

Efficient Resource Development in Electric Utilities Planning Under Uncertainty

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(ABSTRACT)

The thesis aims to introduce an efficient resource development strategy in electric utility long term planning under uncertainty considerations. In recent years, electric utilities have recognized the concepts of robustness, flexibility, and risk exposure, to be considered in their resource development strategy. The concept of robustness means to develop resource plans that can perform well for most, if not all futures, while flexibility is to allow inexpensive changes to be made if the future conditions deviate from the base assumptions. A risk exposure concept is used to quantify the risk hazards in planning alternatives for different kinds of future conditions.

This study focuses on two technical issues identified to be important to the process of efficient resource development: decision-making analysis considering robustness and flexibility, and decision-making analysis considering risk exposure. The technique combines probabilistic methods and tradeoff analysis, thereby producing a decision set analysis concept to determine robustness that includes flexibility measures. In addition, risk impact analysis is incorporated to identify the risk exposure in planning alternatives. Contributions of the work are summarized as follows. *First*, an efficient resource development framework for planning under uncertainty is developed that combines features of utility function, tradeoff analysis, and the analytical hierarchy process, incorporating a performance evaluation approach. *Second*, the multi-attribute risk-impact analysis method is investigated to handle the risk hazards exposed in power system resource planning. *Third*, the penetration levels of wind and photovoltaic generation technologies into the total generation system mix, with their constraints, are determined using the decision-making model. The results from two case studies show the benefits of the proposed framework by offering the decision makers various options for lower cost, lower emission, better reliability, and higher efficiency plans.

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Glossary

LOLP	Loss of load probability
DSM	Demand side management
ERD	Efficient resource development
LRC	Limited resource case study
MCDM	Multi-criteria decision-making
MADM	Multi-attribute decision-making
O&M	Operation and maintenance
DM	Decision maker
AHP	Analytical hierarchical process
T&D	Transmission and distribution

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² May Allah Blessings be upon them

1. Introduction

1.1. Problem Identification

In the past two decades, power system resource planning has changed dramatically. Utilization of more efficient resources and environmental concerns has resulted in a variety of resource options that need to be addressed completely. These consequences of resource development must be examined with multiple criteria, addressing many different players in the planning process. Furthermore, the planning process is also influenced by uncertainty factors regarding future demand, resource availability and economic situations. Adding to that, market based economy considerations for generation, transmission, and distribution are beginning to have significant impacts on the resource development of electric utilities.

Knowing that fact, identifying a minimum-cost plan under particular constraints is not sufficient anymore; other aspects such as environmental impact and socio-political concerns have been added and are of equal importance as the cost minimization objective. In addition to that, the influence of various uncertainty factors of different planning strategies must be carefully examined because these may affect the system performance if the plans are not designed with adequate levels of robustness and flexibility to possible changes from the base assumptions. It is also important to realize that the decision-making process in planning is done with mathematical models as well as human judgment.

In addressing key issues of power system resource planning, five items are of importance.

- To integrate various resource options;
- To compromise among conflicting decision criteria;
- To evaluate the influence of uncertainty factors;
- To satisfy financial, reliability and environment constraints; and
- To predict future conditions in an efficient way.

Efficient strategic planning approaches have become more popular in electric utility resource planning [24] considering the prevailing uncertain planning environments. The approach is a process of multi-attribute decision-making (MADM) under uncertainty that is not concerned with finding optimum solutions, but with exploring the ranges of resource options and uncertainties as well as the tradeoffs among conflicting attributes [49]. The use of analytical tools and decision analysis techniques allows the approach to produce a range of acceptable plans or efficient decisions. The final resource strategy is chosen from among the acceptable plans or efficient decisions based on certain well-defined decision criteria.

Efficient resource development (ERD) is related to the following concerns.

- Resource utilization of conventional and advanced generation technologies, renewable energy sources, non-utility generation through interconnected transmission

grid, and demand-side management (DSM) programs [90]. Advanced generation technology, especially the clean coal technology, gives significant improvement in efficiency of fuel usage and reduction in emissions and pollutants [5, 11]. Renewable energy sources, especially wind and solar technologies, play an important role in the electric utility generation mix and daily operation in reducing the environmental impact from thermal generation. Non-utility generators, such as co-generation and independent power producers, can sell power to electric utilities based on the avoided costs [89, 98]. An efficient and flexible planning strategy in reducing utility-capacity needs, improving system-load factor and environmental quality is realized through DSM programs of energy efficiency and peak-demand shaving [22].

- Environmental regulations and standards govern the siting, design and operation of resources and raise the costs of capacity additions and O&M expenses. Therefore, electric utilities are faced with the requirements of allocating their capital investments and resources to reduce adverse global and regional environmental impacts [3, 123, 129].
- Uncertainty is a major challenge in electric utility long-term resource planning [30, 31]. Some uncertainties, such as load growth, fuel price, capital cost, outage cost, emission control cost, and emissions allowance, could have a strong influence on the outcome of utility resource development.
- Multi-criteria decision-making (MCDM) models are popular in utility resource planning to achieve a compromise solution that represents a reasonable balance among the criteria [15, 59, 69, 116]. The model should display tradeoffs among the criteria, quantitative and qualitative, economic and non-economic, and quantify the values and the preferences among the criteria.
- Risk management is an important part of the planning process in electric utilities, and flexibility and robustness are two major classes of strategies for managing the risk due to uncertainties [14, 16]. Risk exposure level indicates the measure of probability and severity of adverse effects [178]. Robustness shows how well a plan would perform across a variety of possible futures, while flexibility represents how quickly a plan would respond at reasonable cost to various unexpected future events [24].
- Deregulation and competition increase the uncertainty of siting, timing and operating parameters, and thus the level of difficulty of decision-making in generation and transmission expansion projects. Accordingly, planning objectives need to be re-defined and new analytical tools need to be developed to support the market-based resource planning process and reduce the risks of competition.

Common definitions and efficient resource planning procedures will be discussed in the following sections.

1.2. Common Definitions

Some common terms and definitions used in electric utility planning studies [34, 51, 170] are given below.

Options are decisions that an electric utility can control, i.e. supply-side capacity additions, demand-side peak shaving, and energy efficiency programs. Each option has values to be specified. A specified option is an option with specified values, i.e. type, capacity, location, and timing of a new power plant.

A **Plan** is a set of specified options, i.e. building a 100 MW wind turbine at Nevada together with adding one 230 kV transmission line in the year 2008.

Uncertainties are factors of which the utility has little or no foreknowledge, that will have significant influence on the performance of utility systems, i.e. load growth, fuel prices, and regulatory changes. Uncertainties are either modeled with assumed probability distributions or described as “unknown but bounded” variables without assuming a probabilistic structure. A specified uncertainty means a specific value is given to the uncertainty variable, i.e. 3% per year of load growth.

A **Future** is a combination of specified uncertainties, i.e. “3% per year load growth and 4% per year gas price escalation”.

Attributes are the relative “goodness” outcome measures of a particular plan, i.e. financial attributes, economic attributes, performance attributes, environmental attributes, social-economic attributes. Attributes are functions of options and uncertainties and calculated through simulation studies. The objectives of the planning process are to minimize or maximize each attribute.

A **Scenario** is a combination of a single plan and a single future.

Simulation studies are basically production cost, system reliability, environmental impact, revenue requirement, and financial studies, which are conducted using a combination of analytical models and tools depending on the attributes of interest.

1.3. Efficient Resource Planning Procedure

The procedure for efficient resource planning of electric utilities is proposed and illustrated in Figure 1-1. The procedure consists of five function blocks:

- Problem Formulation
- Scenarios Development
- Decision Database Creation
- Acceptable Alternatives Identification
- Resource Strategy Determination

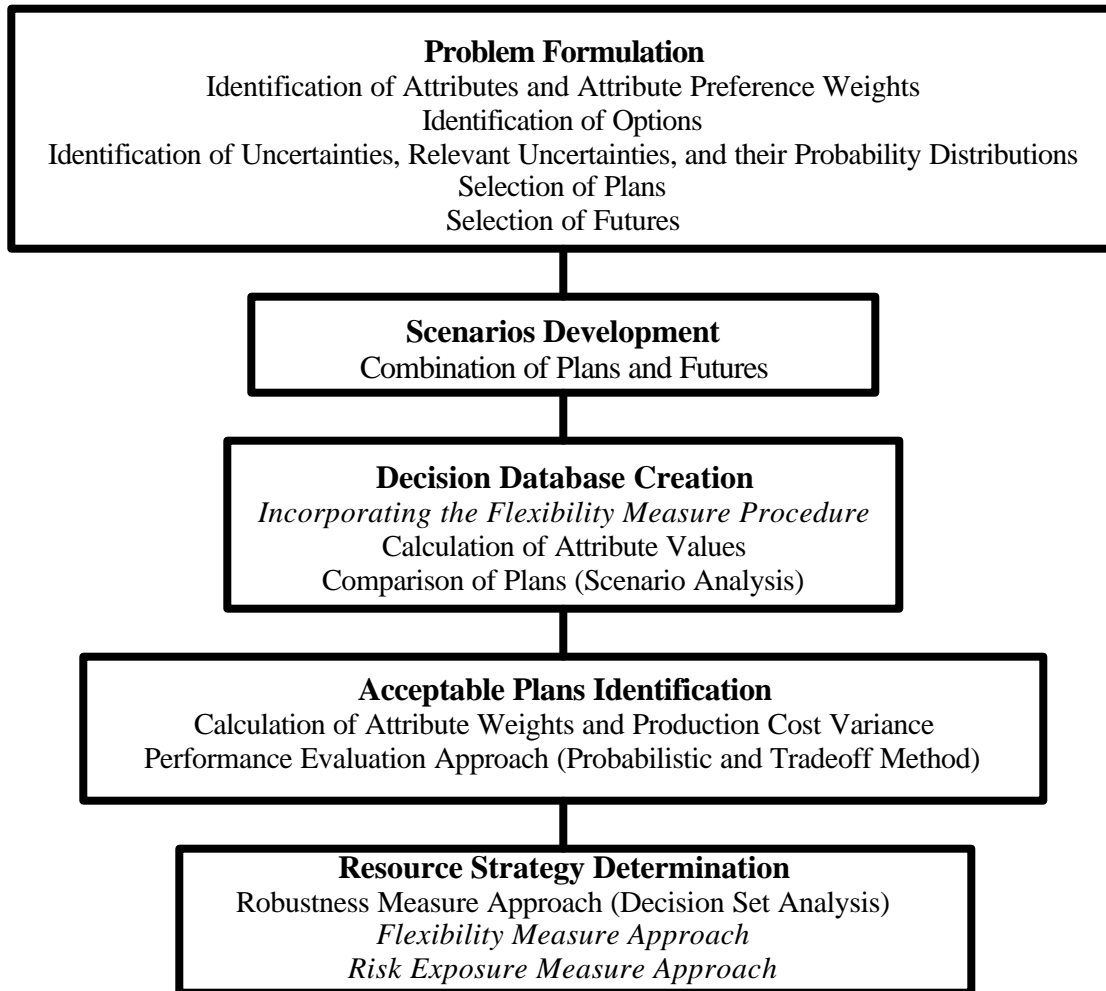


Figure 1-1. Conceptual Procedures of Efficient Resource Planning

Problem Formulation

Identifying sets of attributes, options, and uncertainties starts the decision process. Attribute priority weights can be calculated from the preference ranking that the decision maker (DM) attaches to attributes. Relevant uncertainties can be determined from the DM pair-wise comparisons among their components. The probability distribution for each of the uncertainties is defined from the assigned expert judgment of the DM. Each alternative plan is a set of resource options, and each possible future is a set of uncertainty factors.

Scenarios Development

The combination of a specific plan and a specific future constitutes a particular scenario. A number of scenarios could be created from the combinations of plans and futures, ranging all the possible alternatives.

Decision Database Creation

Each scenario is evaluated with the use of a combination of utility planning tools, such as investment optimization models, production costing simulation and reliability assessment programs, environmental impact analysis and financial analysis models. Flexibility is incorporated into each plan according to its respective scenario. Scenario analysis will establish a decision database where alternative plans are compared based on certain well-defined decision criteria.

Acceptable Alternatives Identification

Identification of acceptable plans, with respect to the attributes and future conditions, is the key element of electric utility planning. Calculation of attribute weights and production cost composite variance is performed to obtain the attribute value range estimate. Then, performance evaluation approach is used as decision analysis that combines a probability approach and tradeoff analysis.

Resource Strategy Determination

Three measures are introduced to help the DM choose the optimal solution from among the acceptable plans: robustness, flexibility, and risk exposure. The DM can identify a better combination of options to invent a more robust or flexible planning strategy or a less risk-exposed planning strategy, or to reformulate/restructure the decision problems by adding additional or deleting trivial attributes, options, and uncertainties. The risk exposure is measured using risk impact analysis by developing the consequence impacts of the options and identifying their probability and effects.

1.4. Scope of Study Topics

Previous work [3] has outlined the identification of attributes, options and uncertainties, and the use of analytical hierarchical process (AHP) for calculating attribute weights and for identifying relevant uncertainties and probability distributions of uncertainty. Then [62] has researched the use of a utility function for attribute certainty equivalent value using AHP. It also used distance value calculated automatically from simulation result and incorporated the work of [44] in production cost variance and priority assessment variance then developed resource strategy based on robustness measure (number of futures accommodated for each strategy). This research has combined those mentioned works from the above three major theses and has added the following.

1. Introduce an efficient resource planning development (ERD) as a modified version of MADM framework for strategic resource planning by expanding its robustness measure capability and adding flexibility and risk exposure measures capability.
2. Incorporate stage-based modeling while evaluating each scenario using simulation models and calculate the amount of additional "cost" for each plan to respond to each scenario [3]. The term "cost" represents quantity of each attribute's value.

3. Incorporate flexibility measures (the strategy that can cope with different futures with minimum cost) by two alternatives. First, by calculating total present value of "flexibility cost" for each plan, and then developing a resource strategy based on the flexibility measure. Second, by the selection of alternative technologies. The DM could either include more quickly installed technology or install technology that makes better use of the existing system.
4. Incorporate the measure of risk exposure as part of the risk estimation assessment, and develop the resource strategy based on risk exposure measure. Risk exposure can be reduced in any of these three ways: expanding the plant mix, reducing dependence on allowance market and external source of power, and adoption of renewable or environmentally friendly technologies.
5. Investigate the issues related to the penetration of renewables to the conventional electric grid, and utilize the efficient resource development methodology that has been developed to address the issues. Some of the issues identified are energy security, generation unit reliability, T&D line expansion reliability, operation limitation, energy efficiency, revenue stream stability, environmental and health impacts, weather impact, etc.

Therefore, the scope of study covers the following topics.

1. An efficient resource development framework for planning under uncertainty has been developed that combines features of utility function, tradeoff analysis and analytical hierarchy process, incorporating a performance evaluation approach to measure robustness, flexibility and risk exposure.
2. A flexibility measure in power system resource planning is incorporated, and a resource strategy based on flexibility measure has been developed.
3. A multi-attribute risk-impact analysis method is investigated to handle the risk exposure in power system resource planning, and a resource strategy based on risk exposure has been developed.
4. The penetration level of renewable technology into the total generation mix has been investigated, with its constraints and application using the proposed decision making model.

The primary objective of this dissertation proposal is to develop an efficient resource development (ERD) framework based on multi-attribute decision-making model for electric utilities, then apply it to analyze the penetration level of renewable technology into the grid system.

The proposed ERD includes aspects that have not been addressed so far, extending its use to evaluate uncertain policy options that are now neglected or only subjective opinions are used. Example are the social and environmental costs of building large power plants like coal or hydro, considering population movement, CO₂ emissions from flooded trees, etc. The proposed model is used for a long term planning study; therefore, it does not address operations issues such as voltage stability, system dynamics, or reliability of supply.

The features of the ERD framework can be described as follows.

- Identification of major study topics that are important to the success of efficient resource development in planning;
- Identification of the attributes with their preference weights and options, uncertainties with their relevancy and probability distributions, and scenarios development, as a systematic approach to forming the problem;
- Calculation of attribute values where flexibility concepts are included and comparison of alternatives using scenario analysis to generate a reliable decision database where plans are stored and classified;
- Calculation of attributes weights and production cost composite variance to incorporate the impact of imprecise information into the decision-making process using an interval-based decision approach in identifying plans with a certain confidence;
- Evaluation of the performance of plans using probabilistic and tradeoff methods to solve the problem of multi-attribute planning under uncertainty, giving the solution constrained as acceptable under the decision set;
- Evaluation of the concepts of robustness, flexibility, and risk exposure to help the DM in selecting the most optimal alternatives;
- Investigation of the penetration level of renewable technology to the generation mix using the proposed model.

1.5. Document Organization

This document is organized in the following chapters.

Chapter 1 (this chapter) presents an overview of the work, including problem identification, basic definitions, the resource planning procedure, contributions from this work, and organization of this document.

Chapter 2 presents literature review in the field of electric utility resource planning with focus on the application of programming models, simulation programs, and decision-making techniques.

Chapter 3 presents the detail of efficient resource development methodology that has been identified in Chapter 1.

Chapter 4 presents an overview of renewable energy trends and describes a case study of a hybrid solar-wind power system design to show the use of the proposed model.

Chapter 5 presents an overview of existing decision-making methodology in Malaysia and shows how the proposed methodology gives alternative outcomes, introducing robustness, flexibility and risk exposures measures in a limited resource case study.

Chapter 6 presents the conclusions of the work and identifies some future research.

2. Literature Review

Broad literature concerning electric utility resource planning covers studies related to the development of utility generation, transmission, and distribution systems. The following work focuses on the proposed and applied techniques related to generation expansion planning (GEP) and integrated resource planning (IRP) of electric utilities.

2.1. Introduction

The goal of electric utility generation expansion planning is to seek an optimal generation capacity expansion system to meet the forecast demand in the most economical manner, subject to reliability and environmental constraints [40, 176]. Two questions are to be answered by the GEP process: Where and when to invest in new generating facilities (location and time), and what type and capacity of generating units to install (fuel and size).

The goal of electric utility integrated resource planning is to integrate supply-side and demand-side options in meeting customer energy-service needs and environmental improvements in a least-cost manner [12, 35]. Two major tasks in the electric utility IRP process are to identify and implement cost-effective DSM programs (i.e. load management, energy conservation, and off-peak uses promotion of electricity), and to reduce the negative influence associated with uncertainties using risk management. Figure 2.1 shows the developments in the system planning process.

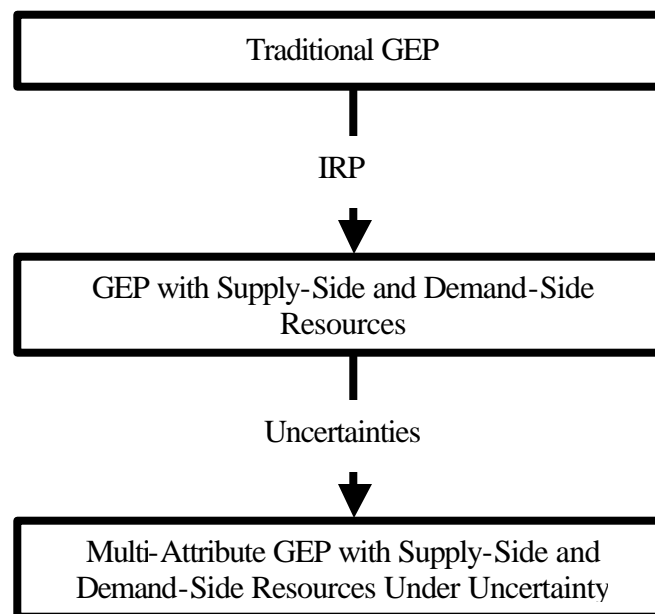


Figure 2.1. Developments in Generation Expansion Planning Process

This chapter presents a literature review of previous research efforts in the field of electric-utility resource planning. Sections are divided based on the methods used in dealing with various aspects of electric utility resource planning, covering capacity expansion optimization models, production costing simulation programs, and decision-making analysis techniques.

2.2. Linear Programming

Linear programming (LP) models have been successfully applied to utility resource planning for more than thirty years. LP popularity is due to its ability to model large and complex planning problems and the availability of effective algorithms. The LP approach is used to solve the problem of minimizing or maximizing a linear objective function with a set of linear equality and inequality constraints. The objective function is the sum of discounted investment and operational costs; the constraints represent the equilibrium between capacity and demand, capacity reserve requirement, environmental limitations, etc. LP models categorize the generation technologies by fuel type, hence, the total capacity of each generation technology, rather than the size or number of a project, are decision variables. However, the investment in a power plant is usually influenced by the location of the power plant even when the generating units are the same category [176]. In addition to that, the generation technologies are commercially available only in certain sizes, and the approximation of capacity requirement by a set of commercially available units may sacrifice the optimization benefits. Therefore, the LP formulation is not a very useful approach for the planning problems where actual project selection needs to be considered [119], although it is an appropriate model to determine the optimal generation mix or energy resource mix.

2.3. Mixed-Integer, Stochastic, and Multi-Objective Programming

Alternative optimization models have been proposed in the literature and have been used in the power industry to cover aspects that cannot be solved by LP models. These models are mixed-integer programming to solve discrete decision variables problems, non-linear programming to solve non-linear objective functions problems, stochastic programming to solve random parameters problems, and multi-objective programming to solve multiple objectives problem [52]. Some of the models, i.e. linear multi-objective programming, still retain a linear programming framework, while others allow non-linearity in dealing with capital costs and engineering constraints.

Mixed-integer programming models assign the project-specific capacities as investment variables with the remainders as continuous variables. A binary variable is assigned to each candidate project as a build/not-build indicator (one and zero, respectively), in a given time period, to simplify the optimization process.

Stochastic programming with recourse is used to solve a multistage decision problem where parameters are known through probability distributions [23]. The approach finds

the optimal resource development path and minimizes the total discounted costs. In some versions of the method, the stochastic problem is transferred into a deterministic equivalent problem.

Multi-objective programming is used to make a decision at the presence of multiple conflicting objectives, through conversion into a single objective problem. The process is done by either assigning weighting parameters to each individual objective, or providing proper constraints on all objectives except the most essential one [42, 64].

2.4. Dynamic Programming

Dynamic programming (DP) converts a multistage optimization problem into a series of simple problems and solves using the recursive application of the principle of optimality on the objective. The approach is flexible in using discrete variables, non-linear objective functions and constraints and is used in conjunction with probabilistic production costing simulation programs, i.e. Electric Generation Expansion Analysis System (EGEAS) and Wien Automatic System Planning Package (WASP) [55, 131]. The approach searches all solutions to find the optimal sequence of decisions from the initial state to the least-cost final state, and this is the major drawback of the approach. Applying insight into the nature of the problem to reduce the state space can do some improvement. For instance, reserve margin can be used to eliminate system configurations that are either well below or well above a preferred level of system capacity; the number of units for each generation type selected each year is specified based on the resource availability and other limitations. Further enhancement can be achieved by introducing multiple objectives and random parameters into the models, as in multi-objective dynamic programming and stochastic dynamic programming models [168, 177].

2.5. Production Costing Simulation Programs

Apart from the similar basic functions of production simulation programs that are commonly used in the power industry, they have many different model structures and simulation algorithms. The classification of production costing simulation models can be done as follows.

- Based on whether or not the random nature of demands and generation capacities is taken into account in the simulation: deterministic production costing models vs. probabilistic production costing models. The probabilistic models are more widely used than the deterministic models as an aid in intermediate- and long-range capacity expansion planning due to the advantage that more reasonable and accurate production cost estimation and system reliability indices can be evaluated.
- Based on the choice of system load representation: equivalent load duration curve approaches vs. chronological simulation approaches. The concept of equivalent load duration curve (ELDC) is more convenient to use for less detailed studies and long-range capacity expansion planning, while the chronological simulation approach is

required for more detailed studies. In the latter case, production costs and fuel consumption are computed repetitively with the assumption that the load patterns are known for an extended period into the future. In theory, chronological simulation models are the off-line application of generation economic dispatch and unit commitment techniques.

2.5.1. Probabilistic Simulation Approach

In the past thirty years, the ELDC based simulation technology has dominated electric utility planning [176]. The ELDC is based on the inverted load duration curve (ILDC) and integrates the random outage of each generating unit with the probability density function of system load by a recursive procedure. Then the production costs and reliability indices are calculated using the resulting ELDC. The amount of computation is rather great in the original ELDC, since the function values at discrete points, which represent the equivalent load duration curve, must be recalculated with each convolution and de-convolution computation. Fourier Series method and cumulant method are the two major contributions from research efforts to improve the computation efficiency of ELDC based production simulation. In Fourier Series method, the original LDC is converted into ILDC by 50 to 100 Fourier series terms such that the convolution computation can be performed in the Fourier frequency domain [55]. However, this method does not show significant savings in the amount of computation, and poor curve fitting has been found when the actual ILDC has a flat tail. In the cumulant method, the system load duration curve and the random outage of generating units are described with random distribution numerical characteristic cumulants [131]. This method has demonstrated substantial savings in computation because the convolution and de-convolution process are simplified to addition and subtraction of several cumulants. However, it may suffer from considerable errors when the system scale is relative small or the system load duration curve exhibits multi-mode distribution.

The time-dependent nature of system operation constraints is considered using a chronological simulation approach. The time varying nature of energy storage technologies, load management, and renewable energy sources requires the use of production simulation on the hourly framework for studying their system values. The chronological simulation models explicitly trace the system states over time by using Monte Carlo techniques to capture the random variation of generation capacities and demand levels [86]. The results of Monte Carlo chronological simulation are more detailed than the results of ELDC-based analysis, with much higher computational requirements. A comparison of different probabilistic production costing simulation methods can be found in [84], where the test results of an investigation are reported in terms of the relative computational speed and solution quality. These include piece-wise linear approximation method, segmentation method, equivalent energy function method, cumulant method, mixture of normal approximation method and fast Fourier transform method. The equivalent energy function method was shown to be preferred, considering both computational efficiency and accuracy. A more recent multi-parameter Beta

distribution function method has been introduced, which was more accurate than the cumulant method with little addition of computation time.

2.5.2. Negative Load and Equivalent Multi-State Unit Approach

Technologies such as solar photovoltaic power systems (PV) and wind turbine generators (WTG) are considered as intermittent technologies, where the power output of these non-conventional generation technologies is dependent on fluctuations in solar radiation and wind speed occurring in the minute-to-minute time frame. It is necessary to analyze the economics of these resources in the process of utility resource planning since these renewable energy sources are capable of supplying a significant proportion of electrical energy in the long-term future. Their common characteristics are high capital investment and low operating costs, and they can cause severe operational problems to utility systems, such as excessive system frequency deviations and spinning reserve margin fluctuations, due to their intermittent power output behavior. To overcome that, the electric utility usually integrates intermittent generation technologies with adequate storage facilities (battery) or other power sources (fuel cell).

Negative load method and equivalent multi-state unit method are the two commonly used modeling approaches for incorporating intermittent generation technologies into production costing simulation programs. The negative load method approach simply treats intermittent generation output as a negative load with the expectation that the electric utility has sufficient on-line capacity to ensure a reliable electricity supply to customers. Then, the expected energy production from each individual technology is estimated, and the system load is modified to simulate the aggregate impacts of combined intermittent generation sources. After the modified load duration curve is obtained, probabilistic production costing models are used to compare alternative expansion strategies, i.e. with and without intermittent generation technologies. The method is adequate only when the penetration of intermittent generation into the grid is insignificant.

Equivalent multi-state unit method calculates the probability density functions of PV and WTG power generation based on long-term historical data on solar radiation and wind speed [83]. Following that, probabilistic production costing simulation program is used where the intermittent generation is modeled by equivalent multi-state units, resulting in a direct comparison of intermittent generation sources with conventional generation technologies as candidate capacity expansion alternatives. To accurately evaluate the economics of intermittent generation sources requires the use of a chronological hourly production simulation approach with the assumption that historical data are available for hourly wind speed, solar insolation, and system load over a certain time interval.

2.6. Decision Making under Uncertainty

Uncertainty has been a major issue faced by electric power industry in the past few years, and factors such as load growth, fuel prices, capital costs and regulatory standards have a strong influence on the outcome of electric utility resource development. As these parameters are influenced by many uncertain conditions associated with the changes in public perceptions, government regulations, energy policies, economic situations, and competitive markets, it is difficult to provide definite data. The methods used in utility industry for evaluating the influence of uncertainties are scenario analysis, sensitivity analysis, and probabilistic analysis [3, 31].

2.6.1. Scenario Analysis

Various scenarios are constructed, each containing a consistent combination of uncertain parameters. Resource options are then identified during the planning horizon for each individual scenario. This method allows the DM to anticipate a broad range of reasonable futures and resource options. Resource options that are appropriate under majority futures are more promising but the method requires a considerable volume of simulations, and a need to discriminate more precisely among alternatives.

2.6.2. Sensitivity Analysis

Several least-cost plans are developed according to some base assumptions and resource strategies, and then the performance of each of these plans is examined in the face of changed conditions. As a result, the procedure allows the DM to see how each of these plans responds to possible variations of primary assumptions. For systems that are as complex as the resource planning of electric utilities, this method requires conducting the repetitive calculations for all adjusted conditions.

2.6.3. Probabilistic Simulations

Probabilistic analysis includes a variety of analytical structures to incorporate the effects of uncertainties, and—unlike scenario analysis and sensitivity analysis—a measure of selecting which plan is optimal under various future conditions, such as deterministic equivalent, Monte Carlo simulation, and stochastic programming. Uncertainties can be addressed by assigning probabilities to discrete points or by providing a continuous probability distribution for each uncertainty factor, depending on the models used. The simplest approach is to calculate the outcomes and use the expected values as the basis for the evaluation of alternative planning strategies. A more sophisticated approach involves attaching probabilistic weights to different scenarios and performing stochastic programming to determine the optimal resource plan. To graphically represent a complex multistage decision problem, decision tree or influence diagram models are used in probabilistic analysis [114].

