (3.18)$$

where $w(i)$ is the weight of criterion i, i = 1, ..., N, and

$$A(k,l) = \left\{ i \middle| k \succ l \cup k \sim l \right\}$$

In effect, $C(k,l)$ is the weighted percentage of criteria for which k is preferred to l, and $0 \leq C(k,l) \leq 1$.

The discordance index

$$D(k,l) = \frac{\max_i \left\{ f_i(x_l) - f_i(x_k) \right\}}{R^*} \qquad (3.19)$$

where $f_i(x_k)$ is the value of criterion f_i under alternative x_k, and R^* is the largest of the N criteria scales.

$D(k,l)$ gives the worst discomfort value in criteria where action l is preferred to k. Minimum and maximum threshold values are specified for $C(k,l)$ and $D(k,l)$, respectively.

3.1.2.2 Techniques for representing uncertainty and generating probability estimates

The requirement of huge amounts of probability estimates, and the lack of practical methods to update them, were among the main reasons for the simplification of probabilistic approaches. The explicit enumeration of all probable combinations in a complex domain (as the utility generation planning) will clearly result in an unacceptably large number of cases to

evaluate. This underscores the need for a method that would generate probability estimates based on expert opinions.

The following paragraphs discuss techniques currently used for generating probability estimates. Some of these techniques are used for producing point estimates of probability while the others are used in generating estimates of intervals of probability. To deal with the problem of generating probability estimates in the absence of data, the techniques employ subjective estimates, the combining of expert opinions and a variety of approaches that break the complex probabilities into more manageable component probabilities.

Bayes Theorem

The basis for Bayesian statistics is the concept of conditional probability $P(h|e)$. This expression gives the probability of hypothesis h given the evidence e. $P(e|h)$ then gives the probability of observing evidence e given hypothesis h. Bayes' theorem states that

$$P(H_i|E) = \frac{P(E|H_i) \cdot P(H_i)}{\sum_{n=1}^{N} P(E|H_n) \cdot P(H_n)} \tag{3.20}$$

where $P(H_i)$ is the a priori probability that hypothesis i is true and N is the number of possible hypotheses.

Monte Carlo Simulation

Monte Carlo simulation involves the assignment of event or component states such that when the state of such event or component is picked at random, the draws will yield the appropriate probability distribution. The probability distribution for a chain of events (or a system of components) is then calculated by randomly picking the states for the events in the chain.

Camm and Hammitt (1986) employed a Monte Carlo aggregation of subjective probability components to develop a subjective probability distribution for ozone depletion. The

first step involved the identification of factors, mainly emissions of potential ozone depleters and other gases influencing ozone depletion. Subjective probability distributions were developed for the uncertain quantities potentially affecting stratospheric ozone depletion. These distributions were then convolved using Monte Carlo analysis.

Goal Programming

Goal programming is a decision analysis technique whereby a goal is set and success is measured by the reduction of deviation from the goal. As applied in assessing scenario probabilities, it involves specifying a constraint set of consistency and definitional relations and conditional probability assessments. The solution will then yield a feasible set of scenario and conditional event probabilities (de Kluyver, 1981).

Event Trees

Another method of developing probability estimates of scenarios is with the use of event trees. The fault trees show the various combinations and sequences of other failures leading to the given failure. Coupling between higher and lower events is provided by OR gates, signifying that the top event can be triggered by either or both of the bottom events, and AND gates which indicate that both events would have to occur for the top event to take place (US Nuclear Regulatory Commission, 1975).

The Certainty Factor Approach

The Certainty Factor Approach (Shortliffe, 1976) provides a way of reasoning from available evidence whether or not to support a given conclusion. The certainty factor CF[h, e] is determined in terms of the measures of belief MB[h, e] and disbelief MD[h, e] in the hypothesis h based on the evidence e, to wit:

$$CF[h,e] = MB[h,e] - MD[h,e] \tag{3.21}$$

The ranges for the measures of belief, disbelief and certainty are $0 \le MB \le 1$, $0 \le MD \le 1$, and $-1 \le CF \le$, respectively.

This technique is easy to use. It is also appealing in that, unlike the probability calculus, evidence that confirms h with a certainty of CF does not confirm $\bar{h}$ with a certainty of $-CF$, since $CF[h, e] \ne 1 - CF[\bar{h}, e]$. However, it makes strong independence assumptions (Rich and Knight, 1991), is purely intuitive in formulating combining functions and has been shown to yield absurd results (Shrestha, 1990).

While the previously-discussed probabilistic techniques and the certainty factor approach deal with point estimates, the following techniques provide an interval in which the probability must lie. Peper and Walicki (1987) and Kashyap (1971) discuss the desirability of these kinds of intervals, instead of a discrete certainty factor, and their possible use. Cheng and Kashyap (1986) attempt to propagate or combine such intervals formed under different evidences. Similarly, Hamburger (1986) represents and combines uncertain estimates into an estimate of parameter values paired with an associated measure of uncertainty. A representation of uncertainty by intervals on probabilities can also be found in Dalkey (1986). The performance of interval-valued uncertainty representation has also been studied by Tong and Appelbaum (1988).

Dempster Shafer Theory

While the previously-discussed probabilistic techniques and the certainty factor approach deal with point estimates, the Dempster Shafer (DS) Theory (Dempster, 1968; Shafer, 1976) provides an interval for the degree of belief. This interval ranges between the expert's belief (Bel) in the hypothesis and the plausibility (Pl) of the hypothesis, i.e., $[Bel, Pl]$. Plausibility is defined as $Pl(h) = 1 - Bel(\bar{h})$.

Bel quantifies our belief in a (set of) proposition(s) based on favorable evidence. *Pl* measures the room left for belief in h based on belief in $\bar{h}$. The belief interval is defined by $Pl(h) - Bel(h) = 1 - Bel(h) - Bel(\bar{h})$ and represents the balance of belief that is not assigned to $Bel(h)$ or to $Bel(\bar{h})$. It represents the level of uncertainty present in the hypothesis.

An exhaustive universe of mutually exclusive hypotheses defines the frame of discernment Θ. The objective of the procedure is to attach some measure of belief to the elements of Θ.

The process uses the probability density function m. This function represents individual elements as well as subsets of the frame of discernment. The belief functions $m_1(x)$ and $m_2(y)$ combine to define the function $m_3(z)$ using the following equation:

$$m_3(z) = \frac{\sum_{x \cap y = z} m_1(x) \cdot m_2(y)}{1 - \sum_{x \cap y = 0} m_1(x) \cdot m_2(y)} \qquad (3.22)$$

Fuzzy Analysis

Fuzzy Analysis (Bellman and Zadeh, 1970) was developed as a special form of uncertainty representation to deal with specifications of conditions which are vague or imprecise. Examples of this are the tallness of a person or the warmth of the weather. In probability, the boundaries would have to be precisely specified when a person becomes tall or the weather becomes warm. Fuzzy theory develops the concept of possibility. The membership function $f: X \rightarrow [0, 1]$ represents the possibility, rather than the probability of an uncertain occurrence.

The rules of Fuzzy Analysis include the following:

Union $\qquad (f \cup g)(x) = \max[f(g), f(x)]$ $\qquad\qquad\qquad$ (3.23a)

Intersection $\qquad (f \cap g)(x) = \min[f(x), g(x)]$ $\qquad\qquad\qquad$ (3.23b)

Complement $\qquad f(\bar{x}) = 1 - f(x)$ $\qquad\qquad\qquad\qquad\qquad$ (3.23c)

In general, $(f \cup \bar{f})(x) \neq 1$. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ (3.23d)

The weakness of this technique is that union results in the maximum and intersection yields the minimum independently of the strengths of the other inputs (Shrestha, 1990).

3.1.2.3 Decision Analysis Models

The decision analysis process is designed to assist decision makers in structuring complex decision problems and formulating decisions under uncertainty. It provides a framework for decision making based on information and opinions on uncertainties, alternative courses of action, values and preferences. It consists of the following basic steps: (1) model formulation, (2) deterministic analysis, (3) probabilistic analysis, and (4) problem analysis (Call and Miller, 1990).

During the model formulation phase, the decision maker (DM) structures his/her problem to identify the alternatives, values and uncertainties and their relationships. Deterministic analysis models the structural relationships among the decision and state variables, and the preferences for one type of outcome against the other. A deterministic sensitivity analysis is then performed to reduce the model by eliminating those variables which do not change the decision at their extreme points.

Probabilistic analysis models the probabilistic relationships among uncertain variables and develops the necessary probabilistic inputs for uncertain variables. Probabilistic relationships specify the dependencies or lack thereof among the variables. Probabilistic inputs are pairs of probability and value points or discretized continuous distributions. (Methods for determining probabilistic inputs have been discussed earlier; the proposed method for generating probability estimates and their range of variations will be discussed in Chapter 4.)

The problem analysis phase involves the determination of the optimal policy, which indicates the best choice for each decision problem, and its expected value. Another output of

this phase is the certain equivalent policy which is based on the risk attitude of the DM when other than risk-neutral. The problem analysis phase also gives the probability distribution of possible decision outcomes. It also determines the value of perfect information. These methods of analysis can be implemented using decision trees and influence diagrams.

Decision Trees

The traditional approach to decision analysis is the use of decision trees (Figure 3.3). Decision trees (Raiffa, 1968) provide a graphical structure for representing decisions, uncertainties and values of a problem as well as for numerical evaluation. The trees branch out to each possible decision or chance outcome. Decision trees allow the representation of both structure and policy results, and can be put to good use in the presence of asymmetries and coalescence. (An asymmetrical tree structure occurs when for certain values of a preceding variable in the tree, the function value does not depend on succeeding variables.) They are, however, limited in the size of the model that can be represented in detail. Furthermore, different structures are necessary for assessing probabilities and for decision making.

Influence Diagrams

The above limitations led to the development of Influence Diagrams (Pearl, 1988; Holtzman, 1981; Oliver and Smith, 1990) for representing probability models and solving decision problems. These diagrams (Figure 3.4) consist of decision nodes (rectangles), chance nodes (ovals or circles) and value nodes (rounded rectangles, hexagons or octagons) whose relationships are shown using arrows that represent either conditioning arcs (into chance and value nodes) or informational arcs (into decision nodes). A solution process based on probabilistic rules simplifies the diagram until the decision node leads directly to a value node, permitting value assessment of the decision (Shachter, 1986).
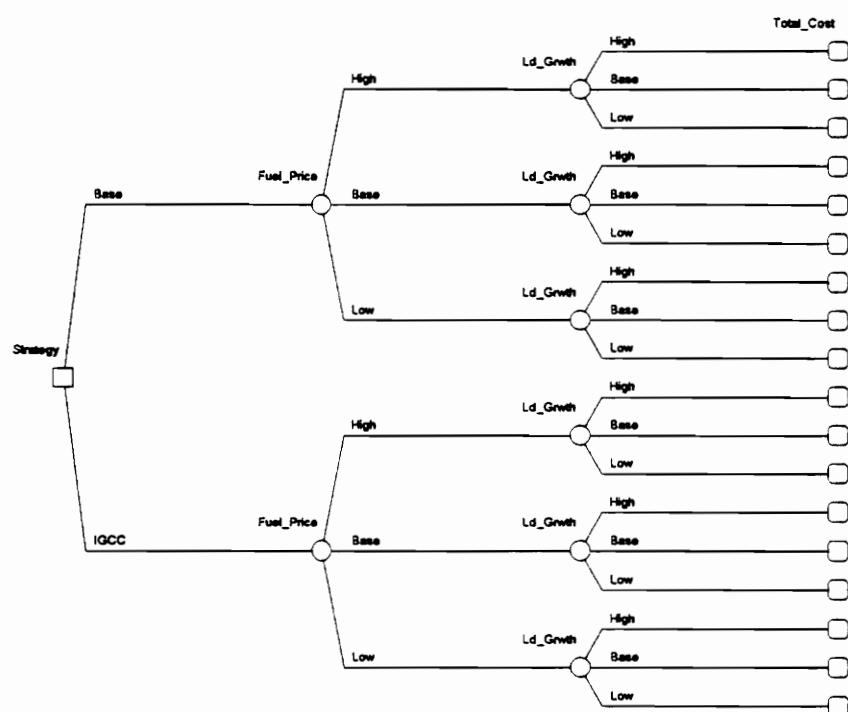
Figure 3.3. Decision Tree for Simple Generation Planning.
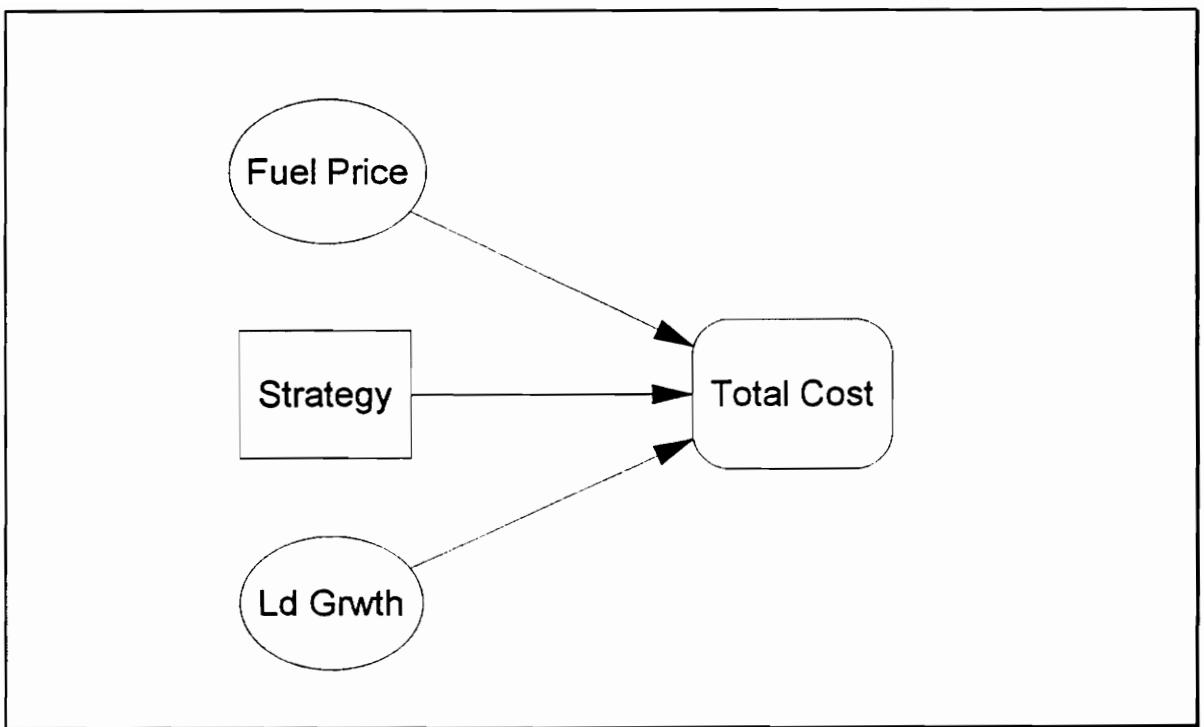
Figure 3.4. Influence Diagram for Generation Planning.

The advantage of the influence diagram is its ability to represent probabilistic dependencies very clearly, and to represent much larger models. Also, theoretically, the influence diagram is expected to solve problems in linear time because its procedure involves node elimination rather than branch enumeration. However, it can not represent the structure of the decision as clearly as the decision tree can. Also, it has been reported that computational complexity for both influence diagrams and decision trees are highly dependent on the implementation, and that because of the natural ability of decision trees to exploit asymmetry, they can be much less complex than influence diagram calculations (Call and Miller, 1990). Both decision trees and influence diagrams, however, need precise estimates of probability or variables that are used in the analysis.

3.1.3   Advantages of Decision Analysis Models

The strength of decision analysis lies in its ability to represent the actual thinking process of the decision maker, and its being founded on the rules of probability. It also provides the tool for determining the sensitivity of the outcomes to the model variables so that the number of variables can be reduced early in the analysis. At the same time, it enables the planner to obtain the expected value of perfect information and determine the point when new information need not be collected. However, the decision process can take a considerable amount of time when the model becomes large. There is also the problem of dealing with inconsistent expert judgment on the importance and probabilities of issues involved, or with the lack of knowledge on certain aspects of the problem. These disadvantages need to be addressed in using decision analysis to solve power system planning problems.

Multiple objectives are normally addressed in Decision Analysis with the use of weights which in effect will assign dollar values to attributes that cannot be valuated directly, such as reliability and environmental impacts. Uncertainty is addressed with the use of discrete

probability estimates of the occurrence of the different conditions. The advantages of this approach are that it is based on the rules of probability and that it suggests a solution to the planner that minimizes the expected value of the cost of his plan. Its disadvantages are the difficulties in presenting the relative performance of the plans with respect to the different desired attributes, and in addressing robustness or flexibility concerns.

3.1.4 Techniques for Group Decision Making

Even in traditional generation planning in electric utilities, decision-making has been performed by a group of individuals. These individuals may differ in their probability assessments for different possible scenarios and in their preferences for outcomes (Raiffa, 1968). Nevertheless, they normally form a cohesive group driven by a common objective and have a consistent assessment of the utility of the outcomes of their decisions. The current environment, however, calls for consideration of preferences of other players, both internal and external (regulators, consumers and the general public) to the utility company. While decision-making ultimately resides in the utility organization, it is evident that decisions have been affected by external players either directly, as in the case of environmental regulations, and indirectly, as in some DSM applications of questionable economic value.

Two of the more popular approaches to group decision making are the Delphi technique (Linstone and Turoff (eds.), 1975) and the analytic hierarchy process (Saaty, 1980). These can be applied in the assessment of both attributes and probabilities.

3.1.4.1 Delphi and Cross Impacts (Dalkey, 1975)

Delphi is a method for structuring a group communication process to effectively allow a group of individuals to deal with a complex problem. Accomplishment of the structured communication is done by allowing feedback of individual contributions, assessment of group judgment, revision of the views and some degree of anonymity. In the most common approach,

Multi-Attribute Planning Under Uncertainty

a core monitoring group designs a questionnaire which is then sent to the larger group of respondents. The group response is examined and a new questionnaire is developed to allow the respondent group to reevaluate its original answers.

In estimation of probabilities, this has been used with cross impacts analysis. While Delphi provides the communications structure, cross impacts analysis is the technique used for analyzing and summarizing response. Cross impact analysis involves the following:

a)   generation of preliminary estimates of absolute probabilities;

b)   estimation of interdependencies with a cross impact matrix;

c)   Monte Carlo simulation of chains of events wherein event probabilities are modified by the cross impact of events occurring previously in the chain; and,

d)   reestimating the absolute probability of each event based on its relative frequency of occurrence in the sample of chains.

3.1.4.2 The Analytic Hierarchy Process

The analytic hierarchy process (AHP) was developed by Thomas Saaty in the early 1970s (Saaty, 1980). It provides a structure defining the dynamics of a system of interest. This structure is then used to study the functional interactions of its components and their impacts on the entire system.

The problem is broken up into layers, each layer influencing the entities in the level immediately above it. Beginning, then, from the second level of the hierarchy, each entity is given a weight by pairwise comparison of the factors in that level with respect to every factor in the upper level. This procedure uses the eigen vector method to calculate the individual and overall influence of factors on the goal.

The Delphi and AHP techniques differ significantly in identifying the variables of interest and in the context of the presentation. In AHP the experts, not the administering core group,

decide on these variables, and the criteria and judgments are established in an open group process (Rahman and Frair, 1984).

3.2 Utility Planning Practices

The traditional utility planning practice has been characterized by "tactical" rather than "strategic " approaches. Tactical planning addresses well-defined problems which can be solved using deterministic optimization methods such as linear programming, dynamic programming and Bender's decomposition techniques. This method is well-suited to the previous era of stable growth and regulated monopolies. Here, the dominant objective has been cost minimization with reliability constraints. However, the increased participation of different players having a variety of objectives has introduced complexities and uncertainties which necessitate a strategic planning approach. Strategic planning addresses such external influences as environmental impacts and socio-political constraints, as well as the uncertainties introduced by government legislation and market forces. This involves numerous applications of tactical planning tools for scenario analysis purposes.

Figure 3.5 charts developments in the system planning process. While the last decade saw the emergence of the concept of integrated resource planning, this has dealt with managing and planning supply (or generation) and demand side resources in the tactical sense.

Uncertainties and legislation on energy and the environment, however, necessitate a strategic approach to the power generation expansion planning problem. This thesis studies decision analysis methods in the strategic planning of utilities with a focus on its environmental implications.

The following sections discuss the approaches that have been employed or studied in dealing with uncertainties and multiple objectives in utility planning. Sensitivity analysis,

scenario analysis and probabilistic simulations essentially deal with uncertainty. Portfolio analysis, the trade-off method and the AHP technique have applications in dealing with both multiple objectives and uncertainty. It will be noted that these techniques are normally used in combination.

3.2.1 Sensitivity Analysis

A popular method of dealing with uncertainty involves conducting sensitivity analysis to determine how a chosen plan will perform when one of the uncertainty variables is changed. This determines, for example, the expected percentage change in cost for each percentage point change in one of the variables.

For systems that can be sufficiently represented using linear or continuous non-linear models, such sensitivities can be readily obtained from shadow costs or gradients of the objective function. However, for systems that are as complex as the model for generation planning of electric utilities, this method would require conducting the evaluation for each new value, and entails repetitive calculations.

Variations to this have been used, including the formulation of some describing polynomial function in terms of the variable being considered (Stone and Webster, 1989). As applied in the Electric Generation Expansion Analysis System (EGEAS) Package, the describing function receives data on input variables and plan attribute values for each scenario resulting from the sensitivity analysis. A weighted least squares algorithm then treats these observations as scenarios and fits the input and attribute data to a user-specified polynomial function.
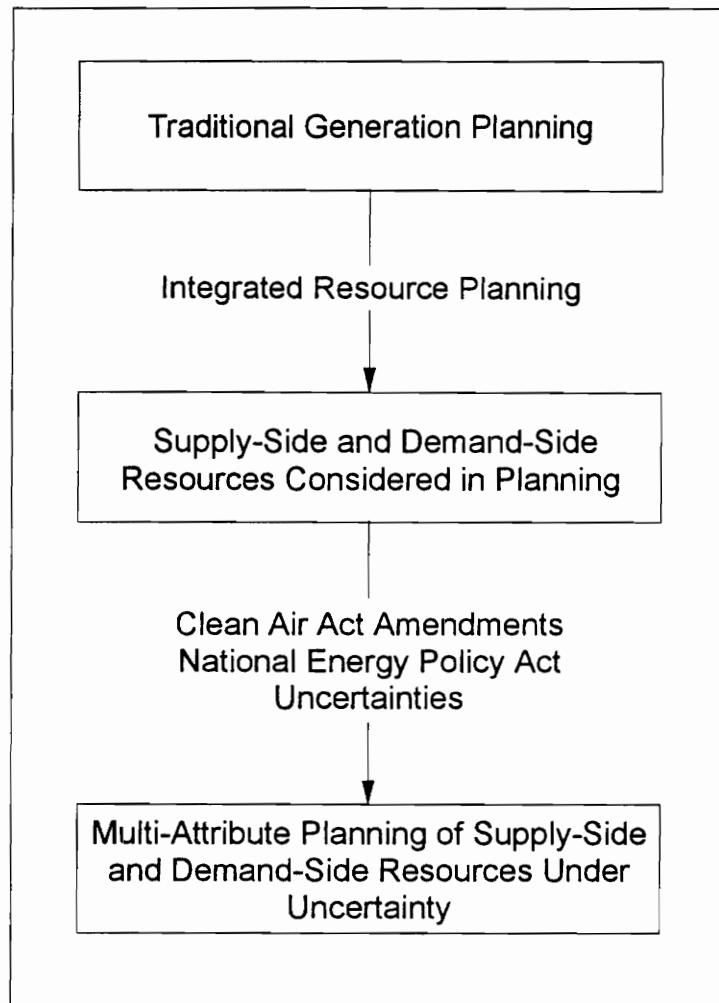
Figure 3.5. Developments in the System Planning Process

Mukerji and Lovell (1988) proposed a high-order piece-wise linear interpolation technique which estimated attribute values of certain scenarios based on results of runs using detailed models.

3.2.2 Scenario Analysis

Scenario analysis involves the construction of alternative, internally consistent futures and then identifying resource options to meet each future. A unified plan then combines the best options. Of the ten utilities studied by Hirst and Schweitzer (1988), two -- Southern California Edison and Bonneville Power Administration were using scenario analysis.

A study performed by the Strategic Decisions Group (1993) for EPRI developed a process for a scenario analysis approach to formulating strategies. The study identifies the uncertainties (economic, technological, environmental and regulatory factors) and the possible future scenarios, stating the objective in such terms as "developing responsive customer business strategies." While allowing us to focus on the uncertainties, this also goes to show that utility planning can no longer be based on purely monetary objectives.

3.2.3 Probabilistic Simulations

Probabilistic analysis may involve a variety of approaches. The simplest approach is to determine expected values for the uncertainty factors and to plan on this basis. The planner may also perform a series of Monte Carlo simulations to plot a probability distribution of consequences of their actions. A more sophisticated approach involves attaching probabilistic weights to different scenarios and performing stochastic programming to determine the optimal resource mix. A fourth approach involves decision analysis.

3.2.3.1 Deterministic Equivalent

The use of deterministic equivalent provides a greatly simplified probabilistic solution to the stochastic programming problem. Murphy, et al. (1982), after comparing the deterministic equivalent with more complex stochastic linear programming solutions conclude that it provides sufficient accuracy under "fairly general conditions." Like tactical planning approaches, however, the validity of this technique becomes questionable in the face of the highly uncertain utility expansion planning environment.

3.2.3.2 Monte Carlo Simulation

In Monte Carlo simulation, values of uncertain variables are generated based on their probability distributions. System simulations are then performed to determine the consequences of these variations. A map of the resulting probability distribution is then made, from which decision makers can evaluate the available alternatives.

3.2.3.3 Stochastic Programming

Stochastic programming involves assigning probabilities to a host of possible scenarios and then solving the resulting weighted objective function. This formulation can be solved in various ways. Borison, et al. (1984) used stochastic dynamic programming and decoupled time periods with Lagrange multipliers to decompose the problem into smaller linked subproblems. Dapkus and Bowe (1984) employed a similar approach in solving the generation expansion planning problem with uncertainties in demand, commercialization dates of new technologies, and possibility of loss of service of nuclear capacity.

Modiano (1987) proposed a two-stage process to deal with *here-and-now* and *wait-and-see* situations. Here-and-now decisions are identified and recourse is determined for decisions that are delayed until future uncertainties are revealed. Bienstock and Shapiro (1988) solved the

stochastic programming problem using a two-stage procedure similar to Modiano's. The first stage involved use of mixed-integer programming to resolve the *here-and-now* problem. Results are then used to formulate second-stage *wait-and-see* utilization planning models. Bender's cuts are written with respect to optimal shadow prices.

Tanabe, et al. (1992) formulated the generation mix problem as a multi-objective optimization problem and solved it using dynamic programming. The multi-objective optimization problem is reduced to one of single-objective optimization using weights. The objective function is the sum of the differences between production costs under uncertainty conditions and least production cost under the base condition.

Gorenstin, et al. (1992) performed planning as a three-stage hierarchy. Stochastic optimization determines the optimal decision vector x over probabilistically weighted scenarios of so called "high frequency phenomena" as thermal operating costs. For low frequency phenomena such as load growth, minimax decision making is employed to minimize the maximum regret associated with each decision over all scenarios. Trade-off analysis is then used to select robust and flexible expansion strategies.

3.2.3.4 Decision Analysis Models

Although decision analysis can be classified under probabilistic techniques, it has become a distinct science in itself. One of the more popular applications of decision analysis in utility planning is EPRI's Multiobjective Integrated Decision Analysis System (MIDAS) (Temple, Barker and Sloane, 1989; Gerber, 1990). MIDAS is a utility planning model based on a decision tree framework. It allows the user to specify objective functions based on any output variable or combination of variables. Compound objective functions can represent multiple objectives. Definition of the objective function is left to the DM.

Where influence diagrams are used, these have been mainly for understanding uncertainties and their interrelationships within the project. Such applications have been reported by (Mobasheri, 1990; and Shwayri, 1993).

Figure 3.6 is a simple influence diagram rendition of the complex set of activities involved in generation planning (Rahman and de Castro, 1994a). It is, however, sufficient to show how some of the inter-related features of this process can be modeled and analyzed. Although it is possible to simply enumerate all emission reduction options under one decision block, they have been grouped according to the sequence in which they are normally made. This also helps to identify the direct impacts of each type of decision.

The first decision node (D1) covers options that directly affect plant capital requirements. It involves decisions on resource mix which would include plant mix, energy purchase options, demand side management and conservation.

In the second decision node (D2), an array of emission abatement options is considered, depending on the resource mix information available from the first. Technology options may include flue gas desulfurization (FGD) or scrubbers and clean coal technologies for SO_2, and low NO_x combustors and selective catalytic reduction (SCR) for NO_x. These technologies have their corresponding costs and emission reduction efficiencies which can be treated as chance variables.

Among the possible operational actions are base dispatch, dispatch modification and the use of low-sulfur coal (D3). Base dispatch involves pure operating cost minimization. Dispatch modification will have an emission minimization objective. Low-sulfur coal results in less emissions but higher fuel costs. The decision to buy or sell emission allowances (D4) is made by considering possible emission levels (C5) and the cost of compliance (V4). During the planning
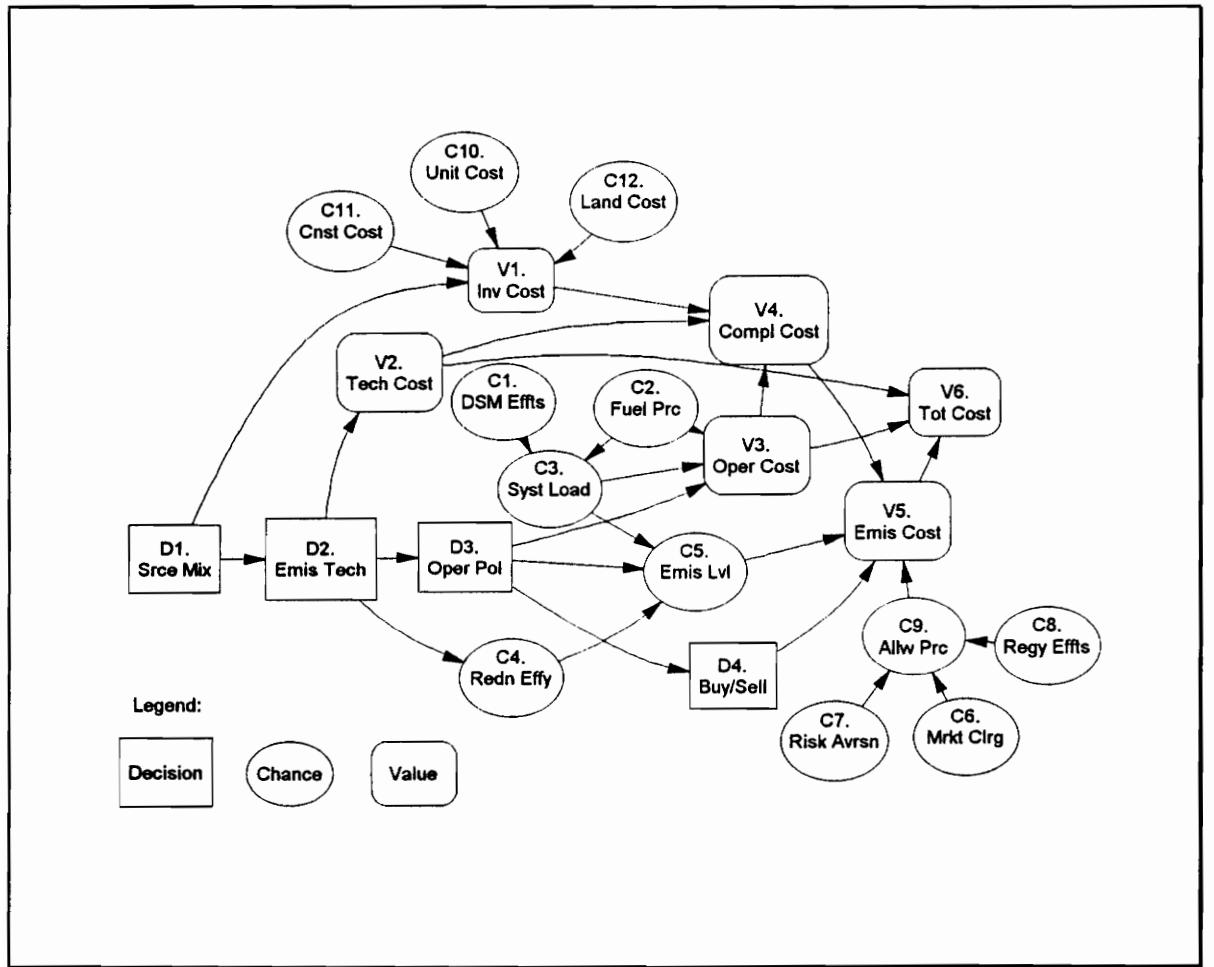
Figure 3.6. Influence Diagram for Generation Planning Framework.

stage, the only certain information available at the point of decision D4 is the set of the three earlier decisions.

In the model shown, the objective criterion is total cost (V6), although it is possible to have a different (set of) objective(s). This cost consists of investment costs (V1), cost of emission technologies (V2), operating cost (V3), and the net increase (decrease) in cost due to the purchase (sale) of emission allowances (V5). The investment cost V1 results directly from the choice of resource mix and is subject to variations in unit (C10), construction (C11), and land (C12) costs. The emission abatement cost V2 depends on which technology options are selected. Operating cost V3 is dependent on the operational policy decision (D3), fuel prices (C2) and system load (C3). In turn, system load is also conditioned on DSM and conservation programs (C1) as well as the competition offered by the direct use of fuels to serve energy requirements (e.g. gas for heating).

The cost for the alternative (V1+V2+V3) net the cost for the base option yields the cost of compliance (V4). This, together with the expected change in the level of emissions (C5), the price of emission allowances (C9) and the buy/sell decision D4 determines the additional (or reduction in) cost V5. The diagram also shows the factors that might influence allowance prices, to wit: the clearing price resulting from the operation of the free market (C6) and the possible effects of risk aversion (C7) and regulations (C8). The alternative to be selected is the one that is able to supply load/energy requirements at the lowest total cost over the planning period.

3.2.4   Portfolio Analysis (Hirst and Schweitzer, 1988)

Portfolio analysis involves specifying a set of objectives and then developing plans or resource -mix portfolios that satisfy each objective. The performance of a portfolio is then

compared with those of others through sensitivity analysis on alternative futures. This technique was used in five of the utilities studied by Hirst and Schweitzer.

