RISK MANAGEMENT OF FUEL PRICE UNCERTAINTY
IN ELECTRIC POWER PLANNING

by

Artur P. Niemczewski
Master of Science in Engineering, Warsaw Technical University, 1989

Submitted to the Department of Nuclear Engineering
and the Technology and Policy Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Technology and Policy

at the

Massachusetts Institute of Technology

June 1995

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Abstract

Long-term strategic planning in the electric power industry is an extremely difficult and controversial process. Because the industry is so vital to the functioning of the society, the planning process is not solely confined to company decision-makers but is also subject of a very heated public policy debate. The planning process is further complicated by significant uncertainty about future events impacting characteristics and delivery of electric service. These uncertainties, when discussed in a public forum, intensify controversies surrounding the industry. Among others, the uncertainty in future fuel prices is a source of considerable economic and environmental risk.

In this thesis we propose a risk management methodology that can be applied to problems involving future forecasting uncertainty (here, fuel price uncertainty) and integrate it with the on-going planning efforts at the MIT Energy Laboratory. Using the Robustness-Criterion, a quantitative volatility measure, and the Probability Sensitivity Analysis, an assessment of susceptibility to forecasting uncertainty, we examine a large number of potential regional power-system development strategies, prepared by the MIT Analysis Group for Regional Electricity Alternatives, and seek a class of decisions leading to options robust against fuel price uncertainty.

We identify two complementary risk-mitigation measures: (1) spot-gas contracting significantly reduces electric service cost volatility whereas (2) aggressive demand-side management (DSM) programs substantially limit environmental
pollution variability. The above result, confirmed by industry experts, is obtained in a very rigorous and quantitative fashion without any prior knowledge or belief. It is the author's hope that the Robustness-Criterion and the Probability Sensitivity Analysis will become valuable analytic tools in the utility-industry public policy debate, where a quantitative proof, not a belief, is required to support often controversial measures. Moreover, the risk management decision support tools developed in this thesis can be applied to a much broader class of problems: whenever critical decisions are dependent upon uncertain variables for which precise forecasts are unavailable.

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Chapter 1

Motivation and goals of the thesis

1.1 Importance of fuel cost risk mitigation

As the oil crisis of the 1970s demonstrated, electric power generation is very susceptible to changes in fuel price and availability [1]. Not only the economic dispatch of existing generating units is affected but also the decisions of capacity additions for future needs. Planning for future generating capacity is of particular importance because of the very nature of capital investments in the electric power industry. Those investments are typically very long lived (20-60 yrs.) with long lead times (3-10 yrs. including licensing). Therefore the choices of generating capacity mix made today determine economic results for decades into the future. The uncertainty in future fuel prices and availability is the source of considerable economic and environmental risks. Not surprisingly electric utility companies and independent power producers seek strategic planning methods which will allow to predict, or at least, manage this risk.

The work presented here focuses specifically on natural gas price uncertainty as this fuel is currently in the center of attention due to the superior environmental and economic performance of gas-combined cycle power plants [2]. Natural gas (and to some extend heating oil) is the primary fuel for most of the planned capacity additions in New England. According to MIT Energy Laboratory analysis
(see Section 3.5), strategic decisions of New England electric utility companies are very susceptible to natural gas cost and availability uncertainties. Moreover, despite recently (2-3 years) observed steady gas prices, there are no intrinsic mechanisms to assure future stability of a gas market.

As an example, Fig. 1-1 demonstrates variability of the electric service costs resulting from the future natural gas cost uncertainty. The plot shows economic (cost of electric service) and environmental (carbon dioxide emission -CO2) performance of 480 potential New England power system development strategies. The center points depict the nominal forecast performance and the error bars, the extreme cost behavior for the potential natural gas price trajectories. The variability in CO2-emissions, which is of the same order as cost variability, is omitted for picture clarity. Even though the graph shows variability of one performance measure only, it clearly reflects a need for an analytic tool to assist in prudent decision-making under conditions of significant uncertainty. Such a tool is proposed in this thesis.

1.2 Power-industry planning and public policy debate

The electric power industry provides public service to a community consisting of residential, commercial, industrial, and institutional customers. As such, it is vital to the very functioning of the society and like other utility industries it is closely monitored by community representatives, i.e., state and federal regulatory agencies. Thus every long-term decision, impacting electricity rate, service reliability, or environmental pollution, is carefully watched by communities and is subjected to a regulatory supervision.
Fig. 1-1: Our lack of knowledge about future events may be a source of significant risk. Here vertical error bars indicate variability in electric service cost, for 480 potential New England power-system development strategies, resulting from natural gas price uncertainty.
The long-term strategic planning, which will be discussed in the thesis, is not solely confined to electric-utility company planners but also involves industry regulators, rate payers, and environmental advocates (see Section 2.1). State regulators actually approve the decisions and examine their prudence. Other stakeholders also participate actively in the debate and often significantly influence the decisions. Since the choices made by power-industry decision-makers do not only have to benefit the industry itself, but most importantly, the recipients of the service, they often spur a very heated and sometimes emotional debate. Even as the US power industry ownership structure changes as a result of on-going restructuring, the electric service is so vital to the functioning of the society that a control mechanism will remain in place, possibly in a somewhat redesigned form [3].

In a regulatory debate often there is a need to prove that the decisions were made using best available information to the best public benefit, in short, that they were prudent choices. These decisions become even more difficult and controversial, when they involve significant uncertainty [4]; which is the case with future fuel cost. Decisions made today based on a single, narrow view of the future may in hind-sight prove to be catastrophic (as was the case, for example, with many nuclear power projects during the 1970s-1980s [5]). On the other hand, twenty years from now, with the advantage of hind-sight, it will be easy to point to what the best power-industry development path could have been. The decisions made today, however, rely on information available today, and reflect our lack of knowledge about future events. Therefore these decisions have to include contingencies, i.e., include an “insurance policy” against unfavorable future outcomes [6].
Quite often industry analysts have the knowledge, dictated by their experience and supported by modeling, of potential well performing and robust future development strategies. In these cases the important problem is not only to identify risk-mitigation measures (e.g. DSM programs, emission reduction technologies) but to prove rigorously their benefit offsetting additional cost. There is a clear need for an analytic tool that can be used not only to support decision-making but also to aid in a regulatory discussion of risk-mitigation issues. Such a tool would help to quantify relative insensitivity or robustness of a given decision or class of decisions against uncertain futures. To avoid additional controversies, the tool has to be well founded in mathematical grounds and has to be accepted by all public policy debate participants.

In this thesis we propose a risk-mitigation analytic tool that hopefully can be of use in a broad sense of decision-making and regulatory debate. It is the author’s wish that the methodology proposed here will be used in practical situations involving decision-making to the public benefit.

1.3 Thesis goals and outline

There are two main goals of this thesis:

(1) Propose a risk management methodology that can be applied to problems involving future forecasting uncertainty and integrate it with the on-going planning efforts at the MIT Energy Laboratory.

(2) Apply the methodology to a very important problem of the fuel price uncertainty in the electric power planning and identify the class of decisions leading to robust strategies against this uncertainty.
The thesis is organized into three main sections:

(1) Review:
Chapter 2 reviews the methodology used by the Analysis Group for Regional Electricity Alternatives (AGREA) at the MIT Energy Laboratory and its participation in public policy debate and power-industry decision-making. Chapter 3 reviews the results of a specific New England power-industry study encompassing the period 1992-2011, presented by the AGREA-team to the advisory group in January 1994. These results are used as a starting point to illustrate the methods of the thesis.

(2) New concepts:
The concepts of variability quantification and risk management using a Robustness-Criterion and a Probability Sensitivity Analysis are introduced in Chapters 4 and 5 with additional results presented in Appendix A.

(3) Results and conclusions:
Chapter 6 draws conclusions based on the input data, reviewed in Chapter 3, using the methodology introduced in Chapters 4 and 5. A class of decisions in the long-term power-industry strategic planning is identified that minimize risk-exposure to fuel cost uncertainty. Finally, Chapter 7 summarizes the methodology proposed here and its potential role in a public policy debate and power-industry decision-making.
Chapter 2

Analysis Group for Regional Electricity Alternatives

2.1 Open planning process

The Analysis Group for Regional Electricity Alternatives (AGREA) was formed in 1988 at the Massachusetts Institute of Technology Energy Laboratory to assist in electric utility planning for the New England region [7]. The task of the AGREA-analysis team is not to take-over the decision-making itself but rather to facilitate and inform the public policy debate about the future shape of the electric power industry in New England.

The planning process is highly interactive - the AGREA analysis team meets on a regular basis with an advisory group of utility executives and planners, large electricity customers, state regulators, and environmental group representatives. Hence the name “Open Planning Process” is often used to describe such a broad debate. The interaction between the analysis team and the advisory group is shown schematically on Fig. 2-1.

During the meetings the advisory group identifies major areas of concern and defines the scope of a quantitative analysis to be performed by the analysis team. Both groups define and quantify input assumptions, range of available decision options and performance attributes (measuring impact of potential future
decisions). At a subsequent meeting the AGREA team presents analysis results and suggests areas of further more detailed studies. Based on the analysis results, input data, decision options, or performance measures may all be redefined (revised) to reflect more detailed or completely new areas of interest to the advisory group (this was the case, for example, with electric vehicle study during the 1994-95 meetings).