2.7. Multi-Criteria Decision Making

Multi-criteria decision making (MCDM) methods are classified into two categories: multi-objective decision making (MODM) approach and multi-attribute decision making (MADM) approach. The common characteristics of MCDM problems are conflicting criteria, incommensurable units, and difficulties in design/selection of alternatives. The difference between MODM and MADM approaches is located in the decision space [27, 65]. The decision space in the MODM approach is continuous and alternatives are not pre-determined, while in the MADM approach, the decision space is discrete, and each candidate alternative can be evaluated using a combination of analytical tools. The decision problem in MODM is solved using multi-objective linear or nonlinear mathematical programming models in which several objective functions are integrated and optimized, subject to a set of constraints. In MADM, each planning or design strategy is associated with a set of attributes whereby various planning or design strategies can be compared. MODM problems are defined and solved by several alternative optimization models, such as compromising programming, constraint method, goal programming, and fuzzy multi-objective programming. For MADM problems, the utility function method, tradeoff analysis method and analytical hierarchy process method can be used.

2.7.1. Compromising Programming

Compromising programming methods are classified as either weighted sum method or composite distance method [27, 41, 65, 122]. Weighted sum method converts multi-objective problems into a single-objective optimization formulation by assigning a set of weights to individual objectives. Composite distance method is based on the concept of ideal solution and measures the composite distance from an ideal point in the direction preferred by the DM. For both methods, the optimization problem is solved by existing planning packages for various combinations of weights or directions to create a set of efficient solutions, defined as a feasible solution where there exists no other feasible solution performing equally or better on all criteria. The best compromise solution or a set of desired compromise solutions are identified from this set of efficient solutions.

2.7.2. Constraint Method

Constraint method takes the most essential objective as the most essential performance index while others are treated as constraints by providing a proper tolerance level to each of them. Then, varying the tolerance levels identifies a set of efficient solutions, which are feasible solutions under the condition that all constraints on the objectives are binding at the optimal solution.

2.7.3. Goal Programming

The goal programming method employs a minimum distance concept based on goals specified by the DM for each objective. Additional unknown variables are defined which represent positive and negative deviations from goals, in order to make them as a linear programming problem.

2.7.4. Fuzzy Multi-Objective Programming.

Fuzzy programming has been developed in recent years to solve a class of multi-objective optimization problems with fuzzy objectives and constraints [67]. The coordination among conflicting objectives is done through the shape of membership functions assigned to objectives and also to constraints. It is useful to treat future demand and other primary parameters as fuzzy numbers such that the influences of uncertainties are included in the optimization process. The application of fuzzy set theory may reduce the decision space as compared with traditional multi-objective programming models.

2.7.5. Utility Function Method

The utility function method selects an optimal planning strategy based on a function known as multi-attribute utility function, which is comprised of the preference functions for individual attributes and the weights that reflect the relative importance of these attributes [39, 110, 111]. When the conditions hold that (1) additive utility attributes are independent and (2) the contributions of an individual attribute to the composite utility are independent with respect to other attribute values, then the linear additive utility model can be used to simplify the procedure. The alternatives to be evaluated in this method are ranked according to their expected utility values, which are computed as a probability-weighted mean of all possible future conditions [123].

2.7.6. Tradeoff Analysis Method

The tradeoff analysis method is developed to support the identification of robust plans under uncertainty [34, 45, 93, 170]. It plots a tradeoff curve in a two-dimensional space and identifies plans near the knee of the tradeoff curve as part of the decision set conditional on a specified future. Knee-set searching algorithms are used for multi-dimensional tradeoff analysis to identify the plans not dominated by any other plans. Tolerance levels are specified by the DM for each individual attribute, which define the relative importance of attributes or indicate how far the DM is willing to trade off one attribute with respect to another. The process is repeated for all futures, and the global decision set is determined by the conditional decision sets. This method can be used to rank the alternatives based on the measure of robustness, i.e., the number of futures supporting the plan.

2.7.7. Analytical Hierarchy Process Method.

Many multi-attribute decision problems are dealt with using Analytical Hierarchy Process (AHP) as a structured approach and when the decision process is defined hierarchically [104, 128, 137, 138]. The AHP technique three-step procedure is as follows.

- Create a judgment matrix by pair-wisely comparing all the factors at one level of the hierarchy with respect to each factor in the immediately preceding level.
- Compute the eigenvector of the judgment matrix for the largest eigenvalue.
- Calculate the composite priority vector from the local priorities associated with each judgment matrix.

In creating the judgment matrix, assigning weights to the factors influencing the problem can be done through answering proper questions. For example, in an application that deals with uncertainty, ill-defined parameters, conflicting objectives and inaccuracies in measurement, a four-layer structure (focus, actors, objectives, and scenarios) is presented [128]. Then the following questions were asked going down the hierarchy: What is the relative importance of each actor in determining the focus? What is the effect of each objective to various actors? What is the effect of each scenario on the objectives? For each questions, relative weights are developed by pair-wise comparisons of items. Explanation of the procedures for eigenvector computation and calculation of composite priority vector is given in Appendix A.

2.8. Risk Impact Analysis Models

Among the different categories of impact assessment are technology assessment, environmental impact assessment, and social impact assessment [5]. Impact analysis is defined as the study of the effect that the decisions have upon the decision-making problem [37]. Impact analysis in a multi-attribute framework is formulated using a multistage multi-objective optimization model, which introduces the concept of stage tradeoff [37, 36, 132]. The stage tradeoff provides a measure of the impacts upon the levels of the objective function at various stages. Using the impact information provided by stage tradeoff, it is possible to proceed in the decision-making process as defined by the surrogate worth tradeoff (SWT) method. Other risk models are risk analysis based on compliance to a known standard [46] and fault tree analysis based on different kinds of event categories [58].

3. Methodology

3.1. Introduction

In order to achieve an efficient resource development strategy in electric utilities, the concept of uncertainty needs to be addressed properly using a multi-attribute decision-making approach. The purpose of multi-attribute decision-making (MADM) methods is to help the decision makers (DM) of electric utilities in selecting the best resource strategy for selected attributes. A useful model should be able to display tradeoffs among different attributes, both quantitative and qualitative, and quantify the preferences. The following questions should be addressed in the decision process.

- Which plan appears to be better than others,
- What is the rationale of ranking the acceptable plans,
- What is the relative importance of one attribute to another,
- What are the relevant factors affecting uncertainties,
- How to measure the plan performance in the presence of uncertainties, and
- How to determine final resource strategy in a robust, flexible and less risky manner.

Utility function/distance value model and tradeoff analysis are the two most commonly used decision analysis methods in the electric power industry for multi-attribute planning in the presence of uncertainties [96]. The concept of the utility function/distance value model is to optimize a value that transforms a multi-attribute decision problem into a scale performance measurement. With this method, the plans are ranked based on the rule of probability where the best solution is the plan that has the optimal expected value. Tradeoff analysis treats all attributes individually and identifies the plans that dominate other plans for each future.

The decision methodology selected combines the tradeoff analysis and the utility function/distance value model using a multi-dimensional knee-set searching algorithm based on the measure of composite distance. With this combined method, the non-dominated plans are ranked based on the measure of robustness (the number of supporting futures), flexibility (the effort in adjusting to different futures), or risk exposure (the impact of adverse effects).

The advantages of utility function/distance value method are as follows.

- It is based on the rule of probability,
- It suggests the best solution to the planner for which the expected utility/distance value is optimal under the influences of various future conditions, and
- It requires establishing a utility function/distance value and assigning a probability value for each uncertainty.

The concern in applying the utility function/distance value method for planning is that it is difficult to show the relative performance of the plans with respect to different

attributes under different future conditions and could lead to low probability of a catastrophic event.

The advantages of the tradeoff method are as follows.

- It provides information on how each plans perform under various futures,
- It requires the planner to specify two tolerance parameters for each attribute where the decision set containing non-dominated plans can be identified, and
- It allows the analysis of uncertainties without explicitly specifying probabilities.

The concern in applying the tradeoff method is that there is no proper statistical background to justify the selection of tolerance levels. Appropriate tolerance parameters are of significant important in performing tradeoff analysis and in the identification of acceptable plans.

The advantages of the combined utility function/distance value and tradeoff methods are as follows.

- It facilitates in characterizing the attitude of utility planners,
- It can identify a plan or plans that are considered as acceptable plans, and
- It provides a global set of alternatives for all future conditions as a decision set which can be used for identification of other enhanced concepts, such as robustness, flexibility, and risk exposure for justifying the decision.

The concern in applying the combined utility function/distance value and tradeoff methods is that the cost for providing robustness, flexibility or risk exposure of some extremely rare conditions could be too high compared with planning solely on the basis of possibility of occurrence.

The proposed model consists of the following characteristics.

Measure the Variance

Imprecise information in many of the problems exists due to inaccurate estimates of attribute values and inconsistent human judgments on attribute priorities. It is not enough to rank the different resource strategies based solely on the point value estimate to distinguish between the outcomes of competing alternatives. Therefore, it is necessary to include the measure of variance into the decision process so as to increase the level of confidence in the final decision.

The methodology of confidence interval-based multi-attribute approach in support of the decision making process is as follows:

- Construct the linear additive utility or distance model to facilitate the process of obtaining preference utility functions and weighting parameters.
- Estimate the composite utility or distance variance by the technique of error propagation, accounting for individual errors from inaccurate attribute measurements and inconsistent priority judgments.

- Determine the likely range of composite utility or distance values given a desired confidence interval.

Measure the Uncertainty

Major planning issues faced by the electric power industry are due to uncertainty such as demand growth, fuel prices, capital costs, regulatory standards, and competitive markets on utility resource development. Deregulated power markets and the increased number of independent power producers increase the uncertainties for generation capacity additions in terms of the siting, timing and operating parameters. It is not sufficient anymore to determine resource development strategies just by using base assumptions and constraints in getting a guaranteed solution. To overcome these concerns, a decision analysis method has been used in planning to deal with multiple objectives under uncertainties, using utility function/distance value model and tradeoff analysis.

The methodology of multi-attribute planning under uncertainty that combines the features of utility function/distance value model and tradeoff analysis is as follows.

- Define the tradeoff region after eliminating all inferior plans due to unacceptable performance of one or more attributes;
- Define the multi-attribute model incorporating variance information using the additive utility function/distance value;
- Compute the value of composite utility/distance, both the point estimate and the likely range estimate, for each feasible plan, assuming the errors from attribute measurements and priority judgments can be properly estimated using interval-based multi-attribute techniques;
- Identify the best plan for which the value of composite distance is minimal;
- Determine the knee set, conditional on the specified future, which contains all data points satisfying the criteria in forming the conditional decision set;
- Determine the global decision set as the union of all alternatives in all conditional decision sets.

Measure the Robustness

A robust resource plan would perform well across a variety of possible futures [19, 24]. Robustness measures the frequency of occurrence of each plan in the global decision set formed from utility function/distance value and tradeoff analysis.

The methodology of robust measurement is as follows.

- Identify the possible range estimate cases, i.e. errors attributed from measurements only, errors attributed from priority judgments only, and both errors included;
- Compute the value of composite utility/distance, both the point estimate and the likely range estimate in all cases, for each feasible plan in the global decision set from each plan preference ranking for supporting futures;
- Compute the number of supporting futures for all the alternative plans in the global decision set and rank them descending from 100%;

- Identify the robust plan or plans as having 100% scale in supporting all future conditions, and when more than one plan is considered as the best strategy, use the available approaches to decide the most robust plan.

Measure the Flexibility

A flexible resource plan would respond quickly at reasonable cost to various unexpected events in the future [24]. To allow an easy and inexpensive change to the future strategies, flexibility is needed. The key features of flexibility are allowing smaller commitment, adaptability, and deferrable decisions. Flexibility can be achieved by building the system from small module component or by using a relatively short lifetime in the planning horizon.

The methodology of flexibility measures is as follows.

- Compute the amount of additional “cost” necessary for each of the plans to respond to each of the scenarios for each stage in the process of attribute value calculation using utility planning tools, such as investment optimization models, production costing simulation and reliability assessment programs, environmental impact analysis and financial analysis models;
- Compute the expected cost of flexibility for each plan at each stage considering the probability of occurrences of that particular future scenario;
- Compute the present value of the flexibility cost at each stage for all attributes, considering the discount rate for the cost attribute only;
- Compute the most flexible plan or plans using the decision criteria identified from among plans in the global decision set using flexibility cost measures.

Measure the Risk Exposure

Another parameter that is important to observe is risk exposure, defined as the measure of probability and severity of adverse effects [178]. Situations of risk are defined as those in which the potential outcomes can be described in reasonably well-known probability distributions. Risk exposure can be measured or estimated by the risk assessment process, that is the total process of risk analysis, which consists of risk level identification and estimation. Risk exposure quantifies the risk hazards. Risk exposure can be reduced using these three strategies: expanding the plant mix, reducing dependence on the allowance market and external source of power, and adoption of renewable or environmentally friendly technologies.

The methodology of risk exposure measures is as follows.

- Identify causative events together with their probability of risk occurrence, where each of the causative events can lead to several possible outcomes;
- Identify possible outcomes and determine their relative probability by considering the exposures of humans, institutions, and the natural environment;
- Identify exposure pathways, the means that risks are transmitted, explicitly, and their corresponding probabilities;

- Identify possible consequences of risk exposure and determine for each risk the probability that consequences will occur;
- Calculate the overall probability from the probability determination steps above;
- Assign the consequence value to the risk exposure.

3.2. Identification of Parameters

3.2.1. Attributes in Planning

Attributes of concern provide the measure to the objective. The list of attributes are grouped as cost and rates, financial integrity, robustness, exposure to risk, flexibility, quality, environmental impacts, and socio-political [3]. It is noted that some of the attributes are conflicting and could be ranked differently among different types of utilities and decision makers (DM).

- Cost and rates attributes include costs (i.e. capital investment and operating costs), rates (i.e. average price to customers) and other ratepayer costs (i.e. DSM options) [51].
- Financial integrity attributes include increased construction costs, long lead times, high interest rates, and regulatory lag.
- Robustness includes any plans that can fit to all reasonable contingency scenarios [30, 51]. The plans that can cope for all the futures are considered as robust plans. Robustness measures could be in terms of percentage of futures that a certain plan can handle.
- Exposure to risk reduction measures includes expanding the plant mix, reducing dependence on the allowance market and external sources of power, and adoption of environmentally benign technologies. The risks considered are trading complications, joint ownership conflicts, reliance on the allowance market, construction lead-time and site disruption, exposed to sabotage, and coal price risks.
- Flexibility is the adaptability to changes during planning to reduce the effects of uncertainty [24]. Flexible plans are the plans that can be easily changed with a minimum cost in case future conditions deviate. Flexibility measures can be in terms of the amount of additional “cost” necessary for a plan to respond to a certain scenario.
- Quality attributes include reliability (i.e. loss-of-load probability – LOLP, expected unserved energy – EUSE, or loss of energy probability – LOEP, expected loss of load – XLOL, and frequency and duration outage – FAD), maintainability (i.e. ease, economy, safety and accuracy), produce ability or construct ability (i.e. effectiveness and efficiency), supportability, viability, technical feasibility (i.e. effective and efficient supply of materials and energy and of maintenance and repair facilities, availability of the technology to sustain the new system).
- Environmental impacts include the use of natural resources (i.e. right-of-way, fuels), damaging the natural environment, localized thermal and particulate emissions from fossil-fuel generation, regional effects of acid precipitation, predicted climatological alterations resulting from global warming. Emissions can damage materials, destroy forests, reduce animal populations, and affect human health.

- Socio-political attributes include macroeconomic effects (i.e. balance of payments for electricity generation, effect on employment), effect on local economy (i.e. level of local industrial and business activity, job creation activities), national independence of self-supplying electricity, effects on policy goals (i.e. policies and objectives set by government-owned utilities and regulators, such as electrification programs that have priority over pure profit considerations).

Identification of Attribute Preference Weights

In the multi-attribute decision-making problem, each attribute is associated with its preference utility function (single utility function) and its weighting parameter that reflects the relative importance of this attribute toward the overall planning objective. The attribute preference utility function is constructed using a certainty equivalent method and pair-wise comparison analysis explained in a later section. As for attribute preference weight, the DM provides pair-wise comparisons of its relative importance to other attributes in the overall planning goal. A detailed description of how to select the weighting parameter is explained as follows.

Among methods to select weights, ratio-questioning and indifference-tradeoff are the most frequently used because they have good reliability and are easy to use [15]. Both methods accept input from the DM to prioritize attributes, but the ratio-questioning method directly acquires the relative importance between each pair of attributes, while the indifference-tradeoff method indirectly assumes the weighting information from tradeoff judgments.

The ratio-questioning method is often used in the analytical hierarchy process (AHP) to break up the complex priority assessment task into several evaluation stages. The stages start from the attribute, through one or more intermediate levels, up to the overall objective. Each layer influences the entities in the layer immediately above it. The procedure is as follows:

- Starting from the second layer of the hierarchy, the DM is asked to compare the relative importance between each pair of factors at that layer with respect to the connected factors on the upper layer. A set of judgment matrices is then created for each layer.
- The priority vectors associated with these judgment matrices are calculated by solving the corresponding eigenvalue problems, as explained in Appendix A. This shows how the composite priority vectors can be calculated, i.e., the priority vector from the bottom layer with respect to the top layer or the normalized attribute weighting parameters.

There are three reasons that make the AHP based ratio-questioning method is favored over the indifferent-tradeoff method for the assessment of attribute priorities:

1. It is a systems approach taking into account various concerns regarding the priorities of conflicting attributes.

2. It can compensate for inconsistent human judgments by asking redundant questions and then retrieving the weighting parameters on a compromise basis using an eigenvector prioritization method.
3. It can incorporate the influence of the range of attribute values on the preference, a major feature of the indifference tradeoff method, into the assessment process with properly revised ratio questions.

3.2.2. Options in Planning

The concepts of least-cost planning and integrated resource planning (IRP) result from reassessing the traditional practice of utility planning due to increased importance of government regulation, private power producers, and public awareness of environmental issues. IRP is the evaluation of combined supply and demand options, which include a wide range of attributes, in the planning process to minimize the overall “cost.” Those options in IRP are the conventional technologies plus a multitude of supply and demand options.

- Supply side options include conventional technologies (i.e. flue gas desulphurisation retrofit, fluidized bed combustion, and integrated gasification combined cycle as a means to re-power the plants, use of low sulphur fuels, use of environmental instead of economic dispatch, replacement or expansion of capacity with low-emitting technologies, allowance trading, retirement of high-SO₂ emitters), power purchase (i.e. peak-shaving practice), non-utility generation (i.e. privatization of electric utilities), alternative energy systems (i.e. photovoltaic generation, solar thermal power systems, wind turbine energy systems).
- Demand-side options include demand-side management (i.e. load shifting, peak shaving, valley filling), and conservation (i.e. efficiency improvement of residential appliances, better energy management control systems, variable-speed motors).

3.2.3. Uncertainties in Planning

Uncertainties in electric utility planning emanate from the load growth, performance of the generating system (reliability), capital and operating costs, environmental regulations and social and political attitudes. For each of the groups, a brief description is as follows.

- Factors affecting load growth are population growth, economic factors (i.e. residential appliance saturations, electricity prices, prices of substitute fuels, disposable income) [166], technological changes (i.e. increased appliance efficiencies, insulation practices) [40], consumer behavior (i.e. improved insulation, customer response to competing energy providers), DSM impacts (i.e. participation of customers in the programs, effects of the programs on the load curve, public attitudes towards the programs) [131].
- Reliability uncertainties are affected from existing utility attrition (i.e. retirement of utility capacity due to age, emissions requirements, regulatory issues for nuclear and hydro unit re-licensing), future availability of utility generation (i.e. expected loss of capacity due to economic reasons, licensing delays, construction risk), existing non-

utility attrition (i.e. expected loss of NUG capacity due to economic conditions, lack of fuel, lifetime of the technology), future availability of non-utility generation (i.e. due to licensing complications, construction schedules, and financing availability), life and performance of plants (i.e. expected life of re-powered plants, forced outage rates of generating units), required reserve (i.e. due to future load shapes, future energy limited resources, unit availabilities, and tie capabilities).

- Cost uncertainties are affected by fuel prices (i.e. due to socio-politic conditions, Clean Air Act amendments), construction costs and time (i.e. the use of smaller more-expensive readily available plant), cost of resources/capital cost (i.e. due to rapidly changing market conditions, technological development), operating and maintenance costs (i.e. due to emergency operation and unscheduled maintenance), capital escalation (i.e. escalation rate, discount rate), cost of replacing power lost due to emission abatement equipment.
- Environmental uncertainties are affected by environmental impacts (i.e. still much uncertainty on the results of models predicting the measurements impacts), environmental regulation (i.e. cost of future emissions allowances).
- Social and political affecting factors are public attitudes (i.e. based on public needs and perceptions), regulation (i.e. environmental compliance, regulatory approvals on facility siting and power needs).

Identify Relevant Uncertainties

Screening an uncertainty to find which of its influential uncertainties have a considerable impact on the solution can be done using pair-wise comparisons of the impacts given by the DM to form a judgment matrix. Those uncertainty factors with a low score can be eliminated.

Identify Probability Distributions of Uncertainties

Another important aspect concerning uncertainty is the assignment of probability distributions. Probabilities are estimated from a number of expert judgments, with the inherent benefit that an error in any particular judgment is compensated by other judgment ratios. Furthermore, the set of probabilities assigned to a particular uncertainty will depend on the probabilities assigned to its factors. In other words, the probability distributions of a particular uncertainty depend on the values selected for the uncertainty factors influenced by it. Two cases explained in Chapters 4 and 5 show how to assign the probability distributions to relevant uncertainties.

3.3. Scenario Development

The combination of a specific plan and a specific future constitutes a particular scenario. A number of scenarios can be created from the combinations of plans and futures, ranging all the possible alternatives.

3.4. Decision Database Issues

Each scenario is evaluated using a combination of utility planning tools, such as investment optimization models, production costing simulation and reliability assessment programs, environmental impact analysis, and financial analysis models. Flexibility is incorporated into each plan reflecting a scenario. Scenario analysis will establish a decision database where alternative plans are compared based on certain well-defined decision criteria.

3.5. Acceptable Alternatives

This section describes the performance evaluation technique using probabilistic approach (composite utility or composite distance together with decision tree) combined with tradeoff analysis to identify the acceptable plans. Furthermore, the calculation of attribute weights and production cost composite variance are given using an error propagation technique.

3.5.1. Probabilistic Approach

In doing decision analysis under uncertainty, the utility function or distance value method is used together with a decision tree modeling approach. This decision process can provide a graphical interpretation of alternative planning strategies, decision variables and uncertainty factors. The technique is termed a probabilistic evaluation approach, where the best solution is determined based on the expected value of composite utility or composite distance of planning strategy under future conditions.

Transforming an n-dimensional vector performance to a scalar performance measurement in dealing with multi-attribute problems has become a common approach, by using the multi-attribute utility function or distance value. The following text describes utility function and distance value methods followed by a decision tree model.

Composite Utility Function and Composite Distance Value

Multi-attribute utility function is comprised of the preference functions associated with the attributes (single utility functions) and the weighting parameters that reflect the relative importance of these attributes toward the overall planning goal or objective. Although the composite utility is a nonlinear function of single utility functions and weighting parameters, a special form of the function, known as linear additive form, can be used if the contributions of an individual attribute to the composite utility are independent of other attribute values. A general expression of the linear additive utility model is expressed in Equation (3-1).

$$U(x) = \sum_{i=1}^n w_i U_i(x_i) \quad (3-1)$$

where $U(x)$ is the composite utility of each alternative as a function of the attributes vector $\mathbf{x} = [x_1, \dots, x_n]$. $U_i(x_i)$ and w_i are the single utility function and weighting parameter of the i^{th} attribute, respectively. Weighting parameter represents the relative importance in comparison to other attributes and satisfies $\sum w_i = 1$.

Many decision problems in electric utility planning have used linear additive utility models, such as generation resource acquisition assessment, energy-conservation program evaluation, selection of new generation technologies, integrated resource planning, and transaction selection in a competitive market [13, 32, 60, 63, 69]. Attributes considered in these studies cover quite different fields of interest, such as project investment, energy production cost, system reliability, environmental impact, and flexibility in resource development; therefore, the independence condition of additive utility is satisfied.

The single utility function $U_i(x_i)$ may be replaced by the normalized attribute distance value r_i , representing the risk-neutral attitude of the DM. Such a form of linear additive utility model can be expressed by linear additive distance value as expressed in Equation (3-2):

$$U_d(x) = \sum_{i=1}^n w_i \left| \frac{x_i - x_i^*}{x_i^r} \right| = \sum_{i=1}^n w_i r_i \quad (3-2)$$

where $U_d(x)$ is the composite distance for a particular plan measured from the ideal solution $\mathbf{x}^* = [x_1^*, x_2^*, \dots, x_n^*]$, x_i and r_i are respectively the measured and normalized values of the i^{th} attribute, x_i^r is the range of variation of measured attribute values with x_i^* as the optimal (maximal for benefit attributes and minimal for cost attributes), and w_i is the weighting parameter of the i^{th} attribute.

The ideal solution \mathbf{x}^* reflects the attribute optimal values, where maximal values are used for benefit attributes and minimal values for cost attributes. The range of attribute variations \mathbf{x}^r is calculated from the difference of maximum and minimum values automatically.

The best solution in Equation (3-1) is the alternative for which the measured composite utility function output is maximum, while the best alternative determined by Equation (3-2) represents a minimum distance from the ideal point in the direction preferred by the DM. Therefore the term ‘‘Composite Utility’’ or $U(x)$ can be replaced by the term ‘‘Composite Distance’’ or $U_d(x)$.

In the construction of linear additive utility models, there are two terms of concern: the single utility functions and the weighting parameters, which are determined through interviews with utility planners using decision analysis techniques. Ratio-questioning method with AHP is used to determine the weighting parameters, where the discussion is done earlier when attribute is been addressed. Therefore the following section explains single utility function calculation.

Single Utility Functions Calculation

The single utility function, $U_i(x_i)$, represents the utility values that the DM attaches to each attribute which reflects his/her attitude toward taking a risk. DM can define the utility value on a normalized scale, as the attribute varies between its lower and upper bounds. Certainty equivalence method is used to evaluate a single utility function [110], although the convergence procedure in assessing a certainty equivalent is time-consuming and cumbersome [39]. Since it is harder for the DM to determine a single value that will represent a confident attitude, it is more convenient for the DM to specify a boundary around the true certainty equivalent. Alternatively, ratio-scale method can be used to measure the DM's preferences [72, 109], but the method seems to work well only when there are a small number of alternatives.

Incorporating pair-wise comparison analysis into the certainty equivalent method has improved the procedure [62]. Some of the benefits of the assessment procedure are:

- Improvement over the traditional method since the value of certainty equivalent is determined by examining several candidates on a compromise basis and therefore will increase the level of confidence in the resulting preference functions;
- Increased reliability over the ratio-scale method because the DM's preference is evaluated over the entire range of attribute values.

The steps of the improved procedure are as follows.

- Identify the range of attribute values, obtained from detailed studies including production costing simulation, investment optimization, reliability evaluation and environmental impact analysis for all alternatives.
- Assess three certainty equivalent values for x_i with respect to $U_i(x_{.5})$, $U_i(x_{.75})$, and $U_i(x_{.25})$, respectively. The DM may select a few candidate values to avoid the tedious convergence procedure, which are around the true certainty equivalent. The judgment matrix can be formed, by comparing each pair of these candidates for their closeness to the expected certainty equivalent, from which the priority vector can be obtained by solving the corresponding eigenvalue problem (AHP techniques).
- Calculate the certainty equivalent as the weighted-average of these candidates, using Equation (3-3):

$$\bar{c} = \mathbf{c} \cdot \mathbf{p}^T \quad (3-3)$$

where $c = [c_1, c_2, \dots, c_m]$ and $p = [p_1, p_2, \dots, p_m]$ are the vector of candidates and the corresponding priority vector, respectively. These three $(x_i, U_i(x_i))$ pairs with the end point utility values of 1 and 0, gives five points on the single utility function for the i^{th} attribute.

- Fit a curve through these points to determine the corresponding equation for $U_i(x_i)$.

Decision Tree Structure

The decision tree model consists of decision nodes, representing resource options, and chance nodes, representing uncertainties. Decision nodes are marked as rectangles, while chance nodes are marked as ovals. The uncertainty is addressed with discrete probability showing the occurrence estimates of different conditions. Total sum of probabilities on branches radiating from a chance node must equal to 1.0. A scenario is a complete path between the tree root and a terminal node, consisting of a combination of options and uncertainty factors that can be traced throughout the tree. A typical decision tree model for utility generation expansion planning is shown in Figure 3-1.

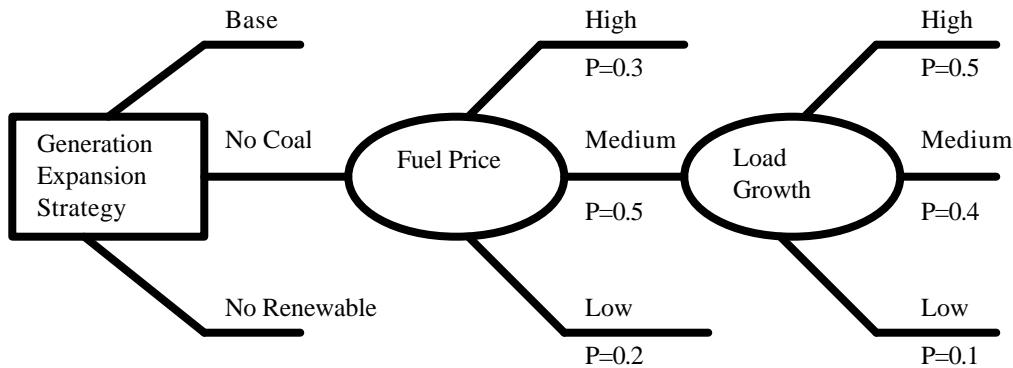


Figure 3-1. Typical Decision Tree Structure

Scenario Evaluation

Each scenario is determined by an overall performance scalar value, called composite utility or composite distance, which is calculated by the utility function model (3-1) or the distance value model (3-2), respectively, taking into account any contributions from different attributes. Each scenario's likelihood is determined by multiplying the probability of uncertainty for branches starting from the end point to the decision node at the beginning of the decision tree.