3.2.5   The Trade-off Method

The trade-off method (Merrill and Wood, 1990; Burke, et al., 1988) can be used to deal with both uncertainties and multiple attributes. The method involves identifying the different options and plotting their attributes on a trade-off curve. Attribute measures form the axes of a trade-off curve. The attribute values of the different alternatives are then plotted on these axes. As shown in Figure 3.7, this curve gives a frontier of non-dominated plans (those at the knee of the plot). Options that are at the knee of the curve are considered superior and form the decision set for the particular attributes. The robustness of a plan is measured in terms of the frequency with which it appears on the trade-off curve. Uncertain factors are considered by simulating each possible scenario and evaluating how each candidate plan performs.

This has been applied in analyzing various strategies for emission reduction (Tabors and Monroe, 1991). Strategies considered included use of nuclear plants, no nuclear/no coal, dispatch modification, early retirement, carbon tax and conservation. EPRI's Electric Generation Expansion Analysis System (EGEAS) (Stone and Webster, 1989) was used to simulate each option and determine cost and emission values.

This method appears to be very powerful. However, the required volume of simulations in EGEAS is quite considerable, and there is a need for further evaluating the options appearing in the decision set.

The advantages of this approach are that it provides the decision maker information on how each of the plans will perform under given (uncertainty) conditions and allows him to make
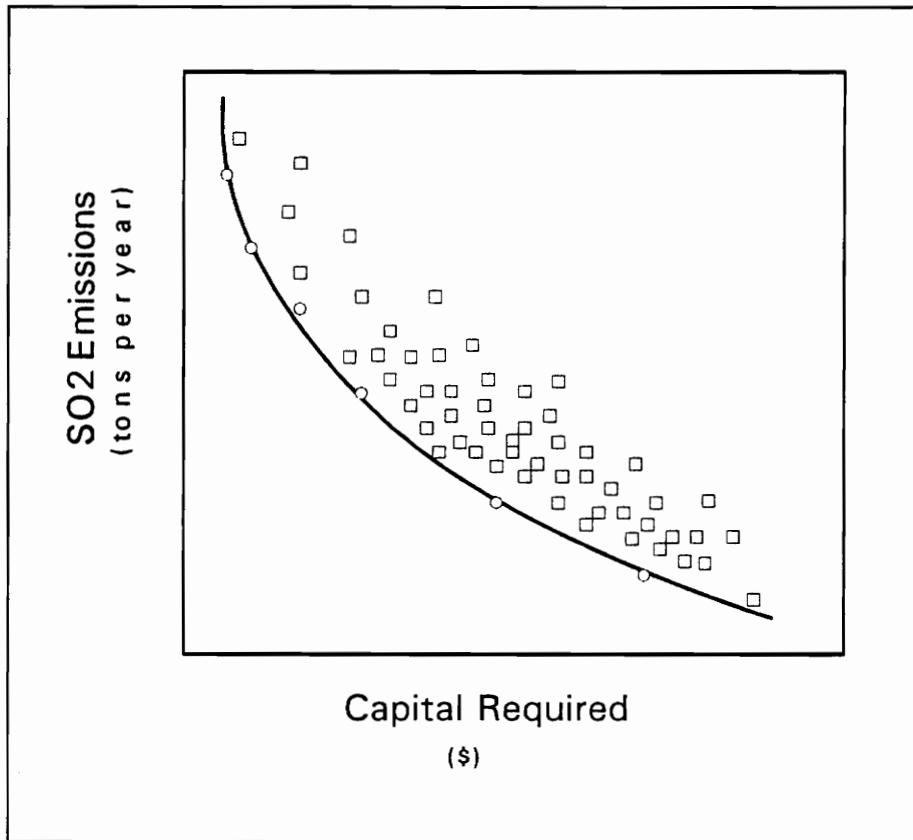
Figure 3.7   Trade-off curve

the decision. It also ensures robustness (defined as "the measure of the over-all power system strength to withstand external impacts (Brancart, et al., 1991)") which caters to the risk aversion generally believed to characterize utility planners. Its main disadvantage is the extremely high cost of providing for robustness, being planned mainly on the basis of the possibility of occurrence of changes in conditions. It does not provide an indication of the likelihood of occurrence of these conditions.

3.2.6 The Analytic Hierarchy Process

Rahman and Frair (1984) studied the application of AHP to deal with uncertainty, ill-defined parameters, conflicting objectives and inaccuracies in measurement in power system planning. In the application, a four-layer structure was designed, the levels being focus, actors, objectives and scenarios. The following questions were then asked going down the hierarchy:

What is the relative importance of each actor in determining the focus (load demand in their study)?

To what extent does each objective affect various actors?

What will be the effect of each scenario option on the identified objectives?

For each question, relative weights are developed by pairwise comparisons of items in the next level, and using the eigenvector method to arrive at the rankings. The eigenvector method is discussed in Appendix A. The extension of the eigenvector method of calculating priority rankings to several levels of hierarchy in AHP is discussed in Appendix B.

3.3   Rationale for an Enhanced Planning Technique

In this chapter, the author has provided an overview of the more popular techniques in decision making and their applications in the planning of electric utilities.

Sensitivity and scenario analyses answer the "what if" questions without providing probability figures or confidence levels in the solution. They cater to the risk-averse behavior of the electric utility industry but, if not handled properly, can result in excessive investments. This is because the selection of probable scenarios or environments must be based on some subjective opinion of the planner. At the same time, decision analysis and probability simulations require probability estimates on chance variables that are used in the evaluation of alternative planning options. Again, these estimates normally require some intuitive judgment on the part of the planner. All of the above techniques assume the availability of the measures of uncertainty and of the experts furnishing them.

Another area of concern is the volume of computations required when uncertainties are taken into consideration. Scenario analysis, for example, entails simulation of each alternative solution for each combination of conditions. This presents a considerable burden on the planner.

A third concern involves the planning for multiple objectives and with multiple decision makers. Almost all of the multi-attribute techniques cited here assume that somehow the DMs can articulate their preferences and that they can formulate a consistent structure combining their preferences.

The next chapter will discuss how AHP and the IDA technique developed at Virginia Tech can be used to enhance decision making in generation expansion planning.

Chapter 4

An Enhanced Planning Technique

The previous chapter discussed methods used to deal with multiple objectives and uncertainty in planning. This chapter identifies some of the issues that need to be addressed to implement these techniques more effectively, and proposes an enhanced technique to address them.

4.1   Features of the Proposed Technique

The following planning needs are identified:

1. A model that would allow the representation of the increasing complexity of the planning process;

2. A method that will extract the probabilities of uncertain events from expert opinions and allow us to attach a level of confidence on expert opinion and on the probability estimates generated;

3. A method to reduce the amount of computations required to account for uncertainties; and,

4. A method that will assist the decision process in multi-attribute generation planning.

The trade-off and decision analysis methods have proven to be very powerful planning tools. The proposed method combines the features of these techniques to provide an enhanced decision-making methodology for generation expansion planning, i.e.,

1. It shows the planner how the changes in his preferences impact on the alternatives in the trade-off curve;

2. It gives an optimal solution while at the same time providing the DM with a range of choices;

3. It uses a structured procedure for generating probability estimates and extracting expert opinions;

4. It provides a model of the complex planning process; and,

5. It reduces the amount of computations needed to account for the uncertainties and the different attributes.

4.2   Framework for Generation Planning

The proposed planning method addresses the multiplicity of objectives and uncertainties of planning. It involves extracting preference rankings and discrete probability distributions of uncertain events from the experts involved. These rankings and probabilities will then be used in an influence diagram for optimal planning. A chart of this process is given in Figure 4.1. The steps are described below.
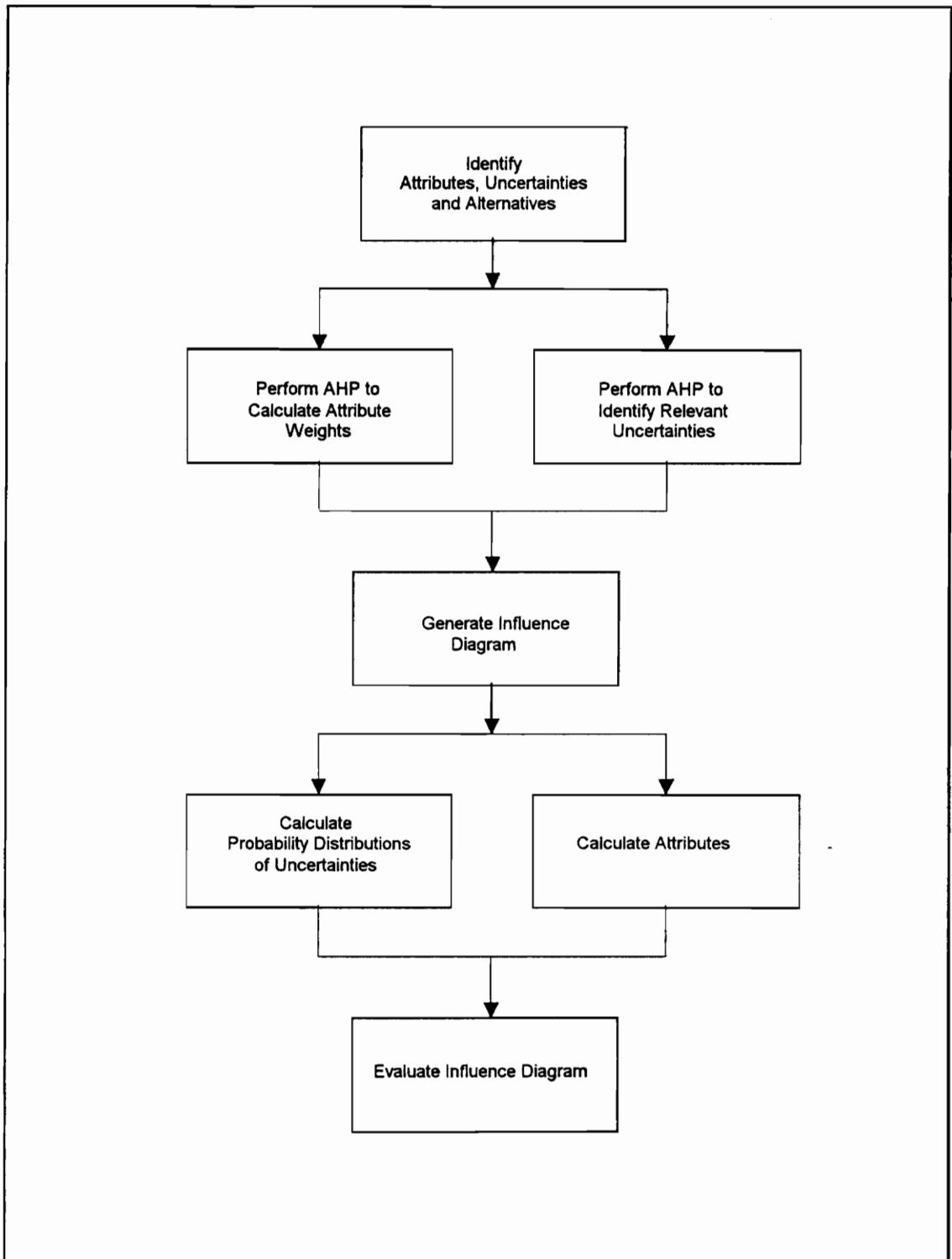
Figure 4.1. Chart of Planning Process

4.2.1 Identify Attributes, Uncertainties and Alternatives.

This step defines the value, chance and decision nodes for influence diagram or decision tree analysis. The resulting influence diagram, however, would be very large and while it may not take very long to evaluate this influence diagram, each scenario will entail an EGEAS optimization or production costing run.

Some of the attributes currently concerning the utility industry were discussed in Chapter 2. For illustration purposes, a sampling is listed here. The units used in quantifying these attributes are also indicated in order to provide a common reference.

- *Economic (Cost)*:

  Revenue requirements   - $/MW-year

  Rate impacts   -   cents/kWh

  Other ratepayer costs   -   cents/kWh

- *Quality (Reliability)*:

  LOLP   -   days per year

  Expected unserved energy (EUSE)   -   GWh

  Min. reserve   -   MW

  Industrial load curtailment   -   MW

- *Financial*:

  Cash flow -- foreign, local, new capital   - $/year

  Construction expenditures   - $/year

- *Environmental*:

  Emissions -- amount of SO_2, CO_2 and NO_x -   ton/year

  ROW requirements (land use)

  Exposure of populations to SO_2, CO_2 and NO_x -   ton/capita

- Societal and political:

Fuel diversity -- proportions of fuels used   (Max % minus Min %) ÷ Ave %

Effect on policy goals

Some of the uncertainties that affect the values of the different attributes are given below (see also Chapter 2). These are the uncertainties that, in the hierarchy, fall directly below each attribute. They are in turn conditioned by other uncertainties.

- *Project cost* - capital costs, annual operating cost, interest rate and escalation rate.

- *Emission level/Environmental impact.* Operating policy decision, system energy use and emission reduction efficiency.

- *Financial impact* - capital cost, source mix decision.

- *System reliability* - forced outage rates, utility attrition, non-utility attrition, utility availability and non-utility availability.

- *Diversity* - function of a source-mix decision.

An influence diagram representation of the above system is provided in Figure 4.2. At this stage, the complexity of multi-attribute planning under uncertainty becomes evident. Each uncertainty would have about three discrete probability states, and the calculations are even more when a factor is conditioned on others.

4.2.2 Perform AHP to Calculate Preference Weights.

This step uses the analytic hierarchy process to determine the preference ranking that the DM attaches to the different attributes of the power system plan. It also allows elimination of attributes of low priority.

The DM provides pair-wise comparisons of the importance given to the different attributes in their planning decisions. These comparisons form the judgment matrix that is used for estimating priority weights for the given attributes.
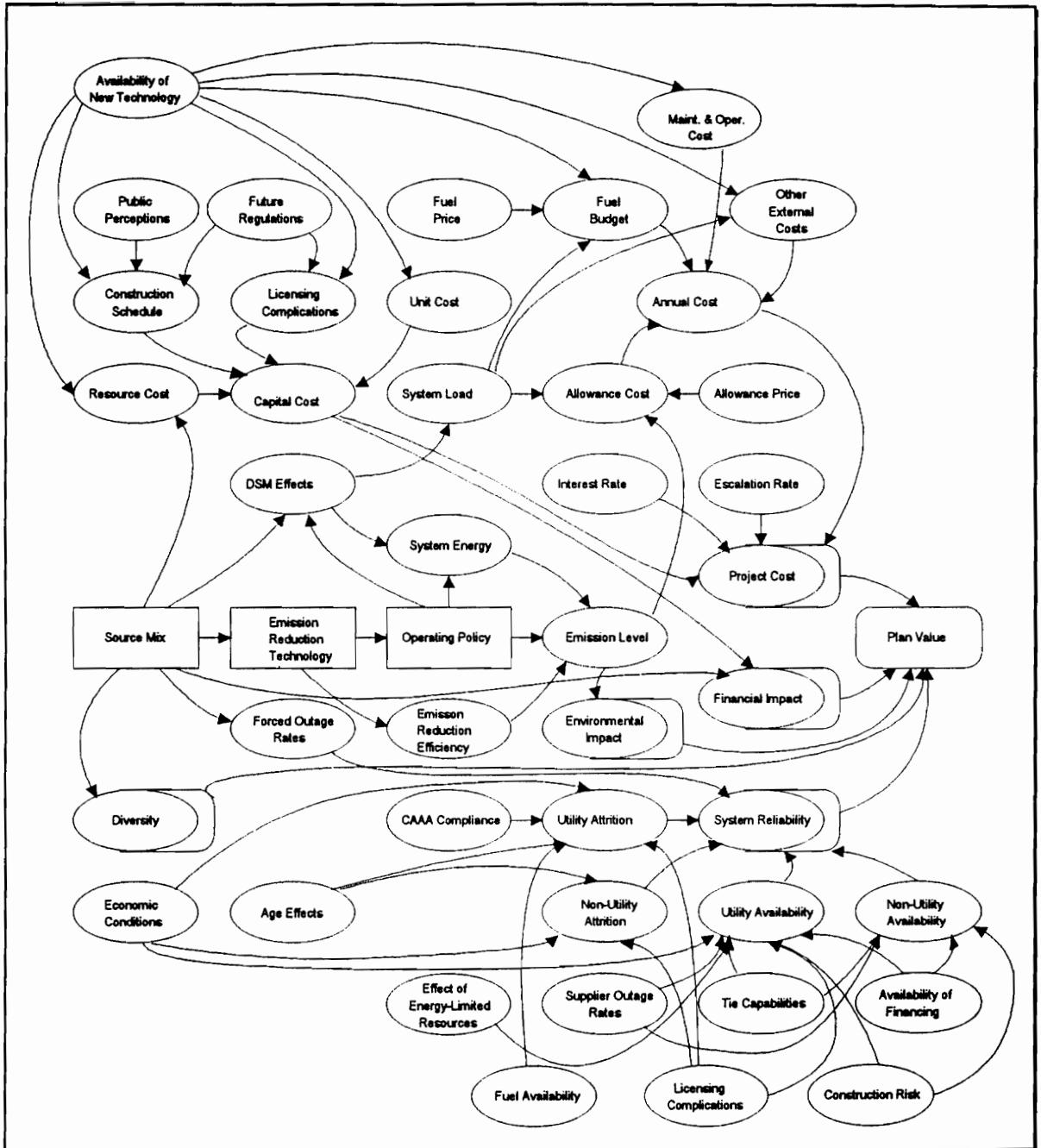
Figure 4.2. Sample influence diagram for multi-attribute decision analysis.

The following is an example of how these will be used in estimating attribute weights. Assume that only cost, reliability and emissions are considered. Say you give the following weight ratios:

Cost vs. reliability   1/5 (Reliability is five times more important than cost.)

Cost vs. emissions   1/5

Reliability vs. emissions   3 (Note that the ratios need not be consistent.)

The following matrix results:

	C	R	E
C	1	1/5	1/5
R	5	1	3
E	5	1/3	1

where C is cost, R is reliability and E is emissions.

Solving for the eigenvector of this matrix gives the ranking of the three attributes, thus:

C	0.1240
R	0.8943
E	0.4299

or C has a normalized weight of 0.0856, R has 0.6175 and E has 0.2969.

4.2.3 Perform AHP to Identify Relevant Uncertainties.

This step also uses the analytic hierarchy process, this time as a screening technique to determine which uncertainties have a considerable impact on the solution. The decision maker (DM) does pair-wise comparisons of the impacts of the different uncertainties, forming a judgment matrix. Evaluation of the eigenvector of the judgment matrix provides weight rankings. Those uncertainties that score low will be eliminated. We distinguish between the importance of

a factor and the importance of its uncertainty, i.e., the DM will decide whether the expected variations of the factor will affect the plan.

The analytic hierarchy process (AHP) is based on the eigenvector method (EVM). It allows us to model the effects of different factors affecting the uncertainty. In essence, the elements in each level of the hierarchy are given weights based on their impacts on the next higher level. The weight of each factor at the lowest level is then determined by multiplying the weights through its path to the highest level.

Consider the simple hierarchy of Figure 4.3 for the availability of system capacity. The uncertainties affecting system availability are plant attrition, plant availability, growth of load demand and growth of energy requirements (Level 2). In turn, these factors are affected by uncertainties on the possibility of new regulations and how they will affect the system, changes in economic conditions, age effects on the performance and reliability of the plants, and DSM impacts mainly on load demand and energy (Level 3).

Say that the judgment matrices and eigenvectors (weights) obtained for Levels 2 and 3 are as given in the following:

Level 2:

Factor	At	Av	MW	kWh		W	W_n**
Plant Attrition (At)	1	1/3	1/9	1/7	$W_{1,2}$*	0.0699	0.0451
Plant Availability (Av)	3	1	1/5	1/3	$W_{2,2}$	0.1708	0.1102
Growth of Demand (MW)	9	5	1	3	$W_{3,2}$	0.8885	0.5734
Growth of Energy (kWh)	7	3	1/3	1	$W_{4,2}$	0.4202	0.2712

*$W_{i,j}$ represents the relative weight of factor i in level j.

**W_n is the normalized eigenvector, i.e., $(\Sigma_i W_{i,l} = 1)$.
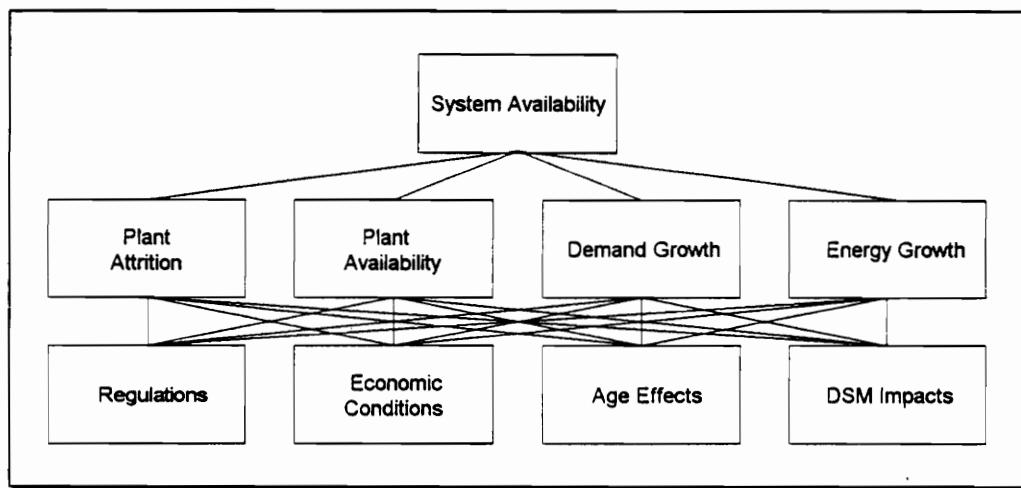
Figure 4.3. Sample Hierarchy for Availability of System Capacity

Level 3:

For Plant Attrition

Factor	R	E	A		W	Wn
Regulations (R)	1	1/5	1/9	$W_{1,3}^{1,2}{}^{*}$	0.0868	0.0629
Economic Conditions (E)	5	1	1/3	$W_{2,3}^{1,2}$	0.3662	0.2655
Age Effects (A)	9	3	1	$W_{3,3}^{1,2}$	0.9265	0.6716

$^{*}W_{k,l}^{i,j}$ represents the relative impact of factor k in level l on factor i in level j (= l - 1).

For Plant Availability

Factor	R	E	A		W	Wn
Regulations (R)	1	7	3	$W_{1,3}^{2,2}$	0.9140	0.6491
Economic Conditions (E)	1/7	1	1/5	$W_{2,3}^{2,2}$	0.1013	0.0719
Age Effects (A)	1/3	5	1	$W_{3,3}^{2,2}$	0.3928	0.2790

For Growth of Demand

Factor	R	E	D		W	Wn
Regulations (R)	1	1/7	1/5	$W_{1,3}^{3,2}$	0.1013	0.0719
Economic Conditions (E)	7	1	3	$W_{2,3}^{3,2}$	0.9140	0.6491
DSM Impacts (D)	5	1/3	1	$W_{4,3}^{3,2}$	0.3928	0.2790

For Growth of Energy Requirements

Factor	R	E	D		W	Wn
Regulations (R)	1	1/9	1/5	$W_{1,3}^{4,2}$	0.0759	0.0581
Economic Conditions (E)	9	1	5	$W_{2,3}^{4,2}$	0.9599	0.7352
DSM Impacts (D)	5	1/5	1	$W_{4,3}^{4,2}$	0.2699	0.2067

The relative weights of the factors in level l are then calculated by using the equation:

$$W_{k,l} = \sum_{i=1}^{l} W_{i,l-1} * W_{k,l}^{i,l-1} \qquad (4.1)$$

Using this equation gives the following vector of weights which might then allow us to eliminate uncertainties due to factor 3,3 (age effects) in the given example because its total impact is small compared to the rest.

Factor	Weight
$W_{1,3}$	0.1314
$W_{2,3}$	0.5915
$W_{3,3}$	0.0611
$W_{4,3}$	0.2160

4.2.4   Generate Influence Diagram.

This step involves generating a smaller, more manageable influence diagram. This diagram will include only those attributes and uncertainties selected in the previous sections.

4.2.5   Calculation of Probability Distributions of Uncertainties.

This step involves determining the discrete probability distributions of the different uncertainties based on the expert judgment of the planner.

Referring to the three-node network of Figure 4.4, consider generating the probabilities for child states c_1, ..., c_5 for a given combination of the parent node states, say p_{11} and p_{21}. A combination of parent node states comprise an environment, and the child node states are the events whose probabilities are to be estimated. Use of the EVM in the estimation of probability involves the pairwise comparison (using judgment ratios) of the likelihoods of occurrence of the different possible states of node C, say c_1 and c_2, for a given combination of the parent node states (environment). The analysis of the judgment matrix formed with these ratios will give the relative measure of the likelihood of occurrence of each child state. In other words, the priority vector will give the probabilities of the different states of the child node.

In addition to being simple, this technique has the advantage that the probability estimates are not done individually in isolation. Instead, probabilities are estimated from a number of expert judgments. Therefore, an error in any particular judgment is compensated for by other judgment ratios in the judgment matrix.

Consider now the probability that the load growth of a utility will be at a given level. For illustration purposes say the load is affected by economic factors, customer behavior (including end-use practices and response to technology changes), and DSM impacts. These factors have their own probability distributions. The hierarchy of Figure 4.5 results.
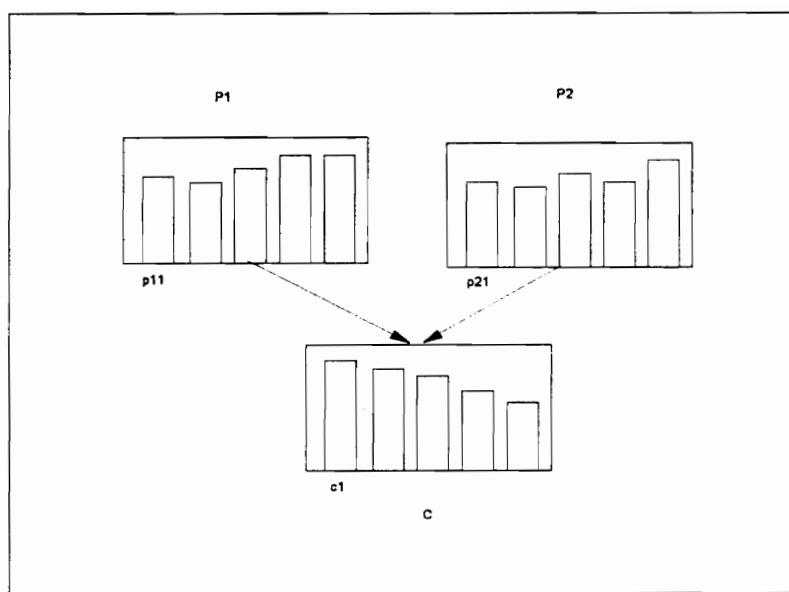
Figure 4.4. Generation of Probabilities.
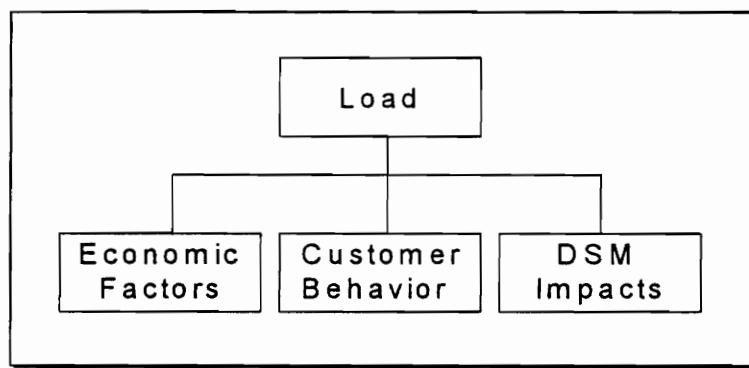
Figure 4.5. Hierarchy for calculating example load probability distribution.

Load uncertainty can be evaluated as follows:

Say the following matrices are found for the factors explaining the load:

Factor	Effect	Prob. High	Judg. Base	Matrix Low	Eigen Vector
Economic	High*	1	1/5	1/3	0.1506
	Base	5	1	3	0.9161
	Low	3	1/3	1	0.3715
Customer Behavior/	High	1	1/7	1/3	0.1067
Technological Advances	Base	7	1	5	0.9628
	Low	3	1/5	1	0.2483
DSM Impacts	High	1	1/5	1/7	0.1013
	Base	5	1	1/3	0.3928
	Low	7	3	1	0.9140

*That is, it will result in higher than base load.

For each combination of factor effects (say "high" economic factor, "low" customer behavior and "low" DSM impacts) we perform another pairwise comparison of likelihoods, eg., we ask the question "How much more likely is it for the load growth to be high (say 4.5%) than base (say 3%)?" This results in a judgment matrix such as the one below for each combination.

	high	base	low		W
high	1	1/3	1/7		0.1067
base	3	1	1/5		0.2483
low	7	5	1		0.9628

This means that if economic factors result in higher load growth, customer behavior results in lower load growth and DSM effects result in lower load growth, the system load growth will have the following discrete probability distribution:

high	0.0810
base	0.1884
low	0.7306

The probability distributions developed for these uncertainties provide inputs for the ensuing decision analysis (using either decision trees or influence diagrams).

4.2.6 Calculation of Attribute Values.

Simulations for each scenario involve production costing runs. These calculations determine the values of the attributes of the scenario. These simulations use EGEAS (Stone & Webster, 1989).

The following paragraphs describe the modeling aspects of these attributes. The section begins with a discussion of the relationship between the preference weights of section 4.2.2 and the trade-off curve. Following that are descriptions of the models proposed to represent these attributes, to wit: cost, reliability, flexibility and diversity. The discussion of environmental quality is postponed for Chapter 5.

4.2.6.1 Preferences, Weights and the Trade-off Curve

In the trade-off curve of Figure 4.6, the squares represent the different expansion plans, plotted against their values in terms of attributes A and B (attribute values need not have the same scales, i.e., attribute A can be the present value of the total plan cost in dollars while
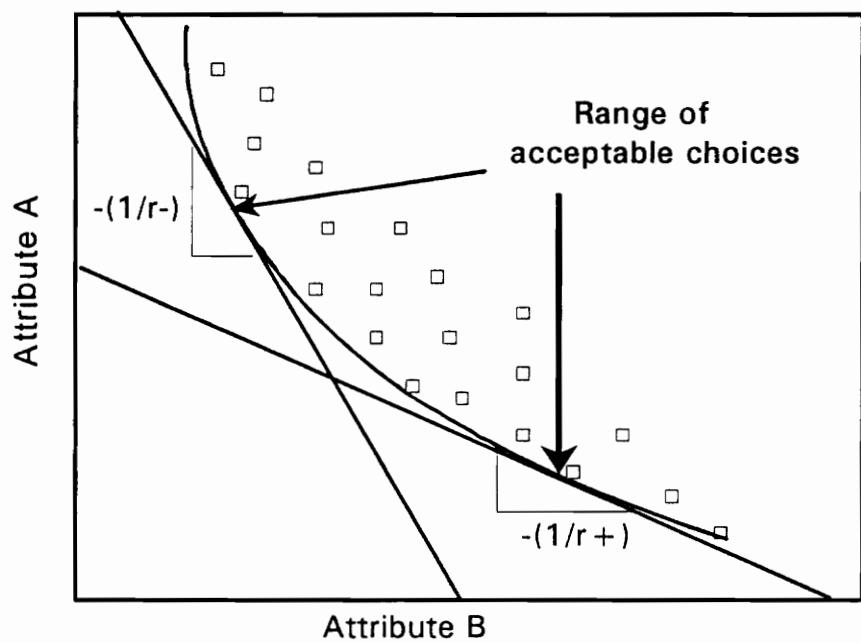
Figure 4.6. Trade-off curve and attribute weight ratios.

attribute B can be emissions in tons of SO_2). The trade-off curve comprises the non-dominated plans. A plan p is non-dominated (for minimization) if $A_p < A_q$ when $B_p \geq B_q$ and $B_p < B_q$ when $A_p \geq A_q \; \forall \; q$. The trade-off curve can be visualized in an n-dimensional space for the n attributes. Each point on the curve is a function of m attribute variables, i.e.:

$$AV_p = f(x_1, x_2, \dots x_k, \dots x_m), \; p = 1, 2 \dots n \qquad (4.2)$$

Trade-off functions $T_{ij}(x)$ can be drawn between the ith and jth variables, which can be calculated from the equation (Haimes, 1974):

$$T_{ij}(x) = \frac{df_i(x)}{df_j(x)} \qquad (4.3)$$

$$\text{where} \quad df_i(x) = \sum_{k=1}^{n} \frac{\partial f_i(x)}{\partial x_k} dx_k$$

Once the solutions at the frontier of non-dominated plans have been identified, the problem remains of selecting from among them. Classical optimization using weight assignments will result in a recommended solution. This, however, does not reflect the variety of values and preferences of the different players in the decision process, nor does it account for inconsistencies in the individual DM's preferences.

The quotient index developed by (Rahman and Shrestha, 1990) provides a middle ground between an exhaustive enumeration of the solutions and a single answer. It permits the definition of an interval within which acceptable solutions will fall (a confidence interval). In effect, priority rankings (weights) among the attributes will be calculated through hierarchical analysis (Appendix B):

$$[A] w = \lambda_{max} \; w \qquad (4.4)$$

where [A] is the matrix formed by the pairwise comparison of the attributes and w is the vector of priority or preference rankings.

The procedure in Appendix B gives the composite priority weights and their variances. Extending this to the ratios of the attributes, it is possible to estimate each ratio r and its variance. Thus, given a desired level of confidence, the confidence interval can be estimated, to wit:

$$r_i - t_{m-1,\frac{a}{2}} \hat{\sigma}_{r_i} \leq r_i \leq r_i + t_{m-1,\frac{a}{2}} \hat{\sigma}_{r_i} \tag{4.5}$$

or
$$r_i^- \leq r_i \leq r_i^+$$

These ratios (r's) can be viewed as slopes of isoprofit lines that provide the range of acceptable choices in the (inverse) production possibilities set representing the attribute trade-off curves. Appendix C discusses this in more detail.

4.2.6.1 Cost

Production costing simulations are performed using EGEAS (Stone and Webster, 1989). EGEAS uses the present worth of revenue requirements. These include capital investments and operating expenses. Summed over all years of both study and extension periods, these can also be transformed to a $/MWh basis by dividing the cost through by the total energy production over the planning period.

4.2.6.2 Reliability

EGEAS uses four measures of reliability: reserve margin, loss-of-load probability (LOLP), relative LOLP and expected unserved energy (EUSE). Reserve margin is the precentage of the excess of generating capacity over peak load. LOLP is the amount of time that the system demand exceeds capacity. Relative LOLP is the ratio of the benchmark LOLP to the study year LOLP. Unserved energy is the area under the equivalent load duration curve remaining after all units have been loaded. The most common bases are LOLP and EUSE.