The whole process: discussion → data → analysis → results → discussion, is repeated continuously. These iterations of the open planning process improve significantly the quality of the end product and assure its relevance to the current needs of power industry and public policy debate.

2.2 EGEAS - the modeling tool used by the AGREA team

For the modeling purposes the analysis team uses the Electric Generation Expansion Analysis System (EGEAS), a multi-platform computer program. EGEAS, now an industry standard production-costing model, was developed by MIT and Stone and Webster, Inc. in the early 1980s [8]. The model simulates the operation and planning of the New England electric power system by dispatching units, building new supply, retiring existing generation, and meeting emissions constraints. EGEAS crudely approximates transmission costs and maintenance but does not model the transmission and distribution system [9].

A very specific input data include fuel costs, unit types, sizes and heat rates at an individual plant level (either for existing or planned capacity) as well as hourly, weekly, and seasonal load characteristics for the entire New England region. The
EGEAS model simulates economic performance for each individual scenario and each possible future (described in the next section). The model delivers a very detailed information (seasonal, annual, or aggregate) about economic performance, environmental impacts, and service reliability of the New England power system. Each individual decision strategy with each specific set of assumed future conditions requires one EGEAS simulation.

2.3 Scenario-based multi-attribute tradeoff analysis

AGREA-group's successful contribution to the industry planning is in part due to the planning methodology pioneered by the group founders: scenario-based multi-attribute tradeoff analysis [10]. Graphically depicted on Fig. 2-2, the analysis involves four important steps, outlined below:

(1) Initially, the debate participants define relevant issues to be included in the analysis. More specifically, the advisory group and the analysis team agree on a set of performance criteria of interest, which may include, for example, financial results, environmental impact, service reliability, etc. These define metrics, against which various strategies will be evaluated.

(2) Next, the two groups identify important decision categories, e.g., new capacity additions, DSM programs, pollution control technologies, etc. Subsequently they define feasible choices that can be made within each of the decision categories. The full list of decision categories and options considered in the analysis described in this thesis is listed in Table 3-1.
Key Steps of the Scenario-Based Multi-Attribute Tradeoff Analysis

1) Identify Issues and Attributes

2) Develop Scenarios

3) Analyze Scenario Data & Invent Better Strategies

4) Assess Tradeoffs & Seek Consensus

Fig. 2-2: Scenario-based multi-attribute tradeoff analysis is the core planning methodology pioneered and implemented by the AGREA-planning group of the MIT Energy Laboratory.
A complete set of decisions, i.e. one choice from every category, forms a strategy, or a decision vector. Since these strategies result from a combination of all possible choices, the full strategy set is very large:

\[ N_{\text{Strategies}} = \prod_{i=1}^{N} n_i \]  \hspace{1cm} (2.1)

where:

- \( N_{\text{Strategies}} \) - is the number of all possible strategies;
- \( N \) - is the number of decision categories;
- \( n_i \) - is the number of possible decisions in category “i”.

The “Diversity” scenario set, described in the following chapter, consists of 480 strategies. Each decision within each option set has a code letter abbreviation. The alternatives considered here and their letter codes are identified again in Table 3-1. The code letters allow for cryptic, but pronounceable names for the strategies, such as GISEVER or WAMIVEC.

Similarly, uncertain variables are grouped into categories, e.g., fuel price, load growth, etc., and possible outcomes within each category are identified. A complete set of realizations of all uncertain variables is referred to as a future, or an assumption vector. The futures combined with the strategies form scenarios. A scenario set results from a combination of all accepted strategies with all considered futures. A full scenario set is bigger than the strategy set:

\[ N_{\text{Scenarios}} = N_{\text{Strategies}} \cdot \prod_{j=1}^{M} m_j \]  \hspace{1cm} (2.2)

where:
NScenarios  - is the number of all possible scenarios;
M      - is the number of uncertain variable categories;
mj   - is the number of possible outcomes in category “j”.

The “Diversity” scenario set (described in Chapter 3), contains 4 futures, differing by gas price trajectory only, resulting in 1920 scenarios.

To better understand the scenario-based multi-attribute tradeoff analysis it may be helpful to invoke a decision-tree analogy. Each strategy can be interpreted as a branch of a decision tree, resulting from having chosen specific options at decision nodes. Each future (uncontrolled variable) can be interpreted as a chance node of a decision tree, leading to a certain future outcome resulting from a combination of decisions made and specific events having occurred in the future. Each individual scenario is then equivalent to a final branch in this decision-tree analogy. Hence the part of the method name: “scenario-based” implies that the scenarios are elementary building blocks of the analysis.

After having defined a comprehensive scenario set, the analysis group models each individual scenario, using the EGEAS program, described in the previous section. EGEAS optimizes performance of each scenario, within its bounds, and calculates the performance criteria defined in Step 1.

(3) As the next step, the analysis group evaluates all scenarios against performance attributes, examining effects of decisions made earlier and effects of uncertain variables. Very specifically no attempt is made to reduce multiple performance criteria to a single objective function, such as a monetary measure. Such approach would require too many unfounded
assumptions about, among others, the time value of money, the societal value of health and clean environment. For example, the widely adopted (and criticized) environmental emission adders are not included in the AGREA analysis. Instead, the analysis results are presented, both graphically and numerically, for all attributes of interest. Hence the part of the method name: “multi-attribute”.

Most of the results are plotted for attribute pairs (as an example on Fig. 3-3 shows) or triplets only because the graphical representation of data is limited to two or three dimensions.

(4) The final step of the analysis requires a deep involvement of the advisory-group members. At this step the results for all scenarios are compared on tradeoff graphs and tables, where a set of superior choices can be identified.

As an example let us concentrate on a pair of attributes only, as two attributes can be conveniently represented on a two-dimensional graph (Fig. 2-2). If axes of the attributes are oriented such that smaller is better, than the optimal strategies will be plotted closest to the origin. All of the plotted strategies can be classified into two groups:

(a) decision set,

(b) dominated set.

The dominated set consists of strategies that are inferior to others with respect to both attributes simultaneously. The remaining strategies constitute the decision set. The decision set outlines the boundary of the entire strategy set nearest to the origin, hence the decision set is often called a decision frontier (this name will also be used in subsequent chapters).
The answer often delivered by the analysis-team is not a single "best strategy" or a single "best decision" but a range of strategies and corresponding class of decisions that optimize the outcome from a specific perspective. Even if it was possible to identify a single most preferred strategy, that would be dangerous because of inherent inaccuracies and uncertainties hidden in the input data (e.g., Section 3.3). Similarly, the work reported in this thesis results in a class of decisions (presented in Chapter 6) rather than in a single "best strategy".

The final consensus decision depends on a specific set of values represented by decision makers. An individual or a group of stakeholders makes final tradeoffs between various attributes based on a set of values that are neither imposed nor even suggested by the AGREA-analysis team. Hence the last adjective "tradeoff" in the methodology name implies that there is no one single best strategy, but the final choice would result from a tradeoff between different performance measures.

As mentioned earlier, the steps 1-4 are continuously repeated, each time focusing on current issues of highest importance to the power-industry debate participants.

In summary, the scenario-based multi-attribute tradeoff analysis involves: preparing scenarios - elementary building blocks of the analysis; evaluating scenarios against multiple attributes; and making final tradeoffs in strategy selection.
2.4 Current treatment of uncertainty within the AGREA-analysis

Refined over the years, the scenario-based multi-attribute tradeoff analysis presents an example of a very sophisticated approach towards power-industry strategic planning. The only slightly underdeveloped part is the treatment of uncertainty, which currently is performed as a sensitivity study within the AGREA-analysis. One of the main goals of the work presented here is to introduce an uncertainty quantification and risk management technique that can be efficiently and effectively integrated with the rest of the scenario-based multi-attribute tradeoff analysis. The main concepts will be presented in Chapters 4 and 5. In this section we briefly outline the existing treatment of uncertainty.

The AGREA-team, advised by the debate participants (by definition each being an expert in one or more aspect of the power industry) prepares a set of possible future realizations of uncertain variables, e.g., gas price trajectories, shown on Fig. 3-1. Members of the AGREA-team assume as little as possible about these price trajectories. In fact they are referred to as uncertainties, not forecasts. The EGEAS modeling is performed for every assumed trajectory separately. The results are then again compared in a tradeoff fashion, where variation in performance of a given strategy is graphically observed (e.g., Figs. 3-2 through 3-4) or assessed in a tabulated form. This approach is actually equivalent to a multiple scenario sensitivity analysis, where varied parameter is the future gas price trajectory.

Whereas the sensitivity analysis approach addresses the problem of uncertainty about future events, it does not distinguish between the controlled and uncontrolled variables. There is no difference between choosing a gas based generation vs. a coal based one and choosing between cheap and expensive gas.
Out of these two decisions only the first one belongs to the decision maker. The second one results from economic conditions encountered in the future.