Expected Utility and Distance Value

The expected utility or distance value of each plan is determined as the sum of utility or distance multiplied by the likelihood of each scenario relevant to that planning strategy, as indicated in Equation (3-4):

$$U(x) = \sum_{k=1}^m p_k U_k(x) = \sum_{k=1}^m p_k \sum_{i=1}^n w_i U_{ki}(x_{ki}) \quad (3-4)$$

where $U(x)$ is the expected utility or distance value for each planning strategy, $U_k(x)$ is the composite utility or composite distance for scenario k characterized by attributes $\mathbf{x} = [x_{k1}, \dots, x_{kn}]$, p_k is the probability of scenario k , $U_{ki}(x)$ is the single utility function or single distance value with respect to the i^{th} attribute, w_i is a weighting parameter for the i^{th} attribute, representing its relative importance to other attributes and satisfying $\sum w_i = 1$.

The plans are then ranked based on their expected utility or distance value. When the best solution has been determined for each future condition, tradeoff analysis can be used to identify more inferior plans. This procedure will lead to the formation of a decision set that consists of plans for all futures. The tradeoff analysis method does not try to find a unique “optimal” plan, but it is an approach for evaluating relationships between attributes and uncertainties. The following is the description of the tradeoff analysis approach.

3.5.2. Tradeoff Analysis

When the objective is to minimize each attribute of the plan, then plan A dominates (is better than) plan B if the attribute value of plan A is less than the attribute value of plan B for every attribute. This leads to two conditions of dominance:

- **Strict Dominance:** plan A strictly dominates plan B conditional on a specific future, if the attribute value of plan A is better (less) than the attribute value of plan B for all attributes.
- **Significant Dominance:** plan A significantly dominates plan B conditional on a specific future, if at least one attribute value of plan B is “much worse” than the corresponding attribute value of plan A, and if no other attribute value of plan B is “significantly better” than the corresponding attribute value of plan A.

A set of tolerance levels needs to be selected by the DM to define the meaning of the terms “much worse” and “significantly better,” which are selected independently for each attribute. As an example, for the attribute “total cost,” a planner could specify that a plan costing a million dollars more than another is much worse, but a plan costing a hundred thousand dollars more than another is not significantly better.

Tradeoff curve is a set of plans that are not strictly dominated by any other plan on a particular future, and knee set or conditional decision set is a set of plans that are not significantly dominated by any other plan on a particular future.

Figure 3-2 illustrates an example of two attributes tradeoff graphs, that consist of the tradeoff curve and knee set determined using the dominance criteria. The following can be observed from the graph:

- The tradeoff curve forms the boundary between the sets of possible and unachievable attributes while the knee set contains plans on and near the knee of the tradeoff curve. The levels of tolerance determine the size of the knee set.
- The knee set boundary allows the planner to perform visual pair-wise comparison of all the plans under consideration and quickly identify the best alternatives. The tolerance for each attribute reflects how far the planner is willing to trade off one attribute with respect to another, or indicates the planner's preference on the relative importance of different attributes.

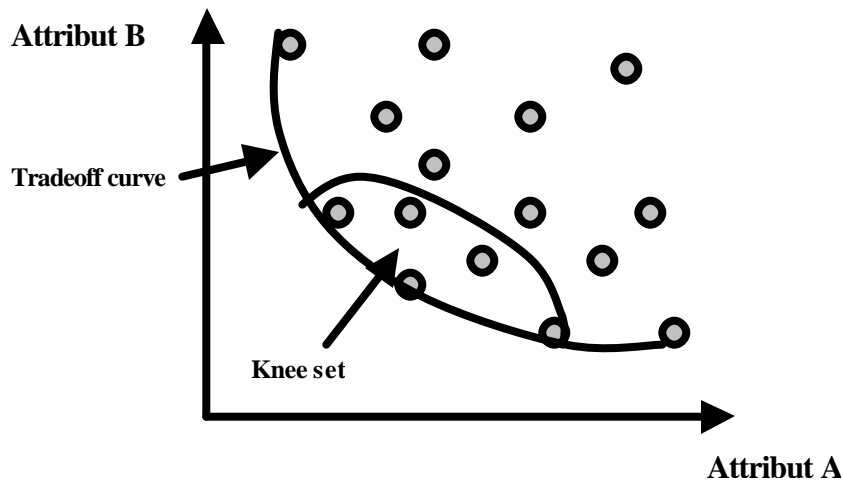


Figure 3-2. Tradeoff Graph with Two Attributes

To overcome the difficulties of finding the knee set for more than two attributes and performing tradeoff analysis for each pair of attributes and every specified future, it is necessary in practical utility planning studies to use some well-defined numerical knee-set searching algorithms instead of visual examination. The variance techniques will be presented first before introducing the numerical knee-set searching algorithms.

3.5.3. Composite Utility and Composite Distance Variance

Errors Propagation Technique

The error propagation technique is used to examine the influence of inaccurate data on the ranking of alternatives. The error propagation principle is described as: “Given some set of numbers and their errors, what is the error in some prescribed function involving these numbers?” [33, 71]. A function $y = f(x_1, x_2, \dots, x_n)$ has a general expression for error propagation as in Equation (3-5):

$$s_y^2 = \sum_{i=1}^n \left(\frac{\partial f}{\partial x_i} s_{x_i} \right)^2 \quad (3-5)$$

where \mathbf{s}_{x_i} and \mathbf{s}_y are the standard deviations of variable x_i and the prescribed function $y = f(x_1, x_2, \dots, x_n)$, respectively.

The composite utility variance for the linear additive utility model in (3-1) can be derived as in the following:

$$\begin{aligned} \mathbf{s}_u^2 &= \sum_{i=1}^n \left(\frac{\partial U}{\partial w_i} \mathbf{s}_{w_i} \right)^2 + \sum_{i=1}^n \left(\frac{\partial U}{\partial x_i} \mathbf{s}_{x_i} \right)^2 \\ \mathbf{s}_u^2 &= \sum_{i=1}^n \left[U_i^2(x_i) \mathbf{s}_{w_i}^2 + \left(w_i \frac{dU_i(x_i)}{dx_i} \right)^2 \mathbf{s}_{x_i}^2 \right] \end{aligned} \quad (3-6)$$

where \mathbf{s}_u , \mathbf{s}_{x_i} and \mathbf{s}_{w_i} are the standard deviations of composite utility values, i^{th} attribute and its weight, respectively. The error \mathbf{s}_{w_i} is created by inconsistent subjective judgments and the error \mathbf{s}_{x_i} is due to inaccurate attribute measurements.

The composite utility values may be approximately measured by the normal distribution. Given a desired level of confidence, the likely range of composite utility values corresponding to (3-1) can be estimated as the following.

$$(U - I_{\alpha/2} \mathbf{s}_u, U + I_{\alpha/2} \mathbf{s}_u) \quad (3-7)$$

In similar fashion, the composite distance variance for the linear additive distance model in (3-2) can be derived as follows:

$$\begin{aligned} \mathbf{s}_d^2 &= \sum_{i=1}^n \left(\frac{\partial U_d}{\partial w_i} \mathbf{s}_{w_i} \right)^2 + \sum_{i=1}^n \left(\frac{\partial U_d}{\partial r_i} \mathbf{s}_{r_i} \right)^2 \\ \mathbf{s}_d^2 &= \sum_{i=1}^n \left[r_i^2 \mathbf{s}_{w_i}^2 + w_i^2 \mathbf{s}_{r_i}^2 \right] \end{aligned} \quad (3-8)$$

where \mathbf{s}_d , \mathbf{s}_{r_i} and \mathbf{s}_{w_i} are the standard deviations of composite distance values, normalized i^{th} attribute and its weight, respectively. Let m be the number of plans evaluated. The standard deviation \mathbf{s}_{r_i} for the j^{th} plan can be estimated by Equation (3-9):

$$\mathbf{s}_{r_i}^2 = \frac{1}{(x_i^{\max} - x_i^{\min})^4} \left[\mathbf{s}_{x_{ij}^{\max}}^2 (x_i^{\max} - x_i^{\min})^2 + \mathbf{s}_{x_{ij}^{\min}}^2 (x_{ij} - x_i^{\min})^2 + \mathbf{s}_{x_{ij}^{\min}}^2 (x_{ij} - x_i^{\max})^2 \right] \quad (3-9)$$

where x_{ij} is the measured i^{th} attribute for alternative j and the error parameter $\mathbf{s}_{x_{ij}}$ is its standard deviation, $x_i^{\min} = \min \{x_{ij}, j = 1, 2, \dots, m\}$, $x_i^{\max} = \max \{x_{ij}, j = 1, 2, \dots, m\}$.

The likely range of composite distance values of Equation (3-2) can be estimated as the following.

$$(U_d - \mathbf{I}_{a/2} \mathbf{s}_d, U_d + \mathbf{I}_{a/2} \mathbf{s}_d) \quad (3-10)$$

Performing multi-attribute electric utility resource planning produces two major error sources, namely production cost variance and priority assessment variance errors. A brief discussion of them is as follows.

Production Cost Variance

The value of production costing related to electric power system is not a single deterministic value, but a random variable, due to the uncertainties in unexpected outages and load variations [175]. The value varies around its mean, which is the expected production cost, and has probability distribution that depends on the load patterns and the stochastic characteristics of the generation units' forced outages in the system. The conventional production costing model's output includes the expected energy production costs, system reliability indices and generation-related emissions. The measure of production cost variance is a useful input to the decision making process in comparing different generation expansion alternatives, and it has been discussed in many publications [85, 102, 175]. Results indicate that the variance of the cost is a very small percent of the mean value. Accordingly, it is important to incorporate the error parameter using the concept of production cost variance in order to estimate the composite utility variance.

Priority Assessment Variance

It has been proved that the AHP technique is a reliable tool for attribute priorities assessment in multi-attribute analysis. Studies carried out at Virginia Tech in modeling the subjective errors from creation of the judgment matrix [44, 125, 126] have shown that a good estimate of the error parameter \mathbf{s}^2 can be calculated by the following:

$$\mathbf{s}^2 = \frac{2}{(n-1)(n-2)} \sum_{i=1}^{n-1} \sum_{j=i+1}^n y_{ij}^2 \quad (3-11)$$

where n is the judgment matrix size, $y_{ij} = \ln(a_{ij}/w_{ij})$, a_{ij} is the judgment ratio $[i, j]$ of the judgment matrix, $w_{ij} = w_i/w_j$ and $\mathbf{w} = [w_1, w_2, \dots, w_n]$ is the priority vector.

Note that the error parameter s^2 is calculated based on only the judgment matrix, where it involves only the judgment ratio a_{ij} and the priority ratio w_{ij} . The priorities associated with judgment matrix variances at any layer of the hierarchy are estimated as follows.

$$s_{w_i}^2 = \frac{n^2 - 1}{n^2} \left[\sum_{i=1}^n w_i^2 - w_i^2 \right] s^2 w_i^2 \quad (3-12)$$

The final step is selecting the best planning strategy based on the optimal (maximal or minimal, as appropriate) expected value as the criterion.

3.5.4. Performance Evaluation Technique

The reasons for selecting this technique are as follows.

- It provides a statistical background in the selection of an appropriate tolerance level of plans by estimating the variance of the multi-attribute model concerning the errors due to inaccurate attribute measurements and inconsistent priority judgments. Other available methods as in [50, 170] have used the tolerance levels termed as “much worse” and “significantly better,” which need to be specified for each attribute by the DM.
- It ranks the acceptable plans contained in the knee set based on the measure of composite distance, which is useful in differentiating among competing plans.

The technique suggests applying the probabilistic approach in parallel with the tradeoff approach on the common decision database, to determine a set of acceptable plans based on the measure of expected performance with further assessments to select a plan or plans that are robust, flexible or less risky.

Four main steps of the technique are described as follows [51, 170]:

- Formulate the attributes, options and uncertainties of the problem.
- Develop a decision database for various scenarios.
- Identify the set of plans left after all inferior plans have been rejected (“decision set”) using the tradeoff concept.
- Eliminate more plans by analyzing the plans in the decision set by the determined resource strategy.

Problem Formulation

Sets of attributes, options and uncertainties are identified before creating various scenarios to be examined. Each plan is a set of resource options, and each future is a set of uncertainty factors. The combination of a specific plan and future represents a scenario.

Creation of Decision Database

The quantitative and qualitative attributes for each scenario are stored in the decision database. They are calculated using analytical planning models or determined using subjective judgments. Some methods have been introduced [50, 112, 127, 62] in the creation of a decision database consisting thousands of scenarios.

Identification of Non-Dominated Plans using Knee-Set Searching Algorithm

1. Eliminate all inferior plans due to lack of performance of one or more attributes and define the tradeoff region.
2. Define the multi-attribute model as in (3-2).
3. Compute the value of composite distance, both the point estimate and variance estimate, for each feasible plan, with some properly estimated errors from attribute measurements and priority judgments.
4. Identify the best plan, that for which the value of composite distance is minimal, $U_{d,min}$.
5. Determine the knee set conditional on each future that consists of all data points following (3-13) below:

$$U_d - I_{a/2} s_d \leq U_{d,min} - I_{a/2} s_{d,min} \tag{3-13}$$

where $I_{a/2}$ is the standard deviation of normal distribution with a desired confidence interval, say 90% or 95%, and s_d and $s_{d,min}$ are the estimated errors of composite distances to the plan being examined and the best plan identified in step 4, respectively.

Figure 3-3 illustrates the conceptual knee-set searching process as discussed above when only two attributes are involved.

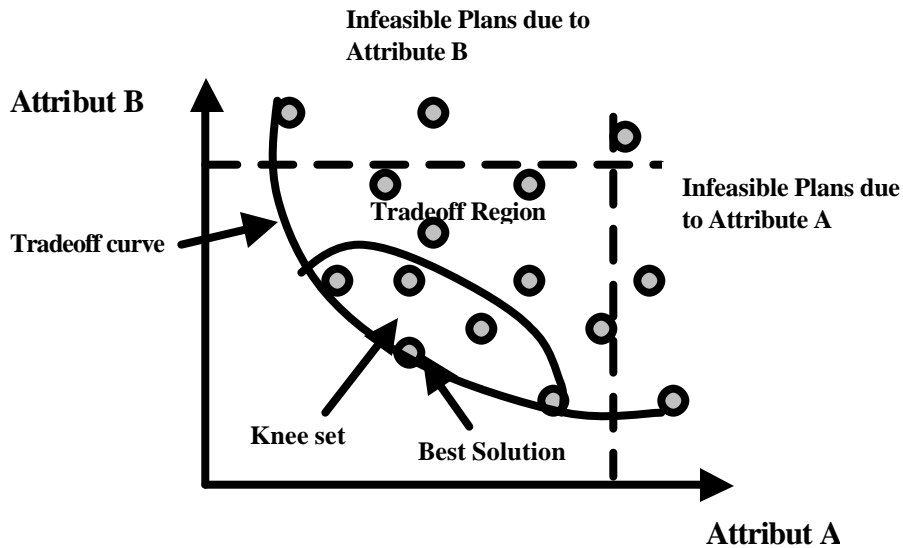


Figure 3-3. Conceptual Procedures in Knee-Set Searching

Decision Set Analysis

The decision set analysis is then applied to measure performance attributes in terms of robustness, flexibility, and risk exposure as the final resource strategy.

The global decision set is the set of plans that are left after all inferior plans have been eliminated. Plan A remains in the global decision set only if there is no other plan which strictly dominates plan A for all futures. It is convenient to say that the union of the conditional decision sets form the global decision set.

3.6. Determination of Resource Strategy

Determination of resource strategy utilizes the integrated performance approach methodology, which can be summarized as follows.

- Formulate the decision problem properly.
- Create a reliable decision database.
- Identify decision sets after eliminating all inferior plans.
- Analyze the decision sets to support the final resource strategy.

The integrated methodology differs from the traditional tradeoff analysis approach in the following aspects.

- It includes a multi-dimensional knee-set searching algorithm based on the measure of composite distance together with statistical background for the selection of appropriate tolerance level.
- It provides a decision-making model, in which the resource plans can be evaluated based on the rule of probability and tradeoff consideration, further expanded for attribute measures such as robustness, flexibility and risk exposure.

The following sections explain the concept introduced for determination of resource strategy in selecting plans that meet the criteria of robustness, flexibility and risk exposure.

3.6.1. Robustness Measure Approach

Decision set analysis supports the resource development strategy by identifying robust and inferior options. The frequency with which the plan appears on the global decision set or the number of supporting futures determines its robustness. A 100% robust plan is a plan that is always in the knee set for all futures.

In the case where multiple plans are identified as the robust plan, or plan that has a 100% scale in supporting all future conditions, the following approach can be used to decide the most robust plan.

- Compare the plans according to their preference ranking and choose the most robust plan as that with majority highest ranking among the future conditions.

- Compare the plans using their range of attribute values and choose the most robust plan for each of the attributes to be considered.
- Compare the plans using probabilistic analysis models by generating different cases where each case represents a specific probability distribution assigned to all the future conditions, and choose the most robust plan based on the assumption of a particular case condition.

In the case when no plan is completely robust, i.e., there is no any single plan that is optimal or nearly so for all possible futures, hedging to reduce the risk must be applied. This is usually the real situation in electric utility planning due to conflicting objectives and diverse future forecasts. One practical and effective risk-mitigating approach is to reassemble the identified robust resource options into new plans that may be expected to perform better or more robustly than any original plans.

3.6.2. Flexibility Measure Approach

Flexibility is defined as the ability of the power system to adapt to new future conditions in the best way. Flexibility can be incorporated at two levels of the electric utility planning process, first in the selection of alternative generation and transmission technologies [24], and second in the evaluation of expansion options [3].

The first level is done by the DM either to include more quickly installed technology or to install technology which makes a better use of the existing system, while the second level is when attribute values are calculated using utility planning tools, such as investment optimization models, production costing simulation and reliability assessment programs, environmental impact analysis and financing analysis models, and within the scope of determination of the final resource strategy.

Selection of Alternative Technologies

In achieving a flexible power system for the benefit of reducing the effects of uncertainty through selection of alternative technologies, the DM could either include more quickly installed technology or install technology that makes better use of the existing system. A comprehensive means to provide flexibility is described in [24].

Evaluation of Expansion Options

In the calculation process for attribute values, the evaluation of expansion options can be done by calculating the additional “cost” necessary for each of the plans to respond to each of the future scenarios to be calculated for each stage. The costs of flexibility for plan i , future scenarios s , and stage k are calculated from the attribute values, such as cost, emissions, or reliability. Let’s say that A_{isk} is considered as the attribute value of cost calculated for plan i , future scenario s , and stage k . Therefore, C_{isk} can be calculated using Equation (3-14):

$$C_{isk} = \sum_{j=1}^S [(A_{ijk} - A_{isk})][U(A_{ijk} - A_{isk})] \quad (3-14)$$

where $U(x)$ is the function follows (3-15) and S is the number of future scenarios.

$$U(x) = \begin{cases} 1 & x \geq 0 \\ 0 & x < 0 \end{cases} \quad (3-15)$$

Now the expected cost of flexibility is calculated for each plan for each stage, incorporating the probabilities of occurrence for all scenarios using Equation (3-16).

$$C_{ik} = \sum_{s=1}^S p_s C_{isk} \quad (3-16)$$

where C_{ik} is the expected cost of flexibility for plan i at stage k , C_{isk} is the cost of flexibility for plan i at stage k under future scenario s , and p_s is the probability of occurrence of future scenario s , with $\sum p_s = 1$.

When C_{ik} considered as the generation cost attribute, then the present value of total flexibility cost for plan i is calculated considering all the stages and incorporating the discount rates using Equation (3-17):

$$C_i = \sum_{k=1}^K \frac{C_{ik}}{(1+r)^{k-1}} \quad (3-17)$$

where C_i is the present value of flexibility total cost for plan i , r is the discount rate, and K is number of stages.

For attributes other than cost, such as emissions and reliability, the final value of flexibility cost for plan i is calculated using Equation (3-18).

$$C_i = \sum_{k=1}^K C_{ik} \quad (3-18)$$

Flexibility measure is implemented for plans that fall under the same future conditions. Let's say some plans fall under 100% robust conditions. Distance value of the flexibility cost is calculated for those plans, and then the following steps can be done for selecting plans based on their flexibility measure and deciding the most flexible plan.

- Compare the plans according to the distance value of the flexibility cost and a fixed probability of futures, then choose the most flexible plan for the lowest distance value.

- Compare the plans using probabilistic analysis models by generating different cases where each case represents a specific probability distribution assigned to all the future conditions, and choose the most flexible plan based on the assumption of a particular case condition.

3.6.3. Risk Exposure Measure Approach

Risk exposure can be measured or estimated by a risk assessment process. Risk assessment is defined as the total process of risk analysis and consists of identification of risk levels, estimation of risk levels, and the social evaluation of risks [43, 178]. Risk identification comprises efforts to identify new risks and identify changes in existing risk parameters. Risk estimation is used to estimate the probability of risk occurrences and the magnitude of risk consequence value. Risk evaluation aims at knowing risk aversion and risk acceptance. Figure 3-4 shows the risk assessment overall diagram.

The manner in which risk are perceived and identified is a major consideration in coping with it, since risk is considered as a potential threat to man, his environment and his well-being. Changes in the levels of risk are identified in three conditions that can occur simultaneously: when a new risk is created or found, when the magnitude of an existing risk changes, and when perception of an existing risk changes. A risk that did not previously exist is considered as a new risk, which is created by man as a result of new technology against the balance of nature. A perception of existing risk is changed when the hazard is identified, the magnitude of hazard changes suddenly, or a slow change in the hazard’s magnitude crosses some threshold of societal concern. Public perception of existing risks may change whether or not the objective level of risk changes, such as when a more dominant risk is eliminated or reduced. The terms “hazard” and “risk” may be used interchangeably, although the term “hazard” means the present existence and “risk” the potential existence, or “threat,” of some unwanted consequence.

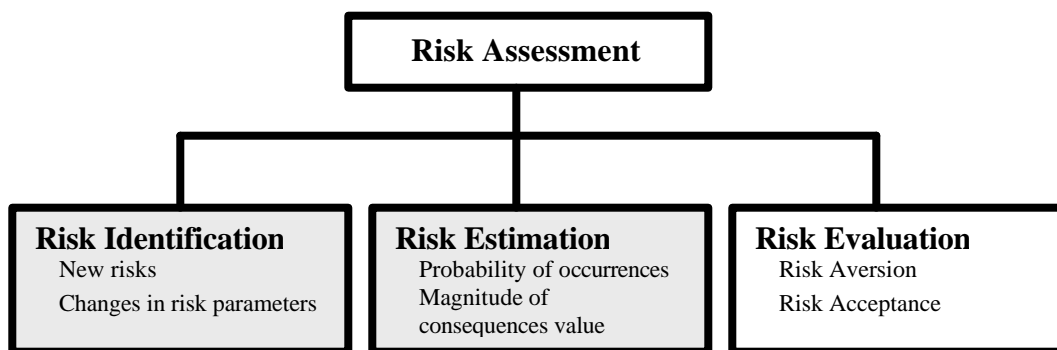


Figure 3-4. Risk Assessment Overall Diagram

The process of risk estimation can be divided into five steps: identifying the cause of the risk, measuring its effects, determining risk exposure, defining the consequences of exposure, and valuing the consequences of exposure. The first four steps are parts of the probability determination, while the last step belongs to consequence value

determination. Probability determination consists the following four steps. First, identify causative events together with their probabilities of risk occurrence, where each of the causative events can lead to several possible outcomes. Second, define these outcomes and determine their relative probabilities by considering the exposures of humans, institutions, and the natural environment. Third, define the exposure pathways with their corresponding probabilities, which implies that risks are transmitted explicitly. Fourth, define the possible consequences of risk exposure and determine for each risk the probability that consequences will occur. Consequence value determination asks the affected individuals or the DM to assign a value to the consequences of the risk exposure. AHP is used for this step.

Risk evaluation is related to human responses. Although man by nature is risk averse, tending to avoid acts or situations whose consequences may threaten his health and safety, he may also choose to take and accept risks to achieve specific benefits. The value judgments required in risk evaluation fall into three classes, namely technical, societal, and managerial, which are used to evaluate the risk exposure measured from the previous identification and estimation steps. The technique developed for measuring the risk exposure is based on risk identification and risk estimation methods.

Identification and Estimation Method

There are two ways that risk identification can be done, using experimental and non-experimental techniques [139]. The experimental risk identification technique is used when data records of cases are available and new experiments can be simulated by experiments. From the results of experiments, other unavailable data within domain of interest can be extrapolated.

The non-experiment risk identification technique relates some variables to other variables in capturing certain information by correlation. For example, the relationship between wind speed and cloud covering at a certain location can be predicted.

Since risk can never been known in certainty, risk estimation always includes assumptions about future behavior and is subject to two kinds of uncertainty: error due to model assumptions, and error due to fluctuations in the database. Confidence interval techniques use those errors to quantify the ranges, and it is preferable to use methods that require fewer assumptions and more data. The following three methods are used in risk estimation: subjective or expert judgment, model analysis, and estimate based on data series. All estimates are accompanied by some measure of their uncertainty. When the estimate is based mostly on judgments and model analysis, sensitivity analysis is used. If the data series is used, uncertainty is estimated by confidence intervals.

Risk exposure quantifies the risk hazards. Risk exposure can be reduced in these three ways: expanding the plant mix, reducing dependence on the allowance market and external source of power, and adoption of renewable or environmentally friendly technologies.

After identifying the risk consequences, risk exposure can be measured using the additive multi-objective value model [46] and calculated using Equation (3-19):

$$V(x) = \sum_1^n w_i v_i(x_i) \quad (3-19)$$

where $V(x)$ is the overall value provided by the consequence alternatives with the set of scores x , w_i are the global weights (product of local weights up the hierarchy of consequences) of the i th consequence measures, $v_i(x_i)$ is the single dimensional value function of the i th consequence measure, and n is the number of the consequence measures.

The single dimensional value functions provide the returns to scale on the score of the consequence measures. Value functions usually occur in four basic mathematical forms: linear (constant return to scale), concave (decreasing returns to scale), convex (increasing returns to scale), and an S-curve (increasing then decreasing returns to scale). The value functions were obtained by asking DM the relative value of increments of the consequence measure scale.

4. Hybrid Solar-Wind Case Study

Increasing interest in power generation from renewable energy sources is caused by six factors: economic reasons (i.e. production cost saving), reliability benefits (i.e. reduction in expected energy not supplied, reduction in system loss of load probability), fuel security (i.e. limited reserves of coal, oil and gas), health and safety (i.e. reduced threat of nuclear accident), fuel price volatility (i.e. increased oil price due to political conditions), and environmental issues (i.e. reduced carbon emissions) [34, 117]. In spite of their advantages, the limited use of the renewable energy sources by the electric utilities is mainly due to their high cost of generated electricity. Further consideration about seasonality of wind and solar data is taken into account using long-term annual average data that smooth out the seasonality but could cause over or under-design of such facilities.

This chapter will look into the renewable energy technologies, currents and future trends affecting them, and issues related to the grid integration of renewable technologies. Further, the chapter will try to analyze some of the technical and economic aspects of wind and solar energy systems, and then use the results to investigate the penetration level of renewable systems into the conventional electrical system using the decision-making process under uncertainty, considering robustness, flexibility and risk exposure criteria.

4.1. Renewable Energy Technologies Overview

Energy derived from resources that are based on self-renewing energy sources such as sunlight, wind, flowing water, the earth's internal heat, and biomass (i.e. crops, agricultural and industrial waste, and municipal waste) are considered as renewable energy. The use of U.S. renewable energy in 1998 comprised hydropower (55%), biomass (38%), geothermal (5%), solar (1%), and wind (0.5%) [153]. More detailed information on facilities that generate U.S. grid-connected electricity from renewable resources is available electronically [159].

Renewable energy resources are abundant, and every region has some energy resources, which can complement one other. By taking them together they can contribute significantly to energy security and regional development, without dependence on foreign energy sources. Also, most renewable energy systems are modular, allowing flexibility in matching load growth. The markets of renewable energy system range from specialized usage to centralized energy production, where the latter is relatively more capital intensive compared to conventional technologies. After the initial investment has been made, the economics of centralized renewable energy systems improve in comparison with conventional technologies because of low maintenance and operating costs, especially for solar and wind systems, for which fuel cost is not only constant, it is zero, while the conventional technologies will be affected by future fuel price increases.

Renewable energy systems also generate little of waste and pollutants that contribute to acid rain, urban smog, and health problems, and do not require environmental cleanup costs or waste disposal fees. Solar, wind and geothermal systems do not contribute any carbon dioxide to the atmosphere, minimizing the potential of global climate change [54].

In the last 20 years, serious developments have been taking place in the application of renewable energy technologies by the industry and government (primarily the U.S. Department of Energy, DOE), which result in large improvements in cost, performance, and reliability [38, 88].

Photovoltaic Energy

Converting sunlight to electricity is the basic principle of photovoltaic devices using semiconductor materials such as silicon. The devices have no moving parts, produce no emissions, and can be used in small cells, panels and arrays. Photovoltaic systems require little maintenance and typically have 20-year lifetimes.

Research efforts are focused on developing more efficient semiconductor materials and device designs, while expanding production capacity, increasing production rates, and improving product quality [148, 144, 158, 2].

A new type of thermo-photovoltaic is in development that uses the energy of heat or infrared radiation to generate electricity, with the advantage that a generator can operate at night or when the sky is cloudy, eliminating the need for batteries. The heat is provided from a fuel such as natural gas, and the devices use semiconductors for conversion rather than conventional diesel generators, resulting in higher fuel-to-electricity conversion efficiencies, modularity, minimal pollutants, quiet operation, and high reliability [133].