4.2.6.3 Diversity

Utilities prefer to have a diverse portfolio as a hedge against fuel price fluctuations and restrictive legislation. A possible measure of diversity is the equation:

$$Diversity = \frac{\%_{max} - \%_{min}}{\%_{ave}} \tag{4.7}$$

where $\%_{max}$ is the highest percentage of resource share

$\%_{min}$ is the lowest percentage of rasource share; and,

$\%_{ave}$ is the average of the resource shares.

4.2.6.4 Flexibility

Brancart, et al. (1991) espouse the use of system flexibility as a criterion of planning instead of robustness. The reason is that designing a system to adapt to possible parameter changes would be much less expensive than giving it the ability to cope with all possible scenarios. Flexibility can be incorporated at two levels of planning: in the short-listing of alternative generation and transmission technologies, and in the actual evaluation of combinations of expansion options. Brancart, et al. (1991) give a good discussion of the former. The following discussion looks into the consideration of flexibility in the latter.

A possible model would quantify the flexibility of a system in terms of the amount of additional "cost" necessary for plan i to respond to scenario j conditions. It would then be possible to construct a matrix C_k of these costs for each stage k in the planning period. The expected cost of flexibility for plan i, denoted by C_{ik}, for each stage k would be the internal product of the ith row and the vector of probabilities of occurrence of the j scenarios:

$$C_{ik} = \sum_{j=1}^{J} p_j \, C_{ijk} \qquad\qquad (4.8)$$

where J = number of scenarios.

The present value of all of these costs for plan i will be:

$$C_i = \sum_{k=1}^{K} \frac{C_{ik}}{(1+r)^{k-1}} \qquad\qquad (4.9)$$

where r = discount rate

and K = number of stages.

The values of C_{ik} will account for over-investments on one hand, and unserved energy and additional capital requirements on the other.

4.2.7 Influence Diagram Simulation.

Out of the list of possible alternatives, Influence Diagram analysis gives the optimal solution that accounts for the preferences/weights generated in the previous step.

Analysis of the planning model can proceed once the necessary states and corresponding probabilities are determined. In a decision tree structure, this will involve the evaluation of combinations of the different states of the chance nodes by taking a backward path in the decision tree to each state of the first decision node. In an influence diagram structure, this involves reducing the network through a series of node eliminations using the rules developed by Shachter (1986). This procedure is summarized in the following paragraphs.

4.2.7.1 Influence Diagram Solution Procedure

The evaluation of the influence diagram involves its transformation by the removal of nodes until only a decision node and a value node remain. Such transformations must conform to the rules of probability so that the diagram remains feasible, i.e., the optimal policy and the joint distribution of the diagram remain the same. When this requirement is met, the reduction is

called a value-preserving reduction. Three node-removal steps are actually involved -- barren node removal, chance-node removal and decision node removal.

Barren node removal

A barren node is a chance or decision node that has no successors. These nodes have no effect on value and may be removed from the diagram. This is equivalent to the removal of irrelevant variables in a decision tree.

Chance node removal

If a chance node precedes only the value node, then the chance node can be removed using conditional expectation. As a result, the value node inherits all the conditional predecessors of node i, creating no new barren nodes. A chance node with other successors may be transformed to meet this condition by applying Bayes' rule to reverse the conditioning arcs between the node and its successors.

Decision node removal

A decision node may be removed if it is a conditional predecessor of the value node, and all of the other conditional predecessors of the value node are informational predecessors of the decision node (i.e., all other conditional predecessors of the value node must have been removed first). The decision node is removed by maximizing expected value. No new conditional predecessors are inherited by the value node as a result of this operation. Once all the predecessors of the value node have been removed, the process ends.

4.2.7.2 Illustrative Example

The following example illustrates the influence diagram solution procedure. Figure 4.7 is an influence diagram of a "Go" or "No Go" utility decision for instituting a DSM program (D1). If the decision is "Go", the next decision to be made is between the types of incentives that will be

used, i.e., between pricing (tariff) and the financing of customer DSM/energy conservation equipment (D2). The penetration level (C3) of the DSM technology among customers is conditioned on these decisions and on the cost of the system (C2) and the fuel price (C1). The net income to the utility is a function of the decisions D1 and D2, of the fuel price (C1) and the penetration level (C3).

Decision Tree Analysis Method

Figure 4.8 shows the equivalent decision tree diagram of the problem. This can be solved with the standard averaging out and folding back procedure (Raiffa, 1968). For the given example, this yields a net income of $ 3 359 180 for a "go" decision using financing as an incentive.

Shachter's Method

Shachter's evaluation method reduces the influence diagram using probability theory until only decision and value nodes remain. This normally requires reversal of arcs to meet the conditions needed for node removal. Such reversal is effected using Bayes' Theorem (Equation 3.20). The following paragraphs show this procedure.

Again referring to Figure 4.7, the system cost node is seen as the foremost candidate for node removal. This requires reversal of the arc from C2 to C3, making the C2 node barren. When this is done, Bayes' Theorem requires the addition of the predecessors of C3, i.e., C1 and D1, among the predecessors of C2, yielding Figure 4.9. At the same time the probability values for C3 should incorporate the effects of removing the cost node.

The original conditional probabilities for nodes C1, C2 and C3 are given in Table 4.1 and Table 4.2, respectively.

Table 4.1

Probabilities of System Cost and Fuel Prices

State	System Cost	Fuel Price
High	0.2583	0.1047
Base	0.6370	0.6370
Low	0.1047	0.2583

Table 4.2

Conditional Probabilities of Penetration Level on Cost, Fuel Price and Decision

Incentive		Tariff			Financing		
Fuel Price		High	Base	Low	High	Base	Low
Cost	**Penetration**						
High	High	0.0810	0.0581	0.0486	0.1562	0.1047	0.0810
	Base	0.1884	0.2067	0.1652	0.1852	0.2583	0.1884
	Low	0.7306	0.7352	0.7862	0.6586	0.6370	0.7306
Base	High	0.1007	0.1047	0.1634	0.1794	0.1852	0.1515
	Base	0.6738	0.6370	0.5396	0.6782	0.6586	0.6301
	Low	0.2255	0.2583	0.2970	0.1424	0.1562	0.2184
Low	High	0.6491	0.6370	0.6250	0.7085	0.3090	0.4806
	Base	0.2790	0.2583	0.2385	0.2311	0.5816	0.4054
	Low	0.0719	0.1047	0.1365	0.0604	0.1094	0.1140
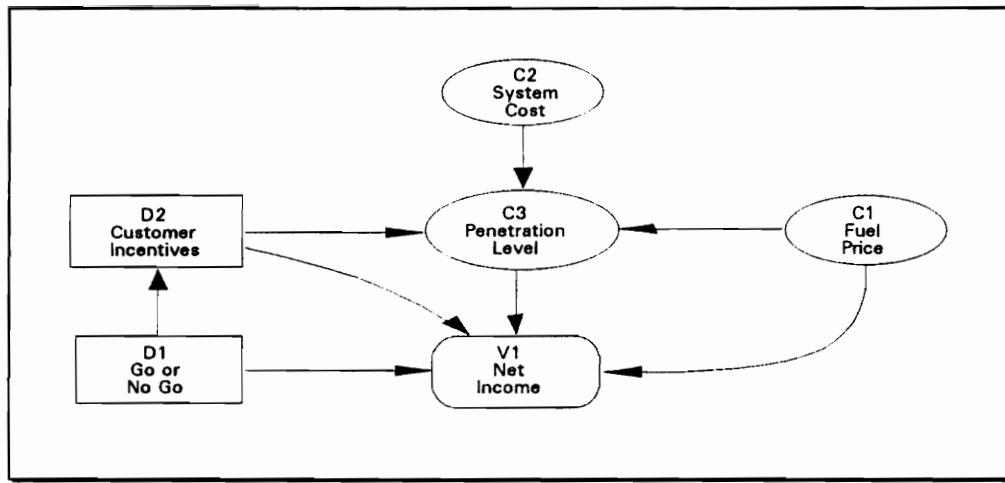
Figure 4.7. Influence Diagram for DSM Go or No-Go decision for the utility
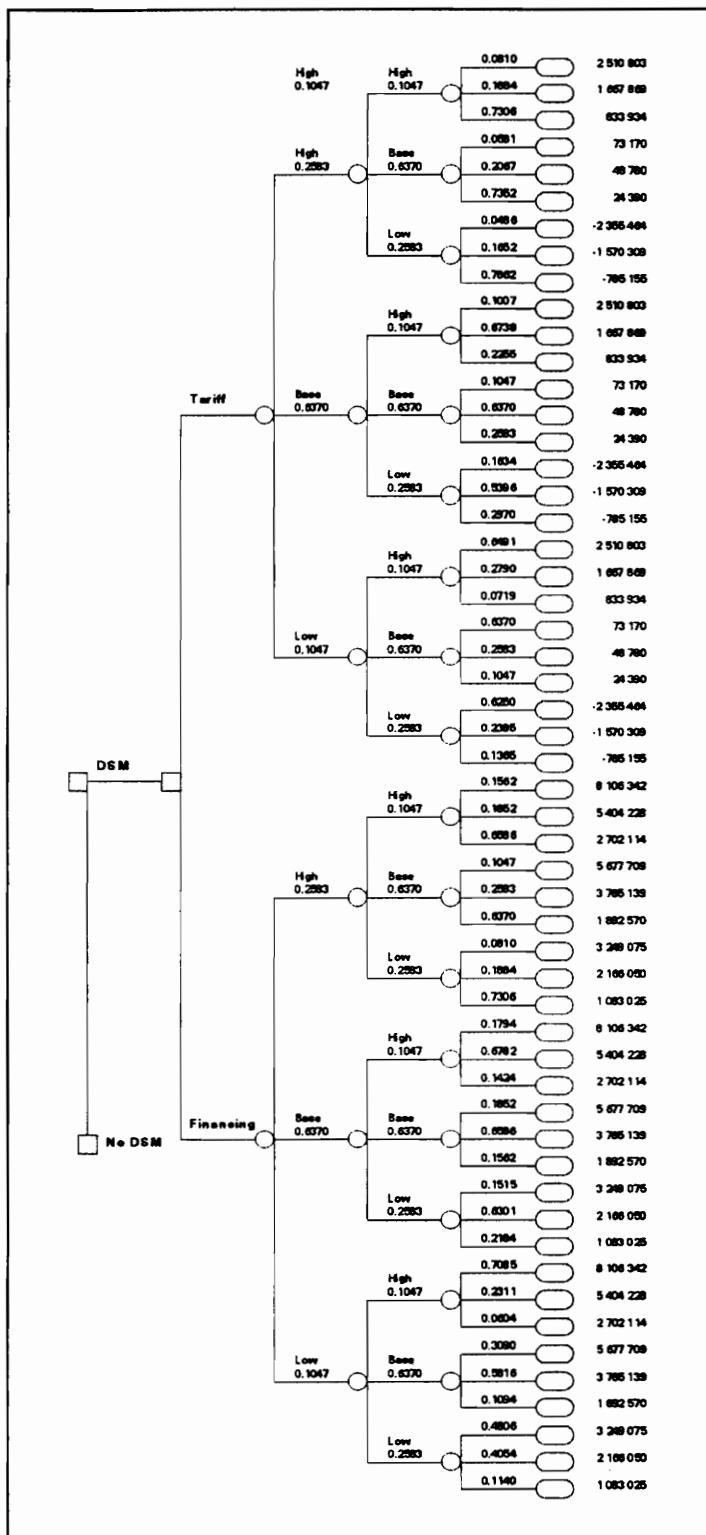
Figure 4.8 Decision Tree of decision problem of Figure 4.7.
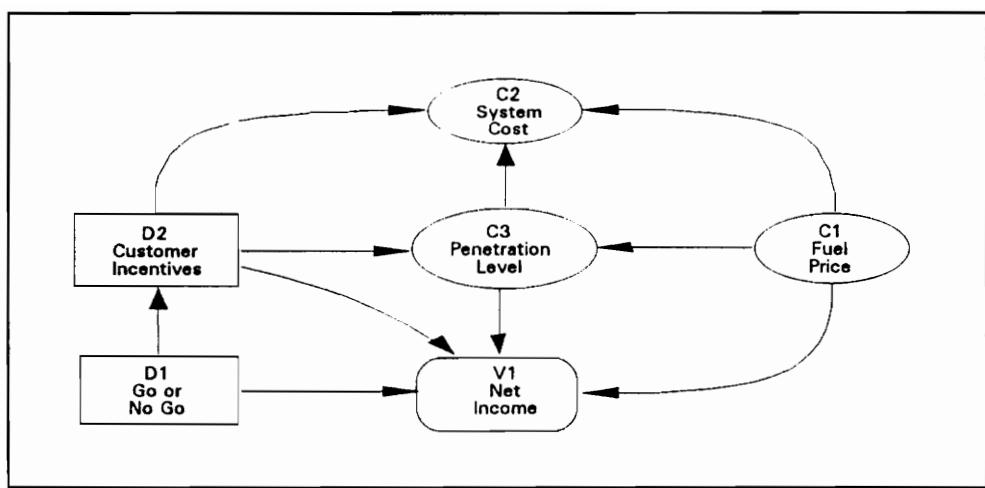
Figure 4.9 Influence Diagram on reversal of C2-C3 arc.

To effect arc reversal, the conditional probabilities for system cost would normally have to be calculated. For the example, however, there is no need to do so because the cost node is now barren. The conditional probabilities for penetration level (C3) are calculated as follows:

P(C3=High | D2=Tariff, C1=High) = P(C3=High | D2=Tariff, C1=High, C2 = High) +

P(C3=High | D2=Tariff, C1=High, C2 = Base) +

P(C3=High | D2=Tariff, C1=High, C2 = Low)

= 0.0810(0.2583) + 0.1007(0.6370) + 0.6491(0.1047)

= 0.1530

Calculation of the rest of the probabilities yields the conditional probabilities of Table 4.3.

Table 4.3

Conditional Probabilities of Penetration Level on Fuel Price and Decision

	Tariff			Financing		
Fuel Price	**High**	**Base**	**Low**	**High**	**Base**	**Low**
Penetration						
High	0.1530	0.1484	0.1821	0.2288	0.1774	0.1677
Base	0.5071	0.4862	0.4114	0.5040	0.5471	0.4925
Low	0.3399	0.3654	0.4065	0.2672	0.2755	0.3398

The reduced influence diagram of Figure 4.10 and the decision tree of Figure 4.11 now result. Further reduction can be obtained by reversing the from C3 to V1. This is equivalent to folding back in the decision tree of Figure 4.11 and gives Figures 4.12 and 4.13. Elimination of the C1 node ultimately yields Figures 4.14 and 4.15.
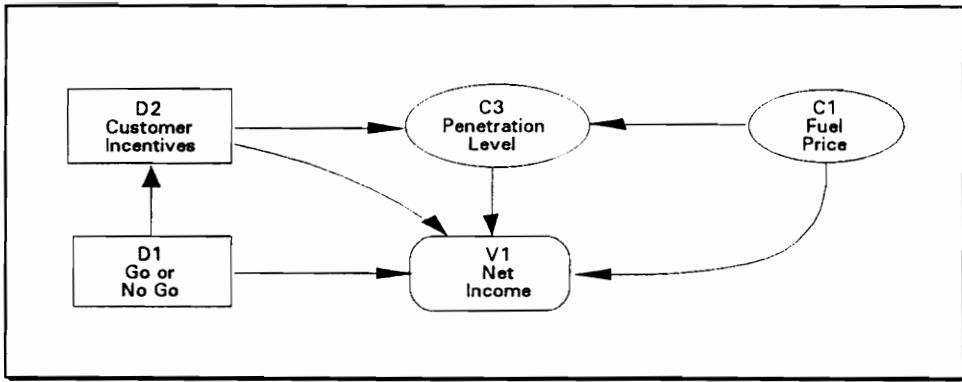
Figure 4.10   Reduced influence diagram of figure 4.9
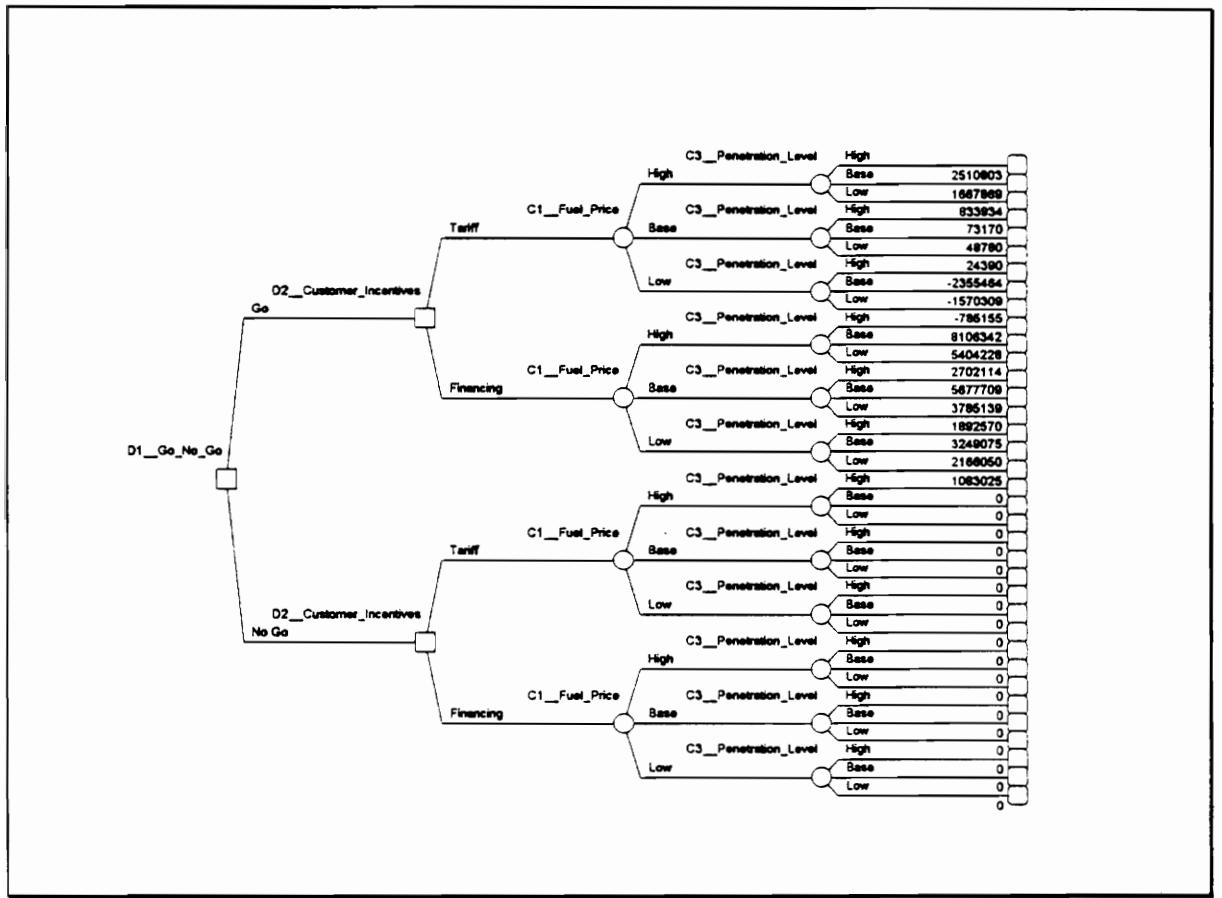
Figure 4.11   Decision Tree of Figure 4.10
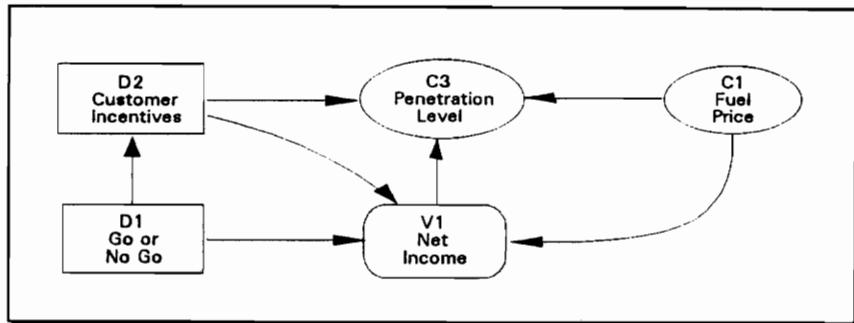
(a)   Influence diagram after reversal of C3-V1 arc
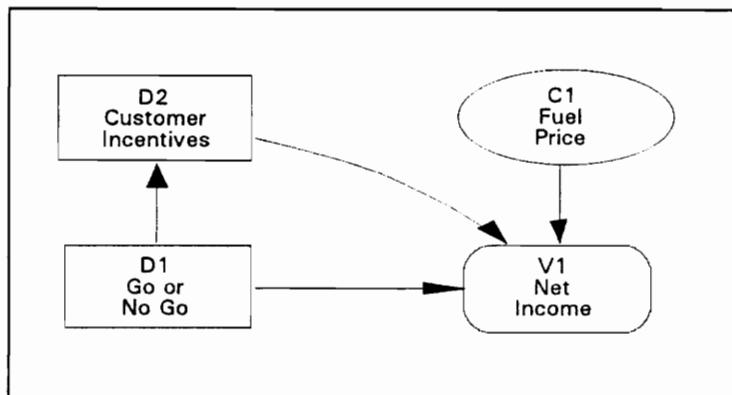
(b)   Reduced influence diagram

Figure 4.12   Arc reversal and reduced influence diagram of figure 4.10
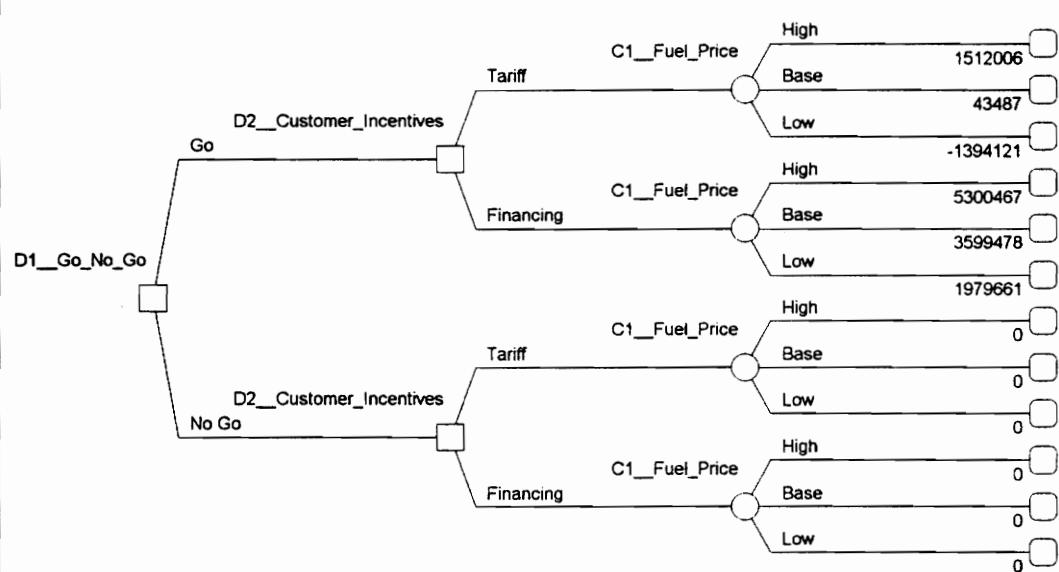
Figure 4.13   Decision Tree of Figure 4.12
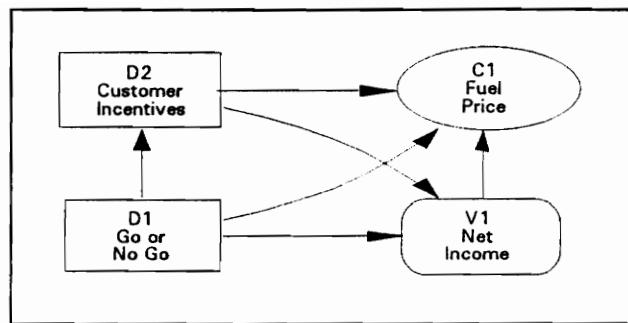
(a) Influence Diagram after reversal of arc from C1
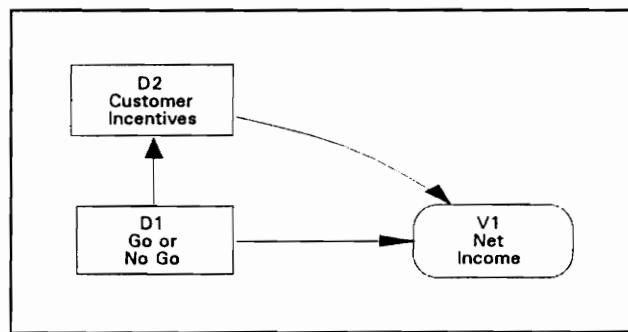
(b) Influence Diagram after removal of fuel price node (C1)

Figure 4.14   Reduced Influence Diagram of Figure 4.12
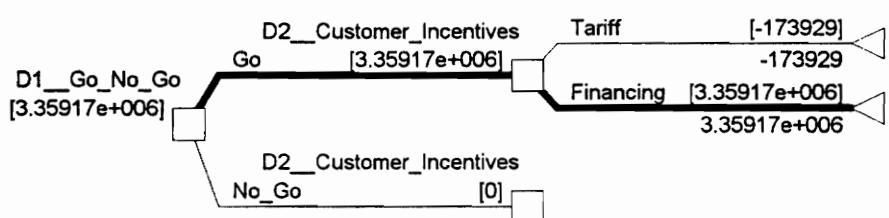
Figure 4.15   Decision Tree of Figure 4.14

Chapter 5

Environment-Sensitive Planning

The quality of the environment is fast becoming an attribute of concern in utility planning. This attribute is unique for two reasons. Firstly, the uncertainties attendant to the issue of environmental impact of electricity generation, while not new, are quite complex. Emissions, being an externality, and more importantly because they are a public "bad", are less determinable and manageable than other uncertainties that the utility industry is facing. Secondly, it is not known how recent legislation and the market for emissions that it creates will perform. Uncertainties in the price of emission allowances need to be addressed, and the possible impact of additional legislation and implementing regulations must be considered.

The modeling of the environmental impact of the generation expansion plan must be considered. Indeed, it is tempting to rely on valuation of emissions based on market prices which are expected to be closely linked to the cost of control, since it is both convenient and very practical from the utility point of view. Such valuation, however, is based on two assumptions - one that the emission cap stipulated in CAAA is optimal and acceptable, and the other that emissions not included in the Act have zero cost. It is obvious that these assumptions may not

be realistic in many situations, and the players in the market place may have other options to consider. Thus, there is a need to provide a more representative model of emissions in evaluating expansion alternatives.

This chapter deals with the modeling of environmental uncertainty in the context of this new focus. The first section deals with the particular role played by electricity in the production and control of emissions. The next then delves on the impacts that these emissions have on the environment and on those that rely on such environment for their survival. Sections three and four then focus on the control of emissions at the policy level and at the utility level, and how these measures are implemented in the U.S. The last section deals with the impacts of these activities on the operation of electric utilities and their modeling in utility planning.

5.1   Electricity Generation and the Environment

5.1.1   The Global Generation of Electricity

Table 5.1 gives the expected global electric energy generation based on growth experienced over the last decade. At the beginning of this decade, the world's electricity generation was a little more than 12 billion megawatt-hours (MWh) (Levine, 1993). During the last decade, the world's electricity generation grew by 3.6% on the average. While the growth in electrical demand in the industrialized countries was in the neighborhood of 3%, the electricity requirements of developing countries increased by 7% annually, on the average. Developing countries will require around 1 300 000 MW of new generating capacity in the next 15 years (Can Independent Power ..., 1989) to serve their growing economies and populations. The world currently spends around $100 billion per year on new generation capacity (Yeager, 1992), with the developing countries accounting for some $50 to $60 billion. To meet the growing demand, developing countries will have to raise this figure to $125 billion per year (Can Independent Power ..., 1989). The investments required for the developed world, however, are still

substantial. If current trends continue, the countries of the Organization for Economic Cooperation and Development (OECD) will need to add about 400 000 MW of new generating capacity in the next 15 years.

Table 5.1

World Electric Energy Projections

Region/ Country	1991 Gen. (TWh)	1981-1991 Growth (%)	1995 Projn. (TWh)	2000 Projn. (TWh)	2005 Projn. (TWh)
OECD Countries	**7 247**	**3.0**	**7 656**	**8 475**	**9 382**
No. America	3 721	2.8	3 907	4 278	4 684
Europe	2 449	2.9	2 618	2 915	3 246
Pacific*	1 077	4.3	1 134	1 277	1 438
Non-OECD Countries	**4 833**	**4.6**	**5 847**	**7 545**	**9 752**
Africa	330	4.7	396	497	624
Latin America	632	5.4	779	1 011	1 312
Asia**	542	8.9	762	1 116	1 784
China	680	8.2	870	1 200	1 510
India	309	9.0	436	670	1 030
Europe	429	1.1	447	471	496
Former USSR	1 682	2.4	1 849	2 083	2 347
Middle East	229	7.7	308	447	649
World	**12 080**	**3.6**	**13 503**	**16 020**	**19 134**

*Japan, Australia and New Zealand.
**Excluding China and India.
***Country submissions for OECD (IEA, 1993a; IEA, 1992), projected from 1981-1991 growth for non-OECD except China (IEA, 1993b;Guangyao, 1993). 2005 projections are all based on past growth except for China.

The estimates in Table 5.1 show a projected increase in the global electricity production from 12 080 billion kWh in 1991 to 19 134 billion kWh in 2005. More than 60% of the world's electricity is generated by burning fossil-fuels (Table 5.2). These combustion processes produce carbon dioxide (CO_2) which are major contributors to global warming. Coal combustion, which accounts for 60% of total fossil generation, also emits sulfur dioxide (SO_2) and nitrous oxides (NOx) which produce acid rain and, in the case of the latter, are also possibly involved in the depletion of the ozone layer. These will be discussed in more detail in section 5.2. This section deals with the particular role that electricity has in the energy balance and in emission reduction.

Table 5.2

Percentages of Electricity Generation by Fuel Type for Selected Countries (1991)*

Country/ Region	Million MWh	Coal	Oil	Gas	Nuclear	Hydro/ Others
World	12 080	38.4	11.3	13.5	17.6	19.2
OECD	7 247	40.3	8.6	10.6	23.7	16.8
Australia	157	76.9	2.4	10.4	0.0	10.3
Canada	508	18.0	2.6	2.0	16.7	60.7
France	455	8.9	3.1	1.4	72.9	13.5
Germany	539	58.1	2.7	8.4	27.3	3.4
Italy	222	13.3	47.0	17.7	0.0	22.0
Japan	888	14.5	30.1	19.3	24.0	12.1
Norway	111	0.3	0.0	0.1	0.0	99.6
Spain	156	38.1	6.5	1.5	35.7	18.2
Sweden	148	2.6	1.4	0.7	52.2	43.1
U K	322	65.1	9.3	1.8	21.9	1.9
U S	3 213	54.6	3.9	11.9	20.2	9.4
Non-OECD	4 833	35.7	15.4	17.8	8.4	22.7
Bangladesh	8	0.0	19.7	70.1	0.0	10.1
China	680	73.7	7.5	0.4	0.0	18.4
India	309	71.3	3.9	1.3	1.7	21.8
Indonesia	39	31.1	48.4	3.5	0.0	17.0
Nepal	1	0.0	3.0	0.0	0.0	97.0
Philippines	27	7.3	51.8	0.0	0.0	40.9
Poland**	135	95.9	1.1	0.4	0.0	2.5
Saudi Arabia	66	0.0	62.1	37.9	0.0	0.0
Singapore	17	0.0	100.0	0.0	0.0	0.0
South Africa	168	92.3	0.0	0.0	5.4	2.3
Former USSR**	1 682	24.3	13.9	33.4	12.6	15.8

*Calculated from data on electricity production from fossil fuels from OECD and UN reports (IEA, 1993a; IEA, 1992; IEA, 1993b; Economic Commission for Europe, 1993).
**Data for the former USSR and Eastern Europe were based on incomplete official data.

The continued growth in electrical demand raises concerns about the ability of the environment to sustain this development without harm to itself. Roughly 63% of the world's electricity is obtained by burning fossil-fuels, 60% of which is coal. In other words, about 38% of

all electricity is generated by coal. Coal and other fossil-fired plants emit carbon dioxide, sulfur dioxide and nitrous oxides which are known contributors to either global warming or acid precipitation, or the depletion of the ozone layer. Fossil plants also emit toxic chemicals aside from heat and ash. In spite of this fact, and also because of it, electricity is an important factor in the supply of clean energy. The following paragraphs illuminate this (Yamaji, 1991).

5.1.2 The Role of Electricity in the Environment

5.1.2.1 The Role of Electricity in Supplying Clean Energy

Electricity has a large share in the energy system. It consumes far more primary fuels than any other single industry. Because of this, implementing emission control measures in the industry will result in considerable reductions in overall emissions.

Centralized use of fossil fuels can take advantage of economies of scale, both in terms of efficiency and in the use of emission control technologies. It is also worth noting that although there are generation and transmission losses, electrification, particularly in industrial processes, usually contributes to overall efficiency improvements.

Electricity likewise allows the economical use of non-fossil energy sources. Many non-conventional sources of energy, such as hydro, geothermal, wind power, tidal power, wave power and ocean thermal energy conversion are site-specific, and need the electrical transmission system to make them available to consumers. Even nuclear and solar power, due to safety and space considerations, respectively, are subject to site constraints.

5.1.2.2 Efficiency Improvements in Electricity Supply

In terms of supply, conventional thermal efficiencies have stabilized at around 35%-40% (electrical energy produced out of total energy in the fuel). However, centralized electricity generation permits the use of larger, more efficient plants due to economies of scale. Also, new

technologies are coming with higher efficiencies. Combined cycle plants generate electricity with more than 40% efficiency. Ceramic blade gas turbines can deliver power at 50% efficiency. Molten Carbonate and Solid Oxide Fuel Cells (MCFC and SOFC) have close to 60% efficiency.

There is also the possibility of direct energy conversion with magnetohydrodynamic generation in the future. In addition, electricity is still one of the most efficient, if not the most efficient, means of transporting energy.

Electricity storage systems allow the efficient operation of base load plants. They permit the operation of thermal plants near rated capacity by acting as a load in the system when the demand is low, and generating during the peak periods.

Cogeneration systems also allow for higher conversion efficiencies by producing both heat and power at the same time. The existence of a strong electrical network ensures the optimum use of this capacity.

5.1.2.3 Efficiency Improvements in Electricity End Use

Another vehicle for cleaner energy through electricity use is the improvement of end-use efficiencies. Among the more promising end uses are lighting, electric household appliances, heat pumps, motors and industrial electric furnaces.