The attempts to quantify impact of uncertain futures within the scenario-based multi-attribute tradeoff analysis framework have been made earlier by Andrews and Schenler. Andrews [11] did include a standard deviation calculation across equally weighted futures, but he did not seek to specifically minimize strategy variability. Schenler [12] used probability distributions of future events elicited from decision stakeholders (in his case: managers at a particular utility company) to build tradeoff graphs that reflected a single individual's (or group's) perspective on future events. Whereas his methodology facilitates decision-making for a specific group, it has a limited practical applicability to risk-management problems.
Chapter 3

Review of the January 1994 “Diversity” scenario set

The AGREA analysis results presented during the January 1994 advisory group meeting contained the most comprehensive set of decision options and potential gas price trajectories. Hence this set of data serves well as a starting point for the demonstration of a risk management technique of fuel price uncertainty. The following chapter reviews only the main points of the January 1994 analysis with its results and recommendations. Full details can be found elsewhere [13].

3.1 Decision categories

During discussions with the power-industry stakeholders the following decision categories were identified as the most significant ones:

1. technology mix of new generating capacity addition;
2. intensity of demand-side management (DSM) programs;
3. type of new natural gas contracts;
4. existing unit longevity;
5. sulfur dioxide emission reduction;
6. nitrogen oxide emission reduction;
7. treatment of emission control cost in dispatch logic;
8. time of nuclear unit decommissioning.

<table>
<thead>
<tr>
<th>Technology Mixes</th>
<th>Levels of DSM</th>
<th>New Gas Contracts</th>
<th>Unit Longevity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas/Oil</td>
<td>G</td>
<td>&quot;Spot&quot; Gas-Dispatch</td>
<td>S</td>
</tr>
<tr>
<td>Gas/Oil &amp; Clean Coal</td>
<td>H</td>
<td>1992 Utility Programs</td>
<td>&quot;Essential&quot; Rpwr/Retire</td>
</tr>
<tr>
<td>Gas/Oil &amp; Wind</td>
<td>W</td>
<td>Double Conservation</td>
<td>&quot;Moderate&quot; Rpwr/Retire</td>
</tr>
<tr>
<td>Gas/Oil, Coal &amp; Wind</td>
<td>D</td>
<td>Triple Conservation</td>
<td>&quot;Aggressive&quot; Rpwr/Retire</td>
</tr>
<tr>
<td>G/O, Coal, Wind &amp; Biom</td>
<td>K</td>
<td>Triple C &amp; I Conservation</td>
<td>Life Extension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Delay 1992 Programs</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Delay Double Conservation</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CAAA Title IV-SO2:</th>
<th>CAAA Title I-NOx:</th>
<th>Emissions O&amp;M Logic</th>
<th>Early Nuclear Decom.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meet Title IV &amp; State Regs.</td>
<td>No NOx Controls°</td>
<td>Economic/Var. O&amp;M</td>
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<tr>
<td>Borderline Fuel Switch (Trading)</td>
<td>Phase I-RACT/State SIPs</td>
<td>Social/Fixed O&amp;M</td>
<td>(Utility Choice)</td>
</tr>
<tr>
<td></td>
<td>Hypothetical Phase II-Firm</td>
<td>V</td>
<td>Five Year Early Decommission</td>
</tr>
<tr>
<td></td>
<td>Hypothetical Phase II-Harc</td>
<td>End of License</td>
<td>(possible sensitivity analysis)</td>
</tr>
</tbody>
</table>

Table 3-1: Decision categories and options considered within the January 1994 “Diversity” scenario set. Only the decision options with letter codes (bullets) were specifically included in the analysis.
Table 3-1 lists the decision categories, together with the options considered in the “Diversity” scenario set. The options with the letter abbreviations (or bullet points) were included in the analysis. The options without the letter abbreviations were not modeled during the January 1994 study period and are not discussed here but are listed for completeness. Some decision categories (SO2-control, dispatch logic, and nuclear decommissioning) contain a single option. These are the issues identified as potentially important, however, not yet fully investigated within the “Diversity” scenario set. Some of these options were subsequently modeled at later stages of the analysis [14].

(1) The most important strategic decision is new generating capacity addition. In the AGREA planning process the absolute level and timing of new capacity installation is predetermined, using an “imperfect” capacity planning program, which recognizes the different lead times of different generation technologies and attempts to balance different generation types with anticipate future load requirements. The analyst provides the information about desired technology mix. Table 3-2 lists five technology-mix options suggested by the advisory group members, together with some of the technical details of the generation technologies considered. Fossil fuel technologies are considered as variable capacity additions (i.e., added in small increments), whereas renewable technologies are added to the system in fixed increments.

(2) Demand-side management (DSM) plays an important role in both reducing peak energy demand and displacing generating capacity. Table 3-3 summarizes impact and cost of considered DSM alternatives. The reference level of energy savings (option R) was based on 1992 projections of utility-
<table>
<thead>
<tr>
<th>Technology Mix Option</th>
<th>Variable Capacity Technologies</th>
<th>Fixed Capacity Techs</th>
<th>Load-Time</th>
<th>Fixed Heat Rate</th>
<th>O&amp;M Cost</th>
<th>O&amp;M Lead-Time</th>
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<tbody>
<tr>
<td>ACT</td>
<td>13% Gas/Oil &amp; Clean Coal Techs</td>
<td>87% Gas/Oil Techs</td>
<td>3.47</td>
<td>10,900</td>
<td>375</td>
<td>5</td>
</tr>
<tr>
<td>G</td>
<td>13% Gas/Oil &amp; Clean Coal Techs</td>
<td>87% Gas/Oil Techs</td>
<td>3.75</td>
<td>10,900</td>
<td>375</td>
<td>5</td>
</tr>
<tr>
<td>H</td>
<td>13% Gas/Oil &amp; Wind Techs</td>
<td>87% Gas/Oil Techs</td>
<td>3.75</td>
<td>10,900</td>
<td>375</td>
<td>5</td>
</tr>
<tr>
<td>W</td>
<td>13% Gas/Oil &amp; Wind Techs</td>
<td>87% Gas/Oil Techs</td>
<td>3.75</td>
<td>10,900</td>
<td>375</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>13% Gas/Oil &amp; Wind Techs</td>
<td>87% Gas/Oil Techs</td>
<td>3.75</td>
<td>10,900</td>
<td>375</td>
<td>5</td>
</tr>
<tr>
<td>K</td>
<td>13% Gas/Oil &amp; Wind Techs</td>
<td>87% Gas/Oil Techs</td>
<td>3.75</td>
<td>10,900</td>
<td>375</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.2: Technology mix options of new generating capacity additions considered within the “Diversity” scenario set together with the technical and economic characteristic of each technology type.
sponsored DSM. Option D corresponds to double conservation from the reference level, and option C, to triple conservation but only for commercial and industrial customers, with residential customer DSM programs held at the reference level.

(3) The next important decision category is type of natural gas contracting. One obvious alternative is spot-market purchasing. The gas units are then subjected to economic dispatch. Second modeled alternative is fixed gas contracting, where 70% of the gas fired capacity is dispatched independent of gas cost (the remaining 30% relies on spot-market purchasing); this corresponds to so-called “take or pay” gas contracting. For simplicity it assumed that the spot-market and fixed-contract natural gas prices follow the same trajectory over the study period.

(4) The existing unit longevity decision category addresses the percentage of the currently operating capacity that may be phased-out during the study period from 0% to 10% and 20% for the I,O, and A options respectively.

(5) For the “Diversity” scenario set only full SO2-control technology compliance with the Title IV (acid rain) of the 1990 Clean Air Act Amendments (CAAA) was considered. See an earlier author’s work for a detailed discussion of decision-making options in complying with this novel SO2-emssion regulation [15].

(6) In addition to CAAA Title I (ozone) reasonably-achievable-control-technology (RACT) of NOx emission, two other options were included in the analysis. Phase-II Firm and Phase-II Hard control aim at reducing NOx emissions by 60% and 80% from 1990 levels by the year 2000, respectively.
<table>
<thead>
<tr>
<th>Level of Demand-Side Mgt.</th>
<th>2011 Peak Demand</th>
<th>Levelized Direct Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peak</td>
<td>Growth</td>
</tr>
<tr>
<td>No Utility DSM: N</td>
<td>32408</td>
<td>2.51</td>
</tr>
<tr>
<td>1992 Reference DSM: R</td>
<td>29140</td>
<td>1.97</td>
</tr>
<tr>
<td>Double Conservation: D</td>
<td>26281</td>
<td>1.44</td>
</tr>
<tr>
<td>Triple C&amp;I Conserv.: C</td>
<td>24170</td>
<td>1.02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Level of Demand-Side Mgt.</th>
<th>2011 Electricity Demand</th>
<th>'92-'11 Cumulative Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Demand</td>
<td>Growth</td>
</tr>
<tr>
<td>No Utility DSM: N</td>
<td>166,554</td>
<td>2.04</td>
</tr>
<tr>
<td>1992 Reference DSM: R</td>
<td>154,772</td>
<td>1.67</td>
</tr>
<tr>
<td>Double Conservation: D</td>
<td>142,730</td>
<td>1.26</td>
</tr>
<tr>
<td>Triple C&amp;I Conserv.: C</td>
<td>134,894</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 3-3: Demand-side management (DSM) options included within the “Diversity” scenario set. Tables summarize projected impact of the considered DSM alternatives, as well as their levelized cost.
The issue of the most efficient and effective NO\textsubscript{X} controls was examined in the AGREA context by Goldman [16].