Wind Energy

Converting kinetic energy of the wind into other forms of energy such as electricity is the principle of wind power systems. The conversion concept is relatively simple, but the turbine design can be quite complex. Most wind turbines use a horizontal-axis configuration with two or three blades, a drive train including a gearbox and generator, and a tower to support the rotor. The electricity is produced within a specific range of wind speeds.

Rapid research progress in the technology has reduced costs until they are competitive with the conventional power [25]. Research aims to increase the aerodynamic efficiency and structural strength of wind turbine blades, develop variable speed generators and electronic power controls, and use taller towers that allow access to the stronger winds found in greater heights [149, 160].

Bio-power

Converting biomass resources, ranging from agricultural and forest product residues to crops grown, into electricity is the principle of biomass power plants. Direct combustion systems are used to burn biomass in boilers to produce steam that is expanded through a turbine/generator to produce power. Alternatively, co-firing substitutes biomass for coal in existing coal-fired boilers, or a gasification process converts biomass to fuel gas that can be substituted for natural gas in combustion turbines [154].

Research efforts are ongoing in the areas of improving conversion efficiency of commercial plants, reducing costs, and resolving issues related to biomass residual ash [145, 161].

Bio-fuels

The use of ethanol as a gasoline additive to raise the octane level of gasoline and promote cleaner combustion is the principle of bio-fuel systems. Another benefit of ethanol blended with gasoline is the reduction of motor vehicle emissions of carbon monoxide by 25% to 30%, with corresponding reductions in ozone levels that contribute to urban smog, for combustion of ethanol produces 90% less carbon dioxide than that of gasoline. Ethanol is produced from corn kernels using traditional fermentation technology, and as corn requires a high amount of energy (as fertilizer and farm equipment fuel) to grow, bio-ethanol has also been produced from corn waste, waste newspaper, rice straw, forest thinning to prevent wildfires, and grasses and trees cultivated as energy crops [87]. The production of bio-ethanol involves hydrolysis of biomass using enzymes or acid catalysts, to form soluble sugars, which are converted to ethanol.

Research focuses on lowering production cost of enzymes for breaking down cellulose, improving microorganism performance, production of suitable energy crops, and demonstration of bio-ethanol production from a variety of biomass feedstocks [146, 56].

Geothermal Energy

Converting steam and water from geothermal resources such as dry steam, hot water, hot dry rock, magma, and ambient ground heat to electricity or useful heat is the principle of geothermal power generation and geothermal heat pumps.

Research focuses on lowering costs, improving methods for finding and characterizing reservoirs, and trapping broader resources [150, 162].

Concentrating Solar Power and Solar Buildings

Converting the sun's heat to electricity or other usages is the motivation for concentrating solar power, as in the "solar thermal" technologies. Three options for a possible system configuration are described briefly. The first type of system consists of rows of highly reflective parabolic troughs, where each trough focuses and concentrates sunlight on a central tube filled with heat-absorbing fluid that is used to generate electricity. The second system configuration, the "power tower," generates a large amount of electricity

using a tall, fluid-filled tower located at the focal point of a large field of mirrors. The third option is the Dish-Stirling system, which uses a small array of mirrors to focus sunlight on a Stirling engine that produces electricity [151, 21, 164].

Solar water heating is the most widespread concept in solar building technology, and research progress is being made in improving the reliability and durability of this type of system.

Hydrogen and Fuel Cells

Converting hydrogen to electricity is the principle of fuel cells. The commercially available fuel cells are phosphoric acid fuel cells that use natural gas as the source of hydrogen, molten carbonate fuel cells, and solid-oxide fuel cells. Another type under development is the proton exchange membrane fuel cell [130].

Research efforts are directed toward the development of technologies to produce hydrogen from sunlight, water, and biomass; development of low-cost and low-weight hydrogen storage technologies for both stationary and vehicle based applications such as carbon nanotubes and metal hydrides; and development of codes and standards to enable the widespread use of hydrogen technologies.

Distributed Power

Modular generating systems sized from less than a kilowatt to tens of megawatts and located at or near consumer sites are considered as distributed power. The system can be either grid connected or operate independently of the grid. The goal is to reinvent the power grid from the present case of producing electricity only at large, central plants and transmitting only one direction, to some degree of customers' energy independence, with the system open to many small suppliers. Technologies available for generating electricity as distributed power are fuel cells, photovoltaic systems, wind turbines, biomass based generators, micro-turbines, engine/generator sets, and electric storage systems [4].

The benefits of distributed power systems are reliability of service, improved power quality, greater efficiency with respect to power generation system heat loss, and the ability to function as standby generation or serve as an uninterruptible power supply. The key barrier is interconnection with the grid; the IEEE is now leading the development of a consensus standard for interconnection to ensure that distributed systems operate safely and reliably and are applied uniformly across the U.S. power system.

4.2. Trends and Issues Affecting Renewable Energy Technologies

The range of issues affecting the development of renewable energy technology includes technological advancement, cost related influences, public support, market uncertainties, policy encouragement, distributed generation, fuel cells, biomass energy, and

international markets. Furthermore, government and independent entities carry out scenarios related to the future renewable energy technology penetration level.

Current Issues Affecting Renewables

Scientific and engineering advances strongly influence the progress of renewable energy technology development including information technology, such as easily accessible web sites, real time metering for electricity pricing, and control equipment in buildings [130]. Costs of electricity and retail price of electricity from renewable systems is still higher than for conventional systems because the hidden costs of fossil fuels (environmental cost, health cost, energy security cost) for conventional system are not included [155, 38].

Renewable energy attracts public support because of the preferences for clean “green” development and energy efficiency [11, 120, 28]. At the same time, renewable technology is a valuable protection against natural disasters because of the extensive use of fossil fuels has impacted the environment in a negative way [26].

Deregulation in power markets makes it more difficult for renewable technologies to penetrate large markets because of the newness and uncertainty surrounding investments in relatively new technologies, the expectation of stiff price competition, and higher initial cost of renewable technologies [29, 163].

Policy measures, such as renewable portfolio standards, are needed to encourage the use of renewable energy electricity. A market-based mechanism may be developed to ensure a minimum level of renewable energy development in the electricity portfolios of power suppliers, as determined by a state or other regulatory entity [152].

Remote or distributed markets will be more favorable to renewable electricity than the centralized electricity market because of the changes in the electricity marketplace [20]. Distributed generating sources may begin to fill in some of the large requirements for capacity replacements expected during the next 20 years [157].

In the transportation sector, the current low price of oil makes it relatively less attractive to develop and use bio-ethanol, bio-diesel, hydrogen, and renewable-powered fuel cells. This situation may change quickly as the increasing amount of oil imports to the U.S. begins to impact the country’s energy security [157, 156, 18].

Increases in biomass energy usage will become significant and will impact the agricultural community, through the utilization of waste products (agricultural, industrial, and municipal wastes) and the harvesting of energy crops (fast-maturing species of trees and grasses that are grown on farms) [115]. In order to address the increased demand for energy in developing countries, and to avoid the environmental problems created by conventional energy systems, it is expected that international markets for renewable energy technologies will be promoted [38, 47, 66, 147, 68].

In summary, current issues affecting renewable energy technologies suggest interesting possibilities in predicting risks [1], which include the following.

- Scientific discoveries and engineering progress
- Development of new economic structures in the electricity sector
- Trends towards decentralization and modularity
- Rapid progress with respect to computers, information and telecommunication
- Globalization of markets
- Overall and persistent support for the environment
- Limited future availability of less expensive fossil fuels

Several government and independent entities have developed scenarios indicating that renewable energy will play a major role in the energy mix, with increasing impacts beginning in 2000-2010 and major impacts by 2050 [171, 172, 173, 95], while contributions from conventional energy resources begin to level off in 20-30 years from now [121]. Factors that increase the use of renewable electricity technologies that could replace coal-based, nuclear and natural gas power plants are distributed energy resources, international markets, continuing technical advances, and public opinion [130].

Climate Change Solution Scenarios

In order to assess the world's reliance on renewable energy for this century, some well-known scenarios have been developed by the United Nation's Intergovernmental Panel on Climate Change (IPCC), the International Institute of Applied Systems Analysis (IIASA), the World Energy Council (WEC), and Shell Oil. It is remarkable to note that the IPCC "Coal Intensive" scenario predicts that 65% of all worldwide primary energy from renewables can be achieved by 2100, starting from 15% at present moment [174]. These scenarios use the estimates of uncertainties that cover the following.

- The role that climate change will play in market evolution
- The price of fossil fuels as the 21st century progresses
- The availability of fossil fuels
- The progress of technological development (both renewable and conventional)
- The extent of and access to renewable energy resources
- The infrastructure developments required in shifting energy markets to renewable energy

Realization of those scenarios requires resource availability, lower technology costs, government support through appropriate policies, and public acceptance and adoption of renewable energy alternatives. Some other barriers that involve cost competitiveness are lack of customer awareness of the attributes and potential of renewable energy, constraints on consumer choice, absence of standards and certification procedures, and external costs (e.g. local air emission) not included in market decisions. Policy initiatives that can promote worldwide renewable energy address research and development (R&D), tax incentives, information campaigns, green power pricing programs, standardization, and certification.

4.3. Issues Related to the Integration of Hybrid Solar-Wind System to the Grid

This section is intended to list some of the critical issues related to the integration of renewable technology, specifically the hybrid solar-wind system, to the conventional grid system. These factors relate to political and social conditions, technical advances and economic, as well as environmental and climatic issues [99].

Analyzing those factors identifies some of the attributes, options (decision variables), and uncertainty variables. The attribute variables represent the measures of feasibility and goodness of the overall systems. Decision variables represent the category of variables on which the DM has a reasonable amount of control, such as the decision to construct a new generating unit, expand the existing generating unit, or retire a generating unit. These decision variables are used to identify options. Uncertainty factors are the variables over which the DM has little or no control.

Some of the attribute variables are listed as follows.

1. Cost
 - total present worth
 - fuel costs
 - capacity costs
 - annual costs
2. Fuel use
 - annual consumption of coal
 - total consumption of oil
3. Reliability
 - loss of load probability
 - expected energy not served
4. Financial impact
 - dividend pay out
 - requirements of new financing
 - requirements of rate relief
 - interest coverage
5. Environmental
 - carbon emission
 - sulfur emission

Some of the decision variables are listed below.

1. Wind area
2. Solar area
3. Substation rating
4. Battery rating
5. Type capacity
6. Location of installation
7. Timing of Installation

Some of uncertainty factors are listed below.

1. Escalation rate of capital cost
2. Construction lead time
3. Capital availability
4. Load growth
5. Fuel prices
6. Source availability
7. Fuel availability
8. Inflation rate
9. Interest rates and rate relief

The following sub-chapters list some identified issues that can influence the integration of renewable technology into the conventional grid system.

4.3.1. Energy Security

Energy security is a measure to address from where the energy comes. Pair-wise comparison matrices, which consist of the variables that influence energy security, need to be constructed to incorporate many aspects. The question is, “what are these aspects, and how are they related?”

4.3.2. Generation Unit Reliability

Reliability is measured by the generating unit’s forced outage rates and maintenance outage rates. It is important to consider how these conventional reliability terms are calculated when the renewable technology is included in the system.

4.3.3. T&D Line Expansion Reliability

Transmission and distribution line reliability is changed when the grid system is penetrated by renewable energy sources. The components that contribute to this change need to be investigated.

4.3.4. Operation Limitation

Integrating renewable technology into the conventional grid system has many technical constraints. In addition, due to intermittent behavior of renewable technology, the grid system can accept only a certain ratio of renewable technology to conventional technology. Therefore, it is necessary to know the operational limitation of renewable technology penetration to the conventional system and what affects this limitation.

4.3.5. Energy Efficiency

As renewable energy technology advances, energy efficiency development is progressing as well. A contentious issue is the pricing of energy efficiency improvements.

4.3.6. Revenue Stream Stability

Investment decisions to include renewable technology are motivated by the stability of the investors' revenue stream. The stability indicator is influenced by many factors, which relate the investment decisions with the associated risks. The characterization of those risks remains to be fully explored.

4.3.7. Environmental and Health Impact

Utilization of renewable sources can be justified on the basis that reduction in electric utility related atmospheric emissions is desirable. Ultimately, customers will have to pay not only the cost of generating the power they use, but also the indirect costs related to environmental cleanup and health effects [124].

4.3.8. Weather Impact

Wind and solar power link the available generation directly to weather patterns and introduce daily seasonality into the supply of electricity. Therefore, it is not possible to fully control the power output and predict the availability for any future date. This inherent feature adds some degree of risk on the supply and demand sides.

4.3.9. Robustness

Robustness measure favors any plans or scenarios that perform well for most, if not all, futures. The number of plans that fall under all futures is used to measure the robustness of a plan.

4.3.10. Flexibility

Flexibility allows inexpensive changes to be made if future conditions deviate from assumptions. It is measured as an additional cost for a plan to respond to certain scenario.

4.3.11. Risk Exposure

Risk exposure quantifies the risk hazards. Risk exposure is measured by considering the probability of the exposure and the consequence value determined by the DM. The exposure may covers many different issues such as ecological, social and health issues.

4.4. Hybrid Solar-Wind Power Systems

Problem Formulation

The system under study is based on references [107, 108], which refer to optimal design of a hybrid solar-wind power system (HSWPS). The system consists of four energy sources: wind generators, PV array, grid-link substation and battery storage. The main goal of the work is to increase utilization levels of renewable energy technologies. Three objectives are considered for the selection of suitable system components: minimization of cost and emissions and maximization of system reliability [100, 101].

Identification of Attributes

Constraints and policy options are identified using priority ordering of three design objectives (attributes). The AHP technique is used for attribute priority assessment to overcome factors influencing the DM's preference regarding the relative importance of different objectives. Figure 4-1 shows the hierarchy for the attribute priority assessment.

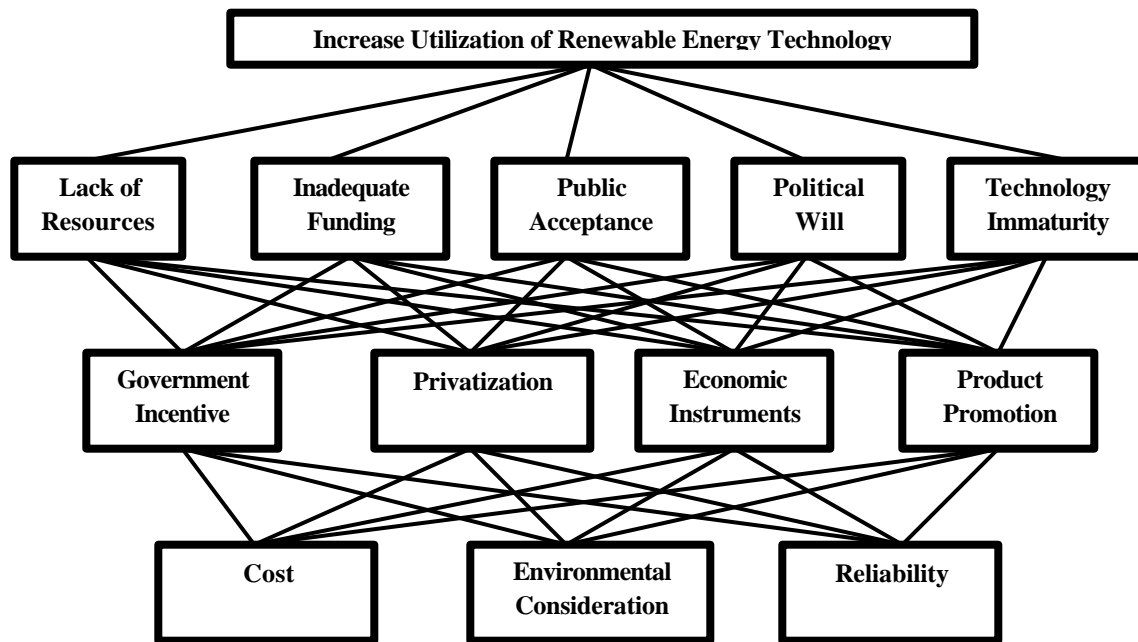


Figure 4-1. Hierarchy for Attribute Priority Assessment

The hierarchical structure consists of four layers, from main goal down to the constraints, including the policies affecting the constraints, and finally the attributes or objectives. Starting from second layer of the hierarchy, ratio questions are asked of the DM

concerning the relative importance between of each pair of factors at that layer with respect to a factor on the adjacent upper layer. The result of these pair-wise comparisons are judgment matrices corresponding to each level, as given in Appendix B1. The local priority vector associated with each judgment matrix for each evaluation level is calculated using the eigenvector prioritization method. The global priority vector is computed by combining the priority vector at the top evaluation level with the priority vectors of levels below. The resulting global priority vector based on given judgment matrices indicates that minimizing the cost of energy supply is ranked first (0.5006), followed by system reliability (0.3094) and then environmental concerns (0.1901).

Identification of Options

Identification of options is based on the design variables for wind area, solar area, substation rating, and battery rating.

Identification of Uncertainties and their Probability Distributions

1. Identify the Relevant Uncertainties

Uncertainty factors considered in this case study are economic situation, resource availability and load growth. For the purpose of showing how to identify relevant uncertainties, load growth is selected. The uncertainties affecting load growth are possibility of new regulations, customer behavior including end-use practices and response to technology changes, changes in economic conditions, and DSM impacts, mainly on load demand and energy. Figure 4-2 shows the hierarchy for load growth with its possible contributing factors. Now expert opinions are used to generate the pair-wise comparisons as shown in matrix A below.

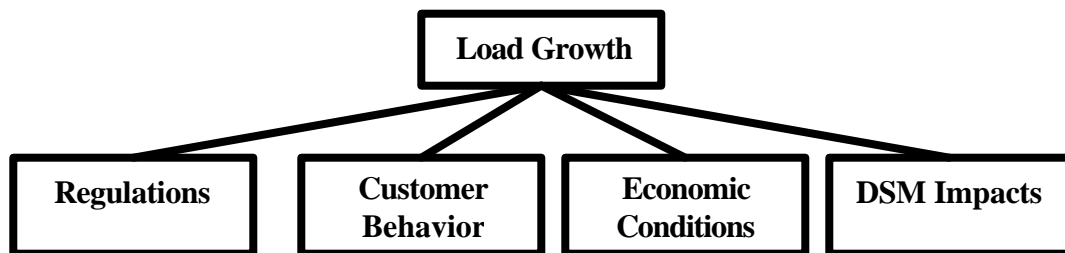


Figure 4-2. Hierarchy of Load Growth

$$[A] = \begin{bmatrix} 1 & 1/3 & 1/9 & 1/7 \\ 3 & 1 & 1/5 & 1/3 \\ 9 & 5 & 1 & 3 \\ 7 & 3 & 1/3 & 1 \end{bmatrix}$$

The ratio scales reflects the assessments that:

- “Regulations” is slightly less important than “Customer Behavior”, not as important as “Economic Conditions” and very much less important than “DSM Impacts.”
- “Customer Behavior” is much less important than “Economic Conditions” and is slightly less important than “DSM Impacts.”
- “Economic Conditions” is slightly important than “DSM Impacts.”

Solving the eigenvalue problem from the above judgment matrix gives the normalized eigenvector (weights) $r = [0.0451, 0.1708, 0.8885, 0.4202]$. The values indicate the weighting factors for Regulations, Customer Behavior, Economic Considerations, and DSM Impacts, respectively. The resulting weighting factors allow for eliminating the uncertainty factor due to new regulations because its total impact is small compared to that of other factors.

2. Calculate the Probability Distributions of Uncertainties

The next step is to show how to calculate the probability distributions of uncertainties. Consider now that the load growth is affected by customer behavior, economic factors and DSM impacts. Each of these factors has its own probability distributions that are derived from the pair-wise comparisons by the DM, as shown in Table 4-1.

Table 4-1. Load Growth Uncertainty Factors.

Uncertainty Factor	Effect	High	Base	Low	Weights
Customer Behavior	High	1	1/7	1/3	0.0810
	Base	7	1	5	0.7306
	Low	3	1/5	1	0.1884
Economic Conditions	High	1	1/5	1/3	0.1047
	Base	5	1	3	0.6370
	Low	3	1/3	1	0.2583
DSM Impacts	High	1	1/5	1/7	0.0719
	Base	5	1	1/3	0.2790
	Low	7	3	1	0.6491

For each of the factor effects, i.e. “high” customer behavior, “high” economic factor and “low” DSM impacts, the DM performs another comparison of likelihood. A question such as, “How much more likely for the load growth to be ‘high’ (i.e. 5%) than ‘base’ (i.e. 3%)?” is asked, and a judgment matrix such as the following is formed for each effect.

$$\begin{matrix}
 \mathit{high} \\
 \mathit{base} \\
 \mathit{low}
 \end{matrix}
 =
 \begin{bmatrix}
 1 & 1/3 & 1/7 \\
 3 & 1 & 1/5 \\
 7 & 5 & 1
 \end{bmatrix}$$

The resulting normalized eigenvector (weights) are given below. This means that if customer behavior results in higher load growth, economic factors result in higher load growth, and DSM effects result in lower load growth, the system load growth will have a probability distribution such as these results.

$$\begin{matrix} \mathit{high} \\ \mathit{base} \\ \mathit{low} \end{matrix} = \begin{bmatrix} 0.0810 \\ 0.1884 \\ 0.7306 \end{bmatrix}$$

The procedure implies that probability distributions of load growth for its “high”, “base”, or “low” conditions, depend on probability distributions of its components (customer behavior, economic condition, and DSM impacts).

Selection of Plans

Design variables are wind area (m²), solar area (m²), substation rating (kW), and battery rating (kWh). The range and step of variation for each design variable is set, from which 960 (=12x5x8x2) alternative plans can be generated. Table 4-2 shows the variation range and step of the selected design variables.

Table 4-2. Range and Step of Variation of the Design Variables

	Wind Area (m ²)	Solar Area (m ²)	Substation Rating (kW)	Battery Rating (kWh)
Min	20,000	0	200	500
Max	75,000	20,000	900	1000
Step	5,000	5,000	100	500

Selection of Futures

Descriptions of selected futures, accounting for the influences of uncertainty factors for economic situation, resource availability and load growth are considered. In this case study, only four futures are selected for uncertainty modeling of the decision problem. The selected futures share the base case assumptions in wind speed, load growth and economic factors, but differ with each other in the level of solar insolation and PV efficiency. Table 4-3 shows the description of selected futures.

Table 4-3. Description of Selected Futures

Future	Solar Insolation (pu)	PV Efficiency (%)	Grid-energy charge (\$/kWh)	PV Cost (\$/m ²)	Interest Rate (%)	Wind Speed (pu)	Load Growth (%)
Base	1.0	12	0.08	450	12	1.0	0
F1	0.9	12	0.08	450	12	1.0	0
F2	1.1	12	0.08	450	12	1.0	0
F3	0.9	17	0.08	450	12	1.0	0
F4	1.1	17	0.08	450	12	1.0	0

Simulation Considering Flexibility

To incorporate flexibility into the design process, the production simulation model will need to be run for every year, and the DM will decide at the end of each simulation year which future to anticipate. In this process, numerous simulations will need to be run; therefore, for the purpose of this study, the process is simplified to two stages, with each stage representing a ten-year planning horizon. At the end of stage one, the DM will arrive at a decision point on selecting the future. Stage one is the period of study from 2003-2012, and stage two is the period of study 2013-2022. Figure 4-3 shows the decision tree schematic representation.

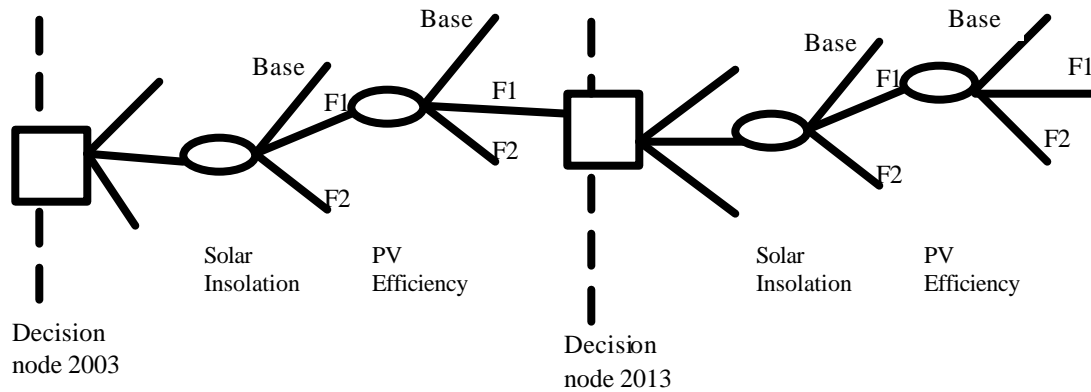


Figure 4-3. Two-stage decision tree

Given the range and variation step of the design variables and possible futures, several thousand scenarios are created and studied using an energy production simulation model for each stage. The outputs of the simulation model include the cost of energy production (\$/kWh), expected energy unserved (%), and CO₂ emissions (kg/year). In addition, the present value of flexibility “cost” is calculated from computing the amount of additional “cost” necessary for each plan to respond to each of the futures at each stage. The “cost” refers to the cost of energy production, expected energy unserved, and CO₂ emissions for this particular case study.

Calculation of Attribute Values

Knowing the attribute values and flexibility cost for each of the attributes obtained from detailed studies including production-costing simulation for all alternatives, the process of identifying the ranges of attribute values or flexibility cost values can be done. Attribute values can be used to measure the robustness, while flexibility cost values can be used to measure flexibility. The next step is to calculate the single utility function or distance value for each of the attributes or flexibility costs. Single utility function calculation is selected when the DM prefers to assign additional certainty equivalent values for each of the attributes. The procedure of incorporating the pair-wise comparison analysis has been discussed in Chapter 3. For single distance value, calculation can be

done automatically after assigning the ideal solution for each attribute value, which enables the algorithm to calculate the normalized value of each attribute, following equation (3-2). For the attributes in this case study, the ideal values are “zero” for cost, emission, and energy not served and “100” for reliability.

1. Using Single Utility Function Method

To illustrate the single utility function calculation procedure, attribute reliability is taken as an example. The value of attribute EENS are calculated to be in the range of 0.2% to 2.5%. The lower bound of EENS represents the best system performance, therefore $U(0.2\%) = 1.0$, while the upper bound of EENS indicates the worst situation of system reliability and thus should have $U(2.5\%) = 0$. The next step is for the DM to assess three certainty equivalent values in the range of EENS measurements with respect to $U(x_{.5})$, $U(x_{.75})$, and $U(x_{.25})$.

The candidates for $x_{.5}$ with respect to $U(x_{.5}) = 0.5$ are selected as $c = [1.2, 1.3, 1.5, 1.6]$ (%), and by comparing each pair of these candidates for their closeness to the expected certainty equivalent using the following assessment, the judgment matrix [A] is formed.

- (1.2% EENS level) is slightly less likely than (1.3% and 1.6% EENS levels), but very much less likely than (1.5% EENS level)
- (1.3% EENS level) is much less than (1.5% EENS level) and is as likely as (1.6% EENS level)
- (1.5% EENS level) is much more likely than (1.6% EENS level)

$$[A] = \begin{bmatrix} 1 & 1/3 & 1/7 & 1/3 \\ 3 & 1 & 1/5 & 1 \\ 7 & 5 & 1 & 5 \\ 3 & 1 & 1/5 & 1 \end{bmatrix}$$

Solving the eigenvalue problem using AHP for the above judgment matrix results in the priority vector $p = [0.0624, 0.1514, 0.6348, 0.1514]$. Then, the certainty equivalent $x_{.5}$ is computed as a weighted-average of these candidates using equation (3-3).

$$x_{.5} = [1.2, 1.3, 1.5, 1.6] \times [0.0624, 0.1514, 0.6348, 0.1514]^T = 1.466\%$$

Similarly, the candidates for $x_{.75}$ and $x_{.25}$ with respect to $U(x_{.75}) = 0.75$ and $U(x_{.25}) = 0.25$ are selected to be $[0.5, 0.7, 0.9, 1.1]$ (%) and $[1.7, 1.9, 2.1, 2.3]$ (%), respectively. The certainty equivalents for these levels are $x_{.75} = 0.875\%$ and $x_{.25} = 2.075\%$. Together with the two end points, these three $(x_i, U(x_i))$ pairs add five points to the single utility function of reliability. The next step is to fit these points by a third order polynomial function that represents the function itself. The procedure is performed for all three attributes, and the single utility functions for cost, emissions and reliability are given below by $U_1(x_1)$, $U_2(x_2)$, and $U_3(x_3)$, respectively. Figure 4-4 shows the plot of single utility function for reliability.

$$U_1(x_1) = -7867.6 x_1^3 + 2953.5 x_1^2 - 390.83 x_1 + 18.728$$

$$U_2(x_2) = 3E-12 x_2^3 - 2E-07 x_2^2 + 0.0028 x_2 - 13.26$$

$$U_3(x_3) = -0.0281x_3^3 + 0.0705x_3^2 - 0.4332x_3 + 1.0858$$

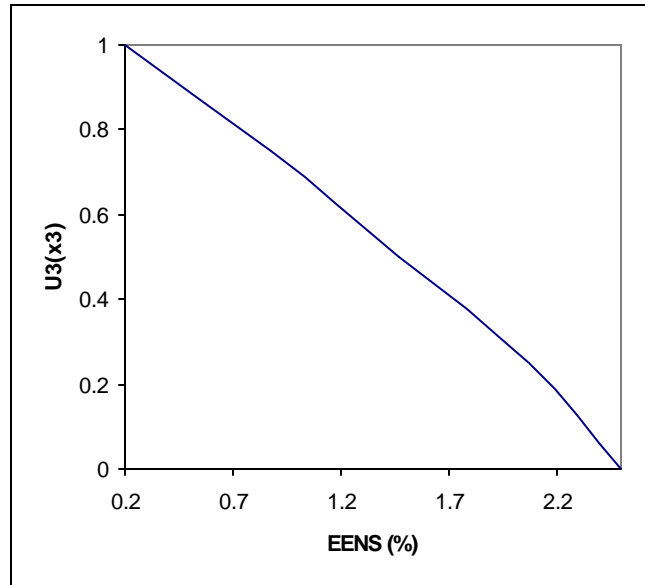


Figure 4-4. Single Utility Function for Reliability

Finally, using the result of weighting parameters of global priority from Figure 4-1 that rank the cost of energy supply as first (0.5006), followed by system reliability (0.3094) and then environmental concerns (0.1901), the linear additive utility function can be written as follows.

$$U(x) = 0.5006 U_1(x_1) + 0.1901 U_2(x_2) + 0.3094 U_3(x_3)$$

2. Using Distance Value Method

In analyzing this case study, single distance value calculation is used instead of single utility function calculation as described previously. The calculation is done automatically following equation (3-2), as indicated below:

$$U_d(r) = 0.5006 r_1 + 0.1901 r_2 + 0.3094 r_3 \quad (4-1)$$

$$U_{dCr}(Cr) = 0.5006 Cr_1 + 0.1901 Cr_2 + 0.3094 Cr_3 \quad (4-2)$$

where r_i and Cr_i are normalized attribute distance value and normalized flexibility distance value, respectively. The above two equations (4-1) and (4-2) are used to determine the robustness and flexibility measures.