The conventional fluorescent lamp consumes less than one-third the energy used by an equivalent incandescent lamp and lasts five times longer. With the introduction of rare earth fluorescent, low temperature compact fluorescent lamps and high-frequency electronic ballasts, efficiencies 50% more than those of conventional fluorescent lamps have been attained.

Efficiency improvements in electric appliances such as refrigerators, televisions and air conditioners have also been achieved. Efficiency improvements of 45% have been reported for

color TV sets, 60% for air conditioners and 66% for refrigerators and freezers over 1973 figures in Japan.

Use of heat pumps for hot water supply and space heating results in much less energy consumption than resistive heaters, and have been claimed in some cases to be more economical than gas heaters (Guha, 1994). With their introduction to the industry sector, they are becoming more effective in reducing the overall consumption of energy for heating purposes.

Improvements in motor control technology are resulting in increased efficiencies of motor operation even at lower loads. Use of variable speed drives instead of throttling to control fluid flow has also been very effective. The technology also permits the use of electricity in the transport sector.

There have been reductions in the specific energy consumption of electric arc furnaces. Use of microwave and far infrared rays is also promising. Household use of the microwave oven has reduced electricity consumption for cooking and there is already talk of microwave clothes dryers.

The next section discusses the effects of electricity generation on the environment in terms of the greenhouse and acid rain emissions of power plants.

5.2 Impacts on the Environment

5.2.1 Emissions from the fossil generation of electricity

The generating plant exhaust stream consists mainly of gases derived from the major elements of the fossil fuel. These include water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2) and some of the nitric oxide (NO). However, the remaining nitric oxide is produced by oxidation of nitrogen molecules in the air used in the burners and not from nitrogen in the fuel. The other exhaust gases include small quantities of hydrogen chloride (HCl),

nitrogen dioxide (NO_2), nitrous oxide N_2O, carbon monoxide (CO) and sulfur trioxide (SO_3). Table 5.3 shows the concentrations of these constituents. The table shows that the major components of the flue gas aside from air and water vapor are carbon dioxide, sulfur dioxide and the nitrogen oxides. From here on, we shall focus on these emissions and their impacts on the environment.

Table 5.3

Chemical composition of stack emissions
from a typical modern coal-fired power station (2000 MW)

Air (oxygen depleted)	~80%
H_2O	~4.5%
CO_2	~12%
CO	40 (max. 1000) p.p.m.
SO_2	1000-1700 p.p.m.
SO_3	1-5 p.p.m.
NO	400-600 p.p.m.
NO_2	~20 p.p.m.
N_2O	~40 p.p.m.
HCl	250 p.p.m.
HF	<20 p.p.m.
Particulate material	<115 mg m^{-3}
Hg (gaseous)	3 p.p.b.

Source: Roberts, et al., 1990

CO_2 and SO_2 Emissions

Table 5.3 shows that practically all of the carbon and sulfur emissions are in the form of CO_2 and SO_2. Carbon monoxide emissions are very small and come only as a result of slight inefficiencies in the combustion process. Sulfur trioxide (SO_3) emissions are clearly much less than sulfur dioxide emissions.

Carbon dioxide and sulfur dioxide are obtained from the elements present in the fossil fuel. The amount of CO_2 and SO_2 emissions can therefore be calculated directly from the fuel's carbon and sulfur contents.

The following example illustrates the calculation for carbon dioxide emissions:

Atomic wt. of carbon = 12

Atomic wt. of oxygen = 16

$C + O_2 \rightarrow CO_2$
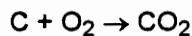
Molecular weight of CO_2 = $12 + 2 \times 16$ = 44. Thus, complete combustion of one ton of carbon produces $3\frac{2}{3}$ tons of CO_2. For one ton of coal having 70% carbon content, the amount of CO_2 emissions would be $(0.7 \times 3.67 =)$ 2.57 tons.

A typical 400 MW coal plant uses more than 800 000 MT of coal per year. If CO_2 recovery equipment (these are not yet required in the CAAA) have 90% removal efficiency, the fraction released would be 0.10. Thus the carbon dioxide emissions will be:

Ton CO_2 emissions = 800 000 x 2.57 x 0.1 = 216 000.

If the same plant above has a 90% efficient scrubber, and the coal has 3% sulfur (atomic weight = 32) content, the annual SO_2 emissions would be:

$S + O_2 \rightarrow SO_2$
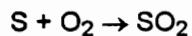
Ton SO_2 emissions = 800 000 x 0.06 x 0.1 = 4 800.

Nitrogen Oxide Emissions (Shannon, 1982)

Nitrogen oxide emissions come from two sources:

a) Nitrogen found in the coal molecule (fuel-bound NO_x))

b) Nitrogen in the air (N_2) oxidized during the combustion process (thermal NO_x)

The amount of fuel-bound N_2 converted to NO_X during combustion varies between 15 and 20% of the nitrogen in the coal. It depends on the characteristics of the coal, the firing systems, furnace conditions, flame patterns and temperatures, burning time and furnace reducing or oxidizing conditions. The fuel-bound component of NO_X emissions can be calculated using a similar method to that for SO_2, this time using the atomic weight of 14 for nitrogen:

$$N_2 + 2O_2 \rightarrow 2NO_2$$
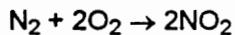
The amount of thermal NOx is dependent on combustion time-temperature factors, furnace combustion conditions - reducing or oxidizing conditions and type of burner and combustion air distribution.

Table 5.4 gives average emissions characteristics of thermal plants throughout the U.S. This table is based on studies sponsored by EPRI (EPRI CSD, 1989).

Table 5.4

Emission Characteristics of Power Plants in the United States (EPRI CSD, 1989)
(grams/kWh)

Plant Type	VOCs	CO	NO$_X$	SO$_2$	CO$_2$
Gas**	0.025	0.20	2.32	0.004	490
			1.00*		
Oil**	0.050	0.19	2.02	5.080	781
			1.00*		
Coal	0.010	0.11	3.54	9.260	1090
			1.00*	2.00*	1030*

*Post-1995
**Assumes a mix of 10% combustion turbines and 90% steam turbines.

Table 5.5 gives estimates of the emissions of carbon dioxide, sulfur dioxide and nitrous oxides world-wide in 1991. The calculations were based on U.S. plant performance data and are presumed to be a conservative representation of world conditions.

Table 5.5

Carbon Dioxide, Sulfur Dioxide and Nitrous Oxide Emissions from Fossil-Fuel Generation of Electricity for Selected Countries (1991)*

Country/ Region	Million MWh	Carbon (10^6 MT)	SO_2 (000 MT)	NO_x (000 MT)
World	12 080	1 890	47 655	21 857
OECD	7 247	1 103	27 854	12 251
Australia	157	39	1 136	473
Canada	508	31	912	373
France	455	16	449	188
Germany	539	102	2 976	1 244
Italy	222	36	804	407
Japan	888	118	227	272
Norway	111	0	3	1
Spain	156	20	602	236
Sweden	148	2	46	20
U K	322	70	2 096	817
U S	3 213	599	16 881	7 348
Non-OECD	4 833	787	19 801	9 606
Bangladesh	8	1	8	17
China	680	160	4 903	1 885
India	309	69	2 103	814
Indonesia	39	8	206	84
Nepal	1	0	0	0
Philippines	27	4	88	35
Poland	135	39	1 204	462
Saudi Arabia	66	12	208	141
Singapore	17	4	84	34
South Africa	168	46	1 439	550
Former USSR	1 682	246	4 968	3 219

*Calculated from data on electricity production from fossil fuels from OECD and UN reports (IEA, 1993a; IEA, 1992; IEA, 1993b; Economic Commission for Europe, 1993). CO_2, SO_2 and NO_x emissions per kWh used to multiply coal, oil and gas-fired generation in each country were based on U.S. experience (EPRI CSD, 1989). Japan data was based on TEPCO report (EPD, 1992). MT represents metric ton.

Table 5.6 presents the projected CO_2, SO_2 and NO_x emissions from the generation of electricity in a sampling of OECD and non-OECD countries.

Table 5.6

Carbon Dioxide, Sulfur Dioxide and Nitrous Oxide Emissions from Fossil-Fuel Generation of Electricity (Projections for 1995 and 2000)

Country/ Region	1995			2000		
	Carbon 10^6 MT	SO_2 000 MT	NO_x 000 MT	Carbon 10^6 MT	SO_2 000 MT	NO_x 000 MT
World	2041	48742	24368	2420	52804	27472
OECD	1084	24357	12724	1200	21248	12696
Australia	47	1378	564	52	1542	632
Canada	32	902	391	37	1067	454
France	13	388	156	20	528	242
Germany	97	2749	1198	104	2886	1292
Italy	48	1088	571	57	1294	695
Japan	117	226	271	124	235	282
Norway	0	2	1	0	2	1
Spain	25	724	301	30	769	376
Sweden	2	36	19	3	52	30
U K	62	1687	740	63	1597	782
U S	566	13250	7580	620	8950	6750
Non-OECD	957	24385	11643	1220	31555	14776
Africa	85	2474	1018	107	3106	1278
Latin America	46	900	537	60	1169	698
Asia	111	2775	1278	170	4247	1956
China	205	6269	2410	283	8646	3324
India	97	2965	1148	149	4555	1763
Europe	89	2593	1083	94	2733	1142
Former USSR	271	5463	3540	305	6153	3987

Projections for OECD countries used expected electric energy generation and fuel shares for the years 1995 and 2000 as provided in the 1991 IEA review of energy policies. Projections for OECD countries for 2005 used 1995-2000 electricity generation growth rates and 1995 fuel shares given in the report (IEA, 1993a). Projections for non-OECD countries except China used 1981-1991 energy generation growth rates and 1991 fuel shares reported in the OECD report on energy statistics of non-OECD countries (IEA, 1992). China projections were based on the OECD report and their presentation in the UN power system planning seminar (IEA, 1993b; Guangyao, 1993). Japan emission rates were based on the TEPCO report (EPD, 1992). U.S. emission rates from 1995 on were based on an EPRI study (Lamarre, 1991). All other calculations used current emission rates of typical U.S. electric generating plants (EPRI CSD, 1989).

5.2.2 Environmental Impacts of Plant Emissions

The environmental issues related to power systems may be classified into local issues covering air/water quality and waste management effects, regional issues of mainly acidic deposition, and global issues which essentially deal with greenhouse gases (Taylor and Fox, 1991). Another classification deals with the more direct effects of these emissions, to wit: pollutants affecting human health, radiatively and chemically active trace gases that cause visibility degradation or affect the ozone layer, and what are known as air toxics - mercury, arsenic, chlorine, etc. Among these emissions, greenhouse and acid rain gases have the greatest impact on the planning and operation of electric utilities.

5.2.2.1 CO_2 Emissions

It is estimated that the earth would have a temperature of -18°C were it not for what are known as the green house gases (Sundararaman, 1991). Carbon dioxide, water vapor and ozone allow higher frequency solar radiation to pass to the earth but absorb the terrestrial infrared radiation. The mechanisms are different but the similarity of the effect has resulted in the use of the term green house -- where heat is retained by preventing convective flows out of the structure (Roberts, et al., 1990). The terrestrial biosphere and the oceans serve as sinks and sources for carbon dioxide, each exchanging with the atmosphere some 100 GtC per year.

Anthropogenic CO_2 emissions from energy use in 1988 were estimated at 6.3 GtC, and growing at the rate of 2.5% per year (OECD, 1991). About 1.7 GtC were contributed by power generation (Rahman and de Castro, 1994). Half of the CO_2 emitted appears to remain in the atmosphere and causes the rising trend in air concentrations of the gas (Roberts, et al., 1990).

Carbon dioxide is only one of several greenhouse gases produced by human activity (anthropogenic emissions). Also included in this category are methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and the chlorofluorocarbons (CFCs). All of these have a greater warming

Environment-Sensitive Planning

effect than CO_2 on a molecule per molecule basis (Sundararaman, 1991). Calculations based on concentration, radiative effectiveness and lifetime, however, show that CO_2 accounted for 66% of greenhouse gas contributions to global warming in the U.S. between 1880 and 1980 (Kane, et al., 1991), and 55% globally between 1980 and 1990 (Sundararaman, 1991).

While models predict that the increase in greenhouse gas concentrations should already have caused global warming, there is some doubt as to whether the experienced trend of slightly less than one degree Fahrenheit (°F) can be attributed to them (Kane, et al., 1991). The models differ in representation, particularly in the effects on cloud cover and the ocean surface, as well as in the assumptions and measurement methods used. As a result, there is much variation in the estimates of predicted temperature changes resulting from the expected doubling of CO_2 concentrations in the next century from as low as 0.2 °C (0.4 °F) (Roberts, et al., 1990) to as high as 9.4 °C (16.9 °F) (Kane, et al., 1991). A commonly accepted figure is 1.5 to 4.5 °C (Douglas, 1992; Elsom, 1987).

Assuming that the expected increase in CO_2 concentrations will result in global warming, the next question is what effects global warming will have. Among the possibilities are worldwide changes in crop productivity, forest ecosystem migration, a rise in the sea level and the extinction of some endangered species (Douglas, 1992; Elsom, 1987).

A direct effect of global warming on the utility industry is the change in the demand for electricity (Roberts, et al., 1990). Once the uncertainties of temperature changes are resolved, however, these would be much easier to quantify. A more difficult problem is the assessment of repercussions on the utility's strategic position of the internalization of the externalities of the previous paragraph.

5.2.2.2 SO₂ Emissions

Sulfur dioxide is a colorless gas produced mainly from the combustion of fossil fuels. It can react catalytically with such oxidants as ozone, hydrogen peroxide and organic free radicals to produce sulfur trioxide (which hydrates quickly to sulfuric acid), sulfuric acid and sulfates:

$$OH + SO_2 \quad \rightarrow \quad HSO_3$$
$$HSO_3 + O_2 \quad \rightarrow \quad HO_2 + SO_3$$
$$SO_3 + H_2O \quad \rightarrow \quad H_2SO_4$$
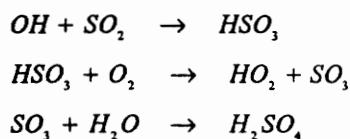
Fog, suspended particulate matter, and sulfur dioxide form smog which is known to have health effects particularly on the elderly, the young and those with respiratory ailments. There are also effects on the vegetation, on structural materials and on the atmosphere. The following paragraphs drawn from Elsom (1987) describe these effects.

The best-known example of the health effects of SO_2 happened in London in 1952 when 4700 deaths occurred above the expected value due to respiratory failure. The largest single contributor was bronchitis, although death from diseases involving the impairment of respiratory functions also rose. The number of deaths due to heart disease increased, possibly due to the strain on the heart caused by the said respiratory problems. Sulfates suspended in the emissions are suspect for increased asthma attacks, aggravation of heart and lung disease and a lowering of resistance to respiratory diseases.

At low added levels of SO_2, it has been seen to enhance plant growth by the addition of soil nutrients. At higher levels, however, SO_2 causes bleaching of plant chlorophyll and lowers soil pH values, resulting in reduced growth and yield. Impacts are more pronounced on plants such as lichen which contain relatively little chlorophyll. Such information has been used to map sulfur dioxide levels by experimental transplantation of lichens and observing their fate.

Sulfur dioxide also leads to corrosion of building stone. It converts the calcium carbonate in limestone, sandstone, roofing slate and mortar into soluble calcium sulfate

(gypsum). The material increases in volume, resulting in scaling, blistering and disintegration. The loose material is then washed away by rain. Sulfur dioxide also affects fabrics (especially man-made textiles such as nylon), leather, paper, electrical contacts, paints and medieval stained glass. It also accelerates the corrosion rates of metals such as iron, steel, zinc, copper and nickel.

Another effect of SO_2 emissions is the reduction in visibility due to light absorption and scattering by sulfates. These suspended particulate matter also enhances condensation and freezing, leading to the formation of cloud and fog, increased precipitation and reduced sunshine levels.

5.2.2.3 NOx Emissions

The most important oxides of nitrogen are nitric oxide and nitrogen dioxide since other oxides are not known to be biologically significant. Anthropogenic nitrogen oxides are produced during combustion when the temperature is higher than about 1000°C. Its principal sources are the combustion of fossil fuels in stationary sources and in motor vehicles. Like sulfur dioxide, nitrogen oxide emissions have impacts on health, on vegetation and on the atmosphere. In addition, they are believed to act as catalysts in the depletion of the ozone layer. A more detailed discussion of this is given in Elsom (1987).

Aside from promoting photochemical pollution, nitrogen oxides have health effects of their own. High concentrations of NOx (600-900 $\mu g/m^3$) have been found to result in increased susceptibility to respiratory infections, increased airway resistance and decreased sensitivity to bronchoconstrictors.

Oxides of nitrogen account for 30% of acid rain precipitation in the U.S. (next to sulfur compounds which account for 65%). A term used to refer to precipitation having a pH value lower than 5.6, acid rain is known to result in the depletion of fish stocks, a reduction in forest

productivity, human health problems, increased material corrosion and erosion, and reduced visibility.

5.2.3   Implications for Electric Utilities

Although many of the effects of emissions on the environment have long been recognized, the institution of measures for abatement has been a long and tedious process. One reason for this is that emissions are externalities and, therefore, do not directly affect the profitability of its producer. This is exacerbated by the fact that it is a public "bad" which is more difficult to quantify.

However, there are now increasing legal and societal pressures on the electric utility industry to explicitly account for the impact of power generation on the environment. The players in the utility industry now include, in addition to governments and funding agencies, private power developers and producers, private investors and an environmentally aware public. As a result, issues of profitability and emissions limiting are now getting greater emphasis. The utility planner is challenged to have an understanding of these various dimensions of the decision. In the following paragraphs, I shall discuss these forces that impact on the electric utility industry.

5.3   Environmental Policy Options

The policy instruments available to the government for implementing environmental policy can be classified into two major groups -- command and control approaches and economic incentive systems. Earlier legislation leaned towards the former, but more recent ones have taken advantage of the market orientation of the latter (Pearce and Turner, 1990; Project 88, 1991).

5.3.1 Command and Control

A command and control approach to pollution abatement involves the setting of standards and direct regulation of polluters. This conventional regulatory mechanism either specifies the technology that must be used (technology-based) or sets a cap on the emission rate that all sources must meet (a uniform performance standard). The command and control approach has included the setting of ambient air and water quality standards, objectives and targets; and the imposition of emission and discharge limits and/or products or process standards through a licensing and monitoring system. Compliance is made mandatory for polluters and non-compliance results in sanctions on the polluters.

5.3.1.1 Uniform Performance Standard

Uniform standards that have been used include:

a) limiting the maximum rate of discharge from a pollution source

b) specification of the degree of pollution control required, such as percentage removal of particles from the emission

c) limitation of the density of pollution discharged or emitted

d) bans on discharges based on pollution concentration or damage costs

e) discharge limits based on the use of specified inputs to or outputs from the production process.

5.3.1.2 Technology Based Pollution Control Approaches

The 1970 Clean Air Act was based on achieving air quality pollution standards through strict formulation of technology standards. National Ambient Air Quality Standards (NAAQS) were to be implemented by states under state implementation plans (SIPs). Ambient standards for ozone and other criteria pollutants were set together with New Source Performance Standards (NSPS).

Between 1970 and 1976 SIPs fell behind schedule, and EPA started to formulate its offset policy. This allowed new and modified sources in 'non-attainment areas' when Lowest Available Emission Rate Technologies (LAERTs) were applied and when any additional emissions were offset.

The amendments of 1977 allowed the extension of deadlines for achieving NAAQSs and the formulation of new technology standards. Existing sources in non-attainment areas were allowed to use Reasonably Available Control Technology (RACT) which considered technological and economic feasibility.

Specifying a uniform performance standard instead of a particular technology allows more flexibility for the firms to decide how they will meet the goal, e.g., a limit on the amount of pollutant that can be emitted per product output. Both of these approaches, however, tend to impose relatively high social costs. For example, the cost to control certain pollutants may vary by a factor of 100 or more because of the differences in location and technology used for the different plants. If the government desired to allocate the pollution control burden effectively, it would have to require all sources to control at the same marginal cost -- something that would require detailed information on the operating cost of each individual source.

5.3.2 Economic Incentive Systems

In order to allocate the control burden more effectively, the U.S. government is now taking advantage of economic-incentive approaches. These policy options use market forces to find the most cost-effective manner of pollution control. Economic-incentive approaches can be grouped into four major categories: pollution charges; subsidies; deposit-refund systems; and market creation. Table 5.7 describes these approaches.

Table 5.7

Types of Economic-Incentive Pollution Control Instruments

(Pearce and Turner, 1990; Project 88, 1991)

Type	Description
Charges	
Effluent Charges	Paid on discharges into the environment and are based on the quantity and/or quality of the effluent
Incentive effluent charges	Revenue collected via the charge is not returned to the polluter
Distributive effluent charges	Revenue collected via the charge is returned to the polluter, in the form of subsidies for new pollution control equipment
User charges	Payments for the cost of collective or public treatment of effluents
Product charges/tax differentiation	Additions to the price of products, which are polluting or are difficult to dispose of, the former have a revenue-raising feature
Administrative charges	Control and authorization fees
Subsidies	
Grants	Non-repayable forms of financial assistance, contingent on the adoption of pollution abatement measures
Soft loans	Loans linked to abatement measures and carrying below-market rates of interest
Tax allowances	Allows accelerated depreciation, tax or exemptions or rebates if certain pollution abatement measures are adopted
Elimination of subsidies	Removal of subsidies that promote economically inefficient and environmentally unsound development
Deposit-refund system	Systems in which surcharges are laid on the price of potentially polluting, a refund of the surcharge is given on the return of the product or its residuals
Market creation	Artificial markets in which actors can buy and sell 'rights' for actual or potential pollution
Emissions trading (bubbles, offsets, netting and banking)	Within a plant, within a firm or among different firms (e.g., CAAA, 1990).
Market intervention	Price intervention to stabilize markets, typically secondary materials (recycled) markets
Liability insurance	Polluter liability leading to insurance market
Removal of barriers	Allow more competion among firms and permit least-cost bidding to promote economic efficiency (e.g., PURPA and EPA).

5.3.3   Legislation Affecting the US Utility Industry

The most recent legislation affecting the US electric utility industry are the Clean Air Act Amendments (CAAA) of 1990 and the Energy Policy Act (EPA) of 1992. Of these two, the CAAA directly addressed emissions and set policies for limiting them, particularly acid rain

emissions. The EPA, on the other hand, set efficiency targets which are expected to have indirect impacts on greenhouse gas emissions.

5.3.3.1 The Clean Air Act Amendments of 1990 (Pytte, 1990)

Among the provisions of the Clean Air Act Amendments of 1990 (CAAA-90), Title IV (Acid Deposition) has the greatest impacts on the utilities. This provision requires that sulfur dioxide emissions be cut 10 million tons below the 1980 levels to 8.9 million tons. This is to be accomplished in two phases.

The first phase began January 1, 1995 and affected the 111 dirtiest power plants. At that time, the said plants would have had to reduce their SO_2 emissions to 2.5 lb per million Btu (lb/MMBtu). The Environmental Protection Agency (EPA) will issue allowances, each permitting one ton of SO_2 emissions. Facilities that cut their emissions further than the 2.5 lb rate can then sell or apply their unused allowances to other facilities that cannot meet their limit. Title IV also allows extra allowances for utilities using conservation and renewable energy resources and for most of the affected sources in the Midwest (Illinois, Indiana and Ohio) for each year from 1995 to 1999. A two-year deadline extension is given to plants that commit to installing flue gas desulfurization (FGD) systems capable of eliminating 90 percent or more of their SO_2 emissions. EPA will allocate for these units allowances approximately equivalent to their uncontrolled annual emissions during the extension period. In addition, qualified units using FGD also receive one bonus allowance in 1997, 1998 and 1999 for each ton of reduction below 1.2 lb/MMBtu.

Phase II, which takes effect January 1, 2000, sets an emissions limit for utilities of 1.2 lb/MMBtu. Bonus allowances are to be given to states where utilities emit less than 0.8 lb/MMBtu. Another 50,000 allowances will be given in Phase II to plants in 10 states (Illinois, Indiana, Ohio, Georgia, Alabama, Missouri, Pennsylvania, West Virginia, Kentucky and Tennessee, with certain plant exceptions) that meet Phase I limits. Plants reducing SO_2 emissions by 90% will receive allowances on a two-for-one basis.

5.3.3.2 The Energy Policy Act of 1992 (Idelson, 1992)

The Energy Policy Act of 1992 was legislated to promote more competition in the electric utility industry, provide tax relief to oil and gas drillers, encourage energy conservation and efficiency, advance renewable energy and the use of alternative fuels on cars, facilitate the construction of nuclear power plants and promote energy-related research and development through the infusion of funds.

While not attacking the issue of greenhouse gases directly, it creates an office on climate protection and requires an administrative study on the methods and costs of curbing greenhouse gas emissions. It also requires the energy secretary to develop a least cost energy strategy that promotes energy efficiency and seeks to limit the emission of carbon dioxide and other greenhouse gases.

The provisions of the Act that have a greater effect on the utilities is the creation of a category of exempt wholesale power producers. This change allows utilities to operate independent wholesale plants outside of their own service territories and encourages the operation of generating plants by independent producers. The provision also allows wholesale electricity generators to request that the Federal Energy Regulatory Commission order a utility to transmit their power.

A range of standards and incentives on energy efficiency, renewable and alternate energy sources and on energy and coal research are also expected to have impacts in the intermediate and the far future.

5.3.3.3 Industry's Response to Environmental Legislation

The CAAA of 1990 resulted in a flurry of activity in the electric utility industry. Utilities and energy companies updated their current planning options and methodologies to find the optimal means of complying with the act. The utility responses included the development and

implementation of a range of emission simulation and production cost software, and the development and use of decision analysis programs and procedures (Buttorff and Latti, 1991; Alvarado, et al., 1992; Hess, et al., 1992; Metzler, et al., 1992; Quartucy, 1992; Rafizadeh, 1992). Other studies centered on the possible global impacts of legislation in terms of total energy production and generating capacity distribution, economic effects and the projected SO_2 emissions (Lock, 1991; Stallard and Ferguson, 1991; Yates, 1991; Desai, 1991; Molburg and Hanson, 1992).

It may seem that with the provisions of the CAAA and its implementing regulations the uncertainties before the utility planner are simplified to those involved in the calculation of market prices of the allowances and of the costs of options for emission abatement. There are indications, however, that more and more regulators are imposing on their utilities to internalize emission externalities in their planning. There is focus on the greenhouse gases, specially CO_2, which have not yet been addressed by legislation. Others also emphasize the advantages of valuation of externalities rather than basing the response in terms only of the cost of control and market prices of allowances (Kane, et al., 1991; Makovich, 1991; Kosobud, et al., 1991; Holstein and Brands, 1992; Horst and Blake, 1992).

5.3.4   Rationale for Incorporating Cost of Externalities in Planning

An externality can be defined as the effect of an agent's actions on another's environment other than by their effect on prices (Varian, 1984). It can be dealt with by the inclusion of a social price, putting a price on the potential income without the externality, or the assignment of property rights to one of the parties. Externalities can be integrated in utility planning through the inclusion of cost of control, valuation of damages, and a regulatory approach which sets emissions limits (Violette and Peterson, 1990). The impacts of the emissions can be estimated through direct, indirect and contingent valuation techniques. These can be internalized in resource planning through any of several methods depending on the

Environment-Sensitive Planning   **115**

intended use and the availability of information. These methods include *qualitative approaches* such as those which simply list or categorize the extent of the impact of potential externalities, *rule-based approaches* which adjust the cost of options meeting given criteria, *rating or weighting* applied to resource options for each potential externality, and *monetization approaches* which assign dollar values to externalities for each resource option (Temple, Barker and Sloan, 1991).

The Clean Air Act Amendments (CAAA) of 1990, by providing for open trading in emissions allowances, gives utilities the means to optimize operations in the presence of emissions caps, while at the same time allowing market forces to do it efficiently. However, it works on a pre-set emissions limit. Thus, what it optimizes is the cost of reducing emissions up to the limit. Cost of control, while much simpler and easier to implement and, therefore, more popular, does not reflect actual social costs. True valuation of environmental externalities can only be obtained from actual environmental damage assessment, although the task is formidable and has only been attempted on a limited basis.

The Clean Air Act also does not address greenhouse gas emissions, which is expected to play a significant role in future energy resource decisions. Already, much of the developed world is committed to CO_2 emissions limits. And while there are concerns regarding the impacts of such limits on the U.S. economy (Douglas, 1992), such requirements are likely to become a reality, if not within the current 15- to 20-year utility planning horizons, within the 30- to 40-year lifetimes of capacity resource alternatives.

Expected environmental impacts of emissions and the limitations of available legislation manifest the compelling social need for furthering efforts to incorporate these externalities in utility planning. The question is whether it would benefit utilities to account for the impact of all emissions, including those that are not covered by current regulations or those that are below the limits that they impose. The arguments against it are the added cost, the appropriateness of such an approach (as against further strengthening of environmental regulations), the inequitable

burden on electricity versus other (more polluting) energy sources, and the uncertainties regarding the actual impacts on the environment (Rabl, 1994).

Nevertheless, decision makers in the utility industry are finding it to be increasingly more prudent to incorporate such externalities in their planning. The number of utility commissions requiring environmental externailty adders in evaluating future capacity additions continues to grow (Horst and Blake, 1992). From two states in 1986, the number of states incorporating environmental considerations in their integrated resource planning (IRP) requirements for utilities has grown to twenty-two in 1992, with four other states considering similar action (Rabl, 1994; Ottinger, 1991). Utility regulators consider the inclusion of environmental factors in resource planning a moral obligation which is economically sensible and which provides "a strategic opportunity to promote broader change..." (Connors, 1993). Future international agreements and federal and state laws and regulations are likely to impose stricter environmental laws over the life of planned capacity additions.

Another reason for incorporating environmental costs is the utility's mandate to serve the public interest, which includes environmental protection. This is further reinforced by the fact that customer surveys show a preference for environmentally friendly goods and services even if they have to pay for such benefits (Horst and Blake, 1992). This in the least entails a redefinition of the term customer, to include the general public, and quality of service, to include environmental benefits. It makes good sense for the utility to develop a technological advantage for pollution control in order to meet customers' expectations and position the utility strategically in the future energy marketplace.

5.3.5   The Cost of Emissions

A variety of studies have been conducted to quantify the cost of emissions. One of the better known studies was performed by the Tellus Institute for the Massachusetts Institute of Technology. Another was conducted by the Pace University Center for Environmental Legal

Studies for the New York State Energy Research and Development Authority. The former involved control cost values and was adopted by the Massachusetts Department of Public Utilities for use of Massachusetts utilities in developing resource plans. The latter uses damage cost values. Table 5.8 summarizes the results of some studies and the values used by some states.

5.4 Utility Options

A variety of options are available to the utility for planning an environmentally sustainable generation system. Supply-side options increase generating capacity while reducing emissions. Demand-side alternatives delay the need for increased capacity although not necessarily limiting the electricity services provided to the customer. The following paragraphs briefly describe these options that are available to the utility industry.

5.4.1 Supply-Side Options

One generation option involves the use of conventional technology employing emission reduction through the removal of particulates, NO_x and SO_2. Flyash and NO_x removal use fabric filters and selective catalytic reduction (SCR) and/or combustion modifications, while SO_2 removal involves stack-gas scrubbers or flue-gas desulfurization systems. The technology for sulfur removal from coal before and during the combustion process is also available and remains to be another option. Other options include low-sulfur coal, plant retirements and fuel substitution (nuclear or gas). A host of new generation technologies such as integrated gasification combined cycle (IGCC) turbines, pressurized fluidized-bed combustion (PFBC) turbines and steam-injected gas turbines are also expected to play major roles in future power systems in view of their greatly reduced SO_2 emissions and their higher efficiencies which essentially reduce CO_2 emissions per kWh of electricity generated.

Table 5.8

Costs of Externalities

Source	Busch, 1993	Holstein, 1992					Trisko, 1993					Fritsche, 1991
	MDPU	NYPSC	Nevada PSC	CA PUC (SDG&E /SCE)	CA PUC (PG&E)	Tellus Inst	So. Coast AQMD	PACE	BPA low	BPA high	Sweden	Germany
SO2	0.781	0.410	0.780	9.150	2.030	0.780	39.200	2.120	0.200	1.800	1.190	1.029
NOx	3.383	0.890	3.400	12.250	3.550	3.400	137.000	0.860	0.030	0.400	3.180	0.823
VOCs	2.787		0.590	8.750	1.650	2.770	15.200					
CO	0.452		0.460									
TSP	2.103	0.160	2.090	2.650	1.190	2.090	23.000	1.240	0.080	0.800		0.206
CO2	0.012	0.001	0.011	0.013	0.013	0.012		0.007	0.003	0.003	0.020	0.002-0.020
CH4	0.116		0.110			0.120		0.000				
N2O	2.082		2.070									
units	1990 $/lb			1989 $/lb					1990 $/lb			1989 $/lb

Although the technology is already available for reducing SO_2 emissions, it puts an additional financial burden on the utility and, ultimately, the electricity consumer. Scrubbers cost around $175 to $200 per kW to install (Stallard and Ferguson, 1991) and penalize the plant efficiency. Lower sulfur coals (those with less than 1% sulfur content) can only be bought at a premium. Electricity prices of American Electric Power Co. (AEP) are expected to increase by about 5% on the average (and up to 20% for some customers) due to acid rain compliance (McManus, 1993). Low NOx burners likewise entail an additional cost.

The other available supply-side options also encounter obstacles. The much touted fusion reactor is still about 50 years to commercialization, and even the supposedly benign hydro is meeting considerable opposition from environmentalists. Solar and other renewable technologies hold considerable promise but still need to take off with large grid connection due to cost constraints.

5.4.2 Demand-Side Options

Aside from the increase of production capacity, the utility can avail of demand-side alternatives which delay the requirement for additional investments. Electric Power Research Institute (EPRI) studies show the benefits of load shifting, peak shaving and valley filling not only in the reduction of the load and in improving operating efficiencies but in emission reduction as well (EPRI CSD, 1991). American utilities plan to meet up to one-third of new capacity needs with DSM (Levine, 1993). Studies show that considerable improvements can also be achieved in the efficiencies of residential appliances such as lighting, refrigerators, air conditioners and heaters (use of heat pump). Better energy management control systems and variable-speed motors can also be used to reduce the total electric energy consumption.

Table 5.9 lists some of the options and their estimated costs. Trends in utility planning integrate both supply-side and demand-side alternatives to maximize benefits to the utility. The

costs of efficiency improvement are evidently very competitive with traditional capacity

expansion options and much more acceptable environmentally. Calculations based on plant

emission rates in lbs/MBtu and plant heat rates in Btu/kWh result in the externality surcharges of

Table 5.10.