(7) For the “Diversity” scenario set only the economic dispatch logic was considered, i.e., variable O&M costs of emission controls were fully included in the dispatch decisions.

(8) At this stage of analysis no nuclear units longevity alterations were examined.

In summary, the above set of decision options is clearly not an exhaustive one, it reflects, however, the most burning issues of the New England power-industry debate, as expressed by the stakeholders. Again, the decision options are not fixed; in contrary, they are updated as analysis progresses to reflect changing focus of the debate. The decision option set described above is merely used to illustrate the points of the thesis.

### 3.2 Performance attributes of interest

Table 3-4 summarizes the key economic performance and environmental impact attributes, that are of interest to the debate stakeholders. This is already a substantially narrowed selection out of over one hundred performance attributes calculated for each scenario by the EGEAS model.

Since the goal of the thesis is primarily to illustrate a risk management methodology, only two attributes were selected for further detailed considerations. Focusing on two attributes greatly simplifies presentation of data; it is important to
<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>NPV Calculation (r=11.4%) Units</th>
<th>Code</th>
<th>Inflation Adjusted (r=3.8%) Units</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total/Regional Direct Cost:</td>
<td>1991$B-NPV</td>
<td>TDCn</td>
<td>1991$B-IA</td>
<td>TDCi</td>
</tr>
<tr>
<td>Total Industry Direct Cost:</td>
<td>1991$B-NPV</td>
<td>TUDCn</td>
<td>1991$B-IA</td>
<td>TUDCi</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>Regional Unit Cost Units</th>
<th>Code</th>
<th>Industry Unit Cost Units</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave. Cost of Electricity:</td>
<td>1991¢/kWh-IA</td>
<td>TDELa</td>
<td>1991¢/kWh-IA</td>
<td>TUELa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Oxides:</td>
<td>Million Tons</td>
<td>NOx</td>
<td>% of 1990 Em.</td>
<td>NOxP94</td>
</tr>
<tr>
<td>Carbon Dioxide:</td>
<td>Million Tons</td>
<td>CO2</td>
<td>% of 1990 Em.</td>
<td>CO2P94</td>
</tr>
<tr>
<td>Sulfur Dioxide:</td>
<td>Million Tons</td>
<td>SO2</td>
<td>% of 1990 Em.</td>
<td>SO2P94</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Performance Attribute</th>
<th>In-Year (‘96,’01,’11) Units</th>
<th>Code</th>
<th>In-Year–1990 Comparison Units</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen Oxides:</td>
<td>Thousand Tons</td>
<td>NOxSxx</td>
<td>% of 1990 Em.</td>
<td>NOxPxx</td>
</tr>
<tr>
<td>Carbon Dioxide:</td>
<td>Thousand Tons</td>
<td>CO2Sxx</td>
<td>% of 1990 Em.</td>
<td>CO2Pxx</td>
</tr>
<tr>
<td>Sulfur Dioxide:</td>
<td>Thousand Tons</td>
<td>SO2Sxx</td>
<td>% of 1990 Em.</td>
<td>SO2Pxx</td>
</tr>
</tbody>
</table>

Table 3-4: Primary economic performance and environmental impact attributes calculated by EGEAS.
stress, however, that the methodology outlined in the subsequent chapters can be applied to any attributes of interest.

"Total Regional Direct Cost of Electric Service - NPV (TDCn)", is possibly the single most aggregate economic performance measure of a strategy. It includes both the utility and customer (e.g., through DSM-participation) costs for both, electricity consumption and conservation. This total regional cost is expressed in 1991 $ at a standard utility cost of capital discount rate: 11.4%.

"Cumulative Carbon Dioxide Emissions (CO2)", reflects environmental impact of a given strategy relative to the issue of global climate change. "CO2" is a simple sum of all power generation carbon dioxide missions (excluding biomass-power emission) over the planning horizon, expressed in tons. Out of the three air pollutants listed in Table 3-4, carbon dioxide is the most controversial one. Sulfur dioxide and nitrogen oxides are already regulated by the 1990 Clean Air Act Amendments and there is little doubt about the necessity of control technology installations. In contrast, a potential future regulation of CO2-emission in the US is a subject of a very heated debate. Thus this pollutant is especially interesting from the perspective of a risk-mitigation planning.

The two performance attributes "TDCn" and "CO2" were selected to illustrate the risk mitigation methodology. As a reference, the AGREA January 1994 results are presented also for these two attributes in Section 3.5.
3.3 Study period and limiting assumptions

Since the AGREA database includes every existing and potentially planned power generating unit in all New England states, its updating is extremely laborious. In contrast to the analysis, which is reiterated four times a year, the full database update is performed at 2-4 year intervals. The last, most complete update was performed in 1991. Hence the year 1992 serves as the beginning of the study period, extending through the year 2011. Similarly, all future projections, including the fuel price trajectories described in the next section, were prepared for the 1992-2011 study period.

One of the most important assumptions underlying any power-sector planning effort is future electric load growth. The investigation of impact of load growth uncertainty, even though possible with the tools proposed here, is not the subject of this thesis. Thus only one load growth trajectory is included in the analysis. The NEPOOL 1993 “CELT” report [17] forecasted a 1.92%/yr. electric energy demand growth with a 2.07%/yr. peak load growth in the New England region. The AGREA analysts chose to adjust this forecast to account for economic cycles. The assumptions included in the “Diversity” scenario set are 1.67%/yr. and 1.97%/yr. for energy demand and peak load growth respectively [18]. Only after the AGREA analysis presented here had been completed, the new NEPOOL 1994 “CELT” report [19] substantially revised previous growth forecasts downward, to 1.28%/yr. and 1.06%/yr. for energy demand and peak load growth respectively. Therefore the absolute results presented in the subsequent chapters have to be used with caution because of this discrepancy in expected load growth.

Additionally, the energy efficiency effects of new legislation were not taken into account during the analysis. The 1992 Energy Policy Act efficiency standards will
affect overall utility DSM portfolios in the future. Thus the 1992 reference utility DSM programs included here (Section 3.1) will most likely be revised.

Despite the above limitations, however, the AGREA January 1994 “Diversity” scenario set is the most complete database of potential regional power-system development strategies and as such it is suitable to test a methodology or to draw qualitative conclusions. Having understood the limitations of the data set at hand we will proceed with caution to examine the main point of this work: fuel price uncertainty.

3.4 Fuel price trajectories

Four potential natural gas price trajectories were prepared by the AGREA-team, following the advisory group guidance. Fig 3-1 shows the four gas trajectories together with the distillate oil (oil 2), residual oil (oil 6 -0.5%S), and coal (3%S) price trajectories, all expressed in 1991 $.

The coal, oil, and reference gas (base trajectory) prices follow the NEPOOL 1992 forecasts [20]. A historical fuel market volatility was examined using data reported by the Department of Energy’s Energy Information Agency [21]. These data were used to build an year-to-year variation distribution function for every fuel. The NEPOOL forecasts were then modified to include stochastic noise, sampled from the distribution function, characteristic for each fuel. The price trajectories shown on Fig. 3-1 result from the superposition of the assumed long-term trends and the expected year-to-year volatility.
C–COMPETITIVE/LOW NATURAL GAS COSTS,
B–STABLE/BASE GAS COSTS, G–GAS CONSTRAINT/HIGH GAS COST,
X–EXTRA-REGIONAL CONSTRAINT/EXORBITANT GAS COSTS

Fig. 3-1: Fuel price trajectories used in the analysis, including four natural gas price uncertainties (C–competitive/low, B-stable/base, G-gas constraint/high, X-extra-regional constraint/exorbitant).
The four natural gas price trajectories were prepared as follows:

B - "Base/stable" is analogous to NEPOOL GTF prediction with year-to-year volatility;

C - "Competitive/low" natural gas costs follow closely the residual oil price;

G - "Gas constraint/high" costs correspond to a 10% premium over the distillate oil cost, due to inter-regional limits on availability;

X - "eXorbitant" cost corresponds to a 15% premium over the distillate oil, due to extra-regional limits on availability.

Both G and X trajectories result from hypothetical gas-pipeline infrastructure constraints. If the natural gas consumption in New England (total of residential, commercial, and utility) continues to increase at its historic pace then the existing pipeline network will reach its capacity limit around the year 2000, unless substantial new capital investments are committed. The difference between G and X futures is that the first assumes inter-regional (pipeline constraints into New England) and the second, extra-regional (constraints into the North-East U.S.) capacity constraints. The G trajectory corresponds to a 10% premium over the distillate oil, and the X trajectory, to a 15% premium over the distillate oil, after the year 2000. The difference in the curve shapes for the two fuels results from their different historical volatility. An approximate natural gas price ceiling is provided by the cost of producing synthetic gas (synfuel) from coal, estimated at around 7.5$(1991)/MMBtu [18].
Fig. 3-2: Total cost of electric service (TDCn) vs. carbon dioxide emissions (CO2) of “Diversity” strategies for competitive/low (C) gas cost uncertainty. Symbols indicate technology mix.
Fig. 3-3: Total cost of electric service (TDCn) vs. carbon dioxide emissions (CO2) of “Diversity” strategies for stable/base (B) gas cost uncertainty. Same symbols are used as on Fig. 3-2.
Fig. 3-4: Total cost of electric service (TDCn) vs. carbon dioxide emissions (CO2) of "Diversity" strategies for constraint/high (G) gas cost uncertainty. Same symbols are used as on Fig. 3-2.
3.5 Results and frontier strategies

Figs. 3-2 through 3-4 show the original results of the January 1994 analysis. Each of the figures depicts cost of electric service (TDCn) vs. carbon dioxide emissions (CO2) of all the strategies for each of the gas price trajectories (except X), described in the previous section. Different symbols are used to distinguish between different technology mixes of new generating capacity additions (Table 3-2). By comparing the plots for different trajectories variability in performance of given strategies was observed in a semi-qualitative fashion. When comparing Figs. 3-4 with 3-2 it is visible that the entire set of strategies has shifted away from the origin. As expected, higher natural gas cost resulted in dirtier and more expensive electric power. What is really important, however, is how each of the individual strategies perform with respect to each other. Does the relative position of the strategies change?