Decision Analysis

Table 4-4. Top 10 Acceptance Plans for Continuous Future

First 10 years	Second 10 years	Wind Area m ²	Solar Area m ²	Substation Rating kW	Battery Rating kWh	Cost \$/kWh	EENS %	CO2 kg/year	Ranking
F1	F1	45000	0	500	500	0.1269	2.4406	185494	1
		45000	0	600	500	0.1292	0.4941	191644	2
		50000	0	500	500	0.1316	2.0025	174301	3
		50000	0	600	500	0.134	0.268	179780	4
		45000	0	500	1000	0.1295	2.4373	185124	5
		30000	5000	500	500	0.1309	1.8062	183309	6
		45000	0	600	1000	0.1319	0.4904	191275	7
		55000	0	500	500	0.1364	1.6408	163580	8
		50000	0	500	1000	0.1341	1.9834	173696	9
		35000	5000	500	500	0.1356	1.5124	171579	10
F2	F2	30000	5000	500	500	0.129	1.676	175041	1
		35000	5000	500	500	0.1338	1.4046	163546	2
		30000	5000	600	500	0.1319	0.571	178536	3
		30000	5000	500	1000	0.1316	1.6677	174335	4
		50000	0	500	500	0.1316	2.0025	174301	5
		50000	0	600	500	0.134	0.268	179780	6
		35000	5000	600	500	0.1367	0.3932	166739	7
		40000	5000	500	500	0.1387	1.176	152455	8
		35000	5000	500	1000	0.1364	1.4046	162672	9
		30000	5000	600	1000	0.1345	0.571	177797	10
F3	F3	30000	5000	500	500	0.1257	1.5746	168184	1
		25000	5000	500	500	0.1227	1.868	179578	2
		25000	5000	600	500	0.1256	0.6968	183275	3
		25000	5000	500	1000	0.1253	1.8614	178906	4
		35000	5000	500	500	0.1324	1.3248	157026	5
		30000	5000	600	500	0.1304	0.5117	171545	6
		35000	5000	500	1000	0.1349	1.3246	146808	7
		30000	5000	500	1000	0.1301	1.5752	167311	8
		35000	5000	400	500	0.1308	4.2791	147716	9
F4	F4	20000	5000	500	500	0.1154	1.9979	180116	1
		25000	5000	500	500	0.1204	1.7129	168991	2
		20000	5000	600	500	0.1184	0.7859	183948	3
		30000	5000	500	500	0.1253	1.4362	158202	4
		25000	5000	600	500	0.1233	0.6008	172520	5
		25000	5000	600	1000	0.1228	1.7116	167848	6
		30000	5000	400	500	0.1236	4.4925	148590	7
		30000	5000	500	1000	0.1278	1.4335	156757	8
		30000	5000	600	500	0.1283	0.4471	161328	9
		25000	5000	600	1000	0.1258	0.6008	171344	10

The tradeoff analysis method is then applied to the decision database to determine the optimal combination of device capacities based on the measures of robustness, flexibility and risk exposure. The steps are as follows.

- Determination of tradeoff region
- Identification of conditional and global decision sets
- Decision sets analysis

Table 4-5. Selected Plans for Changing Futures at Second stage

First 10 years	Second 10 years	Wind Area m ²	Solar Area m ²	Substation Rating kW	Battery Rating kWh	Cost \$/kWh	EENS %	CO2 kg/year	Ranking
F1	F2	30000	5000	500	500	0.12995	1.7411	179175	1
		50000	0	500	500	0.1316	2.0025	174301	2
		50000	0	600	500	0.134	0.268	179780	3
		35000	5000	500	500	0.1347	1.4585	167563	4
F1	F3	30000	5000	500	500	0.1283	1.6904	175747	1
		35000	5000	500	500	0.134	1.4186	164302	2
F1	F4	30000	5000	500	500	0.1281	1.6212	170756	1
F2	F3	30000	5000	500	500	0.12735	1.6253	171613	1
		30000	5000	500	1000	0.13085	1.62145	170823	2
		30000	5000	600	500	0.13115	0.54135	175041	3
		35000	5000	500	500	0.1331	1.3647	160286	4
		35000	5000	500	1000	0.13565	1.3646	154740	5
F2	F4	30000	5000	500	500	0.12715	1.5561	166622	1
		30000	5000	500	1000	0.1297	1.5506	165546	2
		30000	5000	600	500	0.1301	0.50905	169932	3
F3	F4	25000	5000	500	500	0.12155	1.79045	174285	1
		25000	5000	600	500	0.12445	0.6488	177898	2
		30000	5000	500	500	0.1255	1.5054	163193	3
		30000	5000	500	1000	0.12895	1.50435	162034	4
		30000	5000	600	500	0.12935	0.4794	166437	5

Determination of tradeoff region among the feasible plans under different futures is characterized by four design variables, along with three decision attributes. These feasible plans are determined after eliminating all inferior plans due to unacceptable performance of one or more attributes. All plans with a “cost of energy production” higher than 0.15 \$/kWh and/or with the EENS index greater than 5% are rejected. For the decision problem with three attributes, graphical representation of the tradeoff region requires a 3-D graph. Alternatively, 2-D graphs can be used to relate each pair of attributes.

Identification of decision sets consists of the following steps.

- Composite distance value is calculated for every plan contained within the tradeoff region using equation (3-2), which is rewritten for this case study as (4-1).

- Composite distance variance is estimated using the approximate error model. Errors due to inconsistent priority judgment are assumed to be 10% of the expected values, and errors from inaccurate attribute measurements are assumed as 5% of the range of attribute values.
- Decision set is identified, conditional on a specific set of futures, following the criterion of equation (3-9).
- Global decision set is determined as the union of conditional decision sets.

Decision set analysis is done to quantify the robustness of plans and to identify the flexible plans among the robust plans. Table 4-4 and Table 4-5 are given for the top few acceptable plans for plans that do not change futures at their second stage and for the ones that do change futures at their second stage

Robustness Measure

Table 4-6. Global Decision Set for Robustness

Plan No.	Wind Area m2	Solar Area m2	Substation Rating kW	Battery Rating kWh	F1	F2	F3	F4	Robustness
G1	25000	5000	500	500			2	2	50%
G2	25000	5000	600	500			3	5	50%
G3	30000	5000	500	500	6	1	1	4	100%
G4	30000	5000	500	1000	14	4	8	8	100%
G5	30000	5000	600	500	11	3	6	9	100%
G6	35000	5000	500	500	10	2	5	11	100%
G7	35000	5000	500	1000	20	9	7	19	100%
G8	35000	5000	600	500	18	7			50%
G9	40000	5000	500	500	19	8			50%
G10	50000	0	500	500	3	5			50%
G11	50000	0	500	1000	9	14			50%
G12	55000	0	500	500	8	11			50%
G13	50000	0	600	500	4	6			50%

The robustness measure can be done in three steps. First, the list of plans that appear in at least two futures is shown in Table 4-6. The analysis of the global decision set supports the following observations.

- Five robust plans, G3 through G7, are identified from the global decision set. These plans are acceptable for all futures and therefore are recommended as the candidate alternatives for the final decision-making.
- All of the identified robust plans involve four energy sources that indicate the harmonizing characteristics of these resource options in the system operations.

- These candidate plans reflect a conservative design attitude in utilizing wind and solar technologies and emphasize the importance of adequate storage capacity and grid supply.
- Plan G3 is regarded as the best strategy based on its preference ranking.
- Among other four candidate alternatives, plan G6 seems to be superior to plans G4, G5, and G7 because the ranking of G6 is higher than that of G4, G5 and G7 under the majority (at least 3 out of 4) of supporting futures.

Second, to decide among the 100% robust plans, Table 4-7 shows the variation of attribute values associated with the candidate design alternatives (G3 though G7) under different future conditions.

Table 4-7. Range of Attribute Values under Different Future Condition

Plan No.	Wind Area M2	Solar Area m2	Substation Rating kW	Battery Rating kWh	Range of Attribute Values		
					Cost \$/kWh	EENS %	CO2 kg/year
G3	30000	5000	500	500	0.1253 - 0.1309	1.4362 - 1.8062	158202 - 183309
G4	30000	5000	500	1000	0.1278 - 0.1335	1.4335 - 1.8062	156757 - 182805
G5	30000	5000	600	500	0.1283 - 0.1319	0.4471 - 0.6511	161328 - 186939
G6	35000	5000	500	500	0.1304 - 0.1356	1.1889 - 1.5124	147951 - 171579
G7	35000	5000	500	1000	0.1329 - 0.1390	1.1861 - 1.5124	146506 - 171075

It is shown that plan G3 is preferred because reducing the cost of energy production is the dominant design objective. But, plan G5 or plan G6 can be selected as the best solution if the DM considers that improved system reliability index (in plan G5) or reduced CO₂ emission (in plan G6) is more important than the low cost advantage associated with plan G3. Plans G4 and G7 follow closely behind plans G3 and G6, respectively.

The third step is to determine the expected performance for each design strategy. Probabilistic analysis models, which combine utility functions and a decision tree modeling approach for handling multi-attribute planning under uncertainty, are used to evaluate candidate design alternatives. Let's assume that uncertainties are modeled with discrete probability distributions. Since probability distribution assignment is a subjective matter, instead of assigning a single set of values, it is better to conduct the probabilistic analysis by investigating the solution mapping space for a range of probability distributions [167]. Now, let's examine the expected performance of robust plans under five specified probability distributions. The base case assumes an equal chance, i.e. 0.25 for each future condition, while in the other four cases, Case-1 through Case-4, one future is assumed twice as likely to occur as the other three futures. For example, in Case-1, a probability value 0.40 is allocated to future A, and other three futures are assigned a value of 0.20 each. Table 4-8 shows the results of probabilistic analysis.

Table 4-8. Expected Performance of Robust Plans

Plan No.	Base Case	Case-1	Case-2	Case-3	Case-4
G3	0.3954	0.4029	0.3863	0.3896	0.4026
G4	0.4661	0.4718	0.4573	0.4709	0.4641
G5	0.4588	0.4626	0.4491	0.4630	0.4605
G6	0.4595	0.4626	0.4488	0.4634	0.4632
G7	0.5302	0.5315	0.5198	0.5447	0.5247

It is shown that plan G3 is more attractive than other candidate alternatives, while plans G4 and G7 seem non-competitive with others in expected performance of design strategy, in view of their consistent rankings. Also the preference order between plan G5 and plan G6 can change under different future conditions.

Flexibility Measure

Using the flexibility cost calculated during the production costing simulation and the base case assuming an equal chance (i.e. 0.25) of each future condition, total flexibility cost for each of the attributes can be calculated using Equations (3-16), (3-17), and (3-18). Value of composite distance of flexibility cost is calculated for every robust plan using equation (3-2), which rewritten for this case study as (4-2). The ranking is based on the flexibility cost composite distance. Table 4-9 shows the results.

Table 4-9. Flexibility of Alternative Robust Plans

Plan No.	Wind Area m ²	Solar Area m ²	Substation Rating KW	Battery Rating kWh	Flexibility Cost			
					Cost \$/kWh	EENS %	CO ₂ kg/year	Ranking
G3	30000	5000	500	500	0.00502	0.30285	20544	5
G4	30000	5000	500	1000	0.00465	0.30265	21216	4
G5	30000	5000	600	500	0.00442	0.16782	20956	1
G6	35000	5000	500	500	0.00425	0.26257	19351	2
G7	35000	5000	500	1000	0.00442	0.29975	22493	3

The analysis of the global decision set considering flexibility cost produces the following observations.

- Plan G6 is regarded as the most flexible plan considering its cost and emissions, while plan G5 is the most flexible plan for its reliability. The overall flexibility performance ranking selects plan G5 as the most flexible plan.
- Plan G3, which is considered as the most robust plan, is the least flexible plan among all robust alternatives. Plan G3 is shown to have the most expensive flexibility cost among the alternatives.

The next step is to examine the expected performance of flexible plans under five specified probability distributions. The base case assumes an equal chance (i.e. 0.25 to each future condition), while in the other four cases, Case-1 through Case-4, one future is assumed twice as likely to occur as the other three futures, the same as when measuring robustness. Table 4-10 shows the results of probabilistic analysis.

Table 4-10. Expected Performance of Flexible Plans

Plan No.	Base Case	Case-1	Case-2	Case-3	Case-4
G3	0.76074	0.60859	0.66922	0.82088	0.94426
G4	0.73626	0.58901	0.65107	0.74497	0.96001
G5	0.61288	0.49030	0.54183	0.62537	0.79401
G6	0.66180	0.52944	0.58475	0.67027	0.86273
G7	0.72536	0.58029	0.64476	0.75880	0.91761

It is shown that plan G5 is more attractive than other candidate alternatives, followed by plan G6, while plans G3 and G7 are less consistent in their performance ranking compared to other design strategies. Also, the preference order between plan G4 and plan G7 can change under different future conditions.

The following observations can be made in deciding the “optimal” design strategy of HSWPS with and without considering the flexibility measure.

- Considering the robustness measure only (Table 4-6), five acceptable plans are given, and plan G3 is considered as the most robust plan. Adding the flexibility measure among the robust alternatives (Table 4-9) shows plan G5 as the most flexible plan.
- Robust plan G3 reflects a middle design attitude towards utilizing wind and solar technologies and emphasizes the importance of adequate storage capacity and grid supply, while flexible and robust plan G5 reflects the same attitude with more commitment to grid connection compared to plan G3.

Risk Exposure Measure

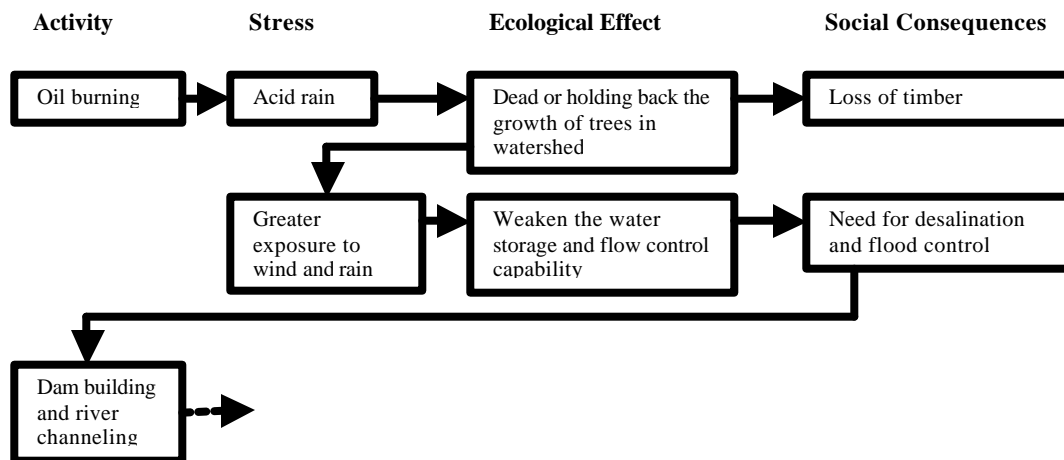


Figure 4-5. Consequences Exposure from Oil Burning

In this example problem, consequences of exposure are evaluated for a grid connection, based on substation rating in kW, assuming that the main contribution is from oil burning in a conventional power plant. Consequences of exposure can be divided into three groups: nature stress, ecological effects, and social consequences. The following Figure 4-5 shows the interconnection between the human activity “oil burning” and its exposures, which will lead to other activities.

The following is a listing of the consequences of ecological amenities loss borne by society [58].

- Depend more on industrial fertilizers, pesticides and herbicides for agriculture (1)
- Depend more on irrigation water for agricultural (1)
- Depend more on wilderness lands for agricultural (1)
- Depend more on desalination or other treatment of water (2)
- Depend more on erosion and flood control measures (2)
- Depend more on artificial climate control (air conditioning, humidifying, etc) (3)
- Content with greater fluctuations and decrease in foods supply (1)
- Content with odors and other aesthetic affronts (5)
- Content with increased incidence of diseases and epidemics of harmful pests (4)
- Content with more unpleasant weather (3)
- Content with poorer air quality (3)
- Content with poorer water quality or reduced water quantity (2)
- Content with reduced natural variety/diversity (6)
- Content with fewer options for future innovation and improvement of life (6)
- Content with increased ecosystem instability (6)
- Content with greater vulnerability to fire or flood (5)

The above consequences to society can be grouped in the agricultural, water, climate, health, living place, and ecosystem categories, as shown in Figure 4-6.

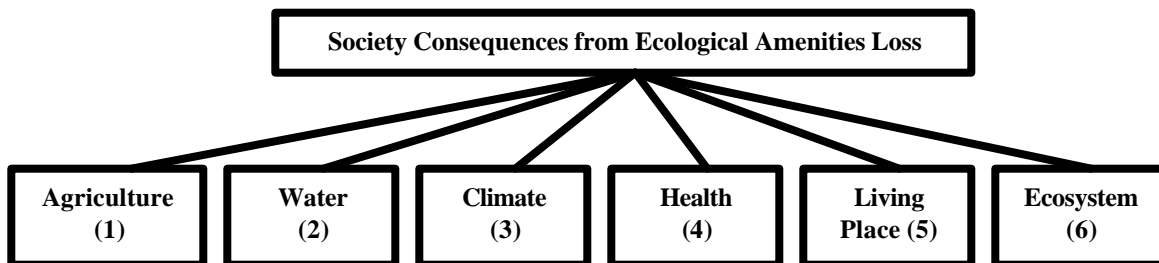


Figure 4-6. Society Consequences of Substation Rating

Then, the risk exposure of social consequences from the substation rating can be identified using subjective expert judgments of the DM. The judgment matrix [A] is formed as indicated below.

$$[A] = \begin{bmatrix} 1 & 1/3 & 1/5 & 3 & 5 & 1/5 \\ 3 & 1 & 5 & 3 & 5 & 7 \\ 5 & 1/5 & 1 & 1/3 & 1/3 & 3 \\ 1/3 & 1/3 & 3 & 1 & 3 & 5 \\ 1/5 & 1/5 & 3 & 1/3 & 1 & 3 \\ 5 & 1/7 & 1/3 & 1/5 & 1/3 & 1 \end{bmatrix}$$

Table 4-11. Consequence Measures

No.	Consequence measure	Weight	Range
1	Number of major systems components	1/24	0-50
2	Percent of major components successfully deployed in installation	1/24	0-100
3	Area of land required (in thousands of meter squared)	1/12	0-50
4	Number of regulations that apply	1/12	0-50
5	Years of plant expected in operation	1/16	0-40
6	Score = probability X consequence Probability = 0.1 X years in operation when time ≤ 10 years, else = 1 Consequence = number of system breakdown when system breakdown < 10 times, else = 10	1/16	0-10
7	Score = probability X consequence Probability = 0.1 X major system components when ≤ 10 components, else = 1 Consequence = number of system breakdown when system breakdown < 10 times, else = 10	1/16	0-10
8	Amount of carbon emissions (in kg/kWh)	1/48	0-100
9	Qualitative ranking based on level of harm imposed on wildlife surrounding the site, 0 indicates that a protected species is endangered while 10 indicate that no wildlife is affected.	1/48	0-10
10	Qualitative ranking based on level of harm imposed on plants surrounding the site, 0 indicates that a protected species is endangered while 10 indicate that no plants are affected.	1/48	0-10
11	Percent of reduction in fertilizer use for agriculture	0.0236	0-100
12	Percent of reduction in food supply	0.0236	0-100
13	Percent of reduction in wilderness land use for agriculture	0.0236	0-100
14	Percent of reduction in flood control to avoid erosion	0.0855	0-100
15	Percent of reduction of poorer water quality	0.0855	0-100
16	Percent of reduction of poorer air quality	0.0700	0-100
17	Percent of reduction of epidemic diseases	0.0840	0-100
18	Percent of reduction of fire hazards	0.0525	0-100
19	Percent of increased of natural diversity	0.0259	0-100
20	Percent of reduction of the ecosystem instability	0.0259	0-100

Solving the eigenvalue problem from the above judgment matrix gives the normalized eigenvector (weights) $w = [0.1416, 0.3420, 0.1400, 0.1680, 0.1050, 0.1036]$. The values indicate the weighting factors for Agriculture, Water, Climate, Health, Living Place, and Ecosystem, respectively. The results of uncertainty weighting factors show the importance of Water considerations, followed by Health and Agricultural issues.

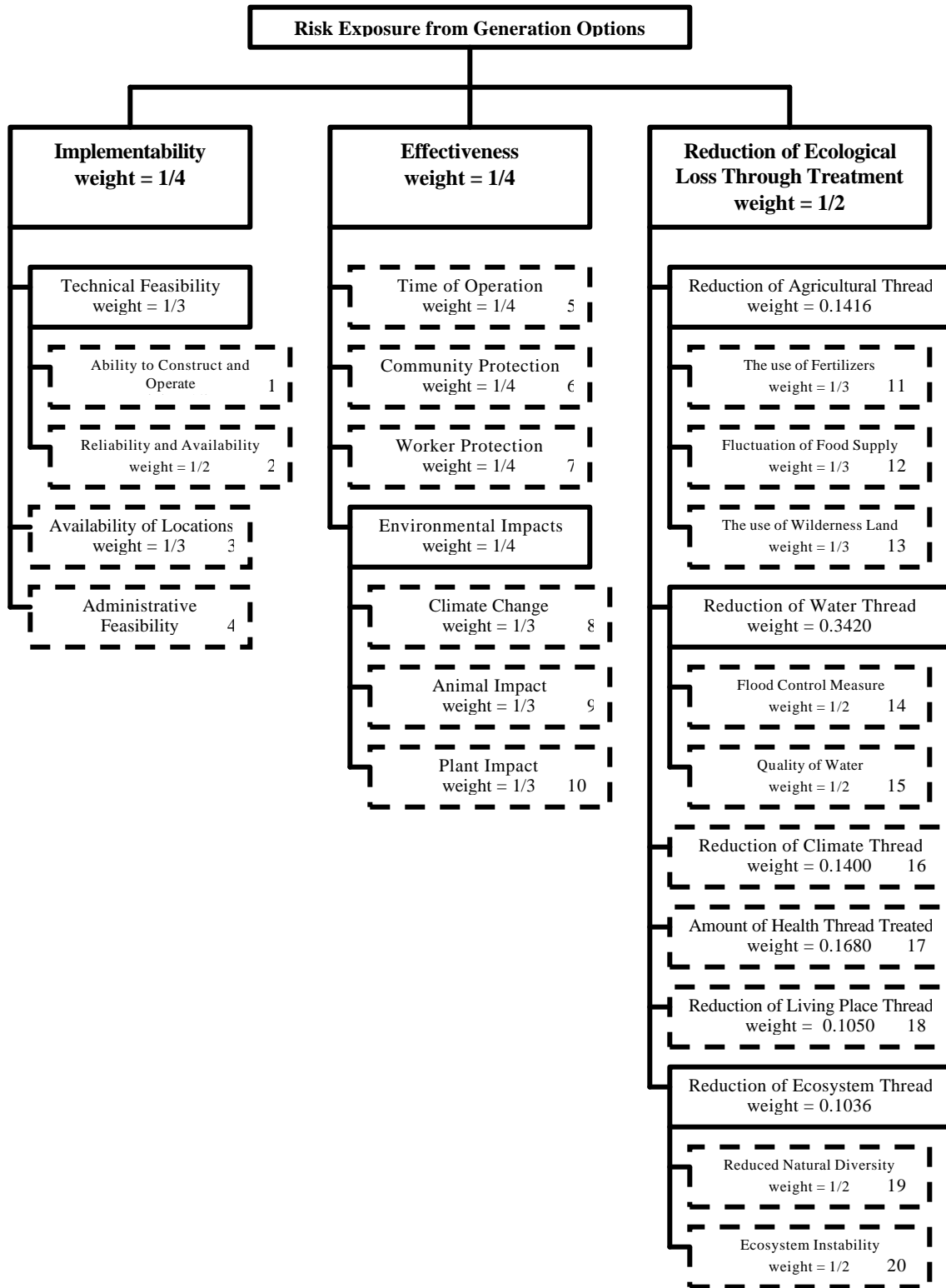


Figure 4-7. Criteria Hierarchy of Consequence Measure

Let us assume that the risk exposure for all types of generation technologies involved in this case study (oil, solar, wind, and battery) are assessed using the criteria governed by their implementability, effectiveness [46], and their treatment efforts to reduce ecological loss, as defined previously. Weights from the above judgment matrix are assigned to the appropriate reduction of ecological loss through treatment efforts, while consequence measures related to implementability and effectiveness are given the equal local weights. Following the process of assigning local weights, global weights are calculated for each of the consequence measures by multiplying the local weights as shown in Table 4-11. Figure 4-7 shows the criteria hierarchy of the consequence measures.

Table 4-12. Score Value for Generation Options

Consequence measure No.	Wind	Solar	Grid (Oil)	Battery
1	27	10	48	5
2	90	90	90	90
3	[m ²]/1000	[m ²]/1000	0.05*[kW]	0.001*[kWh]
4	20	15	45	10
5	30	20	40	5
6	2.7	1	4.8	0.25
7	2.7	1	4.8	0.25
8	0	0	5	0
9	5	5	10	0
10	5	5	10	0
11	0	0	100	0
12	0	0	100	0
13	0	0	100	0
14	0	0	100	0
15	0	0	100	0
16	0	0	100	0
17	0	0	100	0
18	0	0	100	0
19	0	0	100	0
20	0	0	100	0

For each scenario alternative, the overall value expressed by Equation (3-19) is calculated with the value functions for each generation option obtained by asking the DM's preference for certainty equivalent values, as is done for single utility function determination. In this case study, a linear function is used, and the overall value can be expressed as in Equation (4-3). The score values used for each generation option or technology type are listed in Table 4-12.

$$\begin{aligned}
 V(x) = & w_{wind} \left(\sum_1^{20} w_i v_i(x_i) \right)_{wind} + w_{solar} \left(\sum_1^{20} w_i v_i(x_i) \right)_{solar} \\
 & + w_{oil} \left(\sum_1^{20} w_i v_i(x_i) \right)_{oil} + w_{battery} \left(\sum_1^{20} w_i v_i(x_i) \right)_{battery}
 \end{aligned} \tag{4-3}$$

The weights $[w_{wind}, w_{solar}, w_{oil}, w_{battery}]$ are obtained from technology priority assessment, taking into account the cost-to-benefit ratios for each generation option, calculated separately from costs influencing the technology and benefits influencing the technology [9]. Figure 4-8 and Figure 4-9 show the costs and benefits hierarchies, respectively, for the technology priority assessment.

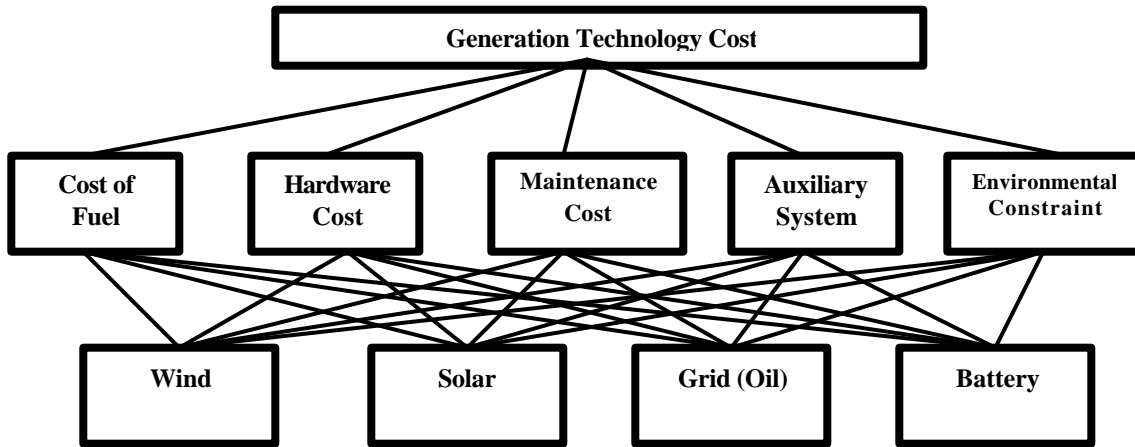


Figure 4-8. Costs Hierarchy for Technology Priority Assessment

The hierarchical structure consists of three layers, from the main goal down to the costs influencing the technology, then the technology or objectives. The resulting global priority vector based on given judgment matrices as in Appendix B2 indicates that grid (oil) technology is ranked first (0.3479), followed by wind (0.3159) then solar (0.2469) and battery (0.0895).