Table 5.9

Costs of Capacity Options

Capacity Option			Cost (c/kWh)
Supply Side	Conventional (Hubbard, 1991)	Coal with compliance	5-7
		Hydro	2-3
		Gas	3-4
		Cogeneration	3
	Alternative (Yeager, 1992)	Photovoltaics	30-40
		Wind	7-9
		Biofuels	5
		Solar Thermal	10
		Geothermal	5-7
Demand Side	Valley Filling (EPRI CSD, 1991)		2-3
	Efficiency Improvement (Levine, 1993)	Refrigerator	3
		Water Heater	1-3
		HVAC	1-2
		Lighting	1-3
		High-Effy Motors	1-3

Table 5.10

Externality Surcharges by Plant Type (cents/kWh)

Plant Type	Busch, 1993 MDPU	Holstein, 1992 New York	Nevada	Ottinger, 1991 PACE	Fritsche, 1991 Germany Low CO_2	High CO_2
Small Coal	7.8					
Medium Coal	6.4	1.4	4.3	5.8	0.8	5.0
Large Coal	6.1					
1950s Oil	5.3					
1960s Oil	4.7			2.7 - 6.7		
1970s Oil	3.8					
CC	2.8		2.2	1.0	0.36	2.3
Peakers	5.2					
Thermal Purchases	5.5					
Thermal IPPs (1990)	3.2					
Thermal IPPs (2005)	2.3					
Adv. CCs	1.1					
Adv CTs	1.9					
IGCC	2.4			2.5	0.8	4.5
Atm. Fluidized Bed			4.9	2.8		
Biomass	0.8					
Refuse	5.3			2.79 - 2.88		
Solar Thermal			0.5	0.0 - 0.4		
Geothermal			0.001			
Cogenerator (coal)					0.32	2.3
Solar photovoltaics					0.03	1.0
Wind Turbine				0.0 - 0.1	0.01	0.1
Micro-Hydro					0.01	0.0
Nuclear Electricity				2.91	0.06	0.3

Chapter 6

Case Study

This section discusses the implementation of the proposed planning framework on an actual electric utility system.

6.1   Sample System

The sample system used for the study is based primarily on the Virginia Power Forecast of Load and Resources (Virginia Power -- PPD, 1992). Peak summer demand is expected to grow from 14 552 MW to 19 812 MW from 1995 to 2009. With implementation of Demand Side Programs, demand is expected to be 14 205 MW in 1995, and go up to 18 920 MW by 2009. Base forecast of annual energy requirements is from 73 499 GWh in 1995 to 99 786 GWh in 2009. When DSM effects are included, energy requirements are expected to be 73 386 GWh in 1995, rising to 100 072 GWh in 2009. DSM effects include those of load factor improvement programs which may increase energy use with little or no effect on peak demand. Table 6.1 gives the yearly forecast .

Total summer capability expected in 1995 is 17 227 MW. Of the expected 1995 generation of 73 386 GWh, nuclear plants will have a share of 28.61%, coal 39.47%, heavy fuel oil 3.54%, light fuel oil 0.01%, natural gas 3.86%, hydro 1.08%, and pumped hydro 2.14%.

Purchased energy is expected to account for 24.65% and pumping energy and non-requirement sales will take 3.38%. A 15% reserve margin is used for base case optimizations. Heat rates for new plants are assumed to be 9720 Btu/kWh for coal and 11950 Btu/kWh for combustion turbines. No unit retirements are planned. Units committed include a 205 MW combined cycle plant in 1992 and 391 MW of coal capacity each in 1995 and 1996, respectively. In addition, there are contracts with non-utility generators for an expected summer capacity of 2054 MW.

Table 6.1

Base Forecast of Virginia Power/North Carolina Power Load

	Base Forecast		Base Forecast with DSM	
Year	Peak Load (MW)	Energy (GWh)	Peak Load (MW)	Energy (GWh)
1995	14552	73499	14205	73386
1996	15137	75816	14712	75707
1997	15623	77765	15128	77671
1998	15934	79875	15342	79795
1999	16189	81924	15508	81867
2000	16638	84137	15903	84107
2001	17104	85809	16343	85810
2002	17537	87714	16761	87750
2003	17943	89560	17153	89630
2004	18027	91650	17220	91756
2005	18354	93189	17530	93331
2006	18772	94917	17930	95095
2007	19194	96536	18335	96750
2008	19633	98449	18758	98699
2009	19812	99786	18920	100072

A price of $175 per kW is assumed for 90% removal wet FGD systems. Coal cost of $1.27 per million Btu is used for 3% sulfur content and $1.53 per million Btu for low (0.6%) sulfur content. Base case optimization runs use a discount rate of 8% and an escalation rate of 4.9%.

6.2 Attribute Selection and Calculation of Weights

Figure 6.1 shows the hierarchy developed as a filter for selecting attributes of concern to the planner and giving weights to these attributes. At the top of the hierarchy is the goal of obtaining the least "cost" plan that considers the different priorities of the players involved in planning. The second level of the hierarchy comprises the players involved in the process, i.e., the utility, the regulators, the customers and the general public. Weights are assigned to them by the DM by pairwise comparison and the eigenvector method.

At the third level of the hierarchy are the different objectives or attributes that the players consider: diversity, flexibility, robustness, cost, reliability, environmental impact, financial impact, electrification requirement and security. Different utility planners would have different priorities. A profit-oriented company may, for example, put most of the weight on the cost of generating each kWh of energy, while a service-oriented utility would put a little more weight on reliability and environmental impact. The attractiveness of this process lies in the flexibility that it affords the planner in varying the weights assigned to the factors based on the preferences of utility management and the socio-political environment in which it is operating.

Table 6.2 shows the results of AHP calculations based on pairwise comparisons of the factors made from the points of view of the different players. AHP results in a final set of weights assigned to the factors that considers the priorities of the players and the weights assigned to the players themselves. Table 6.3 to Table 6.6 show the weight assignments resulting from pairwise comparisons of the different attributes made from the points of view of the players in the decision process. Table 6.7 gives the composite priorities for the different attributes resulting from the Analytic Hierarchy Process.
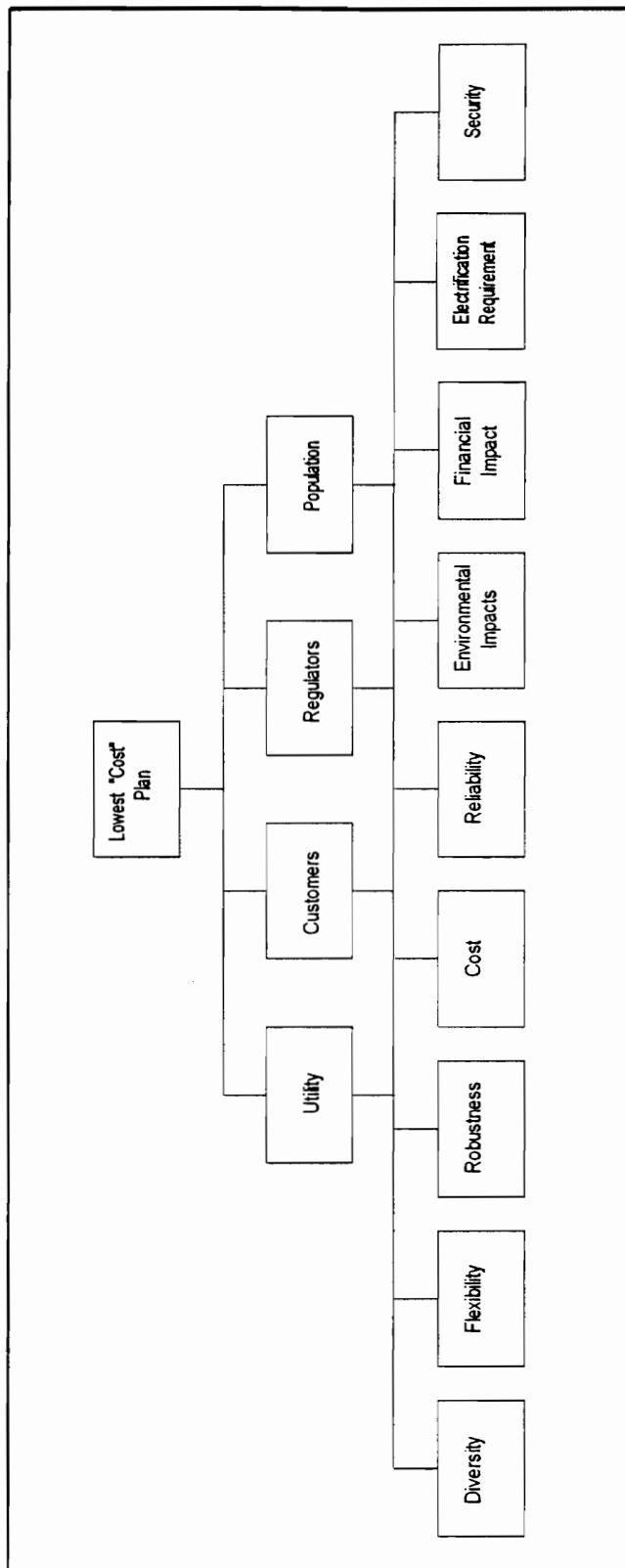
Figure 6.1   Hierarchy for Attribute Selection and Calculation of Weights

Table 6.2

Weights Calculated with Respect to the Least Cost plan

	Weights	Low	High
Utility	.5650	.4033	.7268
Customers	.1175	.0456	.1894
Regulators	.2622	.1135	.4109
General Public	.0553	.0210	.0896

Table 6.3

Weights with Respect to Priorities of the Utility

	Weights	Low	High
Diversity	.0206	.0121	.0291
Flexibility	.1004	.0600	.1409
Robustness	.0470	.0277	.0663
Cost	.3597	.2671	.4523
Reliability	.1376	.0834	.1917
Env impct	.2126	.1348	.2903
Fin impct	.0638	.0378	.0899
Elect req	.0224	.0132	.0316
Security	.0359	.0211	.0506

Table 6.4

Weights with Respect to Priorities of the Customers

	Weights	Low	High
Diversity	.0206	.0121	.0291
Flexibility	.0984	.0586	.1382
Robustness	.0470	.0276	.0663
Cost	.3514	.2584	.4444
Reliability	.1469	.0893	.2045
Env impct	.2134	.1353	.2916
Fin impct	.0639	.0377	.0901
Elect req	.0225	.0132	.0317
Security	.0360	.0211	.0508

Table 6.5

Weights with Respect to Priorities of the Regulators

	Weights	Low	High
Diversity	.0214	.0131	.0296
Flexibility	.1117	.0699	.1534
Robustness	.0499	.0307	.0691
Cost	.2981	.2143	.3819
Reliability	.1553	.0992	.2114
Env impct	.2292	.1539	.3045
Fin impct	.0698	.0431	.0965
Elect req	.0251	.0154	.0348
Security	.0395	.0243	.0548

Table 6.6

Weights with Respect to Priorities of the General Public

	Weights	Low	High
Diversity	.0200	.0103	.0297
Flexibility	.0974	.0512	.1436
Robustness	.0468	.0242	.0694
Cost	.2088	.1185	.2992
Reliability	.1332	.0713	.1950
Env impct	.3659	.2576	.4743
Fin impct	.0636	.0330	.0941
Elect req	.0259	.0134	.0385
Security	.0384	.0198	.0569

Table 6.7

Composite Priorities

	Weights	Low	High
Diversity	.0208	.0154	.0261
Flexibility	.1030	.0771	.1289
Robustness	.0478	.0355	.0600
Cost	.3342	.2762	.3923
Reliability	.1430	.1083	.1779
Env impct	.2255	.1761	.2749
Fin impct	.0654	.0487	.0821
Elect req	.0234	.0174	.0293
Security	.0370	.0275	.0465

Based on the results given in Table 6.7 the attributes of flexibility, cost, reliability and environmental impact are selected for inclusion in the influence diagram analysis. Different

decision makers will produce different judgment matrices and, thus, result in a different set of priority attributes.

6.3   Selection of Uncertainties and Probability Estimation

Among the attributes most affected by uncertainties are project costs. Project costs comprise annual levelized costs, operating and maintenance (O&M) costs, fuel costs and costs of emission allowances. These costs are affected by uncertainties in escalation rates, licensing requirements, construction delays, discount rates, load growth, impacts of DSM programs and future regulations. Figure 6.2 shows this hierarchy for identifying relevant uncertainties using AHP.

Table 6.8 shows the results of eigenvector analysis of the relative effects of the annual levelized cost, operating and maintenance costs, fuel costs and allowance costs on the project cost. Table 6.9 to Table 6.12 then give the relative effects of the different uncertainties on these components of the project cost. Table 6.13 is a tabulation of the composite effects of the uncertainties on the project cost.

Table 6.8

Effects of Uncertainties in Project Cost

Proj Cost	Annl Lev'd	O&M	Fuel	Allowance	Weight	Low	High
Annl Lev'd	1	3	5	6	.5637	.4330	.6944
O&M	1/3	1	3	4	.2576	.1378	.3774
Fuel	1/5	1/3	1	2	.1095	.0546	.1644
Allowance	1/6	1/4	1/2	1	.0692	.0342	.1042
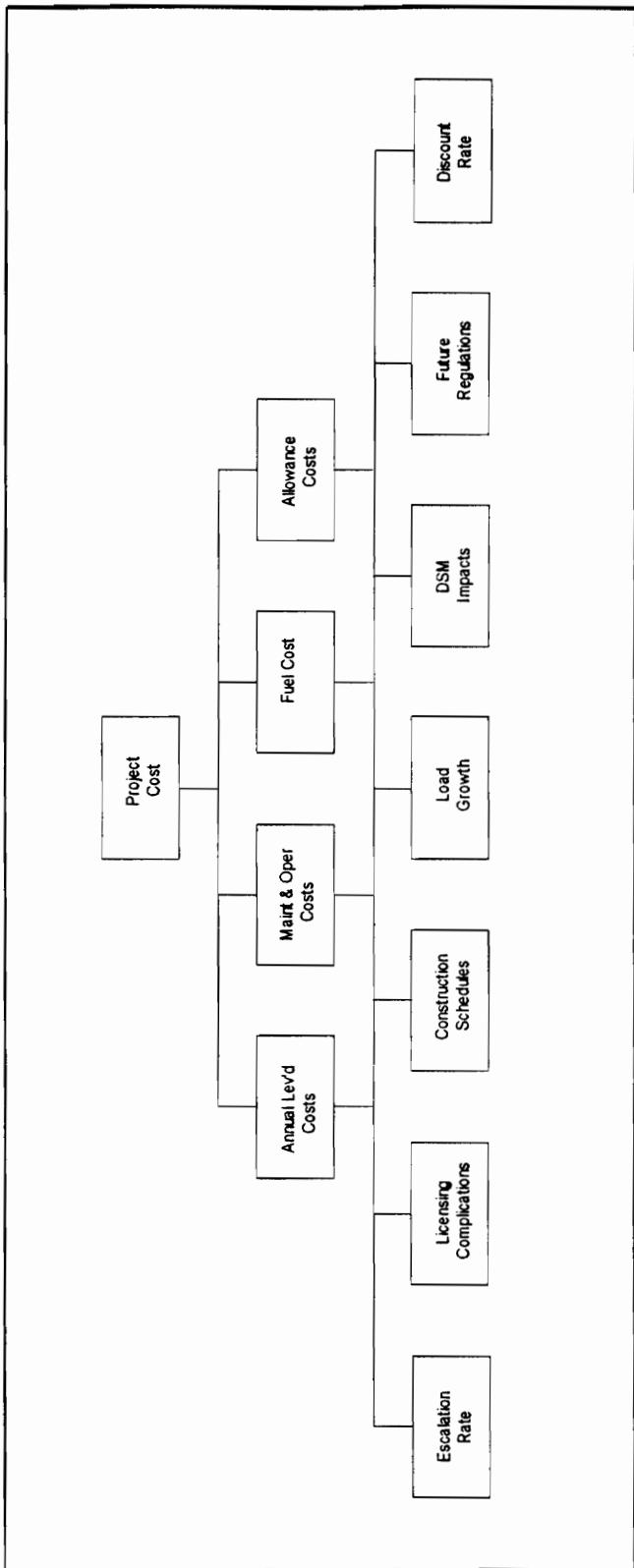
Figure 6.2 Hierarchy for Identification of Relevant Uncertainties

Table 6.9

Effects of Uncertainties in Annual Levelized Cost

	Unit Esc	Lic	Constrctn	Disc Rate	Weight	Low	High
Unit Esc	1	9	7	3	.5831	.3773	.7889
Lic	1/9	1	1/3	1/7	.0425	.0102	.0748
Constrctn	1/7	3	1	1/5	.0849	.0207	.1490
Disc Rate	1/3	7	5	1	.2895	.0914	.4876

Table 6.10

Effects of Uncertainties in O&M Cost

	Esc Rate	Load Gro	DSM Imp	Fut Regn	Disc Rate	Weight	Low	High
Esc Rate	1	2	3	7	5	.4402	.3597	.5206
Load Gro	1/2	1	2	5	3	.2587	.1882	.3292
DSM Imp	1/3	1/2	1	4	2	.1595	.1123	.2067
Fut Regn	1/7	1/5	1/4	1	1/3	.0457	.0316	.0598
Disc Rate	1/5	1/3	1/2	3	1	.0959	.0667	.1251

Table 6.11

Effects of Uncertainties in Fuel Expenses

	Esc Rate	Load Gro	DSM Imp	Fut Regn	Disc Rate	Weight	Low	High
Esc Rate	1	2	3	7	5	.4402	.3597	.5206
Load Gro	1/2	1	2	5	3	.2587	.1882	.3292
DSM Imp	1/3	1/2	1	4	2	.1595	.1123	.2067
Fut Regn	1/7	1/5	1/4	1	1/3	.0457	.0316	.0598
Disc Rate	1/5	1/3	1/2	3	1	.0959	.0667	.1251

Table 6.12

Effects of Uncertainties in Allowance Costs

	Esc Rate	Load Gro	DSM Imp	Fut Regn	Disc Rate	Weight	Low	High
Esc Rate	1	2	3	1/3	5	.2161	.1629	.2694
Load Gro	1/2	1	2	1/5	3	.1235	.0916	.1554
DSM Imp	1/3	1/2	1	1/7	2	.0743	.0549	.0938
Fut Regn	3	5	7	1	9	.5412	.4786	.6037
Disc Rate	1/5	1/3	1/2	1/9	1	.0449	.0331	.0567

Table 6.13

Composite Weights of Uncertainties

	Weight	Low	High
Esc Rate	.5052	.4088	.6017
Licensing	.0240	.0092	.0387
Constr Delays	.0479	.0185	.0772
Load Growth	.1036	.0852	.1218
DSM Impact	.0637	.0515	.0760
Future Regn	.1085	.0488	.0596
Disc Rate	.2015	.1106	.2924

From Table 6.13, the escalation rate, load growth, DSM impacts, effects of future regulation and discount rate are selected for inclusion in the influence diagram analysis. A similar procedure can be performed to determine the uncertainties relevant to environmental impacts, flexibility and reliability. In this sample system, only the uncertainties related to load growth and DSM impacts, inasmuch as they affect the emissions and the reliability of the

Case Study

generation system, and of the discount and escalation rates, inasmuch as they affect the value attached by the different players on these attributes, are considered.

6.4   Identification of Candidate Strategies and System Simulations

The analysis of the system considered three main policy approaches: approach to emissions, approach to DSM and approach to reliability. Emissions policy considered a base allowance purchase policy versus the use of scrubbers and fuel switching. DSM policy options are between go and no-go decisions, with different possibilities for DSM impacts. Approaches to reliability include choices between high, base case and low capacity reserve margins. In all, these three approaches combined resulted in (2x2x3=) 12 possible strategies.

Table 6.14 gives the results of base case simulations of the 12 strategy alternatives. The results of simulations give actual project costs in millions of dollars, the numbers and capacities of gas-fired and coal-fired units, and the expected unserved energy in kWh during the planning period. Since the base energy requirements change with different conditions of load and DSM impacts and with the reliability strategy, the values of the different attributes are normalized by dividing them with the total energy requirements. The equivalent cost of the coal-to-gas ratio is the ratio of coal to gas capacities normalized to reflect an average cost that is equal to the average base case cost of the different alternatives. The customer cost per kWh of EUSE is a conservative $0.50.   Multiplied by the total EUSE and divided by total kWh generation, this gives EUSE in dollars per kWh of energy produced. It is worth noting at this point that the social costs of emissions and of unreliable service are considerably higher than the cost of generating electricity.

Each candidate strategy was simulated using different conditions of escalation rate, discount rate, DSM impact, load growth and future regulation. Each uncertainty was given three probable states. States for escalation rate were 3.9%, 4.9% and 5.9%, respectively. Discount rates used were 8%, 10% and 12%. DSM impact was given low, base and high levels. A base

forecast of 2.5% was used for load growth. Low-end forecast and high-end forecast are 1.5% and 3.5%, respectively. Future regulatory environments of strict, base case and lax requirements were considered, which would affect the cost of compliance.

In all, a total of $(12 \times 3^5 =)$ 2916 simulations were conducted, representing possible scenario combinations of strategies and uncertainties. These simulations were performed using the Electric Generation Expansion Analysis System (EGEAS) Package.

Table 6.14

Base Case Simulation Results for Alternatives

	Cost of Energy	EUSE	Emissions per GWh of Energy Produced			Env Impct	Cost of EUSE	Equiv CGR Cost
OPTION	$ per kWh	%	Ton SO2	Ton NOx	kTon CO2	$ per kWh	$/kWh gen	$/kWh
VBZ3	0.0356	0.1026	3.3803	0.6022	0.5349	0.0245	0.0513	0.0267
VDB3	0.0338	0.1263	3.3716	0.6013	0.5354	0.0245	0.0632	0.0293
VBZ4	0.0349	0.1707	3.3083	0.6009	0.5285	0.0242	0.0854	0.0207
VDB4	0.0331	0.2034	3.3154	0.5997	0.5310	0.0242	0.1017	0.0213
VBZ5	0.0334	0.2861	3.321	0.5987	0.5308	0.0242	0.1430	0.0332
VDB5	0.0327	0.2957	3.3097	0.5980	0.5310	0.0242	0.1478	0.0355
NBZ3	0.0375	0.1026	1.4868	0.6022	0.5538	0.0217	0.0513	0.0267
NDB3	0.0354	0.1243	1.5155	0.6014	0.5563	0.0218	0.0622	0.0293
NBZ4	0.0367	0.1549	1.4988	0.6011	0.5537	0.0217	0.0774	0.0296
NDB4	0.0348	0.2001	1.5251	0.5998	0.5557	0.0218	0.1000	0.0553
NBZ5	0.0354	0.2935	1.5172	0.5985	0.5508	0.0217	0.1468	0.0332
NDB5	0.0345	0.2637	1.5272	0.5985	0.5558	0.0218	0.1318	0.0770

6.5   Influence Diagram Analysis

6.5.1   Attribute Weights

Combining the strategies, hierarchies and assumptions made in section 6.2 thru section 6.4 results in the influence diagram of Figure 6.3. This diagram is reduced considerably from
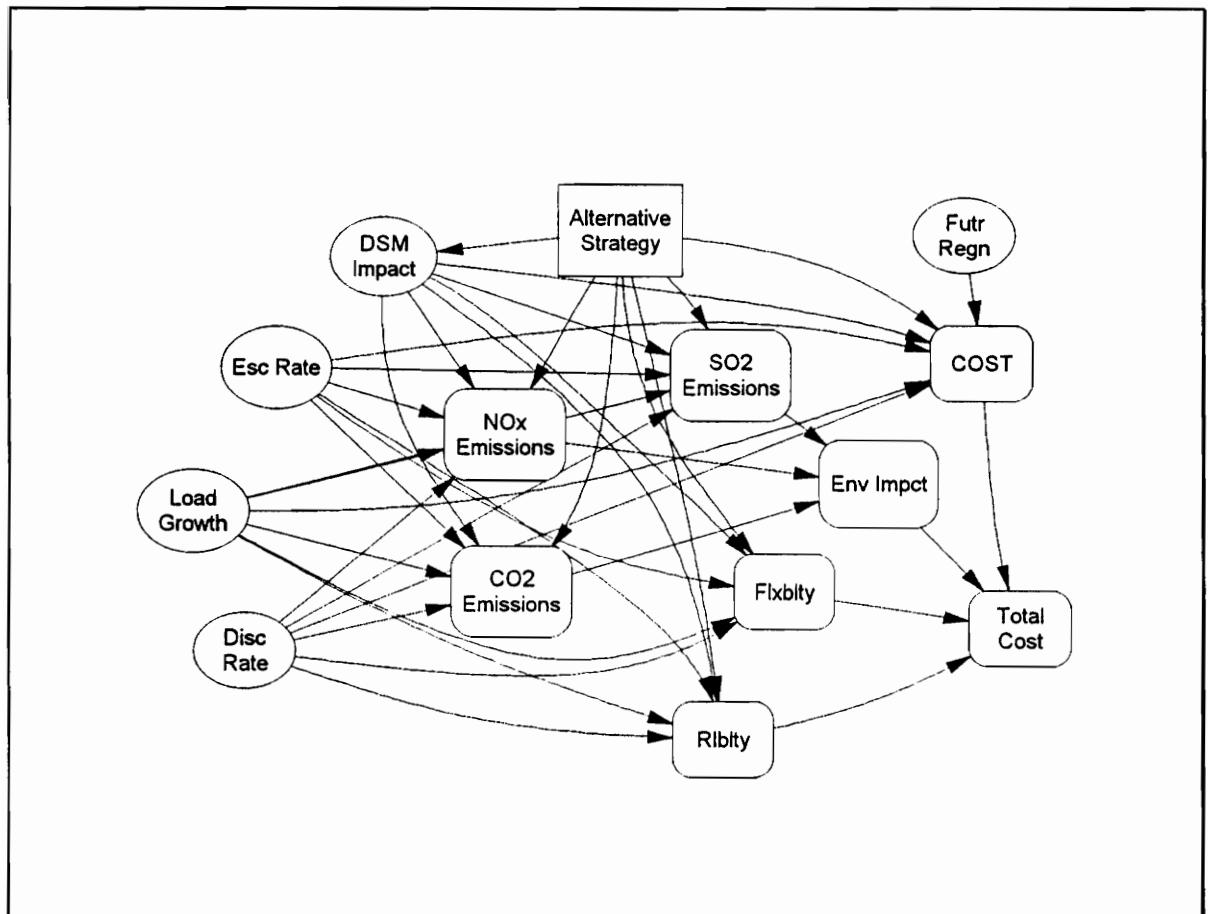
Figure 6.3   Influence diagram for expansion planning of sample electric utility.

that of Figure 4.2 which would have been considerably more involved. Figure 6.4 shows the simplified decision tree of the process.

Calculations for weights of the different attributes were shown in section 6.2. This discussion focuses on the units used to measure these attributes and how they relate to the actual cost of energy production.

As discussed in section 6.2, "COST" as given here includes the annual levelized cost of investments, fuel costs, operating and maintenance costs, as well as the cost of allowances. It is measured here in dollars per kilowatt-hour ($/kWh). Environmental impacts are measured in terms of dollars per ton of emission of SO_2, NOx and CO_2, as estimated in various studies on environmental externalities. Reliability (actually the lack of it) is measured in terms of expected unserved energy (EUSE) and the cost attached to it by the consumer. A rather indirect measure of flexibility is used here -- the ratio of coal to gas capacity -- in view of the ease with which gas plans can be changed and the possibility of conversion of gas plants to other types such as combined cycle plants.

It would be very convenient to add actual social costs of environmental impacts of emissions and of the inability to serve the energy requirements. This, however, may result in an extreme bias in generation planning away from the profit objective. On the other hand, as experience has shown, utility decision makers do incorporate these factors in their planning process and their failure to account for them will eventually result in some increase in cost which may not be directly quantifiable at the moment.

The weights of these factors can be estimated using the opinions of experts on how much value can be attached to them in relation to actual cost. AHP can be used to allow the planner to compare these factors against cost and against each other. This in effect assigns them some monetary value viewed from the utility perspective but considering social effects.
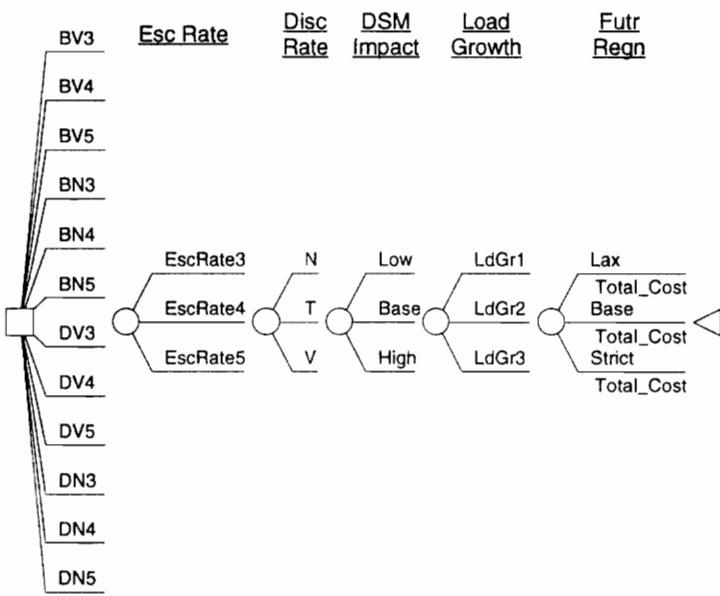
Figure 6.4   Decision Tree for expansion planning of sample electric utility.

6.5.2 Probability Calculations of Uncertainties

The probabilities of the different uncertainty states were determined using EVM and pairwise comparisons on the likelihoods of these states. This process yields Tables 6.15 to 6.19. Each table shows the three possible states of the uncertainty, the judgment matrix and the probability of each state. Again here, the pairwise comparison ratios are provided by the decision maker and will depend on his experience.

Table 6.15

Escalation Rate Probabilities

Esc Rate	Low (3.9)	Base (4.9)	High (5.9)	Probability
Low (3.9)	1	1/3	3	0.2583
Base (4.9)	3	1	5	0.6370
High (5.9)	1/3	1/5	1	0.1047

Table 6.16

Discount Rate Probabilities

Disc Rate	Low (8)	Base (10)	High (12)	Probability
Low (8)	1	1/3	1/2	0.1634
Base (10)	3	1	2	0.5396
High (12)	2	1/2	1	0.2970

Table 6.17

Load Growth Probabilities

Load Grwth	Low (1.5)	Base (2.5)	High (3.5)	Probability
Low (1.5)	1	1/3	3	0.2583
Base (2.5)	3	1	5	0.6370
High (3.5)	1/3	1/5	1	0.1047

Table 6.18

Future Regulation Probabilities

Future Reg	Lax	Base Case	Strict	Probability
Lax	1	1/3	1/7	0.0879
Bse Cse	3	1	1/3	0.2426
Strict	7	3	1	0.6694

Table 6.19

DSM Impact Probabilities

DSM Impct	Low	Base Case	High	Probability
Low	1	1/5	1/3	0.1047
Bse Cse	5	1	3	0.6370
High	3	1/3	1	0.2583

6.5.3   Influence Diagram Simulations

Solution of the influence diagram was performed using Decision Programming Language (DPL) (Call and Miller, 1990).   Four cases were run to evaluate the effects of the different attributes on the optimal plan: involving cost only; cost and environmental impact; cost, environmental impact and expected unserved energy (EUSE), and cost, environmental impact EUSE and coal-to-gas ratio. To be able to account for the priorities given to the other attributes, their values are multiplied by their relative weights as determined during the AHP simulations. A discussion of the results of evaluating the influence diagram under these conditions follows.

6.6   Optimization Results

Case I: Cost Only

Figure 6.5 shows the policy summary for the planning problem involving only the cost of generating a kilowatthour of electric energy.   Figure 6.6 shows the cumulative probability distribution of production cost for the selected alternative. The expected costs for each of the twelve alternatives are provided in Table 6.20.

The base case cost study expectedly results in the plan with the least cost.   This plan also has a low reserve capacity and does not provide for additional emission abatement equipment.