One of the main objectives of the January 1994 “Diversity” study was to identify regional strategies that were aimed at a cost-effective reduction of nitrogen oxide and carbon dioxide emissions. Table 3-5 lists strategies, together with their decision characteristics, that were identified by the analysis-team as the most efficient in emission reduction. Unfortunately, the strategies that were most effective in reducing NOX emission (identified in Table 3-7 as “Cost/NOX Frontier”) did little to reduce CO2. Similarly, strategies strongly limiting CO2 (“Cost/CO2 Frontier” in Table 3-5) were much less effective in reducing NOX. “Integrated” strategies (“Integrated Frontier” in Table 3-5) combine positive
<table>
<thead>
<tr>
<th>Tradeoff Strategies</th>
<th>Supply-Side Tech. Mix</th>
<th>Nat. Gas Contracting</th>
<th>Level of DSM</th>
<th>Level of NOx Control</th>
<th>Existing Unit Longevity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost/NOx Frontier Strategies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GISAVER</td>
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<td>Spot Gas</td>
<td>1992 DSM</td>
<td>RACT only</td>
<td>Life Ext.</td>
</tr>
<tr>
<td>GISEVER</td>
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<td>Spot Gas</td>
<td>1992 DSM</td>
<td>Firm Ph.II</td>
<td>Life Ext.</td>
</tr>
<tr>
<td>GISIVER</td>
<td>Gas/Oil</td>
<td>Spot Gas</td>
<td>1992 DSM</td>
<td>Hard Ph.II</td>
<td>Life Ext.</td>
</tr>
<tr>
<td>WISIVER</td>
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<td>Spot Gas</td>
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<td>Life Ext.</td>
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<td>Spot Gas</td>
<td>Dbl.Cons.</td>
<td>Hard Ph.II</td>
<td>Life Ext.</td>
</tr>
<tr>
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<td>Spot Gas</td>
<td>Triple C&amp;I</td>
<td>Hard Ph.II</td>
<td>Life Ext.</td>
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<tr>
<td>WIMIVEC</td>
<td>Gas/Wind</td>
<td>Firm Gas</td>
<td>Triple C&amp;I</td>
<td>Hard Ph.II</td>
<td>Life Ext.</td>
</tr>
<tr>
<td><strong>Cost/CO2 Frontier Strategies</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>WISAVER</td>
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<td>Firm Gas</td>
<td>Triple C&amp;I</td>
<td>RACT only</td>
<td>Mod.R/R</td>
</tr>
<tr>
<td>KAMAVEC</td>
<td>G/W/C/Biomass</td>
<td>Firm Gas</td>
<td>Triple C&amp;I</td>
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<td>Agg.R/R</td>
</tr>
<tr>
<td><strong>Integrated (Cost/CO2/Nox) Frontier Strategies</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>Spot Gas</td>
<td>Dbl.Cons.</td>
<td>RACT only</td>
<td>Life Ext.</td>
</tr>
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<td>Dbl.Cons.</td>
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<td>Life Ext.</td>
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<td>Mod.R/R</td>
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<tr>
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<td>Life Ext.</td>
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<tr>
<td>WOSEVEC</td>
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<td>Triple C&amp;I</td>
<td>Firm Ph.II</td>
<td>Mod.R/R</td>
</tr>
</tbody>
</table>

Table 3-5: Frontier strategies identified by the AGREA-analysis team. The three frontiers are aimed at a cost-effective NOx-emission reduction, CO2-emission reduction, and simultaneous reduction of both pollutants.
Fig. 3-5: Performance results of the frontier strategies for the stable/base (B) gas price trajectory with error bars indicating extreme cost behavior for C and X trajectories.
Fig. 3-6: Variability is even more pronounced if we plot changes in performance along both axes (for B trajectory with error bars indicating extreme cost & emission behavior for C and X trajectories).
features of the two frontiers above. These perform well in terms of cost, CO$_2$, and NO$_X$ emissions. Since the three frontier strategy sets are of interest to the power-industry debate, we will use them as a reference set to illustrate variability quantification concepts.

Fig. 3-5 illustrates the performance of Frontier Strategies in terms of cost of electric service and CO$_2$-emissions for stable/base gas price trajectory. Vertical error bars indicate extreme cost behavior for competitive (C) and exorbitant (X) gas price trajectories. Variability is even more pronounced if the changes in performance are plotted along both axes (cost and CO$_2$-emission), as shown on Fig. 3-6. As the gas price trajectory changes all three frontier sets change their position on the graph. The most important question is, however, how the relative performance of each individual strategy varies with respect to each other. It is intriguing to note that whereas some strategies vary strongly in both cost and emission, there are others that exhibit smaller variability in one of the two attributes (Fig. 3-6). These features will be analyzed in detail in Chapter 6.
Chapter 4

Quantifying performance variability

Previous examples depict variability in a graphic form, concentrating on extreme events only. A more real transformation is to assume a certain probability distribution of potential gas cost trajectories and calculate performance and variability of a strategy based on this probability distribution. The following chapter describes a practical procedure proposed by the author.

4.1 Expected-value performance

To introduce the probabilistic concepts it is convenient to describe EGEAS modeling as a non-analytic transformation of a decision vector (strategy) and an assumption vector (future) into a resulting attribute vector:

$$ A_{ij}^k = \text{EGEAS}(S_i, F_j) \quad (4.1) $$

where:

- $S_i$ - is the i-th Strategy (e.g., WISAVER, GIMAVEC) or decision vector;
- $F_j$ - is the j-th Future or assumption vector; here it includes only variable gas price trajectory but can also include variable load growth, technology performance, etc.;
- $A_{ij}^k$ - is the k-th Attribute (e.g., $\$, CO$_2$, NO$_x$, etc.) calculated for strategy $S_i$ and future $F_j$;
EGEAS(...) - indicates a non-linear, non-analytic transformation function resulting from an EGEAS simulation.

In the analysis presented here the only uncertain variable under consideration is the gas price trajectory. Thus the complete set of potential futures, F_j, consists of four elements, where j = C,B,G,X corresponds to price trajectories described in Section 3.4.

Next, we assign each gas price trajectory a certain occurrence probability: p_j (j = C,B,G,X), similarly to a chance branch of a decision tree. The expected-value future is simply:

\[ \text{EV}(F) = \sum_{j=1}^{M} p_j \cdot F_j \]  \hspace{1cm} (4.2)

where:

M - is the number of futures under consideration, in our case M=4;

EV(...) - indicates an expected-value result.

Our goal is to calculate the expected-value of a performance attribute of interest - \( \text{EV}(A_i^k) \), for a given decision strategy - \( S_i \), resulting from the assumed probability distribution - \( p_j \). Counterintuitively, the expected-value future - \( \text{EV}(F) \) from Eq. 4.2, cannot be used to calculate the expected-value attribute:

\[ \text{EV}(A_i^k) \neq \text{EGEAS}(S_i, \text{EV}(F)) \]  \hspace{1cm} (4.3)

This is due to an inherent non-linearity of the EGEAS(...) transformation (Eq. 4.1). The correct expected-value attribute should be calculated as follows:

\[ \text{EV}(A_i^k) = \sum_{j=1}^{M} p_j \cdot \text{EGEAS}(S_i, F_j) \]  \hspace{1cm} (4.4)
The following thought experiment helps explain the discrepancy between Eqs. 4.3 and 4.4:

Let us assume that there is a 50/50 chance of natural gas being either cheap or expensive in the future. Power-system operators will use natural gas as a fuel if it is cheap or moderately priced, but will switch away from it if it is expensive. The expected-value future (trajectory) calculation (Eq. 4.3) would predict 100% dispatch of the gas-firing capacity because of the expected moderate gas price (50% cheap + 50% expensive). The expected-value attribute calculation (Eq. 4.4), in contrast, will predict correctly expected 50% dispatch of the gas-firing capacity.

The discrepancy between Eqs. 4.3 and 4.4 arises because the model of the power system (EGEAS) is strongly non-linear, i.e., the transformation in Eq. 4.1 of input variables (decision and assumption vectors) into output variables (attribute vector) can not be reconstructed with a linear function, moreover, it can not be reconstructed with any finite analytic function.

Also, Eq. 4.3, if used, would require an additional EGEAS simulation, which would not generate any new information. Eq. 4.4, in contrast, saves computational resources, allowing us to conduct probabilistic calculations as a post-processor to EGEAS modeling. Eq. 4-4 will also allow us to introduce a standard deviation of performance (Section 4.2).