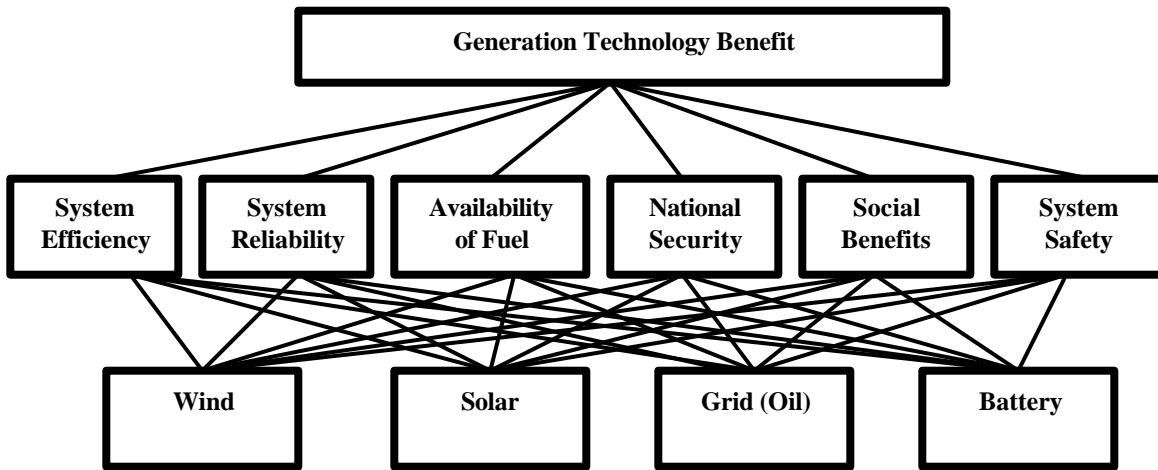


Figure 4-9. Benefits Hierarchy for Technology Priority Assessment

The hierarchical structure consists of three layers, from the main goal to the benefits influencing the technology, and finally the technology or objectives. The resulting global priority vector based on given judgment matrices as in Appendix B3 indicates that solar technology is ranked first (0.4114), followed by wind (0.2976), then battery (0.1935) and oil (0.0976).

The relative cost-to-benefit ratio of the selected technologies is constructed from both of the hierarchies. The resulting relative weights indicate that fossil fuel (oil) ranks the highest (0.6266), followed by wind (0.1866), then solar (0.1055) and battery (0.0813). Figure 4-10 shows the comparison of cost, benefit, and relative cost-to-benefit ratios.

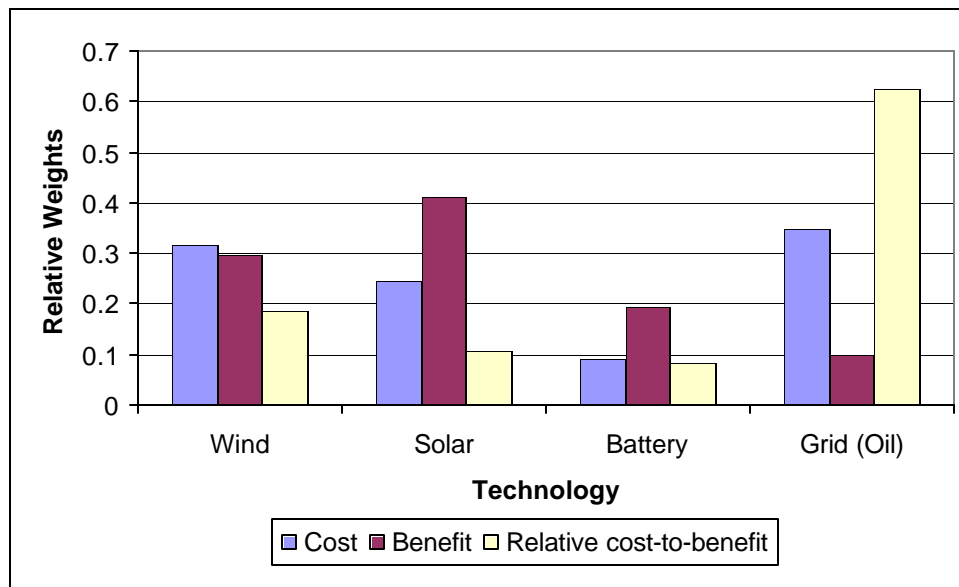


Figure 4-10. Comparisons of Costs, Benefits, and Cost-to benefit ratios

Table 4-13 shows the risk exposure for all the robust alternatives, calculated using Equation (4-3).

Table 4-13. Risk Exposure of Alternative Robust Plans

Plan No.	Wind Area m2	Solar Area m2	Substation Rating kW	Battery Rating kWh	Risk Exposure	Ranking
G3	30000	5000	500	500	0.60509	1
G4	30000	5000	500	1000	0.60516	2
G5	30000	5000	600	500	0.61031	5
G6	35000	5000	500	500	0.60664	3
G7	35000	5000	500	1000	0.60671	4

It is shown that plan G5 is less attractive than other candidate alternatives, while plan G3 ranks as the most attractive, followed by plans G2, G6 and G7.

The following observations can be made in deciding the “optimal” design strategy of HSWPS, considering robustness, flexibility and risk exposure measures.

- Robustness measure favors any plan, which has “fixed” design variables and is able to cope with a “moving” environment. It is shown that plan G3 performs well for these criteria.
- Flexibility measure favors any plan that has the minimum “moving” design variable costs and is able to cope with “moving” environment. It is shown that plan G5 performs well for these criteria.
- Risk exposure measure favors any plan, which has “moving” design variable priority, based on subjective judgment, and is able to cope with “any” environment. It is shown that plan G3 performs well for these criteria.

5. Limited Resources Case Study

The decision of what type of generation needs to be utilized for a given area depends on the availability, security and reliability of resources in that area. An area that has limited resources will present options that require the DM to choose in stages, thereby increasing the flexibility measures of the outcome.

This chapter discusses a case study in Malaysia. It is meant to show the implementation of the methodology in a real-world application. It covers the Third Outline Perspective Plan 2001-2010 in energy sector and sustainable development [79], the Eighth Malaysian Plan 2001-2005 in energy sector, environmental and sustainable resource management [78], the existing framework of decision-making in the energy sector, the application of the Efficient Resource Development Methodology to this case study, and the comparison of results.

5.1. The Third Outline Perspective Plan

The Third Outline Perspective Plan (OPP3) of Malaysia consists of a ten-year plan from 2001-2010 and marks the second stage in realizing Vision 2020 (making Malaysia a developed country by the year 2020) that started in 1991. The following selected strategies have been listed for the energy sector:

- Ensuring the competitiveness of the economy using sustainable development by managing both depletable and renewable energy resources in the following ways:
 - To ensure an adequate, secure, high quality, and cost-effective supply of energy
 - To promote its efficient utilization
 - To minimize the negative impact on the environment
- Increasing oil stock from deep-sea exploration locally, and prospecting for resources overseas to overcome the shortage of oil reserves by 2008.
- Increasing the utilization of gas in the power sector due to increased availability of gas in Peninsular Malaysia with the following considerations:
 - To ensure system security and reliability using an optimal generation mix
 - To consider and intensify utilization of gas by the non-power sector as well, such as the transport sector and petrochemical industries
- Emphasizing the adequacy of electricity supply and improving its productivity and efficiency in the following ways:
 - To encourage new private investments and co-generation systems
 - To improve coverage, reliability and quality of supply through transmission and distribution system improvements
 - To improve the frequency limit and reactive power requirement in The Malaysian Grid and Distribution Codes
 - To establish an Energy Commission to regulate the technical and economic efficiencies of the electricity supply industry
- Encouraging new sources of energy such as renewables to supplement the conventional supply of energy in the following ways:

- To extend the fuel diversification policy from four fuels comprising oil, gas, hydro, and coal to a five-fuels policy that includes renewable energy, *i.e.* biomass, biogas, municipal waste, solar, mini-hydro, palm diesel and hydrogen fuel
- To widen the use of biomass resources in particular, such as oil palm, wood waste and rice husks for electricity generation
- Encouraging efficient utilization of energy through the enforcement of the Energy Efficiency Regulations and implementation of Demand Side Management, in the following ways:
 - To implement retrofitting programs, district cooling programs, and appliance labeling and to change the energy usage pattern
 - To establish new integrated complexes and townships that are managed in an energy-efficient manner
 - To formulate standards on efficient lighting, air-conditioning, and building envelope systems
 - To incorporate energy efficiency provisions into Uniform Building By-laws
- Promoting the development of domestic energy related industries and services to achieve a higher local content in energy sector, by the following initiatives:
 - To introduce the Entrepreneur Development Programs undertaken by *Tenaga Nasional Berhad* (TNB) and the Vendor Development Programs by *Petroleum Nasional Berhad* (PETRONAS)
 - To promote Malaysia as a regional center for energy-related engineering services
 - To urge major companies and independent power producers, to expand their participation in energy-related industries and services in other countries

OPP3 also promotes environmentally sustainable development, to ensure that the environment is clean, healthy, productive, and capable of sustaining the nation's needs and aspirations. Emphases on four major areas are proposed, as outlined in the following sub-chapters. These major areas become the background of the decision makers in energy planning, particularly for generation expansion planning schemes.

5.1.1. Integrated Approach and Strategies

Addressing environmental and resource issues is done in an integrated and holistic manner. The challenge is to identify prudent, cost-effective, and adaptive management approaches that result in multiple benefits for a sustainable future, such as:

- Providing access to clean water
- Providing adequate food without excessive use of chemicals
- Using more organic fertilizers
- Providing energy services without environmental degradation
- Developing healthy urban environments
- Conserving critical natural habitats and resources

Land resources are further improved through integrative land-use planning. The Biodiversity Policy is the basis for integrating and consolidating biodiversity programs and projects in the country. Specifically, the policy promotes intensified efforts to sustain forests and expand multiple use forestry, formulate integrated river basin

management plans to improve water quality and supply, manage water resources, ensure sustainability of coastal resources, and introduce integrated coastal management plans in all states.

5.1.2. Reducing Pollution Intensity

Reduction of energy and materials usage, pollution, and waste intensity in the urban-industrial environment is becoming a critical activity. Measures are being implemented to influence choices in technology and management of new urban and industrial investment, such as steps to promote the reduction, re-use and recycling of materials. A policy of '*pollution-free and reduced-resource intensity*' for technology is one step further than the existing policy on controlling pollution at the source and adopting preventive measures in a process of continuous improvement.

5.1.3. Increased Use of Economic Instruments

The Polluters Pay Principle has been initiated with enforcement efforts to ensure compliance with environmental laws and regulations. In addition, these measures are complemented by the use of innovative economic and tax instruments, *i.e.* removal of distortions and barriers that impede efforts toward improving environmental quality and optimal natural resource use.

5.1.4. Environmental Performance Standards

Environmental performance measurement is encouraged as a basis for harnessing market forces and community engagement in addressing environmental issues. Environmental and resource issues need to be identified, measured, and tracked through the use of sustainable development indicators and various environmental standards. Then, the environmental intensity of economic activity becomes more efficacious in forcing the market, and society at large, through customer demand, community pressure, and supply-chain management.

5.2. The Plan on Energy, Environment and Resource

The five years of the Eighth Malaysian Plan (2001-2005) focus on ensuring the sustainable development of energy resources, both depletable and renewable, in support of the development of a knowledge-based economy. Efforts are made to ensure adequacy, quality and security of energy supply, to encourage larger utilization of gas and renewable energy, to provide adequate electricity generating capacity, and to support the development of industries that produce energy-related products and services.

The plan also addresses the environmental and resource management issues in an integrated manner to identify prudent, cost-effective, and appropriate management approaches. Efforts are made to address air pollution, to mitigate degradation of rivers, to improve marine and groundwater quality, and to deal with waste in a comprehensive manner.

To address the issue of natural resources, the following strategy has been proposed: strengthening land use planning, extending the Biodiversity Action Plan to the various states, expanding the sustainable management of forests, and addressing multiple-use issues in marine areas. Efforts are made to promote environmental performance measurements, promote market-based instruments, and engage communities in addressing environmental and natural resource issues.

5.2.1. Energy

The main objective in the energy sector is to maintain its sustainable development. The focus is on ensuring an adequate, secure, high-quality and cost-effective supply of energy, promoting its efficient utilization, and minimizing negative impacts on the environment. The quality of electricity supply is becoming more crucial as the promotion of high technology and Information and Computer Technology (ICT) driven manufacturing is increasing. The strategies of the energy sector are as follows:

- Ensuring adequacy and security of fuel supply and promoting the utilization of gas and renewable energy
- Ensuring adequacy of electricity supply and improving productivity and efficiency
- Developing energy-related industries and services, and increasing local content
- Promoting centers for energy-related engineering services and making them known regionally
- Encouraging efficient utilization of energy in the industrial and commercial sectors

5.2.2. Environment and Sustainable Resource Management

Two major challenges for the government are to attain the national environmental and natural resource goals efficiently and to reduce the negative environmental impact of development activities. Steps are taken to identify and implement sensible, cost-effective, and appropriate management approaches, such as ensuring access to clean air and water, providing adequate food without excessive use of chemicals, providing energy services without environmental degradation, developing healthy urban environments, and conserving critical natural habitats and resources. The strategic policy thrusts for environmental and sustainable resource management are as follows:

- Reducing energy, materials, pollution, and waste intensity of urban industrial activity to address air pollution and waste disposal and to mitigate deterioration in water quality
- Promoting the use of appropriate market-based instruments and self-regulatory measures among industries
- Promoting environmental performance measurement and strengthening the database for environmental decision-making
- Empowering local authorities and engaging communities in addressing environmental issues
- Enhancing land use planning, intensifying biodiversity conservation, the sustainable management of forests, and improving the management of maritime affairs

5.3. The Existing Decision Framework

Energy is the key ingredient in any economic activity. Adequacy of energy supply is important for acceleration of economic development. Consumption of energy, however, produces some undesirable impacts on the environment and climate. Hence, sustainable use of energy is being given increasing attention. Malaysia is gifted with both conventional (non-renewable) and non-conventional (renewable) sources of energy. The largest non-renewable energy resource is petroleum (i.e. oil and gas). This resource is being actively exploited. Although the country has some coal deposits, only a small percentage is being mined. Renewable sources of energy are also abundant, the most important ones being biomass and solar.

Energy consumption per capita is low compared to any developed countries but is expanding at a rapid rate in tandem with economic development. In addition, energy intensity with respect to gross domestic product has shown an increasing trend historically. For more information on energy resources and the energy balance of Malaysia, one may refer to the Energy Center Malaysia (Pusat Tenaga Malaysia - PTM) website [80] or Department of Energy (EIA) website [142].

Among the principal functions of the Energy Division of the Ministry of Energy, Communications & Multimedia [74, 75] are to formulate policies and strategies, undertake planning of the electricity supply industry, promote energy efficiency and renewable energy, and monitor energy programs and project implementation. Therefore, this division of the government plays a very important role in the process of energy sector decision-making. The following sections show the interaction of the energy planning decision makers and the policies that have been implemented.

5.3.1. Energy Industry Players

The players in the energy sector (i.e. electricity supply industry and gas supply industry at the reticulation stage) are as follows:

- The Government and Energy Commission (G-EC), which acts as a policy maker and regulator
- Energy Supply and Service Companies (ESSC)
- Research and Development Institutions (RDI)
- Consumers

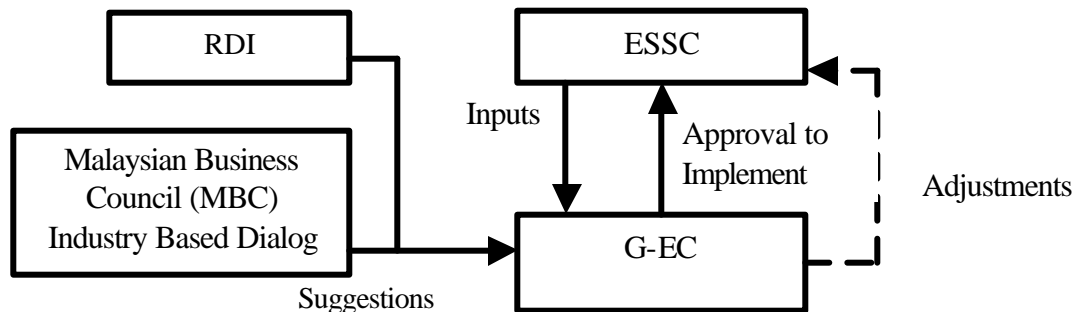


Figure 5-1. The Planning Decision Flow Diagram

The Economic Planning Unit (EPU) under the Prime Minister's Department and other related departments representing the Government are given the authority to decide the direction of energy planning. The input from utility companies is either adjusted or approved by the Government as shown in Figure 5-1. More detail explanations are found in the EPU website [73]. The following sub-sections describe the role and scope of each player.

The Government

Policy making for the energy sector resides with the institutions as shown in Table 5-1 and the economic and technical regulatory functions reside with the institutions as shown in Table 5-2.

Table 5-1. Malaysian Government Decision Makers in Energy Policy

Institutions	Areas of Jurisdiction
Prime Minister's Department (Economic Planning Unit) (www.epu.jpm.my)	<ul style="list-style-type: none"> • Petroleum (oil and gas) • Privatization of the electricity supply industry i.e. IPPs
Ministry of Energy, Communications and Multimedia (MECM) (www.ktkm.gov.my)	<ul style="list-style-type: none"> • Electricity supply industry • Energy efficiency • Renewable energy
Ministry of Rural Development (www.kplb.gov.my)	<ul style="list-style-type: none"> • Rural electricity supply.
Ministry of Primary Industry (www.kpu.gov.my)	<ul style="list-style-type: none"> • Domestic exploitation of coal resources.

Table 5-2. The Economic and Technical Regulatory Functions

Institutions	Areas of Jurisdiction
Energy Commission (www.st.gov.my)	<ul style="list-style-type: none"> • Electricity in all states except Sarawak (technical including safety and economic) • Gas reticulation only (safety and economic)
Department of Occupational Health & Safety	<ul style="list-style-type: none"> • Safety in gas sector (at reticulation stage) • Safety in oil sector (up stream and down stream).
Prime Minister's Department Economic Planning Unit	<ul style="list-style-type: none"> • Natural Gas prices.
Ministry of Domestic Trade & Consumer Affairs	<ul style="list-style-type: none"> • Price of petroleum products.
State Governments	<ul style="list-style-type: none"> • Exploitation of coal resources.
Ministry of International Trade and Industry (www.miti.gov.my)	<ul style="list-style-type: none"> • Licensing on petroleum processing activities.

Energy Supply and Services Company

Energy supply and services companies are divided into the following two categories:

- Petroleum – Oil and Gas Industry: Petronas with 15 other petroleum companies that had entered into Production Sharing Contracts.
- Electricity Supply Industry: Tenaga Nasional Berhad (TNB), serving Peninsula Malaysia, Sabah Electricity Sdn. Bhd. (SESB), Sarawak Electricity Supply Corp. (SESCo), and Kedah's Northern Utility Resources (NUR), with other IPPs and about 30 co-generators.

Research & Development Institutions

There are several R&D institutions in Malaysia involved in both scientific and economic research.

- Malaysian Energy Center - Pusat Tenaga Malaysia (PTM) is involved in energy planning and research, energy efficiency and technological research, development and demonstration. It is a one-stop energy agency for linkages with the universities, research institutions, industries, and other national and international energy organizations.
- TNB Research (TNBR) undertakes R&D activities for TNB. It provides quality assurance, laboratory testing, and consultancy services in energy and environment preservation for TNB and other energy suppliers.
- Petronas Research Scientific Services (PRSS) undertakes R&D activities for the petroleum industry.
- SIRIM Berhad (SIRIM) is involved in R&D activities for the industrial sector in the energy field of, with a focus on renewable energy and energy efficiency.

5.3.2. Energy Industry Policy

National Energy Policy

Three principal energy objectives are instrumental in guiding future energy sector development [76]. They are:

- The Supply Objective: To ensure the provision of adequate, secure, and cost-effective energy supplies through developing indigenous energy resources, both non-renewable and renewable, using the least-cost options and diversification of supply sources within and outside of the country;
- The Utilization Objective: To promote the efficient utilization of energy and to discourage wasteful and non-productive patterns of energy consumption;
- The Environmental Objective: To minimize the negative impacts of energy production, transportation, conversion, utilization and consumption on the environment.

National Objectives Strategies

To achieve the national objectives in energy planning, the Government is pursuing the following strategies [77]:

- Secure supply: Diversification of fuel type and sources, technology, maximize use of indigenous energy resources, adequate reserve capacity to allow for contingencies, adequate reserve margin for generation, upgrading of transmission and distribution networks, and distributed generation (islanding).
- Sufficient supply: Demand forecast, correct energy pricing, and formulation of plans to meet demand.
- Efficient supply: Promoting competition in the electricity supply industry.
- Cost-effective supply: Promoting competition and providing indicative supply plan to meet demand based on a least-cost approach, using computer software for electric power such as WASP.
- Sustainable supply: Promoting the development of renewable energy and co-generation whenever possible.
- Quality of supply (low harmonics, no surges and spikes, minimal voltage variation): Matching quality with customer demand with variable tariffs.
- Efficient utilization of energy: Benchmarking, auditing, financial and fiscal incentives, technology development, promotion of Energy Service Companies (ESCOs), labeling, ratings, correct pricing, energy managers.
- Minimizing Negative Environmental Impacts: Monitoring impacts, improving the efficiency of utilization and conversion, and promoting renewable energy.

Rural Electrification

By the year 2005, 96% of rural households in Malaysia are served with electricity as shown in Table 5-3.

Table 5-3. Rural Electrification Coverage by Region 1990-2000

Region	1990	1995	2000	2005
Peninsular	91	99	100	100
Sabah	48	65	75	84
Sarawak	50	67	80	91
Malaysia	80	92	93	96

Renewable Energy Resources

In the Eighth Malaysian Plan, renewable energy (RE) is introduced as the fifth fuel in the new five-fuel strategy in the energy supply mix. It is targeted that RE will meet 5% of the country's total electricity demand by the year 2005, the end of the Plan period. With this objective in mind, greater effort is being undertaken to encourage the utilization of renewable resources for energy generation, such as biomass, biogas, solar, and mini-hydro.

A program aimed at increasing public awareness of the positive attributes of RE and energy efficiency (EE) measures is being carried out by the Center for Education and

Training in Renewable Energy and Energy Efficiency (CETREE), University Science Malaysia, Penang. The government is currently working on “hands-on” applications of RE with a number of ongoing projects.

A recent RE study identified the renewable energy resource potential in the country, including forest residues, palm oil biomass, solar thermal, mill residues, hydro, solar PV, municipal waste, rice husks, and landfill gas. Palm oil waste has been identified as the biggest resource that can be easily developed. Solar is another important option, particularly for rural electrification and water heating.

Planting-Up Program

Due to the long lead-time for energy projects to come on-stream, long-term planning is vital. Planning and the planting-up program for the electricity supply industry are discussed and evaluated by the Committee for Planning, Implementation for the Supply of Electricity and Tariffs. The Minister of Energy, Communications and Multimedia Malaysia chairs this committee, comprising representatives from the Ministry of Energy, Communications and Multimedia, Economic Planning Unit, Prime Minister's Department, Energy Section, Ministry of Finance, Ministry of International Trade and Industry, Malaysian Industrial Development Authority, PETRONAS, and TNB

Energy Programs

The following are some of the programs related to the policy on energy.

- Center for Education and Training for Renewable Energy and Energy Efficiency (CETREE).
- Project on Capacity Building in Integrated Resources Planning (IRP) at Government and related agencies.
- MECM's Low Energy Office (LEO) Project.
- Small Renewable Energy Program (SREP).
- Demand Side Management (DSM) Project.

5.3.3. Results from the Planning Program

The energy commission and other related institutions in the planning committee have produced the planned generation output for ten years 2001 – 2010 [91], which its summary is listed as in Table 5-4.

Table 5-4. The Planned Generation 2001-2010

Oil MW	Coal MW	Gas MW	Hydro MW	Solar MW	Biomass MW	Nuclear MW	Cost RM/kWh	CO2 ton/year	Efficiency %
0	5600	5656	3000	200	520	0	0.36	79,178,136	0.3179

5.4. Implementation using The Methodology

5.4.1. Problem Formulation

The main goal of the study is to increase the self-sufficiency level with respect to energy supply and energy technology requirements under limited resources conditions. The country under study has six energy sources: oil, coal, gas, hydro, solar and biomass. Nuclear energy can be added as an option regardless of its no-support status from the national policy. The wind energy source has limited availability due to the low wind speed throughout the country. Three objectives are considered in the selection of the suitable energy sources: minimization of cost and emissions and maximization of overall efficiency. The overall efficiency is defined as the total energy output (in Joules) divided by the total energy input (in Joules). The total energy output is the total capacity of all the generation types, while the total energy input is the sum of each generation type's output divided by its efficiency.

5.4.2. Identification of Attributes

Constraints and policies options are identified for three design objectives (attributes), and the AHP technique is used for attribute priority assessment. These constraints and policies options are deduced according to the brief explanation given in the previous sections. Figure 5-2 shows the hierarchy for the attribute priority assessment.

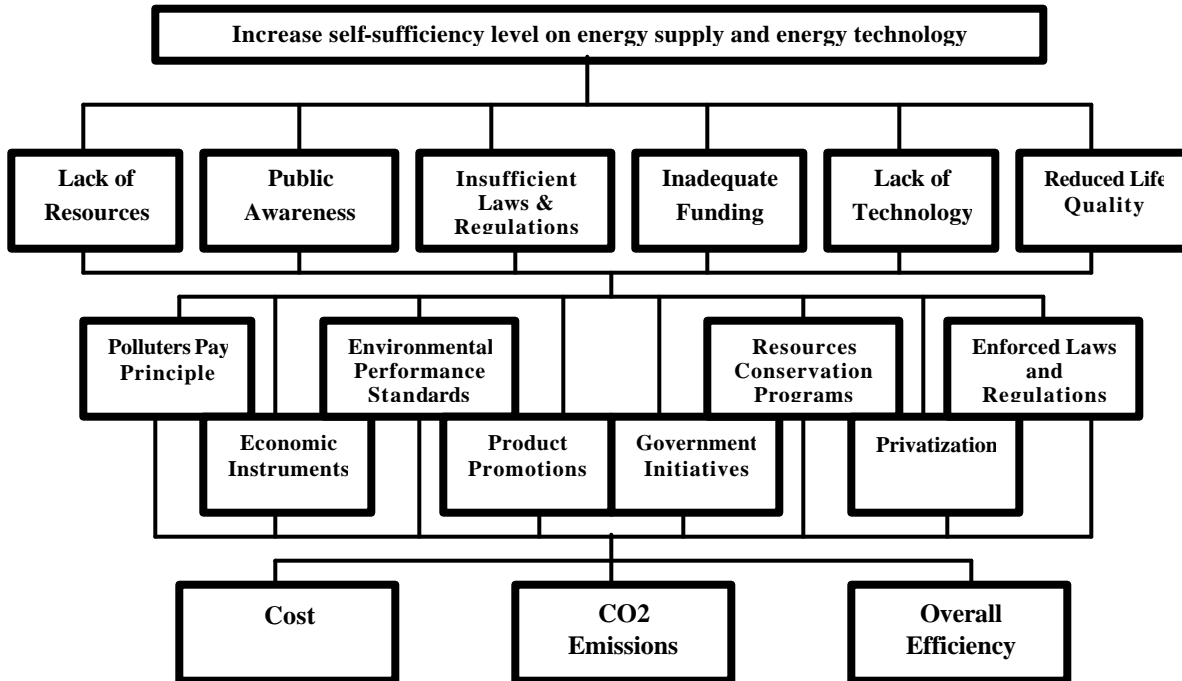


Figure 5-2. Limited Resource Hierarchy

The four layers of the hierarchical structure start with the main goal, then the constraints, then address the policies affecting the constraints, and finally the attributes. Starting from second layer of the hierarchy, ratio questions are asked of the DM concerning the relative

importance between each pair of factors at that layer with respect to each factor at the adjacent upper layer. The judgment matrices corresponding to each level are given in Appendix B4. The resulting global priority vector based on the given judgment matrices indicates that minimizing the cost of energy supply is ranked first (0.4498), followed by overall efficiency (0.3448) and then CO2 emissions (0.2053).

5.4.3. Identification of Options

Identification of options is based on the design variables oil plant capacity, coal capacity, gas capacity, hydro capacity, solar area, biomass quantity, and nuclear plant capacity.

5.4.4. Identification of Uncertainties

Table 5-5. Uncertainty Factors Detail

Category	Uncertainty Factors
Economic situation	PV cost (RM/m ²)
	Oil-plant cost (RM/MW)
	Coal-plant cost (RM/MW)
	Gas-plant cost (RM/MW)
	Hydro-plant cost (RM/MW)
	Biomass cost (RM/MW)
	Nuclear-plant cost (RM/MW)
	PV efficiency (%)
	Oil efficiency (%)
	Coal efficiency (%)
	Gas efficiency (%)
	Hydro efficiency (%)
	Biomass efficiency (%)
Nuclear efficiency (%)	
Resources Availability	Solar insolation (pu)
	Oil-supply (pu)
	Coal-supply (pu)
	Gas-supply (pu)
	Hydro-discharge (pu)
	Biomass supply (pu)
	Nuclear-fuel (pu)
Load growth	Load growth (%)

Uncertainty factors considered in this case study are economic situation, resources availability and load growth. Table 5-5 lists the detail of the uncertainty factors.

5.4.5. Selection of Plans

Design variables are Oil plant capacity (MW), Coal plant capacity (MW), Gas plant capacity (MW), Hydro plant capacity (MW), Solar area (m²), Biomass quantity (ton), and

Nuclear plant capacity (MW). The range and step of variation for each design variable are set, and from these 77,760 (=5x9x4x6x6x6x2) alternative plans can be generated. Table 5-6 shows the variation range and step of the selected design variables.