Case II: Cost and Environmental Impact

In this case, the cost of environmental impacts of emissions is added to the objecctive function, given the relative weight determined through AHP.   Figure 6.7 shows the policy summary for the case. The new expected "Total Costs" for the twelve alternatives are given in Table 6.21. Figure 6.8 gives the cumulative probability distribution for the optimal plan.
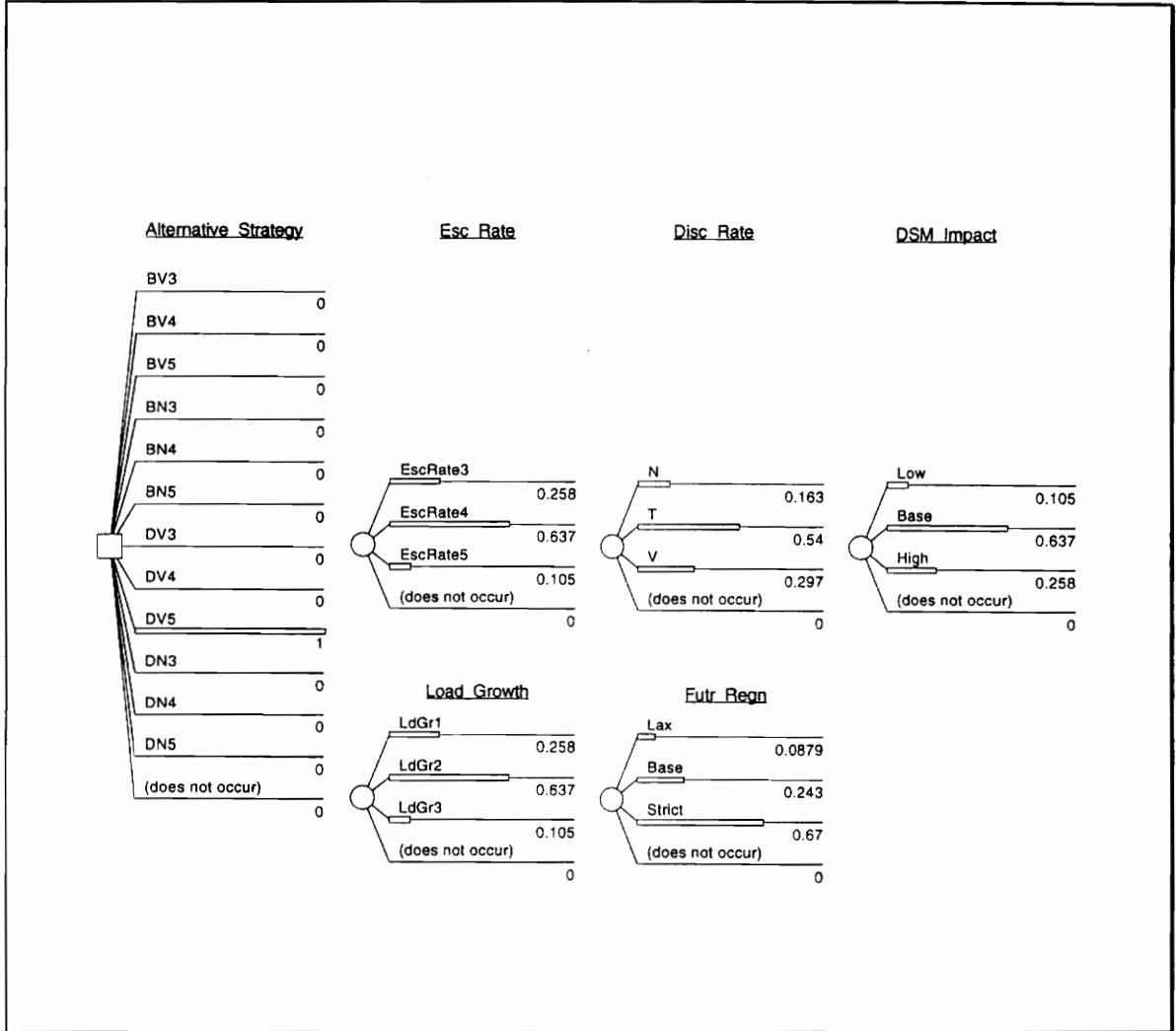
Figure 6.5   Policy summary for expansion planning of sample electric utility with a
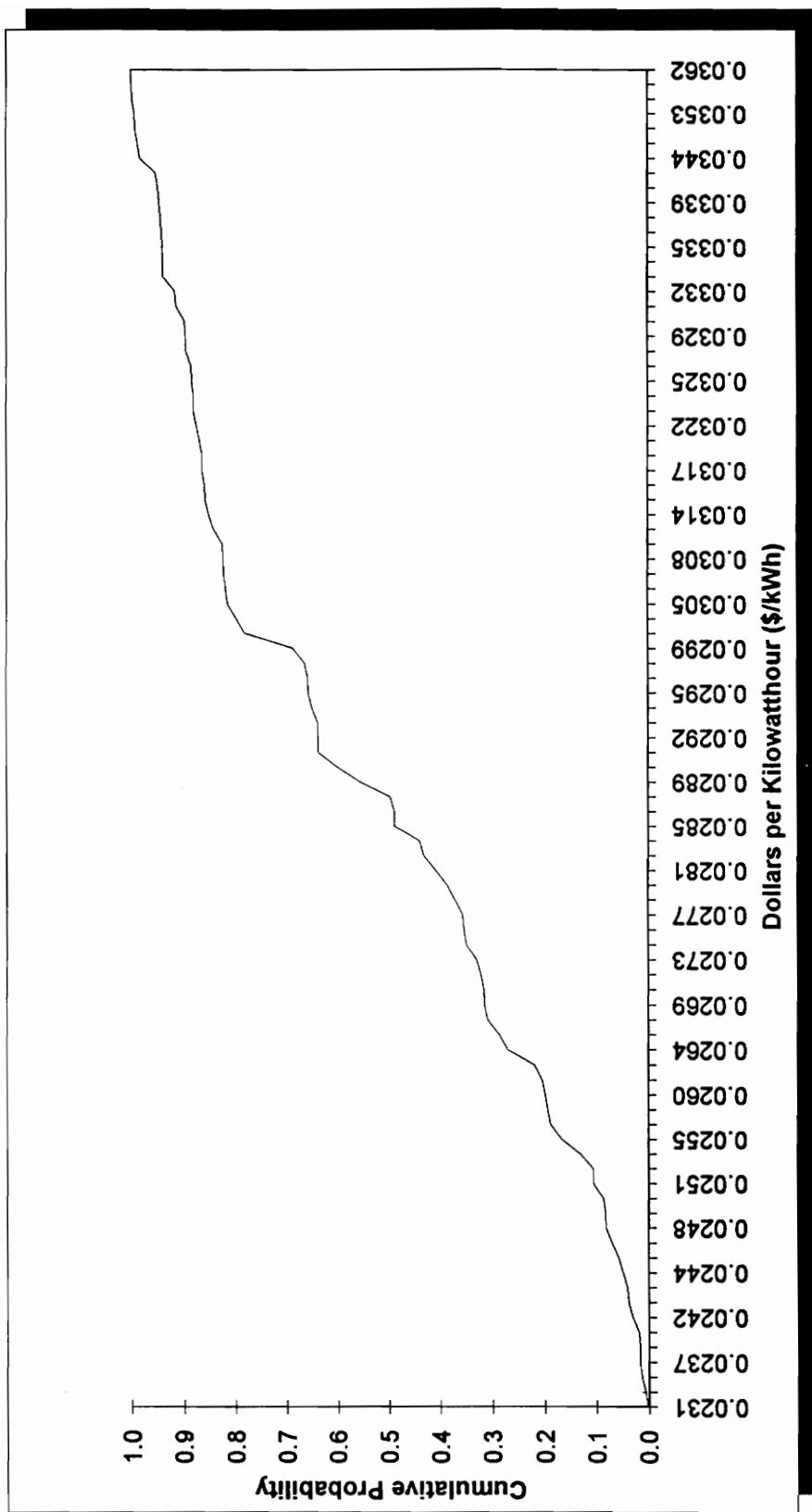production cost minimization objective.

Figure 6.6   Cumulative Distribution: Production Cost

Figure 6.7   Policy summary for expansion planning of sample electric utility for least cost of production and environmental externalities.
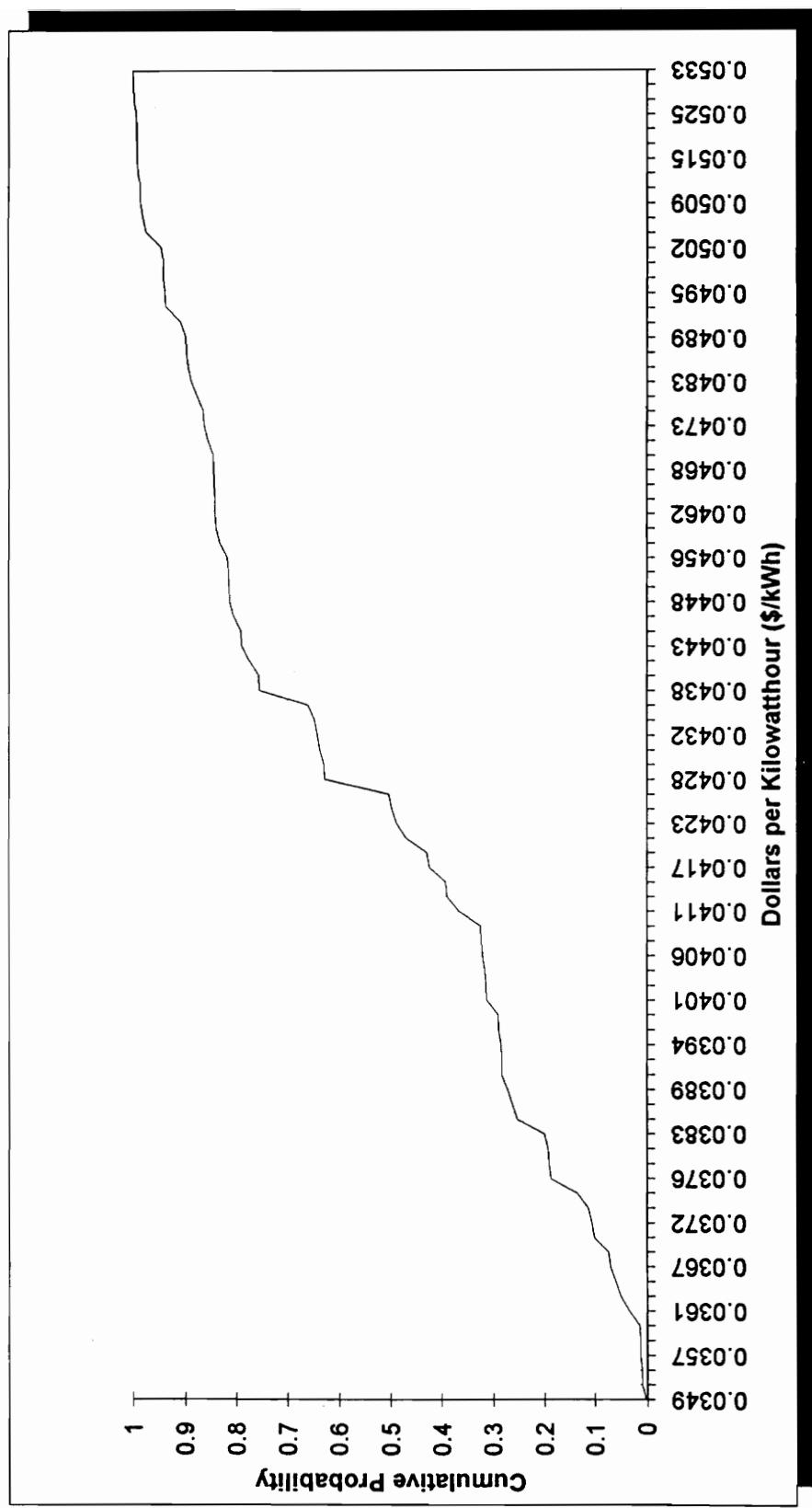
Figure 6.8   Cumulative Distribution: Cost and Environmental Impact

Table 6.20

Costs Per kWh of Strategy Alternatives:

Base Case Cost Objective

Strategy Alternative	$/kWh
VBZ3	0.0315
VBZ4	0.0306
VBZ5	0.0296
NBZ3	0.0328
NBZ4	0.0318
NBZ5	0.0310
VDB3	0.0297
VDB4	0.0292
VDB5	*0.0287*
NDB3	0.0309
NDB4	0.0303
NDB5	0.0299

Legend:
BZ   Base Case No DSM
DB   With DSM Option
V   Allowance Purchase Option
N   Emission Control
3   Low EUSE Limit
4   Base EUSE Limit
5   High EUSE Limit

When these costs of environmentasl impacts are included, the plans tend toward those that employ emission abatement. It may be noted that when environmental externalities are factored in, there is a shift in cost of about 30% based on available estimates.

Case III: Cost, Environmental Impact and Reliability

The resulting policy summary for this case is given in Figure 6.9. Table 6.22 gives the equivalent cost per kilowatthour for each alternative. The cumulative distribution of the expected

Alternative Strategy   Esc Rate   Disc Rate   DSM Impact

BV3
0

BV4
0

BV5
0

BN3
1

BN4
0

BN5
0

DV3
0

DV4
0

DV5
0

DN3
0

DN4
0

DN5
0

(does not occur)
0

Esc Rate

EscRate3
0.258

EscRate4
0.637

EscRate5
0.105

(does not occur)
0

Disc Rate

N
0.163

T
0.54

V
0.297

(does not occur)
0

DSM Impact

Low
1

Base
0

High
0

(does not occur)
0

Load Growth

LdGr1
0.258

LdGr2
0.637

LdGr3
0.105

(does not occur)
0

Futr Regn

Lax
0.0879

Base
0.243

Strict
0.67

(does not occur)
0
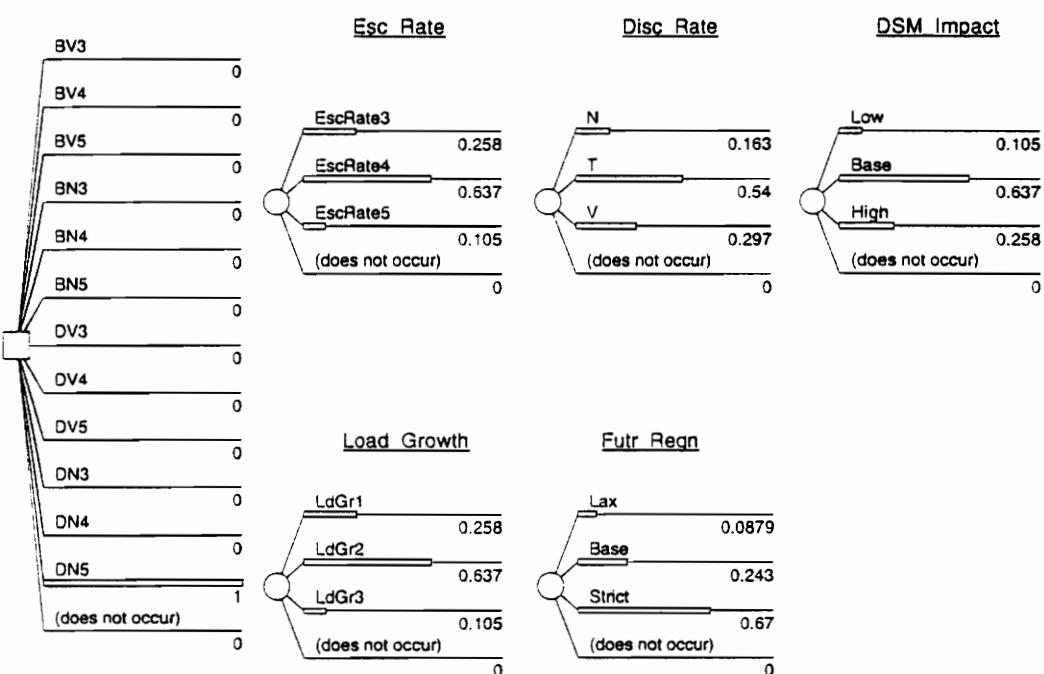
Figure 6.9   Policy summary for expansion planning of sample electric utility for least cost of production, environmental externalities and reliability.

value for the chosen alternative is given in Figure 6.10. Adding reliability as a factor attribute again shifts the strategy, this time towards the high-reserve-margin low-EUSE alternatives.

Table 6.21

Costs Per kWh of Strategy Alternatives:
Cost and Environmental Impacts

Strategy Alternative	$/kWh
VBZ3	0.0457
VBZ4	0.0443
VBZ5	0.0434
NBZ3	0.0452
NBZ4	0.0442
NBZ5	0.0434
VDB3	0.0439
VDB4	0.0429
VDB5	0.0424
NDB3	0.0433
NDB4	0.0428
NDB5	*0.0423*

Legend:
BZ   Base Case No DSM
DB   With DSM Option
V   Allowance Purchase Option
N   Emission Control
3   Low EUSE Limit
4   Base EUSE Limit
5   High EUSE Limit

Case IV: Cost, Environmental Quality, Reliability and Flexibility

The final case studied includes all of the selected attributes. For the given weight assignment and measure used for flexibility, no changes from the previous plan are observed. The policy summary for this case is given in Figure 6.11. Equivalent costs are given in Table 6.23 and the cumulative distribution of the expected value is given in Figure 6.12.

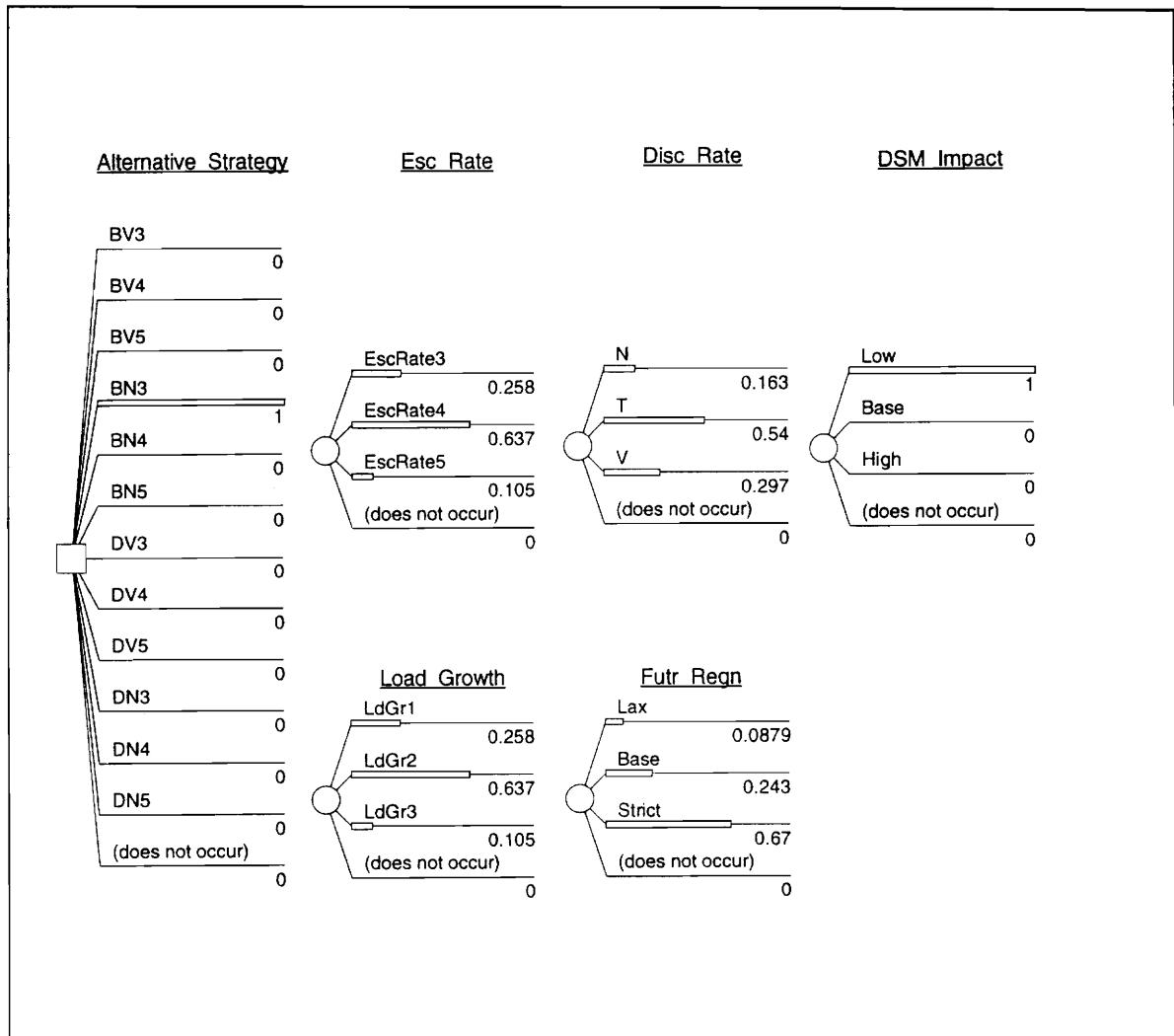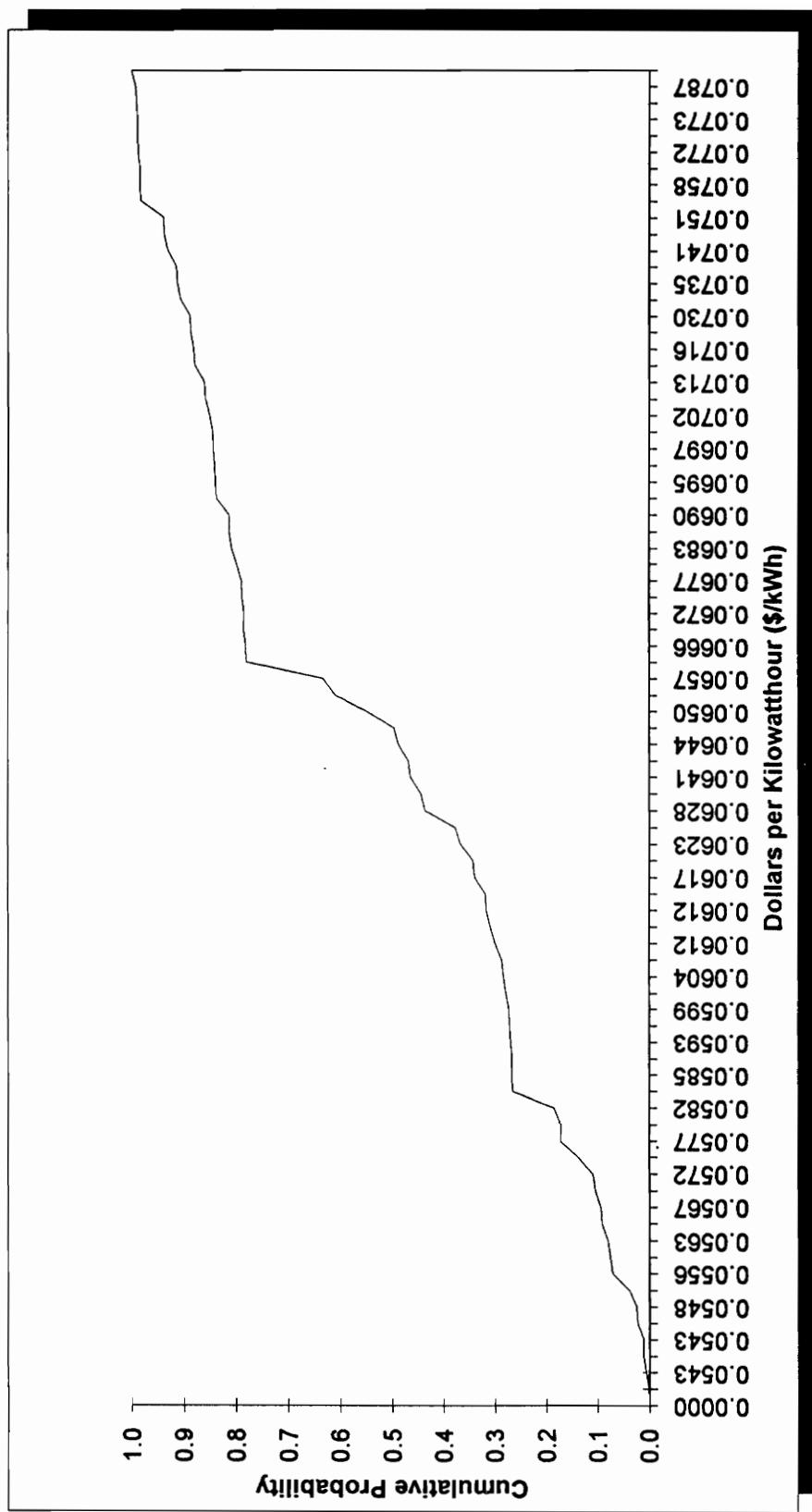Figure 6.10   Cumulative Distribution: Cost, Environmental Impact and Reliability
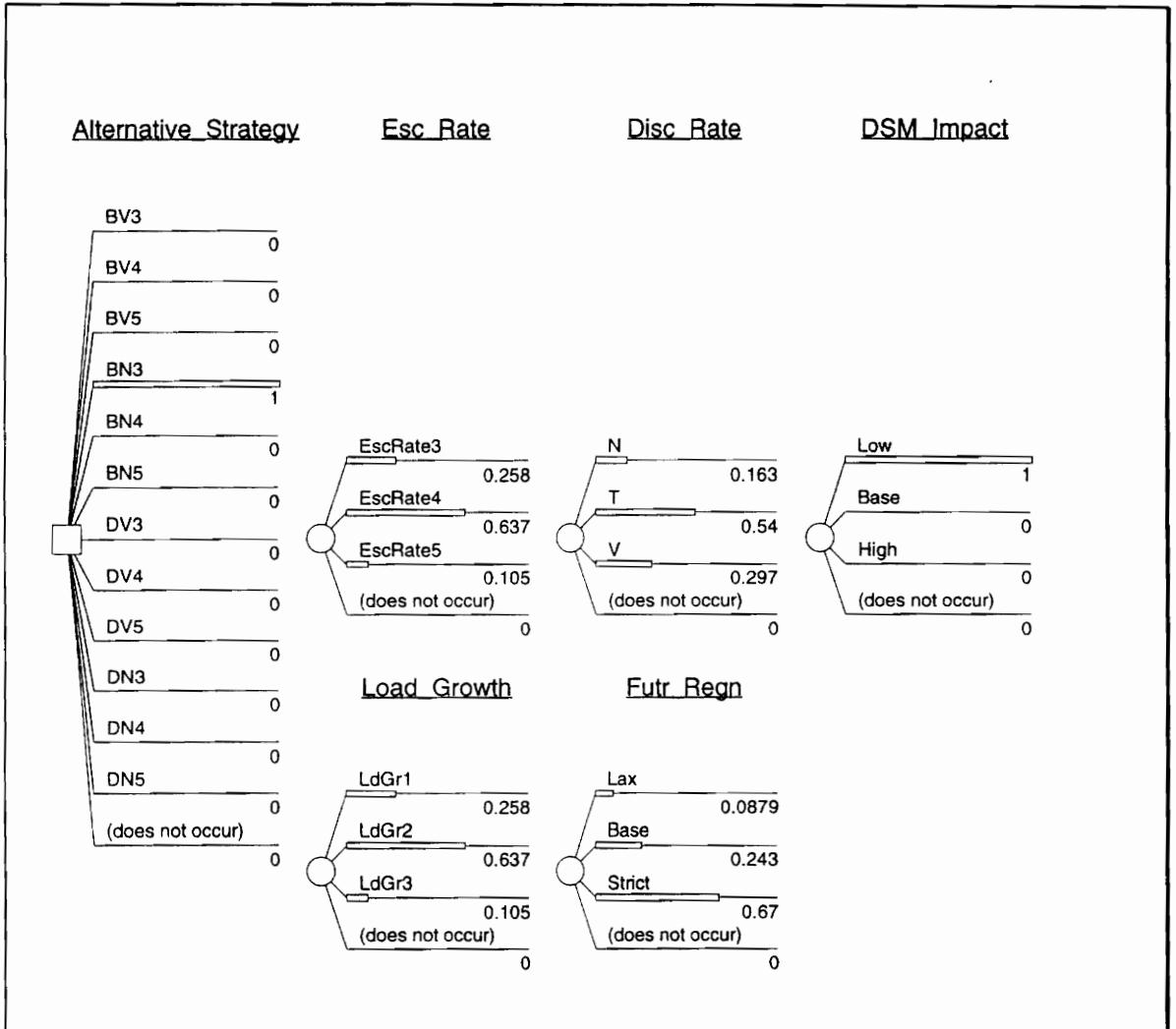
Figure 6.11   Policy summary for expansion planning of sample electric utility for least cost of

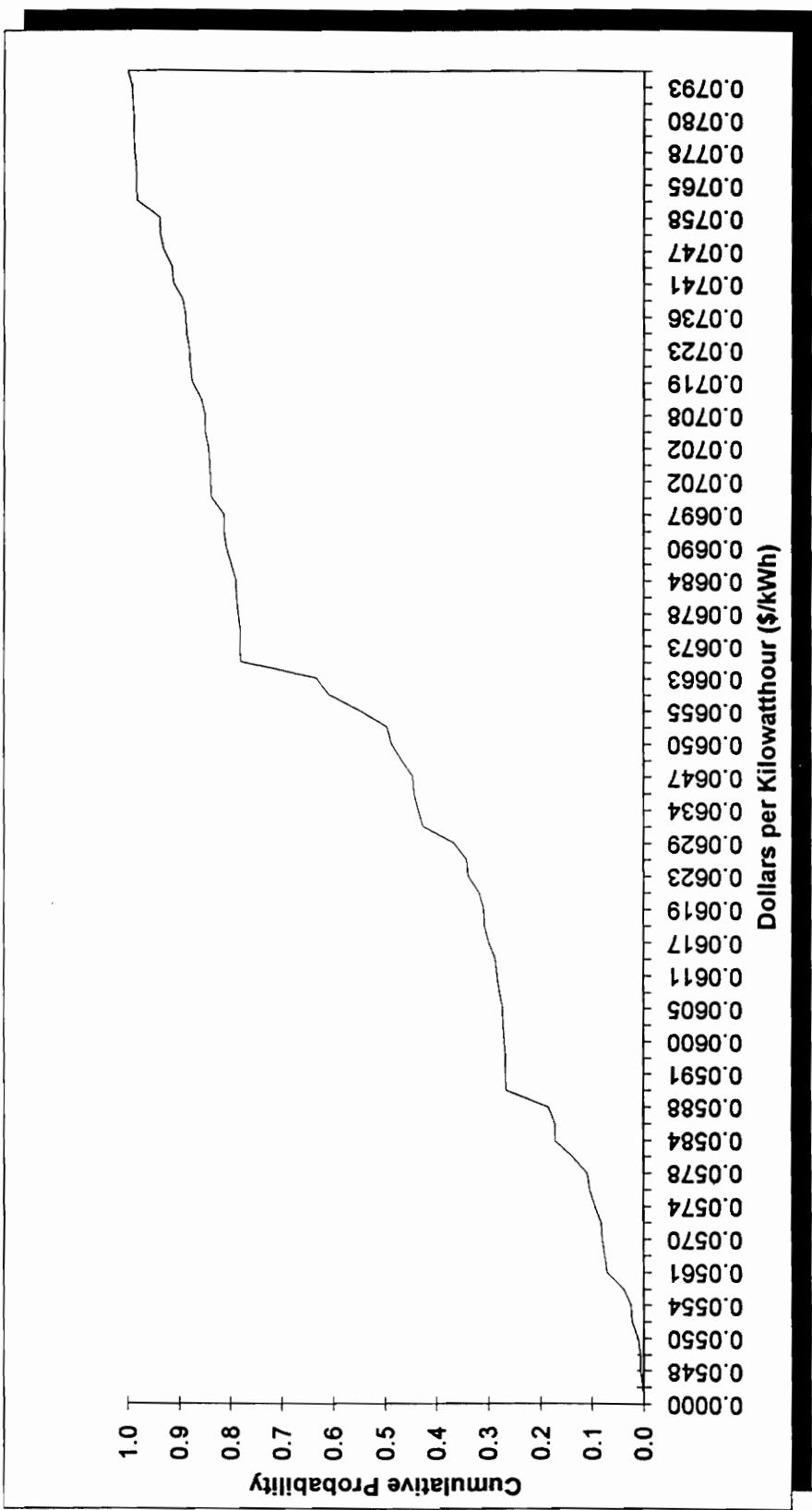production, environmental externalities, reliability and flexibility.

Figure 6.12   Cumulative Distribution: Cost, Environmental Impact, Reliability and Flexibility

Table 6.22

Costs Per kWh of Strategy Alternatives:

Cost, Environmental Impacts and Reliability

Strategy Alternative	$/kWh
VBZ3	0.0643
VBZ4	0.0751
VBZ5	0.0933
NBZ3	*0.0641*
NBZ4	0.0738
NBZ5	0.0934
VDB3	0.0684
VDB4	0.0799
VDB5	0.0949
NDB3	0.0670
NDB4	0.0787
NDB5	0.0915

Legend:
BZ   Base Case No DSM
DB   With DSM Option
V   Allowance Purchase Option
N   Emission Control
3   Low EUSE Limit
4   Base EUSE Limit
5   High EUSE Limit

This section has illustrated the application of AHP in selecting and giving weights to different attributes used in planning, as well as in identifying relevant uncertainties and providing estimates of their discrete probability distributions. The weights and probabilities obtained are then used in the influence diagram for selecting from among several planning alternatives.

One concern with the Influence Diagram (and Decision Tree) type of analysis is that it is seen to focus on one final solution and is not very attractive for risk analysis. This is one reason for the popularity of the trade-off method, which essentially provides a production possibilities

frontier for the decision maker. The next section discusses the extension of AHP and confidence-interval-based analysis to this technique.

Table 6.23

Costs Per kWh of Strategy Alternatives:
Cost, Environmental Impacts, Reliability and Flexibility

Strategy Alternative	$/kWh
VBZ3	0.0649
VBZ4	0.0758
VBZ5	0.0938
NBZ3	*0.0647*
NBZ4	0.0743
NBZ5	0.0939
VDB3	0.0690
VDB4	0.0805
VDB5	0.0954
NDB3	0.0675
NDB4	0.0790
NDB5	0.0919

Legend:
BZ   Base Case No DSM
DB   With DSM Option
V   Allowance Purchase Option
N   Emission Control
3   Low EUSE Limit
4   Base EUSE Limit
5   High EUSE Limit

6.7 Analysis of Trade-Offs

The trade-off curve presents the planner with the set of non-dominated plans when multiple attributes are considered. It does not, however, suggest a course of action based on the planner's priorities. By generating attribute weight ratios and their variances, minimum and

maximum weight ratios can be defined. Optimal plans corresponding to the minimum and maximum weight ratios can then be generated. Non-dominated plans between these points on the trade-off curve then form the set of acceptable choices.

Figures 6.13 to 6.18 show the trade-off curves among the four attributes in the sample system. Table 6.24 gives the table of composite ratios and their minimum and maximum values for a 95% confidence interval.

Table 6.24

Table of Composite Ratios

Attribute 1	vs. Attribute 2	Minimum	Ratio	σ	Maximum
Cost	Env Impact	0.6839	1.4820	0.3932	2.2801
Cost	EUSE	1.0225	2.3358	0.6469	3.6491
Cost	CGR	1.3979	3.2461	0.9105	5.0944
Env Impact	EUSE	0.6422	1.5761	0.4600	2.5100
Env Impact	CGR	0.8777	2.1904	0.6466	3.5030
EUSE	CGR	0.5271	1.3897	0.4249	2.2523

Table 6.25 lists the non-dominated plans for all of the six cases. Table 6.25 also identifies the plans remaining after use of a 95% confidence interval on the weight ratios of the different attribute values.