Eq. 4.4 contains, however, an important implicit assumption, namely, that the power system modeled remains self-similar at the smallest probability level considered (here, 10%), i.e., its sub-system (1/10) has exactly the same characteristic as the entire system. The self-similarity constraint holds for the regional power system but may not be true for a single state or a single utility. For

![Graph showing the probability distribution of future natural gas price trajectories. The probabilities are as follows:
- C - Competitive/low: 0.2
- B - Stable/Base: 0.4
- G - Constraint/high Gas: 0.3
- X - Exorbitant: 0.1

CBGX = 2431

1992-2011 natural gas price trajectory

Fig. 4-1: "Expert" probability distribution of future natural gas price trajectories (CBGX=2431), resulting from expert (advisory-group members) solicitation. Analysis is, however, not limited to this particular distribution only (see Chapter 5 and Appendix A).
example, 1/10 of a utility power system will not contain all types of generators because of minimum size of generating units. The assumption also imposes a practical constraint on the smallest probability assigned to any of the futures; in our case 10%.

Since, in this particular analysis, we rely on the existing AGREA modeling results (Chapter 3), the expected-value attribute calculation does not require new EGEAS simulations:

\[ \text{EV}(A^k_i) = \sum_{j=1}^{M} p_j \cdot A^k_{ij} \] (4.5)

We begin the calculations for a certain, arbitrary probability distribution, shown on Fig. 4-1. This distribution results from expert solicitation (advisory group members) [22]; it will be, however, reexamined in the next chapter. The Base trajectory has the highest chance of occurring (p(B)=40%) than the high Gas (p(G)=30%), Competitive (p(C)=20%) and eXorbitant (p(X)=10%). The performance of each strategy can be calculated in the expected-value sense using Eq. 4.5.

Fig. 4-2 shows the expected-value results for the January 1994 “Diversity” scenario set. As a reference, the performance results of the scenario set for the base/stable gas price trajectory (B) only are plotted on Fig. 4-3. Both plots show cost of electric service (TDCn) vs. carbon dioxide emissions (CO2). Same symbols are used on both plots to distinguish between Gas/oil and gas/Wind new generating capacity additions (Table 3-2); between Spot gas purchases and Must-run gas contracts (Table 3-1); and between various levels of DSM programs (dsm1 = reference DSM program, dsm2 = double conservation, dsm3 = triple C&I conservation - see Table 3-3).
Fig. 4-2: Expected (mean) value cost/CO2 performance of the “Diversity” strategies. Symbols indicate key decision options (listed in Table 3-1).
Fig. 4-3: Cost/CO2 performance of the "Diversity" strategies for the stable/base (B) gas cost trajectory only. Same symbols are used as on the previous figure. Observe the change in CO2 frontier.
It is interesting to note that for the fixed base/stable trajectory (B) the lowest CO2-emissions frontier is composed of "gas/Wind-Spot purchase-dsm3" strategies (Fig. 4-3), whereas in expected-value sense the CO2-emission frontier is dominated by "gas/Wind-Must run-dsm3" strategies (Fig. 4-2). From this comparison it is already clear that choices made based on deterministic analysis (single gas cost trajectory only) may not perform well if we consider an entire spectrum of future events (expected-value result).

### 4.2 Robustness-Criterion

The introduction of the probability distribution of gas price trajectories allows us also to investigate variability of a given strategy across the considered futures. We define standard deviation -Std_Dev(...) of a performance attribute - A_i^k for a given strategy -S_i, across probability distribution -p_j of gas price trajectories:

\[
\text{Std}_\text{Dev}(A_i^k) = \sqrt{\sum_{j=1}^{M} p_j \left( A_{ij}^k - \text{EV}(A_i^k) \right)^2}
\]

(4.6)

Note that an unbiased estimate of a sample variance (Std_Dev^2) would require an additional multiplier N/(N-1) under the square root in Eq. 4.6. In our case, however, the statistical sample size is determined not by the number of futures but by a number of self-similar subsystems comprising the New England power system. This sample size is estimated to be N\geq10 (see the discussion in the previous section). For a large enough sample size (N\geq10) N-1\approx N is a good approximation. This approximation is already included in Eq. 4.6.
We define a Robustness-Criterion for the examined performance attribute $A_i^k$ and the strategy $S_i$, as a standard deviation of the attribute, normalized to its expected-value:

$$\text{Robustness - Criterion}(A_i^k) = \frac{\text{Std. Dev}(A_i^k)}{EV(A_i^k)}$$  \hspace{1cm} (4.7)

The Robustness-Criterion is a direct quantitative measure of a variability of a given strategy caused by the uncertainty in the uncontrolled variable (in our case, fuel price).

The Robustness-Criterion becomes a very convenient dimension-less measure of a volatility a strategy due to fuel price uncertainty. Because it is dimension-less it can be directly compared for a number of attributes that were initially expressed in different units (for example, tons of emission vs. dollars of cost). It can be also expressed as a percent value. The criterion can be easily calculated for all strategies and every attribute of interest. Finally, robustness criteria of selected attributes can be introduced into the tradeoff analysis as new performance measures.

Somewhat similar methodology is often used in operations research for robust quality product design. It was initially proposed by Taguchi [23]. In Taguchi’s “design for quality” approach the controlled design parameters are optimized not only to maximize desired characteristics of a product but also to minimize variability of these characteristics due to uncertainty in uncontrolled, environmental variables. The success of such a design is measured by a signal-to-noise (S/N) ratio [24]. The Robustness-Criterion, proposed here is equivalent
Fig. 4-4: Robustness-Criteria (variability measures), calculated with Eq. 4.7, for cost and CO2 attributes of “Diversity” strategies. Two groupings of strategies can be clearly distinguished (Section 6.1).
to the inverse of the Taguchi's S/N ratio. The important distinction, however, is that the S/N ratio assumes the same chance of occurrence for all uncontrolled events, whereas the Robustness-Criterion includes specifically a prescribed probability distribution of uncertain events.

As an example, the Robustness-Criteria are calculated for the two attributes of interest, TDCn and CO2, across the previously assumed probability distribution (Fig. 4-1). Representative results are shown on Fig. 4-4. The Robustness-Criterion (variability) of the cost of electric service is plotted against the variability in CO2-emissions. The same symbols are used as on Figs. 4-3 and 4-2. The discussion of the results in terms of a robust strategy choice follows in Chapter 6.
Chapter 5

Probability sensitivity analysis

5.1 Confidence-crisis in probability assessment

One of the most important remaining questions is how trustworthy are the probabilities that we used in previous calculations. In the classic probabilistic planning it is most often assumed that the probabilities describing future events are known with absolute confidence. This is clearly far from truth; the probabilities of potential future events are known only approximately.

The decision theory has yet to solve the problem of quantifying the “confidence” of probabilities in forecasting problems. Only recently Nau [25] has treated the issue very thoroughly, however with so far limited practical applications. Morris [26] has proposed a more pragmatic approach, introducing a “credibility” variable, describing the confidence of probability and allowing to calculate “fuzziness-averseness” in addition to the classic risk-averseness of decision-makers. Despite their large potential, the methods of credibility analysis are not yet accepted nor recognized in decision-making practice.
"Exotic" Probability Distribution of Future Gas Price Trajectories.

CBGX = 4114

Fig. 5-1: "Exotic" probability distribution of future natural gas price trajectories (CBGX=4114), used in probability sensitivity analysis. This almost bimodal distribution expects natural gas to be either very cheap or very expensive in the future. More distributions are shown in Appendix A.
5.2 Probability sensitivity analysis - an alternative proposed here

The problem of probability credibility is central to the work reported in this thesis, because the knowledge of fuel price trajectory likelihood is very limited. The probability distribution used for calculations in previous chapter results form expert (advisory group members) estimates, yet it still has rather low credibility.

Rather than assessing credibility a simpler and more robust approach is proposed by the author and will be referred to as a Probability Sensitivity Analysis (PSA).

The probabilities assumed initially are extensively varied and calculations are repeated for each new probability distribution. The detailed results for 5 different distributions are shown in Appendix A. In this section we only present, as an example, results from a rather exotic probability distribution, shown on Fig. 5-1, where there is a high chance of natural gas being either very expensive or very cheap in the future. Fig. 5-2 shows the cost/CO₂ mean value performance and Fig 5-3 shows the cost/CO₂ variability. The comparison of this pair of figures with the corresponding Figs. 4-2 and 4-4 allows us to conclude that despite slight differences in numerical results, the relative ranking of strategies does not change with different distributions. Hence, a decision set of well-performing and robust strategies can be identified with confidence, despite our lack of knowledge about the “best” probability distribution of potential gas cost trajectories.

The nature of the PSA is that the sensitivity analysis is performed on the probabilities themselves instead of on input variables. If the relative performance of the strategies does not vary strongly, than the decision set can be identified with
Fig. 5-2: Expected (mean) value cost/CO2 performance of the "Diversity" strategies calculated using the "Exotic" probability distribution from Fig. 5-1. Compare with Fig. 4-2.
Fig. 5-3: Robustness-Criteria (variability measures) for cost/CO2 attributes of "Diversity" strategies calculated using the "Exotic" probability distribution from Fig. 5-1. Compare with Fig. 4-4.
greater confidence than using classic sensitivity analysis. For example, a robust strategy can be identified with the minimum amount of information about future economic conditions. Therefore the PSA is a perfect decision support tool when precise economic forecast are unavailable. It is important, however, to realize that PSA does not deliver quantitative performance results. The method will only provide a relative ranking of various decision alternatives.