Table 5-6. Range and Step of Variation of the Design Variables

	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (m ²)	Biomass quantity (ton)	Nuclear capacity (MW)
Min	0	0	1500	500	0	800,000	0
Max	2000	5600	6000	3000	5,000,000	4,000,000	6000
Step	500	700	1500	500	1,000,000	640,000	6000

5.4.6. Selection of Futures

Table 5-7. Description of Selected Futures

Uncertainty Factors	Base	F1	F2	F3	F4
PV cost (\$/m ²)	350	350	350	350	350
Oil-plant cost (\$/MW)	846000	846000	846000	846000	846000
Coal-plant cost (\$/MW)	912000	912000	912000	912000	912000
Gas-plant cost (\$/MW)	698000	698000	698000	698000	698000
Hydro-plant cost (\$/MW)	913000	913000	913000	913000	913000
Biomass cost (\$/MW)	1602000	1602000	1602000	1602000	1602000
Nuclear-plant cost (\$/MW)	1623000	1623000	1623000	1623000	1623000
Solar insulation (pu)	1	1	1	1	1
Oil-supply (pu)	1	1	1	1	1
Coal-supply (pu)	1	1	1	1	1
Gas-supply (pu)	1	1	1	1	1
Hydro-discharge (pu)	1	1	1	1	1
Biomass supply (pu)	1	1	1	1	1
Nuclear-fuel (pu)	1	1	1	1	1
PV efficiency (%)	25	25	25	25	25
Oil efficiency (%)	40	40	40	40	40
Coal efficiency (%)	30	30	30	30	30
Gas efficiency (%)	50	50	50	50	50
Hydro efficiency (%)	90	90	90	90	90
Biomass efficiency (%)	4	4	4	20	20
Nuclear efficiency (%)	40	40	40	40	40
Load growth (%)	2.9	5.9	0.9	5.9	0.9

Descriptions of selected futures, accounting for the influences of uncertainty factors in economic situation, resources availability, and load growth are considered. The decision problem selects four futures for uncertainty modeling. The selected futures share base case assumptions in resource availability and economic factors but differ with each other in the load growth and biomass efficiency. The uncertainty in load growth in Malaysia for the past five years has become a major decision factor in forecasting for the next ten years. Biomass technology development, with its uncertain conversion efficiency, is nevertheless likely to be a dominant renewable technology under government focus due to the abundant resource of palm tree waste in the country. Table 5-7 shows the description of selected futures.

5.4.7. Simulation Considering Flexibility

The two-stage process is selected, with each stage covering a five-year planning horizon. At the end of stage one, the DM will have to again make a decision on selecting the future. Stage one is the period of study from 2001-2005, and stage two is the period of study 2006-2010. The present value of flexibility “cost” is calculated from the amount of additional “cost” necessary for each plan to respond to the selected future at each stage. This “cost” refers to the costs of energy production, CO₂ emissions, and overall efficiency.

5.4.8. Calculation of Attributes Value

The next step is to calculate the single distance value for each of the attributes and flexibility costs. Its calculation can be done automatically after assigning the ideal solution for each attribute values, which enables the algorithm to calculate the normalized value of each attribute. The ideal values are zero for cost and emission and one for efficiency. In this case study, single distance value calculation is used instead of single utility function calculation due to its simplicity. It can be used to incorporate the DM’s inputs automatically without much difficulty, according to these equations:

$$U_d(r) = 0.4498r_1 + 0.2053r_2 + 0.3448r_3 \quad (5-1)$$

$$U_{dCr}(Cr) = 0.4498Cr_1 + 0.2053Cr_2 + 0.3448Cr_3 \quad (5-2)$$

where r_i and Cr_i are normalized attribute distance value and normalized flexibility distance value, respectively. The two equations (5-1) and (5-2) are use to determine the robustness and flexibility measures.

5.4.9. Decision Analysis

The tradeoff analysis method is then applied to the decision database to determine the optimal combination of device capacities, based on the measures of robustness, flexibility, and risk exposure. The steps begin with determination of the tradeoff region, then include identification of conditional and global decision sets and finally decision set analysis.

Table 5-8. Top 10 Acceptance Plans for Continuous Future

First 5 years	Second 5 years	Oil (MW)	Coal (MW)	Gas (MW)	Hydro (MW)	Solar (km ²)	Biomass (kton)	Nuclear (MW)	Cost (RM/ kWh)	CO ₂ (10 ¹⁰ kg/y)	Overall Eff.(%)	Rank
F1	F1	1500	0	6000	3000	0	800	0	0.0883	3.25	48.9	1
		1500	0	6000	3000	1	800	0	0.0898	3.23	48.7	2
		2000	0	6000	3000	0	800	0	0.0883	3.38	48.4	3
		1000	700	6000	3000	0	800	0	0.0869	3.34	47.5	4
		1500	0	6000	3000	2	800	0	0.0914	3.21	48.6	5
		2000	0	6000	3000	1	800	0	0.0898	3.36	48.3	6
		2000	1400	4500	3000	0	800	0	0.0796	3.81	44.7	7
		1500	700	6000	3000	0	800	0	0.0868	3.46	47.1	8
		1000	2100	4500	3000	0	800	0	0.0783	3.77	43.8	9
		1000	700	6000	3000	1	800	0	0.0884	3.32	47.3	10
F2	F2	0	0	1500	3000	0	800	0	0.1625	0	51.5	1
		0	0	1500	2500	0	800	0	0.1437	0	49.0	2
		0	0	1500	3000	1	800	0	0.1769	0	51.1	3
		0	0	1500	2000	0	800	0	0.1249	0	46.1	4
		0	0	1500	2500	1	800	0	0.1581	0	48.5	5
		500	0	1500	3000	0	800	0	0.1799	0	50.1	6
		0	0	1500	3000	2	800	0	0.1912	0	50.6	7
		500	0	1500	2500	0	800	0	0.1611	0	47.8	8
		0	0	3000	3000	0	800	0	0.2055	0	51.2	9
		0	0	1500	2000	1	800	0	0.1393	0	45.7	10
F3	F3	1500	0	6000	3000	0	800	0	0.0883	3.25	54.1	1
		1500	0	6000	3000	0	1,440	0	0.0884	3.25	53.4	2
		1500	0	6000	3000	1	800	0	0.0898	3.23	53.9	3
		2000	0	6000	3000	0	800	0	0.0883	3.38	53.3	4
		1500	0	6000	3000	0	2,080	0	0.0885	3.25	52.7	5
		1000	700	6000	3000	0	800	0	0.0869	3.34	52.2	6
		1500	0	6000	3000	1	1,440	0	0.0899	3.23	53.2	7
		1500	0	6000	3000	2	800	0	0.0914	3.21	53.6	8
		2000	0	6000	3000	0	1,440	0	0.0883	3.38	52.6	9
		2000	0	6000	3000	1	800	0	0.0898	3.36	53.0	10
F4	F4	0	0	1500	3000	0	800	0	0.1625	0	67.2	1
		0	0	1500	2500	0	800	0	0.1437	0	65.2	2
		0	0	1500	2000	0	800	0	0.1249	0	62.8	3
		0	0	1500	3000	1	800	0	0.1769	0	66.2	4
		0	0	1500	2500	1	800	0	0.1581	0	64.2	5
		0	0	1500	1500	0	800	0	0.1062	0	59.8	6
		0	0	1500	3000	0	1,440	0	0.1679	0	64.5	7
		0	0	1500	2000	1	800	0	0.1393	0	61.7	8
		0	0	1500	2500	0	1,440	0	0.1492	0	62.4	9
		0	0	1500	3000	2	800	0	0.1912	0	65.3	10

Determination of the tradeoff region among the feasible plans under different futures is characterized by seven design variables, along with three decision attributes. The feasible plans are determined after eliminating all inferior plans due to unacceptable performance of one or more attributes. All plans with the cost of energy production higher than 0.20 RM/kWh and/or with the efficiency index lower than 30%, are rejected. For a three-attribute decision problem, graphical representation of the tradeoff region requires a 3-D graph. Alternatively, 2-D graphs can be used to relate between each pair of attributes.

Identification of decision sets consists the following steps.

- Composite distance value is calculated for every plan contained by the tradeoff region using equation (3-2), which rewritten for this case study as (5-1).
- Composite distance variance is estimated using the approximate error model. Errors due to inconsistent priority judgment are assumed to be 10% of the expected values, and errors from inaccurate attribute measurement are assumed as 5% of the range of attribute value.
- The decision set is identified, conditional on a specific set of futures, following the criterion of equation (3-9).
- The global decision set is determined as the union of conditional decision sets.

Table 5-9. Selected Plans for Changing Futures at Second stage

Future First 5 years	Future Second 5 years	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (m ²)	Biomass quantity (ton)	Nuclear capacity (MW)	Cost (RM/kWh)	CO ₂ emissions (kg/year) (x 10 ¹⁰)	Overall efficiency (%)	Rank
F1	F2	(none)										
F1	F3	1500	0	6000	3000	0	800,000	0	0.0883	3.25	51.5	1
		1500	0	6000	3000	1,000,000	800,000	0	0.0898	3.23	51.3	2
		2000	0	6000	3000	0	800,000	0	0.0883	3.38	50.8	3
		1000	700	6000	3000	0	800,000	0	0.0869	3.34	49.8	4
		1500	0	6000	3000	2,000,000	800,000	0	0.0914	3.21	51.1	5
		2000	0	6000	3000	1,000,000	800,000	0	0.0898	3.36	50.6	6
F1	F4	(none)										
F2	F3	(none)										
F2	F4	0	0	1500	3000	0	800,000	0	0.1625	0	59.4	1
		0	0	1500	2500	0	800,000	0	0.1437	0	57.1	2
		0	0	1500	3000	1,000,000	800,000	0	0.1769	0	58.6	3
		0	0	1500	2000	0	800,000	0	0.1249	0	54.4	4
		0	0	1500	2500	1,000,000	800,000	0	0.1581	0	56.4	5
		0	0	1500	3000	2,000,000	800,000	0	0.1912	0	57.9	6
		0	0	1500	2000	1,000,000	800,000	0	0.1393	0	53.7	7
F3	F4	(none)										

Decision set analysis is done to identify the robustness of plans and to determine the flexible plans among the robust plans. Table 5-8 and Table 5-9 are given for the top few acceptable plans for plans that do not change future on their second stage and for the plans that do change future on their second stage

Robustness Measure

The robustness measure can be determined by listing the plans that appear in at least two futures, as shown in Table 5-10. Analysis of the global decision set results in the following observations.

Table 5-10. Global Decision Set for Robustness

Plan No	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (km ²)	Biomass quantity (kton)	Nuclear capacity (MW)	F1	F2	F3	F4	Robustness
G1	0	0	1500	3000	0	800	0		1		1	50%
G2	0	0	1500	2500	0	800	0		2		2	50%
G3	0	0	1500	3000	1	800	0		3		4	50%
G4	0	0	1500	2000	0	800	0		4		3	50%
G5	0	0	1500	2500	1	800	0		5		5	50%
G6	0	0	1500	3000	2	800	0		7		10	50%
G7	0	0	1500	2000	1	800	0		10		8	50%
G8	1500	0	6000	3000	0	800	0	1		1		50%
G9	1500	0	6000	3000	1	800	0	2		3		50%
G10	2000	0	6000	3000	0	800	0	3		4		50%
G11	1000	700	6000	3000	0	800	0	4		6		50%
G12	1500	0	6000	3000	2	800	0	5		8		50%
G13	2000	0	6000	3000	1	800	0	10		10		50%

- No 100% robust plan can be identified from the global decision set. Only 50% robust plans can be identified, which represents all the plans that can cope with two future conditions.
- The first seven plans of the list (G1 – G7) reflect the same low load growth; therefore, in these plans, conventional energy from gas and hydro are sufficient in meeting the demand. The remainder of the plans (G8 – G13) reflects the high load growth case, in which coal and oil energy sources become necessary.
- All the plans reflect a middle design attitude in utilizing biomass technologies and emphasize the importance of solar energy sources. Nuclear is not preferred at all.
- Plan G1 is regarded as the best strategy, as reflected in its preference ranking.
- Other plans following G1 in preference ranking, G2 to G5, share similar energy source options and show that solar technology can be added into the system without much influence on the preference ranking.

The results in Table 5-10 can be grouped into two future scenarios, low load growth and high load growth, which are summarized in Table 5-11 and Table 5-12.

Table 5-11. Low Load Growth Robust Plans Grouping

Plan Group No	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (km ²)	Biomass quantity (kton)	Nuclear capacity (MW)	Rankings
P1	0	0	1500	2000 - 3000	0	800	0	1
P2	0	0	1500	2000 - 3000	1	800	0	2
P3	0	0	1500	3000	2	800	0	3

The analysis of the global decision set for low load growth results in the following observations.

- Among the low load growth plans, plan group P1 is regarded as the best strategy, as indicated by its preference ranking. It requires a range of hydro capacity and no solar technology.
- The second and third ranked plan groups, P2 and P3, require solar technology to be implemented and reflect a reduction in robustness.

Table 5-12. High Load Growth Robust Plans Grouping

Plan Group No	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (km ²)	Biomass quantity (kton)	Nuclear capacity (MW)	Rankings
P4	1500-2000	0	6000	3000	0	800	0	4
P5	1500-2000	0	6000	3000	1 - 2	800	0	5
P6	1000	700	6000	3000	0	800	0	6

Analysis of the high load growth global decision set leads to the following observations.

- Among the high load growth plans, plan group P4 is regarded as the best strategy according to its preference ranking, with a range of oil capacity required and no solar technology.
- The plan groups that require solar technology, P5 and P6, are ranked fifth and sixth, and their robustness is reduced.
- When coal capacity is added, as in P6, the plan has less robustness compared to other plans.

Flexibility Measure

Using the flexibility cost calculated during the production costing simulation and the base case assuming an equal chance, total flexibility cost for each of the attributes can be calculated using Equations (3-16), (3-17) and (3-18). The value of composite distance of flexibility cost (or normalized flexibility distance value) is calculated for every robust plan using equation (3-2), which is rewritten for this case study as (5-2). The ranking is based on the flexibility cost composite distance. Table 5-13 shows the results.

Table 5-13. Flexibility of Alternative Plans

Plan No.	Oil capacity MW	Coal capacity MW	Gas capacity MW	Hydro capacity MW	Solar area km ²	Biomass quantity kton	Nuclear capacity MW	Flexibility Cost			
								Cost \$/kWh	CO ₂ kg/year	Eff %	Rank
G10	2000	0	6000	3000	0	800	0	0	0	0.048	1
G12	1500	0	6000	3000	2	800	0	0	0	0.048	2
G9	1500	0	6000	3000	1	800	0	0	0	0.048	3
G13	2000	0	6000	3000	1	800	0	0	0	0.051	4
G11	1000	700	6000	3000	0	800	0	0	0	0.051	5
G8	1500	0	6000	3000	0	800	0	0	0	0.052	6
G7	0	0	1500	2000	1	800	0	0	0	0.147	7
G6	0	0	1500	3000	2	800	0	0	0	0.151	8
G5	0	0	1500	2500	1	800	0	0	0	0.156	9
G3	0	0	1500	3000	1	800	0	0	0	0.156	10
G4	0	0	1500	2000	0	800	0	0	0	0.161	11
G2	0	0	1500	2500	0	800	0	0	0	0.162	12
G1	0	0	1500	3000	0	800	0	0	0	0.167	13

Analysis of the global decision set considering flexibility yields the following observations.

- Plan G10 is regarded as the most flexible plan (the one that has the lowest flexibility distance value) for all alternatives and among the high load growth alternatives.
- Plan G7 is the most flexible plan for the low load growth alternatives.
- Plan G1 that is regarded as the most robust plan, is the least flexible plan among all alternatives and also among the low load growth scenarios.
- Plan G8 shows the least flexibility cost among the high load growth alternatives.

Knowing that no 100% robust plan exists, we can group the plans into two 50%-robust plans, namely low load growth plans and high load growth plans. In the following Table 5-14, plans P4 to P6 are the high load growth alternatives, and plans P1 to P3 are the low load growth alternatives.

Table 5-14. High and Low Load Growth Flexible Plans Grouping

Plan Group No	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (km ²)	Biomass quantity (kton)	Nuclear capacity (MW)	Rankings
P4	1500-2000	0	6000	3000	0	800	0	1
P5	1500-2000	0	6000	3000	1 - 2	800	0	2
P6	1000	700	6000	3000	0	800	0	3
P3	0	0	1500	3000	2	800	0	4
P2	0	0	1500	2000 - 3000	1	800	0	5
P1	0	0	1500	2000 - 3000	0	800	0	6

The following observations can be made in deciding the “optimal” design strategy for the Limited Resource case with and without considering flexibility measure.

- Considering the robustness measure only (Table 5-11 and 5-12), six plans are found, and plan P1 is considered as the most robust plan. Adding a flexibility measure among the robust alternatives (Table 5-14) yields plan P4 as the most flexible plan.
- Robust plan P1 reflects a design attitude toward utilizing gas, hydro and biomass supplies and shows no preference for solar technologies, while flexible and robust plan P4 reflects the same attitude with more commitment to gas and oil supply, compared to plan P1.

Risk Exposure Measure

Table 5-15. Consequence Measures of Limited Resource Problem

No.	Consequence measure	Weight	Value Range
1	Number of major systems components	1/24	0-50
2	Percent of major components successfully deployed in installation	1/24	0-100
3	Area of land required (in thousands of meter squared)	1/12	0-50
4	Number of regulations that apply	1/12	0-50
5	Years of plant expected in operation	1/16	0-50
6	Score = probability X consequence Probability = 0.1 X years in operation when time ≤ 10 years, else = 1 Consequence = number of system breakdown when system breakdown < 10 times, else = 10	1/16	0-10
7	Score = probability X consequence Probability = 0.1 X major system components when ≤ 10 components, else = 1 Consequence = number of system breakdown when system breakdown < 10 times, else = 10	1/16	0-10
8	Amount of carbon emissions (in kg/kWh)	1/48	0-100
9	Qualitative ranking based on level of harm imposed on wildlife surrounding the site, 10 indicates that a protected species is endangered while 0 indicate that no wildlife is affected.	1/48	0-10
10	Qualitative ranking based on level of harm imposed on plants surrounding the site, 10 indicates that a protected species is endangered while 0 indicate that no plants are affected.	1/48	0-10
11	Percent of increased in fertilizer use for agriculture	0.0236	0-100
12	Percent of increased in food supply	0.0236	0-100
13	Percent of increased in wilderness land use for agriculture	0.0236	0-100
14	Percent of increased in flood control to avoid erosion	0.0855	0-100
15	Percent of increased of poorer water quality	0.0855	0-100
16	Percent of increased of poorer air quality	0.0700	0-100
17	Percent of increased of epidemic diseases	0.0840	0-100
18	Percent of increased of fire hazards	0.0525	0-100
19	Percent of increased of natural diversity	0.0259	0-100
20	Percent of increased of the ecosystem instability	0.0259	0-100

In this example problem, consequences of exposure are taken from oil, coal and gas supply, based on their substation rating in MW, assuming that the main contribution is from fuel burning consequences. Borrowing the concept introduced in Chapter 4 regarding the consequences of exposure, we will use the consequences measures as listed in Table 5-15.

For each of the scenario alternatives, the overall value expressed by Equation (5-3) is calculated, where the linear value functions are used and the score value for each of the generation options or technology types as listed in Table 5-16.

$$\begin{aligned}
 V(x) = & w_{oil} \left(\sum_1^{20} w_i v_i(x_i) \right)_{oil} + w_{coal} \left(\sum_1^{20} w_i v_i(x_i) \right)_{coal} \\
 & + w_{gas} \left(\sum_1^{20} w_i v_i(x_i) \right)_{gas} + w_{hydro} \left(\sum_1^{20} w_i v_i(x_i) \right)_{hydro} \\
 & + w_{solar} \left(\sum_1^{20} w_i v_i(x_i) \right)_{solar} + w_{biomass} \left(\sum_1^{20} w_i v_i(x_i) \right)_{biomass} \\
 & + w_{nuclear} \left(\sum_1^{20} w_i v_i(x_i) \right)_{nuclear}
 \end{aligned} \tag{5-3}$$

Table 5-16. Score Value for Limited Resource Problem

Consequence measure No.	Oil	Coal	Gas	Hydro	Solar	Biomass	Nuclear
1	48	48	38	20	10	48	40
2	90	90	90	90	90	90	90
3	0.00005 *[MW]	0.00005 *[MW]	0.00003 *[MW]	0.00001 *[MW]	[m ²]/1000	0.0000000065 *[ton]	0.00004 *[MW]
4	45	45	45	45	15	45	48
5	40	40	40	50	20	40	30
6	4.8	4.8	4.8	3	1	4.8	6
7	4.8	4.8	4.8	3	1	4.8	6
8	5	5	4	0.5	0	5	0
9	9	9	9	9	4	9	10
10	9	9	9	9	4	9	10
11	50	50	50	20	0	50	70
12	50	50	50	20	0	50	70
13	50	50	50	20	0	50	70
14	50	50	50	20	0	50	70
15	50	50	50	20	0	50	70
16	50	50	50	20	0	50	70
17	50	50	50	20	0	50	70
18	50	50	50	20	0	50	70
19	50	50	50	20	0	50	70
20	50	50	50	20	0	50	70

The weights $[w_{oil}, w_{coal}, w_{gas}, w_{hydro}, w_{solar}, w_{biomass}, w_{nuclear}]$ are obtained from technology priority assessments that take into account the cost and benefit aspects for each generation option, calculated from costs and benefits influencing each technology. Figure 5-3 shows the costs and benefits hierarchy for the technology priority assessment.

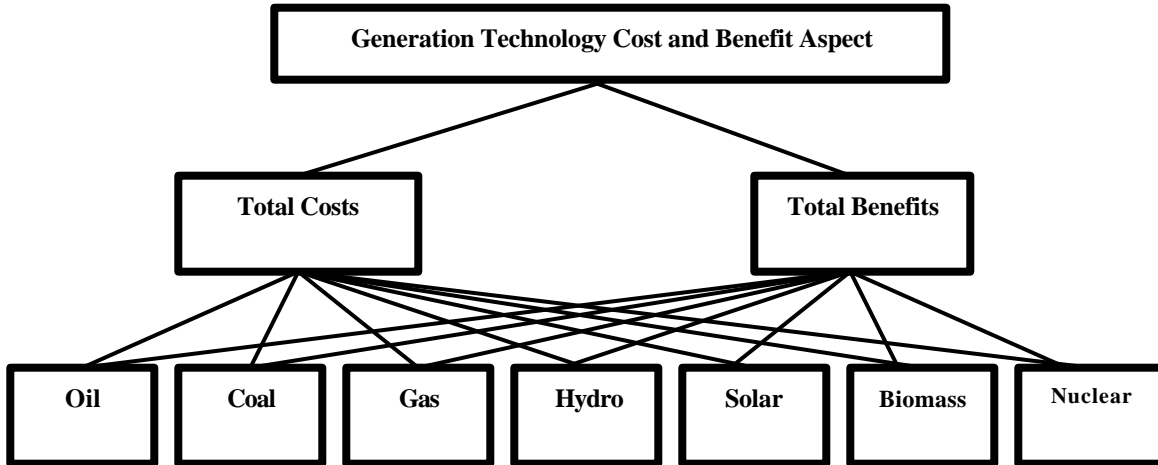


Figure 5-3. Costs and Benefits for Technology Priority Assessment

Table 5-17. Risk Exposure of Alternative Plans

Plan Group No	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (km ²)	Biomass quantity (kton)	Nuclear capacity (MW)	Risk Exposure	Rankings
G4	0	0	1500	2000	0	800	0	30.47453	1
G2	0	0	1500	2500	0	800	0	30.47459	2
G1	0	0	1500	3000	0	800	0	30.47465	3
G11	1000	700	6000	3000	0	800	0	30.47762	4
G8	1500	0	6000	3000	0	800	0	30.47769	5
G10	2000	0	6000	3000	0	800	0	30.47795	6
G7	0	0	1500	2000	1	800	0	49.04953	7
G5	0	0	1500	2500	1	800	0	49.04959	8
G3	0	0	1500	3000	1	800	0	49.04965	9
G9	1500	0	6000	3000	1	800	0	49.05269	10
G13	2000	0	6000	3000	1	800	0	49.05295	11
G6	0	0	1500	3000	2	800	0	67.62465	12
G12	1500	0	6000	3000	2	800	0	67.62769	13

The hierarchical structure consists of three layers, from main goal, to the aspects influencing the technology, and finally the technology or objectives. The resulting global priority vector based on given judgment matrices, as in Appendix B5, indicates that solar technology is ranked first (0.2229), followed by gas (0.2019), nuclear (0.1829), hydro (0.1450), oil (0.1226), coal (0.0639), and finally biomass (0.0608). The degree of uncertainty built into these numbers is determined by their confidence intervals as listed

in Appendix B5. Table 5-17 shows the risk exposure for all the robust alternatives, calculated using Equation (5-3).

The analysis of the global decision set considering the risk exposure arrives at the following observations.

- It is shown that plan G12 is less attractive than other candidate alternatives, while plan G4 is ranked the most attractive.
- It is also observed that plans that have lesser solar capacity are less risky than the ones that have higher solar capacity.

Table 5-18 lists the results for division of plans into high load growth and low load growth alternative groups. Table 5-19 summarizes the ordering of the group plans when robustness, flexibility and risk exposure are considered.

Table 5-18. High and Low Load Growth Risk Plans Grouping

Plan Group No	Oil capacity (MW)	Coal capacity (MW)	Gas capacity (MW)	Hydro capacity (MW)	Solar area (km ²)	Biomass quantity (kton)	Nuclear capacity (MW)	Rankings
P1	0	0	1500	2000 - 3000	0	800	0	1
P6	1000	700	6000	3000	0	800	0	2
P4	1500-2000	0	6000	3000	0	800	0	3
P2	0	0	1500	2000 - 3000	1	800	0	4
P5	1500-2000	0	6000	3000	1 - 2	800	0	5
P3	0	0	1500	3000	2	800	0	6

Table 5-19. Summary of Group Plan Ranking Order

Measures	Group Plan Ranking Order
Robustness	P1, P2, P3, P4, P5, P6
Robustness & Flexibility	P4, P5, P6, P3, P2, P1
Robustness, Flexibility & Risk Exposure	P1, P6, P4, P2, P5, P3

The following observations can be made in deciding the “optimal” design strategy for the case of Limited Resources, considering robustness, flexibility and risk exposure measures.

- Considering the robustness measure only (Table 5-11 and 5-12), six group plans are found, and plan P1 is considered as the most robust plan. Adding a flexibility measure to the robust alternatives (Table 5-14) shows group plan P4 as the most flexible plan. When risk exposure is added (Table 5-18), group plan P1 is again considered as the best plan.
- Robust & less risky group plan P1 reflects a design attitude towards utilizing gas, hydro and biomass supplies and gives no preference to solar technologies. Flexible and robust plan P4 reflects the same attitude, but with more commitment to gas and oil supply, compared to group plan P1.

- The robustness measure favors plans according to the least use of gas, oil and coal capacity.
- The robustness and flexibility measures favor plans according to the highest usage of oil, gas, coal, then solar capacity.
- The robustness, flexibility and risk exposure measures favor plans with the least use of solar, followed by oil, coal, gas and hydro capacity.

5.5. Comparison Results

Malaysia power authority's (TNB) planned generation for 10 years from Table 5-4 is shown again in Table 5-20. The best plans' results from the proposed design strategy for low load growth and high load growth are listed in Table 5-21 and Table 5-22, respectively.

Table 5-20. TNB Planned Generation 2001-2010

	Oil MW	Coal MW	Gas MW	Hydro MW	Solar MW	Biomass MW	Nuclear MW	Cost RM/kWh	CO2 ton/year	Efficiency %
P0	0	5600	5656	3000	200	520	0	0.36	79,178,136	0.3179

Table 5-21. Low Load Growth Best Plan Generation 2001-2010

	Oil MW	Coal MW	Gas MW	Hydro MW	Solar MW	Biomass MW	Nuclear MW	Cost RM/kWh	CO2 ton/year	Efficiency %
P1	0	0	1500	3000	0	104	0	0.16	0	0.5936
P2	0	0	1500	3000	40	104	0	0.18	0	0.5864
P3	0	0	1500	3000	80	104	0	0.19	0	0.5796

Table 5-22. High Load Growth Best Plan Generation 2001-2010

	Oil MW	Coal MW	Gas MW	Hydro MW	Solar MW	Biomass MW	Nuclear MW	Cost RM/kWh	CO2 ton/year	Efficiency %
P6	1000	700	6000	3000	0	104	0	0.087	33,400,000	0.4984
P4	2000	0	6000	3000	0	104	0	0.088	33,800,000	0.5150
P5	2000	0	6000	3000	80	104	0	0.091	33,600,000	0.5129

The following observations can be made in comparing the two decision results, one based on traditional resource planning, the other one based on the optimal design strategy considering robustness, flexibility and risk exposure measures.

- The total generation addition proposed by the TNB for 10 years is 14,976 MW, which is 33.9% greater than the highest high load growth scenario (plan P5 = 11,184 MW). The selection of a high load growth value of 5.9% (Futures 1 and 3) represents the highest possible load growth value for Malaysia; therefore, it is not necessary to build more capacity above that value.
- Using optimal design strategy, TNB will have the flexibility to choose plans depending on the uncertainty of occurrences, such as low load growth or high load growth. Therefore, more choices are provided among the best plans, knowing their robustness, flexibility and risk exposure.

- The penetration level of renewable resources (solar and biomass) for the best plans range from 1.65% for high load growth plans to 3.93% for low load growth plans, to ensure robustness, flexibility and risk exposure, while the proposed plan from TNB which specifies 5% of power coming from renewable sources will not fall under a robust and flexible plan.
- Using the current practiced planning scheme, TNB will not be able to achieve the 5% renewable contribution, unless they adopt the proposed method to find the most robust and flexible and least risky plans by running the scenarios with the 5% renewable contribution option.

Using this proposed method for selecting robust plans that have 5% renewable contributions yields the result shown in Table 5-23.

Table 5-23. Robust Plans of 5% Renewable Contribution

	Oil MW	Coal MW	Gas MW	Hydro MW	Solar MW	Biomass MW	Nuclear MW	Cost RM/kWh	CO2 ton/year	Efficiency %
R1	1000	1400	6000	3000	80	520	0	0.2619	35,167,000	0.4035
R2	1500	1400	6000	2500	80	520	0	0.2623	39,085,000	0.3941

The following observations can be made regarding a comparison of robust plans of the proposed method (Table 5-23), with current planned generation (Table 5-20).