This example has shown how the utility decision-maker can narrow down his/her choices to those that are non-dominated and those that are within a certain range of the priority weights (or weight ratios) assigned to the different attributes.
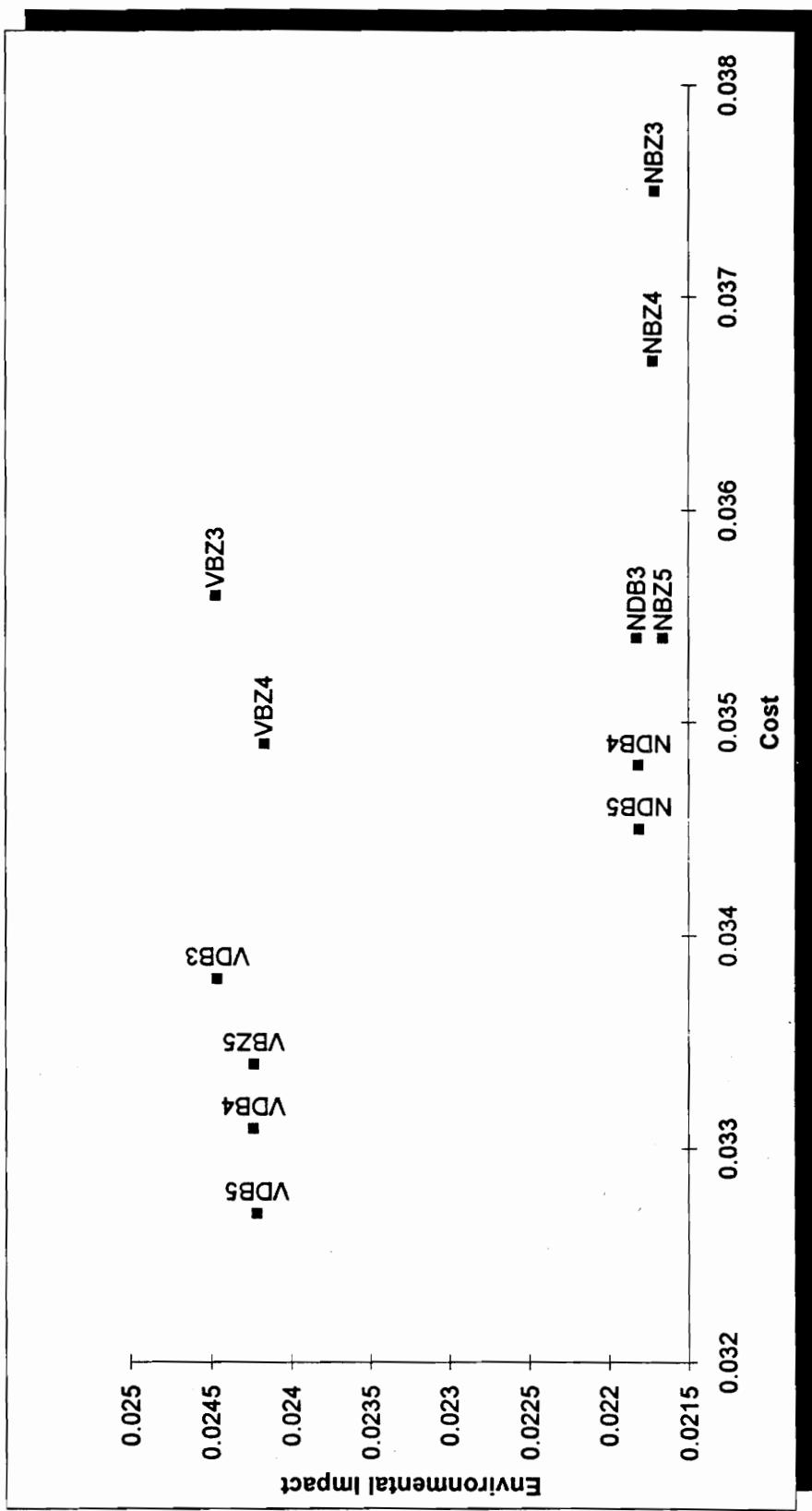
Figure 6.13   Trade-off set of cost vs. environmental impact
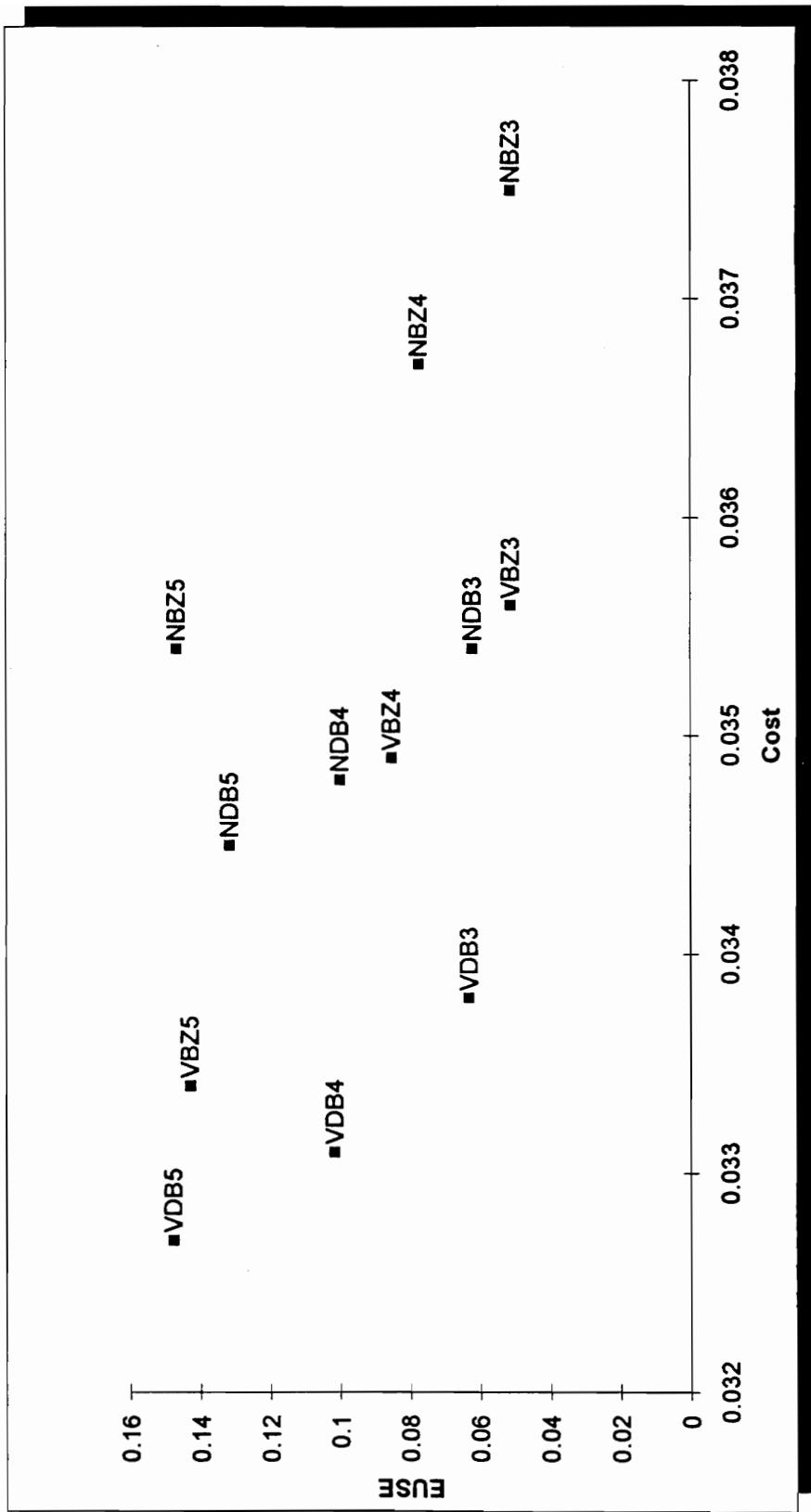
Figure 6.14   Trade-off set of cost vs. EUSE
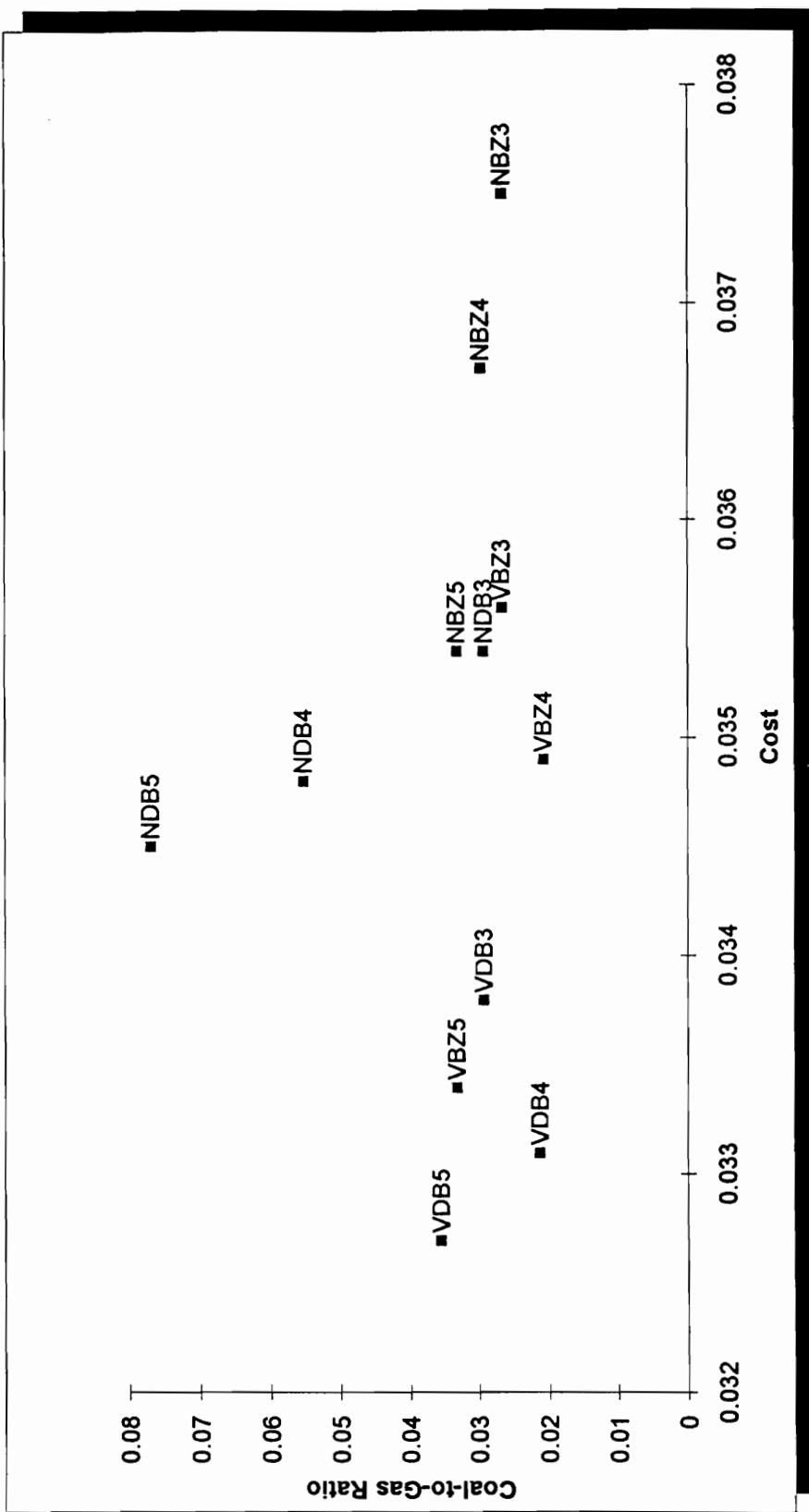
Figure 6.15   Trade-off set of cost vs. coal-to-gas ratio
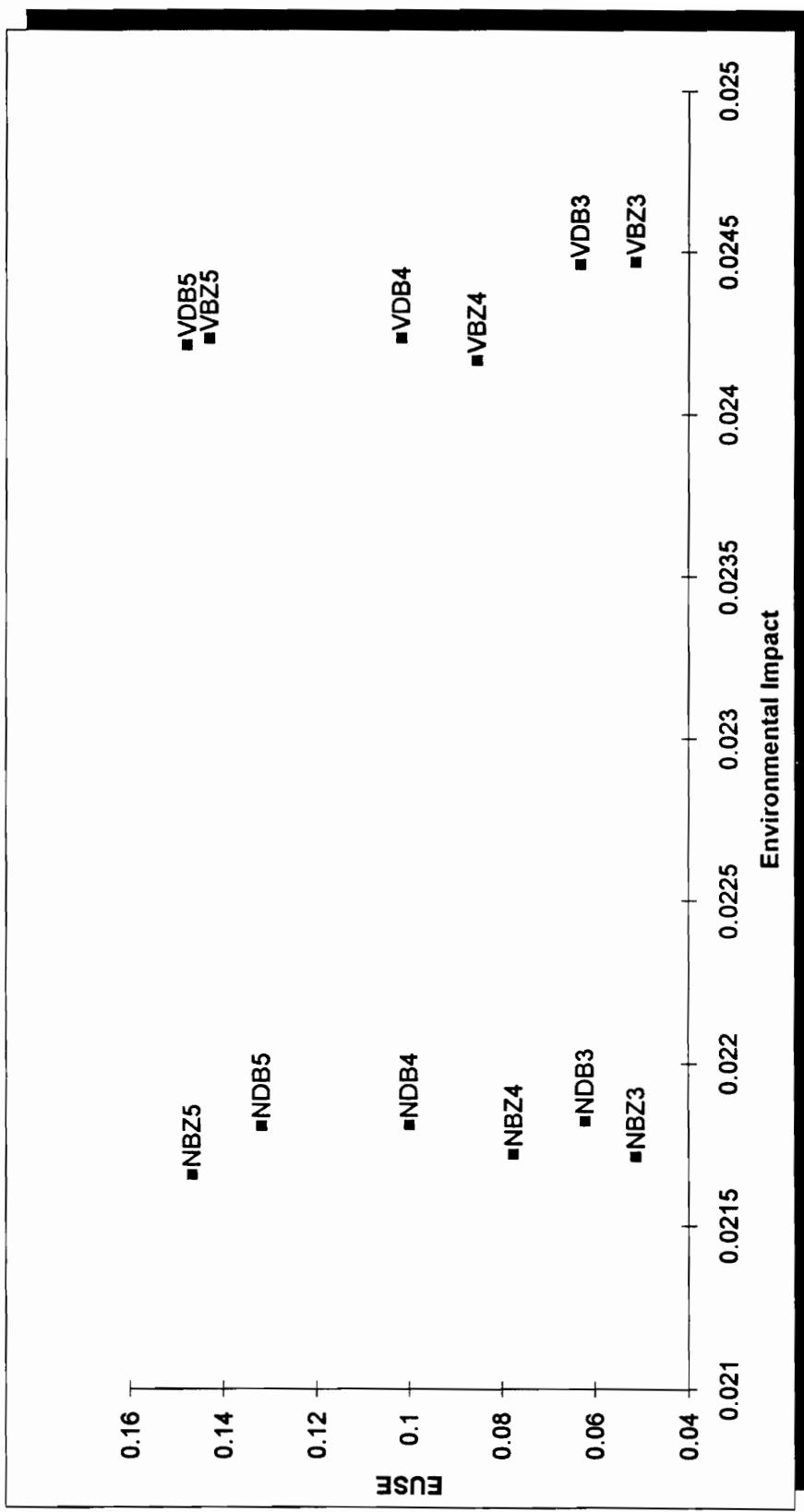
Figure 6.16   Trade-off set of environmental impact vs. EUSE
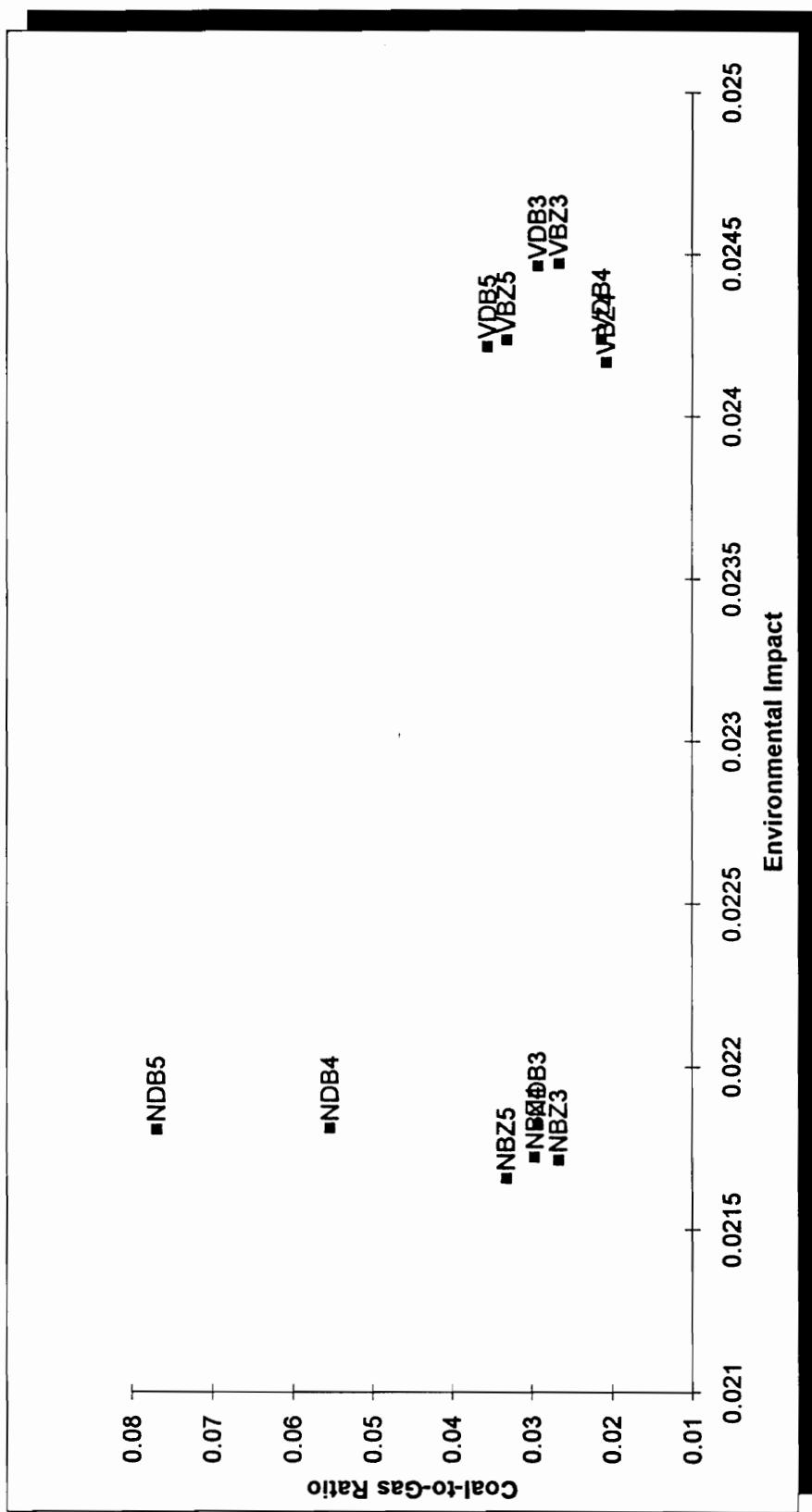
Figure 6.17   Trade-off set of environmental impact vs. coal-to-gas ratio
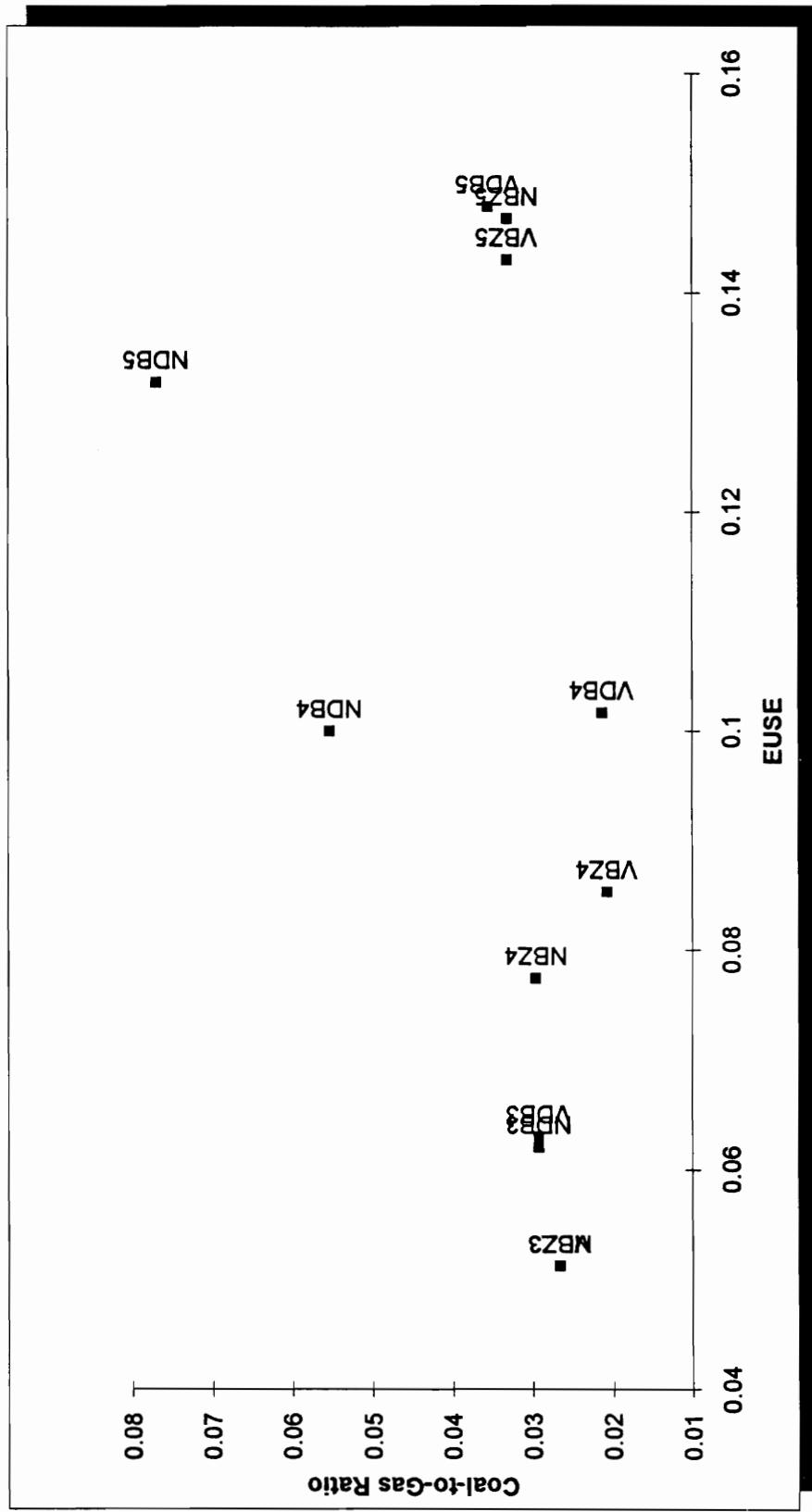
Figure 6.18   Trade-off set of EUSE vs. coal-to-gas ratio

Table 6.25

Non-Dominated Plans for Different Attribute Pairs

Option	Cost vs. Env Impact	Cost vs. EUSE	Cost vs. CGR	Env Impact vs. EUSE	Env Impact vs. CGR	EUSE vs. CGR
VBZ3		••		•		••
VDB3		••				
VBZ4			•		••	•
VDB4	•	••	••		•	
VBZ5	•					
VDB5	••	••	•			
NBZ3	•	•		••	••	••
NDB3	•	•				
NBZ4	•			•	•	
NDB4	•					
NBZ5	•			•	•	
NDB5	•					

Legend:

•   Non-Dominated Plan

••   Non-Dominated Plan within Range of Priority Ratios

Chapter 7

Conclusion and Recommendations

7.1 An Enhanced Framework for Multi-Attribute Generation Expansion Planning under Uncertainty

Complexities introduced by multiple players, conflicting objectives, variety of alternatives and uncertainty of the future necessitate a strategic approach to generation expansion planning. Among the techniques for strategic planning, the most popular are the probabilistic decision analysis and the trade-off methods because of their ability to address the multiplicity of objectives and to handle uncertainties. Probabilistic decision making through influence diagram analyses suggest an optimal plan by the assignment of probabilities to uncertain events that might affect it. In the case of generation planning, these uncertainties are quite numerous and result in rather large models. Weights are assigned to the different attributes to provide a common basis for evaluation. The advantages of decision analysis are its foundation on the rules of probability and, when using influence diagram analysis, the ability to represent the

dynamics of the decision process. At the end of the process, this method suggests a plan whose expected value is the highest (or expected cost is lowest) among those of the candidate plans. It also permits sensitivity analysis of the optimal plan and allows the DM to determine the value of perfect information. Its disadvantages are the amount of computations, the requirement for probability information and its inability to examine distinct possibilities of scenario occurrences.

The trade-off method, on the other hand, analyzes different scenarios and performs dominance tests to identify plans to include in the trade-off curve. By simulating a variety of uncertainties it can identify plans that meet the requirements of the different conditions. After selecting this " robust" plan, the technique hedges against scenarios that the plan does not meet by planning for additional generators or more flexible expansion technologies. The advantages of the trade-off technique are its applicability to systems where attribute metrics are not well-defined and where probability information is not readily available. However, it does not present the DM with an optimal plan based on a quantification of its preferences, and tends toward higher cost plans in the search for robustness.

This thesis has presented a framework for multi-attribute generation expansion planning under uncertainty. It has put into perspective the trade-off technique and the method of weights used for multi-attribute decision making as elements of the economic theory of the firm and then applied this unified concept in a hybrid approach that combines features of probabilistic decision making and scenario/trade-off analysis.

The technique uses influence diagrams to solve the strategic planning problem, assigning preference weights to the different attributes. Attribute weights and scenario probabilities are generated using hierarchical analysis. The same weights are used to eliminate attributes of low priority and uncertainties of low significance in order to streamline the decision analysis process.

The trade-off technique is used for risk analysis, identifying the impacts of each plan on the different attributes used to measure its value. An extension of the confidence-interval-based analysis to optimization results allows the planner to examine non-dominated plans that fall within his range of priority ratios.

A special focus of the study is the current concern on environmental impacts of electricity generation. This issue has been so significant that it resulted in a series of legislations to control emissions of acid rain precursors (SO_2 and NO_X) and other pollutants. Regulators have also been active in this respect, requiring electric utilities to internalize environmental externalities. The potential for new legislation on currently uncontrolled effluents like CO_2 likewise remains. Environmental impacts are thus included in the decision analysis model as an attribute as well as a source of uncertainty.

The technique was applied to the Virginia Power/North Carolina Power electric utility system. With a projected 2009 load of 100 000 GWh, The utility currently generates around 73500 GWh with a mixture of coal, nuclear, purchased energy, oil, gas and hydro generation. Expansion alternatives considered were base coal with allowance purchase, coal with FGD, gas, DSM and power purchases. Screening of attributes resulted in the inclusion of cost, environmental impact, reliability and flexibility objectives. Uncertainties were in load growth, DSM impacts, effect of future regulation, and discount and escalation rates. Base decision analysis for the particular case favors a base case no DSM option with emission controls and a low unserved energy (EUSE) constraint. Trade-offs analysis identifies DSM with high EUSE, DSM with medium EUSE and NON-DSM with low EUSE constraints, all with allowance purchase, as other contending options.

The case study has shown the usefulness of the technique in allowing the decision maker to incorporate objectives other than cost in planning the system, assign probability distributions to uncertainties and generate the optimum plan based on the given information. By

allowing the identification of other plans that satisfy planning priorities within the DM's range of preferences, it provides for more informed decision making in generation expansion planning.

7.2   Recommendations for Further Investigation

7.2.1   Calculation of Variance of Ratios of Composite Priorities

Gauss's approximation formula was used in order to arrive at an estimate of the variance of the composite priority ratios. This approximation method is good if the distributions of the random variables are concentrated around the means of the random variables, and the function for which the mean and variance are to be estimated is approximately linear near these means. Another assumption is that the random variables are independent, which is not necessarily the case. Further investigation can be directed at identifying an appropriate formula for calculating the variance of the ratios of the composite priorities.

7.2.2   Identification of Acceptable Alternatives

Analysis of the trade-off curves for near-optimal alternatives was based on the evaluation of the various options for the different attribute pairs. It is also possible to identify alternatives based on the efficient " surface" that can be formed when considering three or more attributes at the same time, particularly in well-behaved, convex trade-off functions. Further investigation of the technique can address the definition of the boundaries of this surface which will allow a more comprehensive enumeration of the acceptable alternatives.

7.2.3   Representation of Attributes

The attributes used in the case study were measured using the standard book definitions of cost and reliability, published estimates of external costs of emissions of CO_2, SO_2 and NO_X, and some simplified metric for flexibility. The main intent in the investigation was to facilitate the illustration of the technique. The actual utility planning environment, however, would require

better representation of the actual costs involved, and more accurate valuation of the other attributes. As an example, total system cost is often not visible (Blanchard, 1990), and its individual components are often not completely addressed. This can be taken into account by looking at all possible operation, support and retirement costs or by being conscious of such invisible costs in the assignment of weights.

Similar attention can be given to the other attributes as well. The valuation of environmental externalities has been discussed earlier and results of studies in this respect have been summarized by Busch (1993), Holstein (1992), Trisko (1993) Fritsche (1991) and Ottinger (1991). Sanghvi, et al. (1991) and Woo, et al. (1991) have studied the valuation of the reliability of electric service. The flexibility issue has been addressed by Brancart, et al. (1991) and Tanabe, et al. (1992). The future investigator can draw from these references and from an abundance of further literature on these as well as on the other attributes cited in this work.

7.2.4 Applications

The framework developed was implemented using data published by Virginia Power/North Carolina Power and some information on the industry from literature and from some contacts with planners. Most of the priority data, however, were supplied from personal knowledge and experience, and might not reflect actual industry conditions. Further investigation can be directed at the quantification of attribute priorities and the significance attached to the uncertainties.

7.2.5 Generalizing the Procedure for Model Reduction

In reducing the numbers of attributes and uncertainties to consider, arbitrary values were set by this investigator as cut-off points on the generated weights. In actual implementation, these numbers will be driven by user's choice and will not necessarily result in the same

numbers arrived at in the given case study. Further investigation can address the issue of size reduction and determining the relevance of attributes and uncertainties.

An alternative procedure can, in fact, be used to arrive at relevant uncertainties, as mentioned section 3.1.3. Given the probabilities of the states of the original chance variables, decision analysis can determine the sensitivity of the outcome to these variables and reduce their size early in the analysis. The investigator, therefore, has the choice between generating these probability estimates and running sensitivity analysis on one hand, and determining the relevant uncertainties by pairwise comparison on the other. Whatever incremental benefit the former method allows should be evaluated against the additional complexity that it entails.

7.2.6   Comparison with Other Methods

The strategic planning framework developed here applied Saaty's eigenvector method and analytic hierarchy process for selecting attributes and uncertainties. The variances of the ratios of composite priorities used for determining the interval for examining candidate plans is then estimated from the variances of composite priorities calculated using the method developed by Shrestha. Other methods for calculating weights and uncertainties, and the corresponding variances of the ratios of composite priorities can be investigated.

References

"Can Independent Power Satisfy World Demand?" (1989). (Power International Edition: Power Generation Technology) <u>Power</u>, v133, n12, December, p. S42(3).

Alvarado, Michael P., et al. (1992). "A Strategic Approach to CAA Compliance Plan Development, Evaluation and Implementation," <u>Proceedings of the American Power Conference</u>, Vol. 54-I, 54<u>th</u> Annual Meeting, Chicago, pp. 349-365.

Bellman, R. E. and L. A. Zadeh (1970). "Decision-Making in a Fuzzy Environment," <u>Management Science</u>, Vol. 17, No. 4, December, pp. B-141 -- B-164.

Bienstock D. and J. Shapiro (1988). "Optimizing Resource Acquisition Decisions by Stochastic Programming," <u>Management Science</u>, Vol. 34, No. 2, February.

Blanchard, B. S. and Fabryky, W. J. (1990). <u>Systems Engineering and Analysis</u>, Second Edition, Prentice Hall, New Jersey.

Blom, Gunnar (1989). <u>Probability and Statistics: Theory and Applications</u>, Springer-Verlag, New York.

Bolbrock, R.J. (1993). "NEPOOL Resource Adequacy Assessment (1993 - 2007)," Presented at the <u>IEEE/PES Winter Meeting</u>, Columbus, Ohio, February.

Borison, A., et al. (1984). "A State-of-the-World Decomposition Approach to Dynamics and Uncertainty in Electric Utility Generation Expansion Planning," <u>Operations Research</u>, Vol. 32, No. 5, 1052-1068.

Brancart, D., et al. (Working Group 01 of Study Committee 37) (1991). "Flexibility of Power Systems - Principles, Means of Achievement and Approaches for Facing Uncertainty by Planning Flexible Development of Power Systems," <u>Electra</u>, No 135, April, pp. 75-101.

Burke, W.J., et al. (1988). "Trade-off Methods in System Planning," IEEE Transactions on Power Systems, Vol. 3, No. 3, August, pp. 1284-1290.

Busch, John F. and Florentin L. Krause (1993). "Environmental Externality Surcharges in Power System Planning: A Case Study of New England," IEEE Transactions on Power Systems, Vol. 8, No. 3, August, pp. 798-795.

Buttorff, L.A. and A.W. Latti (1991). "Meeting Environmental Standards in an Integrated Resource Planning Process," Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, pp. 317-320.

Call, H. J. and W. A. Miller (1990). "A Comparison of Approaches and Implementations for Automating Decision Analysis," Reliability Engineering and System Safety, Vol. 30.

Camm, Frank and James K. Hammitt (1986). "An Analytic Method for Constructing Scenarios from a Subjective Joint Probability Distribution," A Rand Note prepared for the U. S. Environmental Protection Agency, May.

Cheng, Y. and R.L. Kashyap (1986). "Study of the Different Methods for Combining Evidence," Proceedings of SPIE, Vol. 635.

Connors, Stephen R. (1993). "Externality Adders and Cost-Effective Emissions Reductions: Using Tradeoff Analysis to Promote Environmental Improvement and Risk Mitigation," Proceedings of the American Power Conference, Vol. 55-I, 55th Annual Meeting, Chicago, pp. 697-702.

Dalkey, N.C. (1975). "An Elementary Cross Impact Model," in The Delphi Method: Techniques and Applications, Linstone, Harold A. and Murray Turoff (eds.), Addison Wesley Publishing Company, London.

Dalkey, N.C. (1986). "Inductive Inference and the Representation of Uncertainty," Proceedings of SPIE, Vol. 635, pp. 393-397.

Dapkus, W.A. and T.R. Bowe (1984). "Planning for New Electric Generation Technologies: A Stochastic Dynamic Programming Approach," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, No. 6, June, pp. 1447-1453.

Davis, Ged R. (1991). "Energy for Planet Earth," Readings from Scientific American: Energy for Planet Earth, W.H. Freeman and Company, New York, pp. 1-10.

de Castro, A. (1989). "Power System Planning," Lecture delivered at the TAC-UNIDO Seminar on Power Plant Engineering and Design, University of the Philippines.

de Kluyver, Cornelis A. and Herbert Moskowitz (1981). "Assessing Scenario Probabilities via Interactive Pre-Emptive Goal Programming," Paper No. 765, Krannert Graduate School of Management, Purdue University, Lafayette, Indiana, June.

Dempster, A. P. (1968). "A Generalization of Bayesian Inference," Journal of the Royal Statistical Society, Series B, Vol. 30, pp. 205-247.

Desai, M.S., et al. (1991). "Clean Air Act Amendments and their Impacts," Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, pp. 339-344.

Douglas, John (1992). "The Cost of Greenhouse Insurance," Electric Power Research Institute (EPRI) Journal, Dec, pp. 26-33.

Economic Commission for Europe (1993). Annual Bulletin of Electric Energy Statistics for Europe, vol. XXXVII, United Nations, New York.

Elsom, Derek M. (1987). Atmospheric Pollution: Causes, Effects and Control Policies, Basil Blackwell, New York.

Environmental Protection Department, Tokyo Electric Power Company (1992). Energy and the Environment, Tokyo, Japan, July.

EPRI Customer Systems Division (CSD) (1989). "Technical Brief: Electric Van and Gasoline Van Emissions: A Comparison," Electric Power Research Institute (EPRI).