With the Probability Sensitivity Analysis decisions can be made with adequate confidence without the necessity of a very difficult credibility assessment.
Chapter 6

Strategy choice consideration

Having performed the calculations a number of important question still remains:

* What is the prudent choice of a well performing and robust strategy or set of strategies?
* What are the common features of robust strategies?
* Which decisions impact performance variability?

6.1 Spot vs. firm gas contracting

Examining Figs. 4-4 and 5-3 (from the two pervious chapters) in more details, two groups of strategies can be easily distinguished:

1. *spot-gas contracting* strategies have little variability on cost-side but more variability in emissions (open symbols on Figs. 4-4 and 5-3);
2. *must-run gas* strategies exhibit almost no variability in emission-levels but cost may vary strongly (dark symbols on Figs. 4-4 and 5-3).

This fundamental difference between the two strategy groups can be easily explained:

Within the spot-gas strategy group it is assumed that the natural gas is purchased on a spot-market. When the natural gas becomes expensive, some of the generating capacity switches to a substitute fuel (distillate oil 2), while some becomes less frequently dispatched. This operational procedure, which
Fig. 6-1: Cost/CO2 performance variability (Robustness-Criteria) of the January 1994 "Frontier" strategies (Table 3-5), calculated using the "Expert" probability distribution (Fig. 4-1).
limits the operational cost increase, results in increased emissions variability because of the fuel swap. Within the must-run strategies, on the other hand, it is assumed that 70% of the gas fired generating capacity is bounded by long term contracts and must be dispatched independent of current natural gas price. This operational procedure increases the financial risk exposure but fixes the emissions because of almost constant fuel mix.

6.2 Robust choice prescription

We also examine robustness of the "Diversity" set frontier strategies identified in January 1994 (see Section 3.5). Fig. 6-1 shows variability (Robustness-Criteria) in cost and CO2-emissions of the frontier strategies. These strategies belong to both categories distinguished on Figs. 4-4 and 5-3: “spot-gas” and “must-run”. It is clear that the frontier strategies have varying levels of sensitivity to the gas price uncertainty. We will seek the most robust ones.

The cost/CO2 variability plot, e.g., Fig. 4-4, looks somewhat different from the corresponding absolute performance graph, e.g., Fig. 4-2. Unlike before, there is no clear frontier in the tradeoff sense. However, we are still looking for the strategies that lie closest to the origin. Here we propose the following prescription, outlined on Fig. 6-2:

(1) We define maximum allowable variability limits (decision-maker’s risk tolerance); as an illustration we set, for example:

\[ R_{\text{TDCn}} \geq 1.5\%; \quad R_{\text{CO2}} \geq 4.5\% \]  

   (6.1)
Fig. 6-2: “Robustness” frontier prescription: select strategies bounded by allowable variability limits: $R_{TDCn} \geq 1.5\%$ & $R_{CO2} \geq 4.5\%$. January 1994 “Frontier” strategies are shown for reference.
where:

\[ R_{TDCn} \] - is Robustness-Criterion (variability) of total regional direct cost of electric service (TDCn);

\[ R_{CO2} \] - is Robustness-Criterion (variability) of cumulative carbon dioxide emissions (CO2).

(2) We classify a new subset of the strategies bounded by the variability limits as a "Robustness Frontier" (black stars on Fig. 6-2).

This selection criterion is obviously somewhat arbitrary, but it is introduced here mainly for the purpose of methodology illustration. Also, Fig. 6-2 shows variability results for a specific probability distribution only (CBGX=2431). For a different probability distribution the values of robustness criteria will change (Appendix A), the robustness frontier, however, will still be defined as a subset closest to the origin, similar to the one on Fig. 6-2. Hence the variability limits are approximate numbers only that help us identify the least variable strategies in an ordinal not a cardinal sense.

On Fig. 6-3 we over-plot the robustness frontier on a standard expected-value tradeoff graph and examine the absolute performance of the robust strategies. Clearly, there is a large number of robust strategies, but those that vary little around their expected dirty and expensive performance are of little interest to decision-makers. The most interesting ones are strategies that belong to both groups: one of the "Diversity" set frontiers (Table 3-5) and the "Robustness" frontier. Only very few from within the frontier strategies, identified by the AGREA-analysis team in January 1994 (listed in Table 3-5), are classified as robust ones. These "Synergistic" strategies combine superior absolute performance
Fig. 6-3: The “Robustness-Frontier” strategy set overplotted on a standard tradoff graph helps us identify resulting synergies with the January 1994 “Frontier” strategy set.
with relative insensitivity to fuel cost uncertainty. The final set of “Synergistic” strategies is rather limited:

- out-of the “Diversity NO\(_x\)-Frontier” set only GISIVEC is classified as a robust strategy,
- out-of the “Diversity CO2-Frontier” set only two strategies are classified as robust ones: GISAVEC and WISAVEC,
- out-of the “Diversity INTegrated-Frontier” set only WISEVEC belongs to “Robust-Frontier”.

The above “Synergistic” strategies and their main features are summarized in Table 6-1.

### 6.3 Risk-mitigation measures

As mentioned before, one of the main goals of the analysis is to identify class of decisions and prudent choices that lead to robust and well performing strategies. Having performed the analysis, we find the following common features of the “Synergistic” strategies (listed in Table 6-1):

1. gas/oil or gas/wind technology mix,
2. life-extension of existing units (no retire/repower),
3. variable levels of NO\(_x\) controls (depend on the specific frontier group),
4. spot gas contracting only,
5. triple commercial and industrial DSM conservation.

By comparing characteristics of the “Synergistic” strategy set, listed in Table 6-1, with characteristics of the January 1994 “Frontier” strategy sets, listed in Table 3-5, we are able to determine which of the above features result from the absolute performance requirement and which are due to the robustness requirement.
<table>
<thead>
<tr>
<th>&quot;Synergistic&quot; Strategies</th>
<th>Supply-Side Tech. Mix</th>
<th>Nat. Gas Contracting</th>
<th>Level of DSM</th>
<th>Level of NOx Control</th>
<th>Existing Unit Longevity</th>
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<td>Spot Gas</td>
<td>Triple C&amp;I</td>
<td>Hard Ph.II</td>
<td>Life Ext.</td>
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<tr>
<td>ROBUST &amp; Cost/CO2 Frontier Strategies</td>
<td></td>
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</tr>
<tr>
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<td>Gas/Oil</td>
<td>Spot Gas</td>
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<td>RACT only</td>
<td>Life Ext.</td>
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<tr>
<td>WISAVEC</td>
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<td>Spot Gas</td>
<td>Triple C&amp;I</td>
<td>RACT only</td>
<td>Life Ext.</td>
</tr>
<tr>
<td>ROBUST &amp; Integrated (Cost/CO2/Nox) Frontier Strategies</td>
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<tr>
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<td>Spot Gas</td>
<td>Triple C&amp;I</td>
<td>Firm Ph.II</td>
<td>Life Ext.</td>
</tr>
</tbody>
</table>

**Common features of "Synergistic" Strategies**

| W/GISxVEC | G/Oil or G/Wind | Spot Gas | Triple C&I | variable | Life Ext. |

Table 6-1: Only very few from within the frontier strategies, identified by the AGREA-analysis team in January 1994 (listed in Table 3-5), are classified as robust ones. These "Synergistic" strategies, combining superior absolute performance with adequate robustness, exhibit important common features: gas/oil or gas/wind technology mix, spot gas contracting, triple C&I DSM program, and life extension of existing units.
The choice of new capacity technology mix (1), life extension of existing units (2) and level of NO\textsubscript{x} control (3) result from the strategy selection made in January 1994, i.e., from the absolute performance of the strategies requirement.

From the “Robustness” frontier perspective there are two most important features: (4) all the strategies are spot-gas contracting only - this allows to limit financial risk exposure; (5) all strategies are characterized by triple commercial and industrial DSM conservation - this is substantial in limiting CO\textsubscript{2}-emissions risk exposure. Combined, these two main features complement each other and provide choices that have small variability on cost and emissions side.

As we recall from Section 3.3, the final results are obtained for higher load-growth forecasts then the ones accepted today, and lower electric efficiency standards then expected in a near future. This does not, however, significantly impact the results qualitatively, nor does it affect the validity of the method.

The bottom-line result in terms of risk-mitigation measures (aggressive DSM and spot gas contracting) came as no surprise and have been intuitively obvious to many power-industry experts [27]. The important new contribution of the analysis introduced here is that it arrived at these results in a very quantitative and rigorous fashion, without prior knowledge or belief. In a regulatory debate, where a quantitative proof, not a belief, is required to introduce often controversial measures (e.g., very aggressive DSM programs), the Robustness-Criterion combined with the Probability Sensitivity Analysis may be the right tools to provide such a proof.
Chapter 7

Summary

7.1 Managing risk - summary of the method

The Robustness-Criterion combined with the Probability Sensitivity Analysis - the risk management methodology developed in the course of this work can be applied to a much broader range of problems: whenever critical decisions are dependent upon uncertain variables whose exact values will only be known in the future. It is important, however, to realize that the methodology does not deliver absolute quantitative results. It does provide an analyst with an ordinal ranking of the most robust choices. Also, most likely, the strategy chosen will not be the best one for the actual economic conditions encountered in future. It will be a strategy, which is least variable or most predictable for the widest possible range of conditions. The difference in performance between the best strategy chosen in hind-sight and the robust one chosen in advance can be interpreted as an “insurance premium” paid for not knowing the future conditions precisely.