- The total generation addition is 12,000 MW, which is 2976 MW (or 19.87%) lower than the current planned generation. Currently, TNB is experiencing over-reserve capacity conditions (larger than 20%) that have prevented them from promoting demand side management and energy conservation measures nationwide. In this situation, this proposed method should be able to help TNB or the Malaysian government in their future generation planning scheme.
- The two 100% robust plans proposed have higher efficiencies than the current proposed plan by 7% to 8%, with CO₂ emissions lowered by around 100%, and around 25% lower generation cost. This situation occurs due to reduction of coal generation for the robust plan compared to the TNB plan by 75% (from 5600 MW to 1400 MW) and the reduction of total generation (from 14,976 MW to 12,000 MW). Using this proposed strategy, TNB will not suffer as it does now when load growth is declining, or when other future events change, for it has been set in advance to anticipate different future event occurrences.
- To improve the generation mix and efficiency, it is better for TNB to add about a 10% share of the total generation in oil and coal, as given by the proposed method. The current planned generation adds up to 37% of coal alone, which contributes to poorer efficiency and less robustness to future changes such as load growth, etc.
- The addition of solar technology for the robust plan accounts only for 0.7%, whereas the in the current TNB planned addition, it is around 1.3%. The existence of some uncertainties in planning horizon shows that a moderate level of solar technology is preferable and more practical, since this is the first period in which TNB includes the use of solar technology in its renewable target.

5.6. Proposed Planning Flow Diagram

Further observations from the current practice of the decision-making process show that it is important to consider influence from citizen interest groups, which will collectively represent social and environmental concerns, such as the issues of carbon tax, allowance markets, population movement, etc. Figure 5-4 shows the proposed planning decision flow diagram for Malaysia.

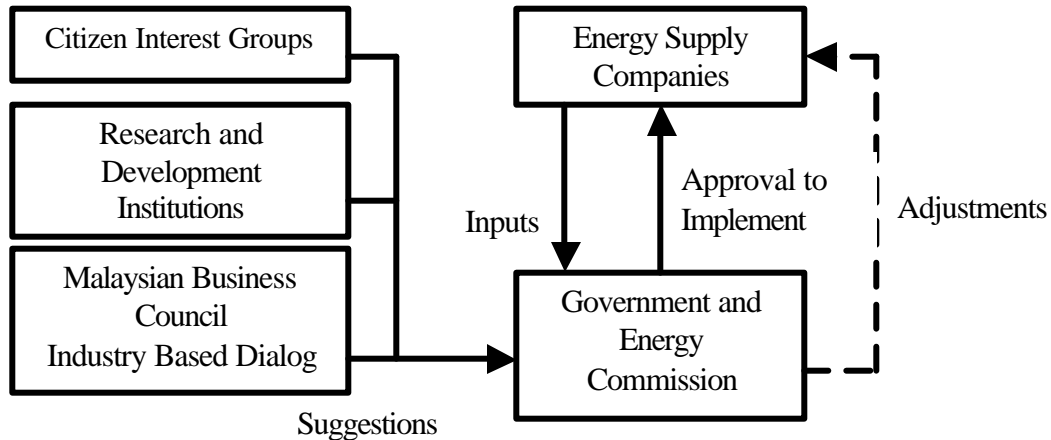


Figure 5-4. The Proposed Planning Decision Flow Diagram

Table 5-24. The Differences of TNB Planned with 5% Renewable Robust Plans

	Oil MW	Coal MW	Gas MW	Hydro MW	Solar MW	Biomass MW	Nuclear MW	Cost RM/kWh	CO2 ton/year	Efficiency %
D1	-1000	4200	-344	0	120	0	0	0.0981	44,011,136	-0.0856
D2	-1500	4200	-344	500	120	0	0	0.0977	40,093,136	-0.0762

The differences between the TNB planned generation and the proposed plan with 5% renewable contributions are listed in Table 5-24. The following can be concluded.

- D1 is the differences of plan P0 (from Table 5-20) with respect to plan R1 (from Table 5-23), and D2 is the differences of plan P0 with respect to plan R2.
- The proposed plans are different from the current planned generation due to the availability of choices from thousand of plans, which are ranked on different future conditions based on robustness, although it is not necessarily the planned generation emphasizes on the robustness issues.
- It is shown that the robustness measures guarantees balanced generation mix representing different types of generation.
- The major differences are in the use of oil and coal plant generation (by increasing oil, and reducing coal), which causes a large reduction in CO₂ emissions, improvement in the overall efficiency by about 8%, and cheaper costs by about 10 cents/kWh.
- Achieving an almost 20% reduction in output shows that the TNB planned generation has used too high for its reserve capacity.

6. Conclusion and Future Work

6.1 Conclusion

A method of efficient resource development for electric utilities' planning under uncertainty has been developed in this dissertation. Four technical issues are considered as important to the success of efficient strategic planning, namely: flexible resource development, multi-attribute risk impact analysis, efficient resource planning framework, and renewable technology assessment. The proposed ERD includes aspects that have not been addressed so far; the framework can be used to address uncertain policy options that are now neglected or evaluated with only subjective opinions. This framework, developed using AHP techniques, can be used to model any uncertainties that are not yet modeled. The results of the two case studies show the benefits of the proposed framework by giving various options to the decision makers to achieve lower cost, lower emission, better reliability and higher efficiency plans. The main contributions from this dissertation work are summarized as follows.

Flexible Resource Development

A flexibility measure in power system resource planning is incorporated, and a resource strategy based on flexibility measures has been developed. A flexible resource plan allows easy and inexpensive changes to be made if future conditions deviate from the base assumptions. Three common flexibility enhancement options include smaller commitments, adaptability, and decision deferment. The efficient resource-planning framework developed in this dissertation, which is a combined scenario analysis and external optimization modeling approach, is capable of evaluating flexibility measures in resource development. A multi-stage decision analysis is required to address the influences of various uncertainty factors and flexibility enhancement options. However, due to its computational complexity, which increases exponentially with the number of uncertainties, decision options, and time periods represented in the decision model, a practical solution is to develop a two-stage decision analysis model. This is a compromise between the simplified one-period modeling approach and the complicated multistage modeling approach. The focus will be on the decision made at the first stage of the decision process and examining the outcomes of different planning strategies over the entire planning horizon, with proper flexibility enhancement measures implemented at the end of the first time period. The additional "cost" necessary for each of the plans to respond to each of the future scenarios is calculated for each stage using an evaluation of expansion options process.

Multi-attribute Risk Impact Analysis

A multi-attribute risk-impact analysis method is investigated to handle the risk exposure in power system resource planning. A resource strategy based on risk exposure has been developed. Risk exposure quantifies the risk hazards. Risk exposure can be reduced using one of these methods: expanding the plant mix, reducing dependence on the allowance

market and external source of power, and adoption of renewable or environmental friendly technologies. After identifying the risk consequences, risk exposure can be measured using an additive multi-objective value model. The single dimensional value functions provide the returns to scale on the score of the consequence measures. Value functions usually occur in four basic mathematical forms: linear (constant return to scale), concave (decreasing returns to scale), convex (increasing returns to scale), and an S-curve (increasing then decreasing returns to scale). The value functions are obtained by asking the DM the relative value of increments of the consequence measures scale.

Efficient Resource Planning Framework

An efficient resource development framework for planning under uncertainty has been developed, combining features of the utility function, tradeoff analysis, and analytical hierarchy process, incorporating a performance evaluation approach to measure robustness, flexibility and risk exposure.

- The identification of relevant uncertainties has been implemented by screening an uncertainty to find which of its influential uncertainty factors have a considerable impact on the solution. This is done using pair-wise comparisons of the impacts given by the DM to form a judgment matrix. Those uncertainty factors that have low scores can be eliminated.
- The identification of probability distributions of uncertainties has been implemented from a number of expert judgments. If there is an error in any particular judgment, it is compensated by other judgment ratios. Therefore, a set of probabilities assigned to a particular uncertainty will depend on the probabilities assigned to its uncertainty factors. In other words, the probability distributions of a particular uncertainty depend on the values selected for the uncertainty factors influencing it.
- The AHP technique has been incorporated into the procedure to facilitate the assessment process of preference functions and weighting parameters for the given attributes. A multi-dimensional numerical knee-set searching algorithm, which is based on the measure of likely range of composite distance, is used to identify acceptable plans or designs with respect to the given attributes under the specified future condition.
- The interval-based multi-attribute methodology has been utilized in support of the decision process with imprecise information. The developed methodology is based on the linear additive utility function model and extends the problem formulation with the measure of composite utility variance, accounting for individual errors from inaccurate attribute measurements and inconsistent priority judgments. This methodology will help the DM gain insight into how the imprecise data may affect the choice of best solution on one hand, and how a set of acceptable alternatives may be identified on the other.
- The flexible resource development in power system resource planning has been incorporated, and a resource strategy based on flexibility measure has been developed.
- The multi-attribute risk-impact analysis method has been investigated to handle the risk exposure in power system resource planning, and a resource strategy based on risk exposure has been developed.

Renewable Technology Assessment

The penetration level of renewable technology into the total generation system mix has been investigated, with renewable technology constraints and application using the proposed decision-making model. Some of the issues that can influence the integration of renewable technologies into the conventional grid system have been identified, including energy security, generation unit reliability, T&D line expansion reliability, operation limitation, energy efficiency, revenue stream stability, environmental and health impacts, weather impact, robustness, flexibility, and risk exposure. This dissertation has shown the issue of robustness, flexibility and risk exposure application using two case study examples incorporating cost, reliability, emissions, and energy efficiency.

6.2 Future Work

Market-Based Planning Approach

Electric utilities are forced to perform market driven resource investment decisions due to deregulation and competition [82, 136]. The need for new generation and transmission capacity is determined by an engineering reliability criterion based on a least-cost planning strategy in a vertically integrated utility. As for the timing and type of new generation additions are driven more by expectations of market prices, generating plant capital, operating costs and resulting profit margins in competitive electric markets. A combination of traditional transmission-related reliability criteria and market-based opportunities for energy trading is most likely used for transmission expansion investment decisions. Therefore, new analytical models need to be developed and new decision attributes need to be defined in support of market-based investment decision-making process. The decision analysis technique developed in this dissertation, which developed using AHP techniques, could be very helpful in market-based generation and transmission planning process by providing a structured project evaluation framework for performing uncertainty analysis and risk management. Efficient planning in deregulated markets requires the integration of financial and engineering analysis that can simultaneously consider the economics and physical laws of power generation and transmission throughout the grid. Such an integrated engineering and economic analysis tool should help the utility to identify and evaluate potential generation and transmission opportunities in terms of project location, timing and optimal project capacity.

Risk-Based Renewable Resource Planning Approach

The scope of risk exposure in power systems has grown wider, especially at this time of power sector restructuring. The range of options in a bulk power system, such as installed capacity, available transfer capacity, penalties, and interruption costs, can be determined using a proper risk analysis [10, 48]. An approach that recognizes generation unit outages and hourly load fluctuations probabilistically along with first contingency transmission outages should be included in the planning process. Further use of risk and reliability analysis can detect the weak point in the system using outage information, and then

improvement measures can be done. The risk exposure criteria developed in this thesis, which is based on the utility function, can be extended to include other gain-versus-risk tradeoff approaches, such as minimizing the maximum regret and value at risk (VaR) [92]. The concept of distribution utilities is widely recognized for improvement of energy efficiency and promotion of renewable technologies [105]. In this competitive environment, regulated distributors will likely remain responsible for acquiring a least-cost portfolio of distribution system improvements, efficiency measures, and distributed generation (renewable and conventional). The risk-based approach in this thesis can be extended to include the new risks introduced by renewable technologies such as solar and wind [113, 70]. Attributes related to health issues, ecological risks, natural disasters, and sabotage can be modeled using expert opinions and made a part of the decision-making process.

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Appendices

An Analytic Hierarchy Process

The analytic hierarchy process (AHP) introduced by Saaty [137] is a structured approach for dealing with complicated multi-attribute decision problems. In AHP, the decision problem is broken up into layers, each layer influencing the entities in the layer immediately above it. From the second layer of the hierarchy, the Decision Maker (DM) will be asked to compare the relative importance between each pair of factors at that layer with respect to every connected factor on the upper layer. For example, the following ratio questions may be asked in the assessment of attribute priorities: How much stronger or important does this attribute contribute to, dominate, influence, satisfy, or benefit the overall design objective than does the attribute with which it is being compared to? This process will create a judgment matrix A with a row and a column for each attribute. For a decision problem with an n -layer hierarchy, a set of judgment matrices will be generated for each of $n-1$ evaluation levels.

Creation of Judgments

To create a judgment matrix with m factors, at least $(m-1)$ ratio questions need to be asked. However, in compensation for any bias or inconsistency, redundant pair-wise comparisons are usually performed thus increasing the ratio questions up to $m(m-1)/2$.

If we denote the relative importance of i^{th} factor with respect to j^{th} factor by a_{ij} , then the relative importance of j^{th} attribute with respect to i^{th} factor would be $1/a_{ij}$, and the importance of every factor with itself a_{ii} is equal to one. The matrix obtained in this way is called “reciprocal judgment matrix” or “pair-wise comparison matrix” as given below.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \Rightarrow A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \quad (\text{A-1})$$

For the entries of the judgment matrix, a set of integer numbers are recommended by Saaty [137] to represent the relative importance of one factor with respect to another. Table A-1 gives the scales and their descriptions used for pair-wise comparisons.

Table A-1 Scales and Descriptions

Intensity of importance	Definition	Explanation
1	Equal importance	Two attribute contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one criterion over another
5	Essential or strong importance	Experience and judgment strongly favor one criterion over another
7	Demonstrated importance	An attribute is strongly favored and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one attribute over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed between the two adjacent judgments

Eigenvalue Prioritization Method

The eigenvalue prioritization method is a unique technique to determine the relative ranking of factors associated with each judgment matrix by normalizing the principal eigenvector \mathbf{p} of judgment matrix \mathbf{A} that is obtained by solving the following eigenvalue problem

$$\mathbf{A} \cdot \mathbf{p} = \lambda_{\max} \cdot \mathbf{p} \tag{A-2}$$

where λ_{\max} is the principal or the largest real eigenvalue of judgment matrix \mathbf{A} . For an n -layer hierarchy, the composite priority vector from the bottom layer with respect to the top layer can be calculated using the following matrix equation:

$$\begin{bmatrix} p_{1,n}^{1,1} \\ p_{2,n}^{1,1} \\ \vdots \\ p_{n,n}^{1,1} \end{bmatrix} = \begin{bmatrix} p_{1,n}^{1,n-1} & p_{1,n}^{2,n-1} & \cdots & p_{1,n}^{m_n-1,n-1} \\ p_{2,n}^{1,n-1} & p_{2,n}^{2,n-1} & \cdots & p_{2,n}^{m_n-1,n-1} \\ \cdots & \cdots & \cdots & \cdots \\ p_{m_n,n}^{1,n-1} & p_{m_n,n}^{2,n-1} & \cdots & p_{m_n,n}^{m_n-1,n-1} \end{bmatrix} \cdots \begin{bmatrix} p_{1,3}^{1,2} & p_{1,3}^{2,2} & \cdots & p_{1,3}^{m_2,2} \\ p_{2,3}^{1,2} & p_{2,3}^{2,2} & \cdots & p_{2,3}^{m_2,2} \\ \cdots & \cdots & \cdots & \cdots \\ p_{m_3,3}^{1,2} & p_{m_3,3}^{2,2} & \cdots & p_{m_3,3}^{m_2,2} \end{bmatrix} \begin{bmatrix} p_{1,2}^{1,1} \\ p_{2,2}^{1,1} \\ \vdots \\ p_{m_2,2}^{1,1} \end{bmatrix} \tag{A-3}$$

where m_i is the number of elements at layer i and $p_{i,j}^{k,l}$ is the priority of element i at layer j with respect to element k at layer l .

B Judgment Matrices and Priority Vectors

B1. Hybrid Systems Attribute Weights

The judgment matrices of the hybrid system are taken from the previous study done in [62].

Level 2.1: Increased Utilization of Renewable Energy Technologies

Lack of Resource	1	1/7	3	1	1/3	0.0921
Inadequate Funding	7	1	9	5	1	0.4327
Public Acceptance	1/3	1/9	1	1/5	1/5	0.0389
Political Will	1	1/5	5	1	1/5	0.1032
Technology Immaturity	3	1	5	5	1	0.3330

Level 3.1: Lack of Resources

Government Incentive	1	1/7	1/5	1/9	0.0406
Privatization	7	1	3	1/3	0.2853
Economic Instruments	5	1/3	1	1/3	0.1490
Products Promotion	9	3	3	1	0.5252

Level 3.2: Inadequate Funding

Government Incentive	1	1/7	1/9	1/9	0.0351
Privatization	7	1	1/3	1/5	0.1446
Economic Instruments	9	3	1	1	0.3755
Products Promotion	9	5	1	1	0.4447

Level 3.3: Public Acceptance

Government Incentive	1	1/7	1/9	1/9	0.0368
Privatization	7	1	1	1	0.2933
Economic Instruments	9	1	1	1/3	0.2425
Products Promotion	9	1	3	1	0.4275

Level 3.4: Political Will

Government Incentive	1	7	7	5	0.6569
Privatization	1/7	1	1/3	1/3	0.0569
Economic Instruments	1/7	3	1	3	0.1776
Products Promotion	1/5	3	1/3	1	0.1086

Level 3.5: Technology Immaturity

Government Incentive	1	1/3	1/3	1/3	0.0927
Privatization	3	1	3	5	0.5356
Economic Instruments	3	1/3	1	1	0.1942
Products Promotion	3	1/5	1	1	0.1775

Level 4.1: Government Incentive

Cost	1	7	3	0.6694
Environmental Consideration	1/7	1	1/3	0.0879
Reliability	1/3	3	1	0.2426

Level 4.2: Privatization

Cost	1	7	5	0.7147
Environmental Consideration	1/7	1	1/5	0.0668
Reliability	1/5	5	1	0.2185

Level 4.3: Economic Instruments

Cost	1	7	5	0.7147
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Environmental Consideration	1/7	1	1/5	0.0668
Reliability	1/7	5	1	0.2185
<i>Level 4.4: Promotion of Products</i>				
Cost	1	1/5	1/7	0.0778
Environmental Consideration	5	1	1	0.4353
Reliability	7	1	1	0.4869

B2. Technology Cost Weights

The judgment matrices of the technology cost weights are taken from the previous study done in [9].

Level 2.1: Generation Technology Cost

Cost of Fuel	1	1/7	3	1	1/3	0.0921
Hardware Cost	7	1	9	5	1	0.4327
Maintenance Cost	1/3	1/9	1	1/5	1/5	0.0389
Auxiliary System	1	1/5	5	1	1/5	0.1032
Environmental Constraint	3	1	5	5	1	0.3330

Level 3.1: Cost of Fuel

Wind	1	1	1/9	1/7	0.0454
Solar	1	1	1/9	1/7	0.0454
Grid (Oil)	9	9	1	7	0.6920
Battery	7	7	1/7	1	0.2173

Level 3.2: Hardware Cost

Wind	1	3	1/3	7	0.3306
Solar	1/3	1	1/3	5	0.1804
Grid (Oil)	3	3	1	1	0.3811
Battery	1/7	1/5	1	1	0.1079

Level 3.3: Maintenance Cost

Wind	1	1	1/5	3	0.1574
Solar	1	1	1/5	3	0.1574
Grid (Oil)	5	5	1	5	0.6132
Battery	1/3	1/3	1/5	1	0.0721

Level 3.4: Auxiliary System

Wind	1	5	1/3	7	0.3037
Solar	1/5	1	1/5	5	0.1099
Grid (Oil)	3	5	1	9	0.5481
Battery	1/7	1/5	1/9	1	0.0383

Level 3.5: Environmental Constraint

Wind	1	1	7	5	0.3935
Solar	1	1/7	9	5	0.4419
Grid (Oil)	1/7	1/9	1	7	0.1164
Battery	1/5	1/5	1/7	1	0.0483

B3. Technology Benefit Weights

The judgment matrices of the technology benefit weights are taken from the previous study done in [9].

Level 2.1: Generation Technology Benefit

System Efficiency	1	3	1/3	1/7	3	1/7	0.0717
System Reliability	1/3	1	3	1/7	3	1/9	0.0743
Availability of Fuel	3	1/3	1	1/5	5	1/7	0.0844
National Security	7	7	5	1	9	3	0.4216
Social Benefits	1/3	1/3	1/5	1/9	1	1/3	0.0340
System Safety	7	9	7	1/3	3	1	0.3139

Level 3.1: System Efficiency

Wind	1	1/3	1/5	1/9	0.0576
Solar	3	1	1/3	1	0.1831
Grid (Oil)	5	3	1	3	0.4955
Battery	9	1	1/3	1	0.2638

Level 3.2: System Reliability

Wind	1	1/7	1/3	1/5	0.0539
Solar	7	3	7	3	0.5921
Grid (Oil)	3	1/7	1	1/3	0.1049
Battery	5	1/3	3	1	0.2490

Level 3.3: Availability of Fuel

Wind	1	3	9	5	0.5588
Solar	1/3	1	7	3	0.2645
Grid (Oil)	1/9	1/7	1	1/7	0.0367
Battery	1/5	1/3	7	1	0.1400

Level 3.4: National Security

Wind	1	3	9	3	0.5291
Solar	1/3	1	9	3	0.2999
Grid (Oil)	1/9	1/9	1	1/3	0.0428
Battery	1/3	1/3	3	1	0.1283

Level 3.5: Social Benefits

Wind	1	1/3	7	1/3	0.1836
Solar	3	1	7	1/3	0.3061
Grid (Oil)	1/7	1/7	1	1/3	0.0601
Battery	3	3	3	1	0.4502

Level 3.6: System Safety

Wind	1	1/9	1/7	1/3	0.0412
Solar	9	1	9	5	0.6214
Grid (Oil)	7	1/9	1	1/7	0.0991
Battery	3	5	7	1	0.2384

B4. Limited Resources Attribute Weights

The judgment matrices of the limited resources are taken from the compilation of Malaysia planning scheme in [78] and [79]. The author has used his scale from the importance aspects emphasized in the planning scheme for ten years planning horizon.

Level 2.1: Increase Self-sufficiency Level on Energy supply and Energy technology Requirements

Lack of Resources	1	5	3	1	1	7	0.2731
Public Awareness	1/5	1	1/5	1/3	1.7	1	0.0455
Insufficient Laws & Regulations	1/3	5	1	1/3	1/5	1/3	0.0828
Inadequate Funding	1	3	3	1	1/3	3	0.1776
Lack of Technology	1	7	5	3	1	5	0.3403
Reduced Life Quality	1/7	1	3	1/3	1/5	1	0.0807

Level 3.1: Lack of Resources

Polluters Pay Principles	1	1/9	1	3	5	1	1/3	1	0.1148
Economic Instruments	9	1	7	1	1/3	1/7	3	9	0.2069
Environmental Performance Standards	1	1/7	1	1	1	1/3	1/3	1	0.0478
Products Promotions	1/3	1	1	1	1	1/3	1/3	3	0.0623
Government Initiatives	1/5	3	1	1	1	1/5	1	3	0.1004
Resource Conservation Programs	1	7	3	3	5	1	7	9	0.3353
Privatization	3	1/3	3	3	1	1/7	1	5	0.1031
Enforced Laws and Regulations	1	1/9	1	1/3	1/3	1/9	1/5	1	0.0295

Level 3.2: Public Awareness

Polluters Pay Principles	1	1/5	3	1/5	1/3	3	5	1	0.0909
Economic Instruments	5	1	7	1/3	1	5	7	3	0.2299
Environmental Performance Standards	1/3	1/7	1	1/5	1/3	1	1/3	1/5	0.0311
Products Promotions	5	3	5	1	1	9	3	1	0.2541
Government Initiatives	3	1	3	1	1	5	3	3	0.1911
Resource Conservation Programs	1/3	1/5	1	1/9	1/5	1	1/3	1/7	0.0264
Privatization	1/5	1/7	3	1/3	1/3	3	1	1/3	0.0523
Enforced Laws and Regulations	1	1/3	5	1	1/3	7	3	1	0.1242

Level 3.3: Insufficient Laws & Regulations

Polluters Pay Principles	1	5	3	7	7	1	9	1	0.2656
Economic Instruments	1/5	1	1/7	1	1/3	1/3	3	1/7	0.0425
Environmental Performance Standards	1/3	7	1	5	3	1	3	1/3	0.1453
Products Promotions	1/7	1	1/5	1	1	1/3	1/3	3	0.0944
Government Initiatives	1/7	3	1/3	1	1	1	3	1/5	0.0643
Resource Conservation Programs	1	3	1	3	1	1	3	1/3	0.1159
Privatization	1/9	1/3	1/3	3	1/3	1/3	1	1/9	0.0482
Enforced Laws and Regulations	1	7	3	1/3	5	3	9	1	0.2238

Level 3.4: Inadequate Funding

Polluters Pay Principles	1	1	3	5	5	7	1/3	9	0.2356
Economic Instruments	1	1	5	3	3	5	1/3	7	0.1944
Environmental Performance Standards	1/3	1/5	1	1/3	1/5	3	1/3	1/5	0.0409
Products Promotions	1/5	1/3	3	1	1	3	1/5	1/3	0.0561
Government Initiatives	1/5	1/3	5	1	1	3	1/5	1	0.0709
Resource Conservation Programs	1/7	1/5	1/3	1/3	1/3	1	1/7	1/3	0.0240
Privatization	3	3	3	5	5	7	1	3	0.2975
Enforced Laws and Regulations	1/9	1/7	5	3	1	3	1/3	1	0.0809

Level 3.5: Lack of Technology

Polluters Pay Principles	1	1/3	5	5	3	7	1/3	1	0.1533
Economic Instruments	3	1	5	7	5	9	1	5	0.3029
Environmental Performance Standards	1/5	1/5	1	1/5	1/7	1	1/5	1/3	0.0259
Products Promotions	1/5	1/7	5	1	1/3	3	1/3	3	0.0734
Government Initiatives	1/3	1/5	7	3	1	3	1/3	5	0.1235
Resource Conservation Programs	1/7	1/9	1	1/3	1/3	1	1/7	1/9	0.0225
Privatization	3	1	5	3	3	7	1	3	0.2241

Enforced Laws and Regulations	1	1/5	3	1/3	1/5	9	1/3	1	0.0743
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Level 3.6: Reduced Life Quality

Polluters Pay Principles	1	1	5	5	3	1/5	3	1/3	0.1503
Economic Instruments	1	1	3	5	1/3	1/5	5	5	0.1416
Environmental Performance Standards	1/5	1/3	1	5	3	1/3	3	1	0.1010
Products Promotions	1/5	1/5	1/5	1	1/3	1/7	3	3	0.0501
Government Initiatives	1/3	3	1/3	3	1	1/3	7	3	0.1234
Resource Conservation Programs	5	5	3	7	3	1	9	5	0.3266
Privatization	1/3	1/5	1/3	1/3	1/7	1/9	1	1/5	0.0210
Enforced Laws and Regulations	3	1/5	1	1/3	1/3	1/5	5	1	0.0851

Level 4.1: Polluters Pay Principles

Cost	1	1	7	0.4869
CO2 Emissions	1	1	5	0.4353
Efficiency	1/7	1/5	1	0.0778

Level 4.2: Economic Instruments

Cost	1	9	3	0.6554
CO2 Emissions	1/9	1	1/7	0.0549
Efficiency	1/3	7	1	0.2897

Level 4.3: Environmental Performance Standards

Cost	1	1/3	3	0.2426
CO2 Emissions	3	1	7	0.6694
Efficiency	1/3	1/7	1	0.0879

Level 4.4: Products Promotions

Cost	1	5	1/3	0.2969
CO2 Emissions	1/5	1	1/5	0.0856
Efficiency	1/3	5	1	0.6175

Level 4.5: Government Initiatives

Cost	1	3	1	0.4286
CO2 Emissions	1/3	1	1/3	0.1429
Efficiency	1	3	1	0.4286

Level 4.6: Resource Conservation Programs

Cost	1	3	1/5	0.1884
CO2 Emissions	1/3	1	1/7	0.0810
Efficiency	5	7	1	0.7306

Level 4.7: Privatization

Cost	1	9	3	0.6716
CO2 Emissions	1/9	1	1/5	0.0629
Efficiency	1/3	5	1	0.2654

Level 4.8: Enforced Laws and Regulations

Cost	1	1/3	1/5	0.1104
CO2 Emissions	3	1	3	0.5666
Efficiency	5	1/3	1	0.3230

B5. Limited Resources Generation Cost and Benefit Weights

The judgment matrices of the limited resources generation cost and benefit are taken from the compilation of Malaysia planning scheme in [78]. The author has used his scale

from the importance aspects emphasized in the generation mix priority of Malaysia. The validity of this assumption is based on the current condition.

Level 2.1: Generation Cost and Benefit Aspect

Total Cost			1	1				0.5
Total Benefit			1	1				0.5

Level 3.1: Total Cost

Oil	1	3	1/3	7	9	5	1/3	0.1815
Coal	1/3	1	1/5	3	7	3	1/3	0.0971
Gas	3	5	1	5	7	7	1/2	0.2878
Hydro	1/7	1/3	1/5	1	2	1/3	1/7	0.0332
Solar	1/9	1/7	1/7	1/2	1	1/7	1/9	0.0203
Biomass	1/5	1/3	1/7	3	7	1	1/5	0.0619
Nuclear	3	3	2	1/7	9	5	1	0.3184

Level 3.2: Total Benefit

Oil	1	2	1/2	1/5	1/7	2	1	0.0637
Coal	1/2	1	1/5	1/7	1/9	1/2	1/2	0.0308
Gas	2	5	1	1/3	1/5	3	2	0.1161
Hydro	5	7	3	1	1/2	3	7	0.2568
Solar	7	9	5	2	1	7	9	0.4255
Biomass	1/2	2	1/3	1/3	1/7	1	2	0.0597
Nuclear	1	2	1/2	1/7	1/9	1/2	1	0.0475