EPRI Customer Systems Division (CSD) (1991). "Technical Brief: Load Management and the Environment," Electric Power Research Institute (EPRI) Report RP2788.

Evans, Gerald W., et al. (1982). "Multiobjective Energy Generation Planning Under Uncertainty," IIE Transactions, Vol. 14, No. 3, September, pp. 183 - 192.

Fritsche, Uwe (1991). "Incorporating Externalities in Least-cost Planning: The Use of Control Costs, Standards, and Multi-Attribute Approaches," External Environmental Costs of Electric Power: Analysis and Internalization, Proceedings of a German-American Workshop, Held at Ladenburg, FRG, October 23-25, 1990, Springer-Verlag, pp. 191-209.

Gerber, Mark S. (1990). "Decision Analysis -- The MIDAS Way," Conference on Decision Support Methods for the Eletric Power Industry, sponsored by EPRI, May 29 - 31, Cambridge, Mass., 11p.

Gorenstin, B.G., et al. (1992). "Power System Expansion Planning Under Uncertainty," paper presented at the IEEE/PES 1992 Winter Meeting, New York, New York, January 26-30.

Greenberger, Leonard S. (1992). "The Birth of Independent Power," Public Utilities Fortnightly, Mar 15, pp.17-19.

Guangyao, Wei (1993). "Electric Power in China," presented at the United Nations Seminar on System Planning in the Power Sector, 8-12 November, UN Headquarters, New York, USA.

Guha, Manoj K. (1994). "Can We Maintain an Environmentally Acceptable Environment with Emerging New Electric Generation Technologies," presented at Virginia Tech.

Haimes, Y.Y. and W.A. Hall (1974). "Multiobjectives in Water Resource Systems Analysis: The Surrogate Worth Trade Off Method," Water Resources Research, Vol. 10, No.4, August.

Hamburger, H. (1986). "Representing, Combining and Using Uncertain Estimates," in Uncertainty in Artificial Intelligence, L.N. Kanal and J.F. Lemmer, (Editors), North Holland, pp. 399-414.

Hess, Steve W., et al. (1992). "Planning System Operations to Meet Environmental Constraints," Proceedings of the American Power Conference, Vol. 54-I, 54th Annual Meeting, Chicago, pp. 366-370.

Hirst, Eric and Martin Schweitzer (1988). "Uncertainty in Long-Term Resource Planning for Electric Utilities," ORNL/CON -- 272 DE89 007858, Oak Ridge National Laboratory, Oak Ridge Tennessee, December, 66p.

Hobbs, B.F. (1992). "Emissions Dispatch Under the Underutilization Provision of the 1990 U.S. Clean Air Act Amendments: Models and Analysis," Presented at the IEEE/PES 1992 Winter Meeting, New York, NY, Jan 26-30, 7p.

Hobbs, Benjamin F. and Pravin Maheshwari (1990). "A Decision Analysis of the Effect of Uncertainty Upon Electric Utility Planning," Energy, Vol. 15, No. 9, pp. 785-801.

Holdren, John P. (1991). "Energy in Transition," Readings from the Scientific American: Energy for Planet Earth, W. H. Freeman and Co., New York.

Holstein, Michael P. and William J. Brands (1992). "Impacts on Least Cost Planning and System Operations of Monetizing Environmental Externalities," Proceedings of the American Power Conference, Vol. 54-II, 54th Annual Meeting, Chicago, pp. 1048-1054.

Holtzman, S. (1981). Intelligent Decision Systems. Addison-Wesley, Menlo Park, CA.

Horst, Thomas J. and Eugene T. Blake (1992). "The Environmental Advantage in the Competitive Equation," Proceedings of the American Power Conference, Vol. 54-II, 54th Annual Meeting, Chicago, pp. 1150-1152.

Hubbard, Harold M. (1991). "The Real Cost of Energy," Scientific American, vol 264 no 4, April, p36(6).

Idelson, Holly (1992). "National Energy Strategy Provisions," CQ, November, pp. 3722-3730.

International Atomic Energy Agency (1984). Expansion Planning for Electric Generating Systems: A Guidebook, Vienna.

International Energy Agency (1992). Energy Policies of IEA Countries, 1991 Review, OECD, Paris.

International Energy Agency (1993a). Energy Statistics of OECD Countries: 1990-1991, OECD, Paris.

International Energy Agency (1993b). Energy Statistics and Balances in Non-OECD Countries: 1990-1991, OECD, Paris.

Kane, R.L., et al. (1991). "Global Climate Change: A Discussion of Major Uncertainties," Proceedings of the American Power Conference 53rd Annual Meeting, v53-I, April 29 - May 1, Chicago, pp. 646 - 652.

Kashyap, R.L. (1971). "Prior Probability and Uncertainty," IEEE Trans. Information Theory, Vol. IT-17, pp. 641-650.

Kavrakoglu, Ibrahim and Gülseren Kiziltan (1983). "Multiobjective Strategies in Power Systems Planning," European Journal of Operational Research 12 pp. 159 - 170.

Keeney, Ralph L. and Howard Raiffa (1976). Decisions with Multiple Objectives: Preferences and Value Tradeoffs, John Wiley and Sons, New York.

Ko, Chung-Duck, et al. (1983). "Integration of Financial Constraints into Optimal Generation Planning, "Paper presented at the IEEE/PES 1983 Winter Meeting, New York, New York, Jan 30 to Feb 4, 9p.

Kosobud, R.F., et al. (1991). "Tradeable Permits for Global Warming Control: Implications for Regional Economies and Public Utilities," Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, Chicago, pp. 658-663.

Lamarre, Leslie (1991). "Responding to the Clean Air Challenge," EPRI Journal, April/May pp. 21-29

Levine, Mark D. (1993). "Electricity End-Use Efficiency: Experience with Technologies, Markets, and Policies Throughout the World," presented at the Annual Meeting of the Institute of Electrical Engineers, Japan, March, 43p.

Linstone, Harold A. and Murray Turoff (eds.) (1975). The Delphi Method: Techniques and Applications, Addison Wesley Publishing Company, London.

Lock, Reinier (1991). "Utility Regulation and the Clean Air Act Amendments of 1990," Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, Chicago, pp. 321-325.

MacGregor, P.R., et al. (1993). "Electric Utility Integrated Resource Planning in the U.S.," GE Industrial Power Systems Report GER-3740A.

Makovich, Lawrence J. (1991). "Development of Least Cost Greenhouse Control Strategies in U.S. Electric Production," Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, Chicago, pp. 653-657.

McManus, John M. (1993). "American Electric Power's Acid Rain Compliance Program," October, presented at Virginia Tech Power Systems Graduate Seminar.

Megdal, Lori McCreary and Yang Ziming (1991). "Incorporating Environmental Impacts into Integrated Resource Planning: The Use of an Optimization Matrix for IRP and the Development of a Costing Model for Local Environmental Impacts," presented at the 1991 Energy Program Evaluation Conference, Chicago, 8p.

Merril, H.M., et al. (1982). "Energy Strategy Planning for Electric Utilities, Part I: SMARTE Methodology" IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 2, February.

Merril, H.M., et al. (1982). "Energy Strategy Planning for Electric Utilities, Part II: SMARTE Methodology Case Study," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-101, No. 2, February.

Merrill, H. M. and A. J. Wood (1990). "Risk and Uncertainty in Power System Planning," Paper presented at the 10th Power Systems Computation Conference, Graz, Austria, Aug. 19-24.

Metzler, A.R., et al. (1992). "Decision-Making for Complying with SO_2 Provisions of the Clean Air Act," Proceedings of the American Power Conference, Vol. 54-II, 54th Annual Meeting, pp. 1153-1158.

Mobasheri, Fred and Bradley R. Williams (1990). "Using Decision Analysis for Evaluation of Transmission Projects," Conference on Decision Support Methods for the Eletric Power Industry, sponsored by EPRI, May 29 - 31, Cambridge, Mass., 14p.

Modiano, E.M. (1987). "Derived Demand and Capacity Planning under Uncertainty", Operations Research, Vol. 35, No. 2, March/April.

Molburg, J. and D. Hanson (1992). "A National Aggregate Projection of Utility Compliance Decisions," Proceedings of the American Power Conference, Vol. 54-I, 54th Annual Meeting, pp. 360-365.

Mukerji, Rana and Byrne Lovell (1988). "Creating Data Bases for Power Systems Planning Using High Order Linear Interpolation," IEEE Transactions on Power Systems, Vol. 3, No. 4, Nov. pp. 1699 - 1705.

Mulligan, George, et al. (1981). "Applications of Improved Financial Simulation Techniques to the Evaluatiojn of Electric Energy Alternatives in New York State," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, No. 4, April, pp. 1614-1623.

Murphy, F., S. Sen and A. L. Soyter (1982). "Electric Utility Capacity Expansion Planning with Uncertain Load Forecasts," IIE Transactions, Vol. 14, pp. 52-59.

Office of the President, National Power Corp. (1993). Power Development Program, Generation Projects (1993-2005), as of October 13, personal correspondence.

Oliver, R.M. and Smith, J.Q., eds. (1990). Influence Diagrams, Belief Nets and Decision Analysis. John Wiley and Sons, Chichester, West Sussex, England.

Ottinger, Richard L. (1991). "Incorporation of Environmental Externalities in the United States of America," External Environmental Costs of Electric Power: Analysis and Internalization, Proceedings of a German-American Workshop, Held at Ladenburg, FRG, October 23-25, 1990, Springer-Verlag, pp. 353-374.

Pearce, David W. and R. Kerry Turner (1990). Economics of Natural Resources and the Environment, The Johns Hopkins University Press, Baltimore.

Pearl, J. (1988). Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference. Morgan Kaufmann Publishers, Inc., San Mateo, CA.

Peper, G.L. and J.S. Walicki (1987). "Inexact Reasonings in Expert Systems," Proc. IEEE International Conference on Industrial Electronics, Control and Instrumentation, Cambridge Mass., Vol. SPIE-857, Nov., pp. 802-809.

Project 88 -- Round II, Incentives for Action: Designing Market-Based Environment Strategies (1991). A Public Policy Study sponsored by Senator Timothy E. Wirth, Colorado, and John Heinz, Pennsylvania, Washington, D.C., May.

Pytte, Alyson (1990). "Clean Air Act Amendments," Congressional Quarterly, Nov 24, pp. 3934-63.

Quartucy, Greg C., et al. (1992). "Clean Air Strategies Study," Proceedings of the American Power Conference, Vol. 54-II, 54th Annual Meeting, Chicago, pp. 1171-1176.

Rabl, Veronica A. (1994). "IRP, DSM and the Environment," in Integrated Electricity Resource Planning, Proceedings of the NATO Advanced Research Workshop on Models for Integrated Electricity Resource Planning, Espinho, Portugal, June 28 - July 2, 1993, Kluwer Academic Publishers, pp. 35-48.

Rafizadeh, Hamid A. (1992). "Multi-Disciplinary Management Needs of Power Systems: A New Challenge," Proceedings of the American Power Conference, Vol. 54-I, 54th Annual Meeting, Chicago, pp. 377-382.

Rahman, S. and A. de Castro (1994a). "A Framework for Incorporating Environmental Factors in the Utility Planning Process," IEEE Trans. on Power Systems, Vol. 9, No. 1, Feb., pp 352-358.

Rahman, S. and A. de Castro (1994b). "Environmental Impacts of Electricity Generation: A Global Perspective," Paper presented at the IEEE/PES 1994 Summer Meeting, San Francisco, California, July 24-28.

Rahman, S. and G. Shrestha (1990). "An Uncertainty Evaluation Technique for Determining Probability Estimates," presented at the First International Symposium on Uncertainty Modeling and Analysis, University of Maryland, December 3-5, 5p.

Rahman, S. and L. C. Frair (1984). "A Hierarchical Approach to Electric Utility Planning," Energy Research, Vol. 8, pp. 185 - 196.

Rahman, S. (1992). Alternate Energy Systems Course Notes, VPI&SU.

Raiffa, H. (1968). Decision Analysis. Addison-Wesley, Reading MA.

Rich, Elaine, and Kevin Knight (1991). Artificial Intelligence, McGraw-Hill, Inc., New York.

Roberts, L.E.J., P.S. Liss and P.A.H. Saunders (1990). Power Generation and the Environment, Oxford University Press.

Saaty, T. L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation, McGraw-Hill, New York.

Sanghvi, Arun P., et al. (1991). "Power System Reliability Practices in North America," IEEE Trans. PWRS, vol. 6, no. 4, November, pp. 1485-1492.

Shachter, R.D. (1986). "Evaluating Influence Diagrams," Operations Research, 34(6) (Nov-Dec).

Shafer, G. (1976). A Mathematical Theory of Evidence, Princeton University Press, Princeton, New Jersey.

Shannon, R.H. (1982). Handbook of Coal-Based Electric Power Generation, Noyes Publications, New Jersey.

Shortliffe, E.H. (1976). Computer-Based Medical Consultation: MYCIN, New York: Elsevier.

Shrestha, Govinda (1990). Formulation and Analysis of a Probabilistic Uncertainty Evaluation Technique, Doctoral Dissertation, Virginia Polytechnic Institute and State University.

Shwayri, N.S. (1993). "IDEAS: Integrated Decision Analysis System in Least-Cost Risk-Adjusted Resource Planning," Presented at the IEEE/PES Winter Meeting, Columbus, Ohio, February.

Siskos, J., and Ph. Hubert (1983), "Multi-criteria Analysis of the Impacts of Energy Alternatives: A Survey and a New Comparative Approach," European Journal of Operational Research 13, pp. 278 - 299.

Stallard, G. Scott and Alan W. Ferguson (1991). "Addressing the Challenges of the New Clean Air Act," Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, pp. 326-333.

Statistics Directorate (1993). National Accounts: Main Aggregates Volume 1, 1960-1991, OECD, Paris.

Stojka, J.P. (1993). "Emission Allowances...Impacts on System Operations," Presented at the 1993 IEEE Winter Power Meeting, Columbus, Ohio, February 4.

Stoll, H.G. (1989). Least-Cost Electric Utility Planning, John Wiley and Sons, New York.

Stone and Webster Engineering Corp. (1989). "Electric Generation Expansion Analysis System, Version 4: Capabilities Manual," EPRI Report RPI 1529-2, April.

Strategic Decisions Group (1993). "Windows on the Future, Using Scenarios to Envision the Impact of Future Uncertainties on Utility Markets, " EPRI Report TR-102567, September.

Sundararaman, N. (1991). "Energy and Global Climate Change Issues," in Electricity and the Environment, Proceedings of the Senior Expert Symposium, Helsinki, Finland, 13-17 May, International Atomic Energy Agency, Vienna, 1991, pp. 203-217.

Szidarovsky, Ferenc, Mark E. Gershon and Lucien Duckstein (1986). Techniques for Multiobjective Decision Making in Systems Management, Elsevier, Amsterdam.

Tabors, R.D. and B. L. Monroe (1991). "Planning for Future Uncertainties in Electric Power Generation: An Analysis of Transitional Strategies for Reduction of Carbon and Sulfur Emissions," IEEE/PES 1991 Winter Meeting.

Tanabe, R. et al. (1992). "Flexible Generation Mix Under Multi Objectives and Uncertainties," paper presented at the IEEE/PES 1992 Winter Meeting, New York, New York, January 26-30.

Taylor, G.E. and C.A. Fox (1991). "Air Pollution and Greenhouse Gases: the Environmental Uncertainty in Planning for Power Systems," presented at the NSF/EEI Workshop on Research Needs for Coping with Uncertainty in Power Systems, Univ. of Oklahoma, Norman, Okla., July 15-17.

Taylor, G.E. and C.A. Fox, "Air Pollution and Greenhouse Gases: the Environmental Uncertainty in Planning for Power Systems," presented at the NSF/EEI Workshop on Research Needs for Coping with Uncertainty in Power Systems, Univ. of Oklahoma, Norman, Okla., July 15-17, 1991.

Temple, Barker and Sloane, Inc., Environmental Externalities: An Overview of Theory and Practice, Electric Power Research Institute (EPRI) CU/EN-7294, Research Project 2982-6, Final Report, May 1991.

Temple, Barker and Sloane and M. S. Gerber and Associates, MIDAS Model Documentation, EPRI, 1988.

The Environmental and Conservation Services Department and the Electric Utility Department, City of Austin, The Technical Development Plan to Create an Integrated Resource Planning (IRP) Process: The IRP Development Plan for the City of Austin, Austin, Texas, May 1990.

Tong, R.M. and L.A. Appelbaum, "Experiments with Interval Valued Uncertainty," in Uncertainty in Artificial Intelligence 2, L.N. Kanal and J.F. Lemmer, (Editors), North Holland, 1988.

Trisko, Eugene M., "Environmental Externalities: Thinking Globally, Taxing Locally," in Sience and Technology, Public Utilities Fortnightly, March 1, 1993, pp. 52-55.

U. S. Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accident Risks in U. S. Commercial Nuclear Power Plants, WASH-1400 (NUREG 75/014), October 1975.

Varian, H., Microeconomic Analysis. Second Ed., 1984.

Virginia Power -- Power Planning Department (PPD), Long-Range Forecast of Load and Resources: 1992-2011, Virginia Power/North Carolina Power, 1992.

Violette, Daniel M. and Donald C. Peterson, Jr., "Utility Planning and Evaluating Environmental Externalities," presented at the Conference on Decision Support Methods for the Electric Power Industry, Sponsored by EPRI, hosted by Boston Edison Co., May 29-31, 1990, Cambridge Mass.

Woo, Chi-Keung, et al., "How Much Do Electric Customers Want to Pay for Reliability? New Evicence on an Old Controversy," Energy Systems and Policy, Volume 15, 1991, pp. 145-159.

Yamaji, K., "Role of Electricity in Minimizing Environmental Impacts," in Electricity and the Environment, Proceedings of the Senior Expert Symposium, Helsinki, Finland, 13-17 May 1991, International Atomic Energy Agency, Vienna, 1991, pp. 97-112.

Yates, Ralph .L., "Will the Electric Utility Industry Survive the Clean Air Act Amendments of 1990?" Proceedings of the American Power Conference, Vol. 53-I, 53rd Annual Meeting, April 29-May 1, 1991, Chicago, pp. 334-338.

Yeager, Kurt E., "Electric Vehicles and Solar Power," IEEE Power Engineering Review, v12, n10, October 1992, pp. 13-18.

Zmuda, J.T., "Acid Rain Compliance Planning: Compliance Issues and Options," Proceedings of the American Power Conference, Vol. 54-I, 54th Annual Meeting, 1992, pp. 371-376.

Appendix A

The Eigenvector Method

The Analytic Hierarchy Process is based on the Eigen Vector Method (EVM). This method was developed by Saaty (1980) to determine the relative ranking of factors relevant to some objective (criterion). The EVM method operates by using pairwise comparison judgment to consider factors which are not effectively quantified. Factors subject to uncertainty, conflicting objectives and inexactness in measurement may be considered with the judgmental process. The purpose is to obtain the priority vector, which will represent the relative likelihoods of the scenarios to occur.

If we denote the expert input comparing i^{th} factor with respect to j^{th} factor by a_{ij}, then the relative importance of jth factor with respect to i^{th} factor is represented as $1/a_{ij}$. The $(n \times n)$ matrix obtained by arranging these pairwise comparison ratios is called the reciprocal judgment matrix [A] which can be written as the following.

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \tag{A.1}$$

The reciprocal matrix is said to be consistent if $a_{ij}\, a_{jk} = a_{ik}$ for all i, j, k, = 1, ..., n.

The priority vector which gives the ranking of the relevant factors is obtained by normalizing the principal eigenvector W of A which is computed using the eigenvalue problem:

$$[A] \cdot W = \lambda_{max} \cdot W$$

where λ_{max} is the principal or largest real eigenvalue of [A]. Normalization is obtained by imposing the constraint $\sum w_i = 1$ on the elements of W.

If all the priorities p_i's are known, then the pairwise comparison judgment ratios become $a_{ij} = p_i / p_j$ and the above eignevalue problem reduces to the following set of equations:

$$\begin{bmatrix} p_1/p_1 & p_1/p_2 & \cdots & p_1/p_n \\ p_2/p_1 & p_2/p_2 & \cdots & p_2/p_n \\ \cdots & \cdots & \cdots & \cdots \\ p_n/p_1 & p_n/p_1 & \cdots & p_n/p_n \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \cdots \\ p_n \end{bmatrix} = n \begin{bmatrix} p_1 \\ p_2 \\ \cdots \\ p_n \end{bmatrix} \tag{A.2}$$

The solution of these equations yield the eigenvector, which is the priority vector.

The scale of numbers 1/9, 1/8, ..., 1, 2, ..., 9 is used in making pairwise comparisons to quantify qualitative judgments. Saaty suggests the scales of comparison in Table A.1.

Table A.1

Suggested Scales of Comparison

a_{ij}	Definition	Explanation
1	Equal	Attribute i is as important as attribute j
3	Weak Importance	Attribute i is slightly more important than attribute j
5	Strong Importance	Attribute i is strongly more important than attribute j
7	Very Strong Importance	Attribute i is very strongly more important than attribute j
9	Absolute Importance	Attribute i is dominantly important than attribute j

The intermediate numbers 2, 4, 6, and 8 are used when further refinement and resolution are needed.

Appendix B

The Analytic Hierarchy Process

The analytic hierarchy process provides a structure defining the dynamics of a system of interest. The problem is broken up into layers, each layer influencing the entities in the level immediately above it. Beginning, then, from the second level of the hierarchy, each entity is given a weight by pairwise comparison of the factors in that level with respect to every factor in the upper level. This procedure uses the eigen vector method to calculate the individual and overall influence of factors on the goal.

The priorities in the n-level hierarchy in Figure B.1 can be calculated using the following matrix equation:

$$
\begin{bmatrix} p_{1,n}^{1,1} \\ p_{2,n}^{1,1} \\ \dots \\ p_{n,n}^{1,1} \end{bmatrix} = \begin{bmatrix} p_{1,n}^{1,n-1} & p_{1,n}^{2,n-1} & \dots & p_{1,n}^{m_{n-1},n-1} \\ p_{2,n}^{1,n-1} & p_{2,n}^{2,n-1} & \dots & p_{2,n}^{m_{n-1},n-1} \\ \dots & \dots & \dots & \dots \\ p_{m_n,n}^{1,n-1} & p_{m_n,n}^{2,n-1} & \dots & p_{m_n,n}^{m_{n-1},n-1} \end{bmatrix} \dots \begin{bmatrix} p_{1,3}^{1,2} & p_{1,3}^{2,2} & \dots & p_{1,3}^{m_2,2} \\ p_{2,3}^{1,2} & p_{2,3}^{2,2} & \dots & p_{2,3}^{m_2,2} \\ \dots & \dots & \dots & \dots \\ p_{m_3,3}^{1,2} & p_{m_3,3}^{2,2} & \dots & p_{m_3,3}^{m_2,2} \end{bmatrix} \begin{bmatrix} p_{1,2}^{1,1} \\ p_{2,2}^{1,1} \\ \dots \\ p_{m_2,2}^{1,1} \end{bmatrix} \quad (B.1)
$$

where, m_i is the number of elements at level i

$p_{i,j}^{k,l}$ is the priority of element i at level j with respect to element k at level l.
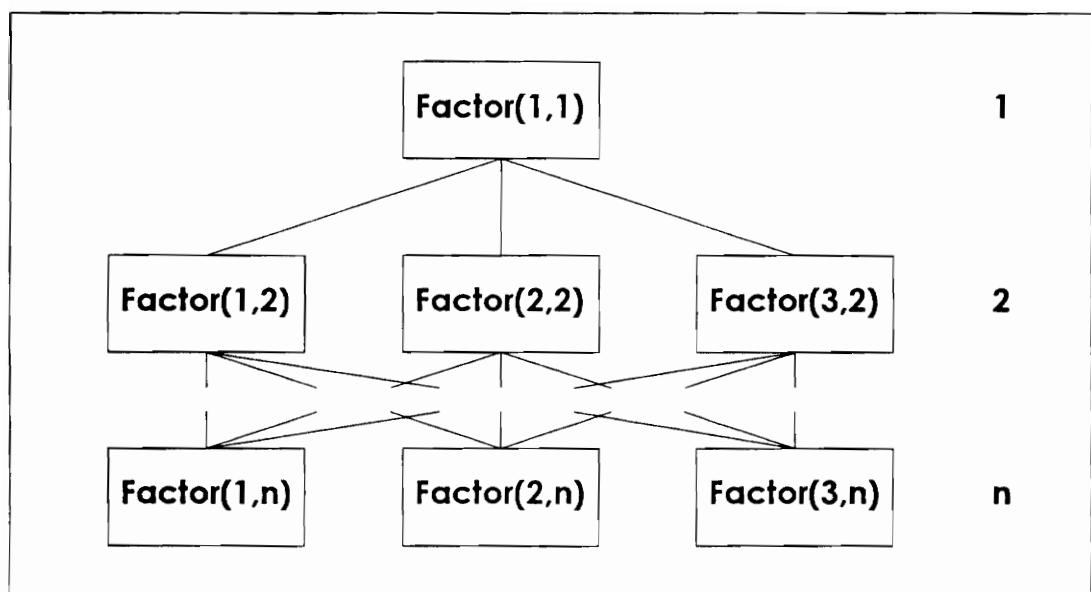
Figure B.1   Typical Hierarchical Structure

For a three-level hierarchy, equation (B.1) reduces to the following:

$$
\begin{bmatrix} p_{1,3}^{1,1} \\ p_{2,3}^{1,1} \\ p_{3,3}^{1,1} \end{bmatrix} = \begin{bmatrix} p_{1,3}^{1,2} & p_{1,3}^{2,2} & p_{1,3}^{3,2} \\ p_{2,3}^{1,2} & p_{2,3}^{2,2} & p_{2,3}^{3,2} \\ p_{3,3}^{1,2} & p_{3,3}^{2,2} & p_{3,3}^{3,2} \end{bmatrix} \begin{bmatrix} p_{1,2}^{1,1} \\ p_{2,2}^{1,1} \\ p_{3,2}^{1,1} \end{bmatrix}
\tag{B.2}
$$

The priority weights at any level have been shown to have the variance (Shrestha, 1990):

$$
\hat{\sigma}_{w_i} = \frac{n^2 - 1}{n^2} \left[\sum_{j=1}^{n} w_j^2 - w_i^2 \right] \hat{\sigma}^2 \, w_i^2
\tag{B.3}
$$

and the variances of the composite priorities can be calculated by evaluating the variances of the products of random variables, giving the following:

$$
\begin{bmatrix} \left(\sigma_{1,3}^{1,1}\right)^2 \\ \left(\sigma_{2,3}^{1,1}\right)^2 \\ \left(\sigma_{3,3}^{1,1}\right)^2 \end{bmatrix} = \begin{bmatrix} \left(p_{1,3}^{1,2}\right)^2 & \left(p_{1,3}^{2,2}\right)^2 & \left(p_{1,3}^{3,2}\right)^2 \\ \left(p_{2,3}^{1,2}\right)^2 & \left(p_{2,3}^{2,2}\right)^2 & \left(p_{2,3}^{3,2}\right)^2 \\ \left(p_{3,3}^{1,2}\right)^2 & \left(p_{3,3}^{2,2}\right)^2 & \left(p_{3,3}^{3,2}\right)^2 \end{bmatrix} \begin{bmatrix} \left(\sigma_{1,2}^{1,1}\right)^2 \\ \left(\sigma_{2,2}^{1,1}\right)^2 \\ \left(\sigma_{3,2}^{1,1}\right)^2 \end{bmatrix}
$$
$$
+ \begin{bmatrix} \left(\sigma_{1,3}^{1,2}\right)^2 & \left(\sigma_{1,3}^{2,2}\right)^2 & \left(\sigma_{1,3}^{3,2}\right)^2 \\ \left(\sigma_{2,3}^{1,2}\right)^2 & \left(\sigma_{2,3}^{2,2}\right)^2 & \left(\sigma_{2,3}^{3,2}\right)^2 \\ \left(\sigma_{3,3}^{1,2}\right)^2 & \left(\sigma_{3,3}^{2,2}\right)^2 & \left(\sigma_{3,3}^{3,2}\right)^2 \end{bmatrix} \begin{bmatrix} \left(p_{1,2}^{1,1}\right)^2 \\ \left(p_{2,2}^{1,1}\right)^2 \\ \left(p_{3,2}^{1,1}\right)^2 \end{bmatrix}
\tag{B.4}
$$

Appendix C

Procedure for Estimating Composite Ratio Variances

In his dissertation, Shrestha (1990) provided estimates of the variances of priority weights in the different levels of the hierarchy used in AHP. For purposes of the hybrid trade-offs and linear weights analysis, these estimates must be extended to the ratios of these composite weights. This appendix discusses the significance of these priority weights in the trade-off curve and describes a possible method for estimating their variance.

C.1   Priority Weights and the Trade-Off Curve

Assume that the non-dominated plans form a convex set defined by the continuous function:

$$f(x_1, x_2) = 0 \tag{C.1}$$

Suppose further that the preference weights p_1 and p_2 are assigned to x_1 and x_2, respectively, in a linear relationship. The function to be optimized can then be written as follows:

$$\begin{aligned} \min \quad & p_1 x_1 + p_2 x_2 \\ \text{s.t.} \quad & f\left(x_1, x_2\right) = 0 \end{aligned} \tag{C.2}$$

This results in the Lagrangian function:

$$\mathcal{L}\left(x_1, x_2\right) = p_1 x_1 + p_2 x_2 + \lambda f\left(x_1, x_2\right) \tag{C.3}$$

which has the solution:

$$p_1 = -\lambda \frac{\partial f\left(x_1, x_2\right)}{\partial x_1} \tag{C.4}$$

$$p_2 = -\lambda \frac{\partial f\left(x_1, x_2\right)}{\partial x_2} \tag{C.5}$$

$$f\left(x_1, x_2\right) = 0 \tag{C.6}$$

If x_1 and x_2 are changed but are to remain in the set, dx_1 and dx_2 must leave the value of $f\left(x_1, x_2\right)$ unchanged at 0. As such, they must satisfy the equation:

$$\frac{\partial f\left(x_1, x_2\right)}{\partial x_1} dx_1 + \frac{\partial f\left(x_1, x_2\right)}{\partial x_2} dx_2 = 0 \tag{C.7}$$

This gives:

$$\frac{dx_1}{dx_2} = (-) \frac{\dfrac{\partial f\left(x_1, x_2\right)}{\partial x_1}}{\dfrac{\partial f\left(x_1, x_2\right)}{\partial x_2}} \tag{C.8}$$

Dividing eqn. (C.4) by eqn. (C.5) and substituting into eqn. (C.8) yields:

$$r = \frac{p_1}{p_2} = -\frac{dx_2}{dx_1} \tag{C.9}$$

Equation (C.9) shows that the optimum occurs at the point of tangency between the trade-off curve and the weighted objective function, i.e., where the slope of the trade-off curve is equal to the negative of the reciprocal of the ratio of preference weights.

C.2   Estimating the Variance of the Weight Ratios

In this thesis, the ratios of the priorities are used together with the trade-off curves to provide the optimum points on the curves. Together with variance estimates of these ratios, they provide the DM with a selection of alternatives that meet his/her priority ranking to a certain degree of confidence.

The variances of the composite ratios are estimated using Gauss's approximation formulae (Blom, 1989).

$$r_{i-j,k}^{1,1} = \frac{p_{i,k}^{1,1}}{p_{j,k}^{1,1}}$$

$$\sigma_{i-j,k}^{1,1} = \frac{\left(\sigma_{i,k}^{1,1}\right)^2}{\left(p_{j,k}^{1,1}\right)^2} + \frac{p_{i,k}^{1,1}\left(\sigma_{j,k}^{1,1}\right)^2}{\left(p_{j,k}^{1,1}\right)^4} \tag{C.10}$$

where i and j are entities in the composite level k.

Given a desired level of confidence, the confidence interval can then be estimated, to wit:

$$r_i - t_{m-1,\frac{\alpha}{2}}\hat{\sigma}_{r_i} \le r_i \le r_i + t_{m-1,\frac{\alpha}{2}}\hat{\sigma}_{r_i} \tag{C.11}$$

or $$r_i^- \le r_i \le r_i^+$$

These ratios (r's) can be viewed as slopes of isoprofit lines that provide the range of acceptable choices in the (inverse) production possibilities set representing the attribute trade-off curves (please see Figure C.1).
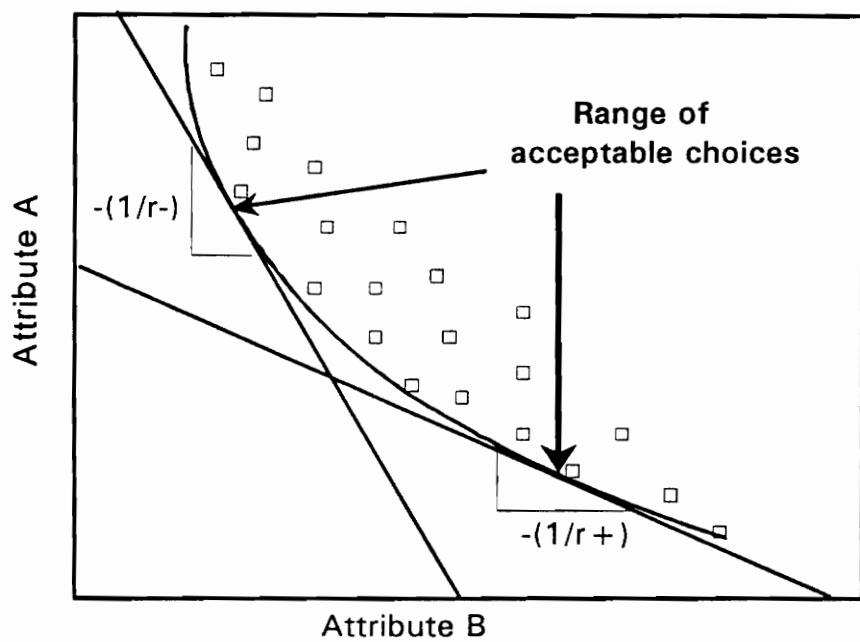
Figure C.1. Trade-off curve and attribute weight ratios.

Vita

Arnulfo de Castro obtained his B.S. and M.S. degrees in Electrical Engineering from the University of the Philippines in 1977 and in 1983, respectively. He took graduate courses in Economics at the University of the Philippines before coming to Virginia Tech to pursue his Ph.D. in Electrical Engineering. He is an Assistant Professor of Electrical Engineering at the University of the Philippines where he has been teaching since 1983.

Arnulfo de Castro has worked for more than ten years in software development and utility consulting. His experience includes generation, transmission and distribution planning, and economic operations studies for electric utilities. He was also active in performing energy studies for government and for industry. His principal areas of interest are power system planning, energy systems, environmental aspects of electricity generation, optimization techniques and decision analysis.