The limitations of the “Robustness-Criterion/Probability-Sensitivity” approach can be summarized as follows:

- delivers only a relative ranking of various decision alternatives (options), does not deliver absolute performance results – i.e., ordinal not cardinal result;
• requires large amount of input data, but well suited for an AGREA-type process, where data are already available.

The above minor limitations of the approach are clearly outweighed by its advantages:

• quantifies variability in a standard form, simplifying comparison of options (Robustness-Criterion can be included as one more tradeoff attribute);
• condenses large amount of information into a comprehensible form;
• robust strategy can be identified with a very limited knowledge about future events (ranking is independent of assumed input probabilities);
• very versatile, can be easily adopted to other risk-mitigation problems (e.g., load-growth, electric vehicle cost, and other uncertainties).

In summary, the Robustness-Criterion and the Probability Sensitivity Analysis are the risk management decision support tools developed specifically for the cases where precise forecasts are unavailable. It is an attempt to break the ever-present modeling barrier, GIGO: Garbage-In-Garbage-Out. Instead in the case of the Probability Sensitivity Analysis GIGO can be translated as Guess-In-Guidance-Out.

7.2 Public policy debate conclusions

The AGREA January 1994 “Diversity” scenario set served very well (despite its limitations listed in Section 3.3) as a testing ground for the newly introduced methodology. The Robustness-Criterion/Probability-Sensitivity study proved rigorously the important risk-mitigation characteristic of spot-gas contracting combined with aggressive DSM programs. Especially DSM programs spur a lot of
controversy in a regulatory debate due to their uncertain benefits. Here we clearly demonstrated the environmental risk-mitigation potential of the demand-side management programs. Combined with spot gas contracting, limiting financial risks exposure, the two measures complement each other.

It is very encouraging that the Robustness-Criterion combined with the Probability Sensitivity Analysis delivered the results expected by the industry experts without any author's prejudice or prior knowledge. The analysis performed in this thesis demonstrated that the Robustness-Criterion with the Probability Sensitivity Analysis may be very valuable analytic tools for complex problems involving significant forecasting uncertainty. It is the author's hope that the tools will be used by decision-makers to the public benefit.
Bibliography


Bibliography - cont.


Bibliography - cont.


Appendix A

Additional probability distributions

This appendix presents additional probability sensitivity results to complement the subset described in Chapter 5. Fig. A0-1 shows the probability distributions, for which the calculations have been carried out; two of which were already used in Chapter 5. The probability distribution naming key contains the probability values used for the four gas price trajectories without the decimal point. For example, CBGX=1531 (middle distribution on Fig. A0-1) corresponds to: p(C)=.1, p(B)=.5, p(G)=.3, and p(X)=.1.

The first series of Figs. A1-1 through A1-10 shows results for the “Diversity” strategies in terms of cost of electric service (TDCn) and carbon dioxide emissions (CO2). The key decision options are depicted using the same symbols as on Fig. 4-2. The symbols distinguish between Gas/oil and gas/Wind new generating capacity additions (Table 3-2); between Spot gas purchases and Must-run gas contracts (Table 3-1); and between various levels of DSM programs (dsm1 = reference DSM program, dsm2 = double conservation, dsm3 = triple C&I conservation - see Table 3-3). The odd-numbered A1 figures show expected-value performance calculated with Equation 4.5, each time using the corresponding probability distribution. The even-numbered A1 figures show performance variability, expressed as the Robustness-Criterion, calculated with Equation 4.7, for corresponding probability distributions. The expected-value results vary very little across different probability distributions (odd-numbered A1 plots), so does the
Skewed towards "Expensive" Gas Probability Distribution

Skewed towards "Stable" Gas Probability Distribution

Probability Distribution resulting from "Expert" Advice

"Symmetric" & Stable Probability Distribution

"Exotic" Bimodal Probability Distribution


Fig. A0-1: Five probability distributions of potential natural gas price trajectories, used for the probability sensitivity analysis (PSA).
relative performance of the strategies. The variability results differ to some extent
in absolute numbers. As one might have expected, the distribution CBGX=4114
leads to a higher normalized standard deviation on both axes than the distribution
CBGX=1441. The relative position of the strategies, however, does not change.

The second series of Figs. A2-1 through A2-10 presents the same results as Figs.
A1, except now the “Diversity” scenario set “Frontier” strategies (Section 3.5) are
identified with symbols. As before, the odd-numbered A2 figures show absolute
performance (Equation 4.5), whereas the even-numbered A2 figures show
performance variability (Equation 4.7) of strategies of interest. Similarly to Fig. 3-
6, the error bars on Figs. A2 indicate strategy performance behavior for the
extreme cost trajectories (C and X on Fig. 3-1). The mid-points, however, indicate
the expected-value performance calculated using the respective probability
distributions, not the base-case result as on Fig. 3-6. It is clearly seen that the
relative position of the frontier strategies does not depend on the probability
distribution used for calculations.
Fig. A1-1: Cost/CO₂ expected-value performance of the "Diversity" strategies calculated with the "Expensive" probability distribution (CBGX=1432). Symbols indicate key decision options.
Fig. A1-2: Variability (Robustness-Criterion) in Cost/CO₂ performance of the “Diversity” strategies calculated with the “Expensive” distribution (CBGX=1432). Symbols indicate key options.
Fig. A1-3: Cost/CO₂ expected-value performance of the "Diversity" strategies calculated with the "Expert" probability distribution (CBGX=2431). Symbols indicate key decision options.
Fig. A1-4: Variability (Robustness-Criterion) in Cost/CO₂ performance of the “Diversity” strategies calculated with the “Expert” distribution (CBGX=2431). Symbols indicate key options.
Fig. A1-5: Cost/CO₂ expected-value performance of the “Diversity” strategies calculated with the “Stable” probability distribution (CBGX=1531). Symbols indicate key decision options.
Fig. A1-6: Variability (Robustness-Criterion) in Cost/CO₂ performance of the “Diversity” strategies calculated with the “Stable” distribution (CBGX=1531). Symbols indicate key options.
Fig. A1-7: Cost/CO₂ expected-value performance of the "Diversity" strategies calculated with the "Symmetric" probability distribution (CBGX=1441). Symbols indicate key decision options.
Fig. A1-8: Variability (Robustness-Criterion) in Cost/CO₂ performance of the "Diversity" strategies calculated with the "Symmetric" distribution (CBGX=1441). Symbols indicate key options.
Fig. A1-9: Cost/CO₂ expected-value performance of the "Diversity" strategies calculated with the "Exotic" probability distribution (CBGX=4114). Symbols indicate key decision options.
Fig. A1-10: Variability (Robustness-Criterion) in Cost/CO₂ performance of the "Diversity" strategies calculated with the "Exotic" distribution (CBGX=4114). Symbols indicate key options.
Fig. A2-1: Cost/CO₂ expected-value performance of the "Diversity" Frontier strategies calculated with the "Expensive" distribution (CBGX=1432). Error bars indicate extreme gas cost performance.
Fig. A2-2: Variability (Robustness-Criterion) in Cost/CO₂ performance of the “Diversity” Frontier strategies calculated with the “Expensive” probability distribution (CBGX=1432).
Fig. A2-3: Cost/CO₂ expected-value performance of the “Diversity” Frontier strategies calculated with the “Expert” distribution (CBGX=2431). Error bars indicate extreme gas cost performance.
Fig. A2-4: Variability (Robustness-Criterion) in Cost/CO₂ performance of the "Diversity" Frontier strategies calculated with the "Expert" probability distribution (CBGX=2431).
Fig. A2-5: Cost/CO₂ expected-value performance of the “Diversity” Frontier strategies calculated with the “Stable” distribution (CBGX=1531). Error bars indicate extreme gas cost performance.
Fig. A2-6: Variability (Robustness-Criterion) in Cost/CO₂ performance of the "Diversity" Frontier strategies calculated with the "Stable" probability distribution (CBGX=1531).
Fig. A2-7: Cost/CO$_2$ expected-value performance of the “Diversity” Frontier strategies calculated with the “Symmetric” distribution (CBGX=1441). Error bars indicate extreme gas cost performance.
Fig. A2-8: Variability (Robustness-Criterion) in Cost/CO₂ performance of the “Diversity” Frontier strategies calculated with the “Symmetric” probability distribution (CBGX=1441).
Fig. A2-9: Cost/CO₂ expected-value performance of the “Diversity” Frontier strategies calculated with the “Exotic” distribution (CBGX=4114). Error bars indicate extreme gas cost performance.
Fig. A2-10: Variability (Robustness-Criterion) in Cost/CO₂ performance of the “Diversity” Frontier strategies calculated with the “Exotic” probability distribution (CBGX=4114).