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Energy/Environment Management: Application of Decision Analysis

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ENERGY/ENVIRONMENT MANAGEMENT: APPLICATION OF DECISION ANALYSIS

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MAY 1976

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Preface

This report is one of a series describing a multidisciplinary multinational IIASA research study on the Management of Energy/Environment Systems. The primary objective of the research is the development of quantitative tools for regional energy and environment policy design and analysis--or, in a broader sense, the development of a coherent, realistic approach to energy/environment management. Particular attention is being devoted to the design and use of these tools at the regional level. The outputs of this research program include concepts, applied methodologies, and case studies. During 1975, case studies were emphasized; they focussed on three greatly differing regions, namely, the German Democratic Republic, the Rhône-Alpes region in southern France, and the state of Wisconsin in the U.S.A. The IIASA research was conducted within a network of collaborating institutions composed of the Institut für Energetik, Leipzig; the Institut Économique et Juridique de l'Énergie, Grenoble; and the University of Wisconsin-Madison.

This report is concerned with the means for more efficiently embedding the energy/environment models and information systems into the decision and policy design structure of a region.

Other publications on the management of energy/environment systems are listed in the Appendix to this report.

W.K. Foell
June 1976

SUMMARY

A procedure is presented for coping with the complexities of energy/environment decision processes. A convenient framework based on multiattribute decision analysis has been developed to help a decision maker evaluate energy/environment alternatives in terms of the degree to which each of a set of objectives is met. The resulting composite environmental impact model links a preference model with a descriptive environmental impact model. The preference model allows one to evaluate alternative strategies by formally incorporating the decision maker's utilities (i.e. preferences) with the quantified environmental impacts (supplied by the descriptive impact model), the unquantified effects, and the conventional costs. Utility assessments were performed for individuals in the Rhône-Alpes region of France, the German Democratic Republic, and the state of Wisconsin in the U.S.A. The benefits of the process and its implementation appear significant.

TABLE OF CONTENTS

Page

Preface iii

Summary v

1. Introduction 1

1.1 Complexity of the Management Problem 1
1.2 A Specific Example: The Choice of Alternative Electricity Supply Strategies 2
1.3 Multiattribute Decision Analysis: A Supplemental Tool for Energy/Environment Policy Design 4
1.4 Organization of the Paper 5

2. Multiattribute Decision Analysis 6

2.1 Terminology of Multiattribute Utility 7
2.2 Multiattribute Utility Theory 8
2.3 Assessing a Utility Function 9

3. Application of Multiattribute Decision Analysis to Illustrative Energy/Environment Policies 11

3.1 Introduction 11
3.2 The Electricity Impact Model 11
3.3 Construction of the Preference Model 11
3.4 Application of Utility Functions to Policies . 14

4. Benefits of the Process and Implementation 20

4.1 Communication 20
4.2 Identifying and Sensitizing Individuals to Important Issues 20
4.3 Isolating and Resolving Conflict 21
4.4 Improvements in Impact Models 22
4.5 Generating Alternatives 22

5. Potential Implementation of the Methodology 22

5.1 Wisconsin 23
5.2 Rhône-Alpes 23
5.3 The German Democratic Republic 24

Appendix 25

Energy/Environment Management: Application of Decision Analysis

1. INTRODUCTION

The IIASA research program on management of energy/environment systems [1] has focussed during 1975 on three regions: the German Democratic Republic, the Rhône-Alpes in France, and the state of Wisconsin in the U.S.A. The system descriptions as well as the descriptions of institutional structure, models and scenarios developed for each of the regions in this study constitute an extremely large collection of information. Because of the limited nature of the policy questions addressed in the research, this information represents only the tip of the iceberg if one considers the energy/environment system in its entirety. The size and complexity of these information systems can be overwhelming. This report discusses the use of decision analysis as a means of more efficiently embedding the models and information systems in the decision and policy design structure of a region.

1.1 Complexity of the Management Problem

By our definition the energy/environment system contains the socio-economic, technological, and ecological attributes of a region. It is clearly a major task to describe a system and its internal interdependencies. In addition, in moving from this *descriptive* process to a *prescriptive* procedure whereby actual options and strategies are evaluated and chosen, the difficulty increases manyfold. If one adds the difficulty of embedding the descriptive and prescriptive process in an institutional structure for implementation, the overall management problem is truly formidable.

The complexity of the management problem can be explained or described in part by the following characteristics:

a. *The strong and manifold interdependencies among the economic, technological, and ecological characteristics of a region.* These interdependencies are not only extremely difficult to quantify, but they also imply that conflicting objectives need to be considered within the management process itself. As a well-known example, we mention the current controversies about whether high rates of economic growth are compatible with a high quality environment. On a regional level, are certain environmental protection measures compatible with local economic growth and maintenance of jobs?

b. *Difficulties in identifying costs and benefits and in associating them with specific societal groups.* Accounting in a quantitative way for attributes such as air quality, aesthetic values, and resource conservation is difficult to do today and becomes even more complex as they evolve through time. In addition, some of the costs are equally difficult to quantify. Even with perfect information about the costs and benefits, one can see that they are associated with different groups of people and that the costs and the benefits are not always bestowed upon individuals or groups in an equitable manner.

c. *Uncertainties -- changes over time.* We may be uncertain about the benefits and costs of any particular management policy. Even if there exists today a good understanding of the system interdependencies, they may change strongly over time in a manner that we do not understand or may not even expect. Some of the long-term environmental effects could have delays associated with them so that it is difficult to estimate or quantify them with present information.

d. *Difficulties in communicating this complex material.* Even if the above information is known, it is extremely difficult to communicate it to individuals and institutions that must either make a decision on the management problem or implement a strategy. The problem of communicating quantitative and technical information to people who are not specialists is indeed a formidable one. As the complexity of our technologically oriented society increases, this problem is increasing in importance.

e. *Multiple decision makers often within overlapping institutional frameworks, for example, multiple levels of government.* Because the energy/environment system cuts across many parts of the human enterprise, institutional structures that have evolved are seemingly as complex as the physical system. This results in a multiplicity and sometimes unidentified array of decision and policy makers who have strong involvement in the management problem.

1.2 A Specific Example: The Choice of Alternative Electricity Supply Strategies

Each of the three regions provides a wealth of examples of the complexity of this management problem. One problem that arises in all three regions and which is becoming increasingly important and visible for a broad spectrum of decision makers and the public is the evaluation of alternative electricity supply strategies.

In Wisconsin, much of the discussion of this question has focussed on the relative advantages and disadvantages of nuclear and coal electricity-supply systems; the relative environmental impacts of the two systems have been the major topics. More recently, the question of the desirability of continued growth of electricity supply has been brought into the discussion. In the eyes of a significant fraction of the Wisconsin community, the societal choice of levels of energy usage is a major component of environmental management. It is one of the most complex aspects of the problem [2].

In the Rhône-Alpes, the question is of a similar nature although the specific alternative strategies differ slightly in form from those in Wisconsin. The current strategy favored by the government is to implement an increasing penetration of electricity usage in the energy market, with a major fraction of the electricity supplied by nuclear power. The current plan of Electricité de France is to have in the Rhône-Alpes area an installed capacity of approximately 6,000 MW(e) by 1980, and possible continued expansion thereafter. However, a recent study by the Institut Economique et Juridique de l'Energie in Grenoble provided a vivid picture of an alternative plan that involved significant energy conservation and increased emphasis on non-electrical forms of energy [3]. Although the discussion and analysis of environmental impacts of alternative systems were initially not as intensive as those in Wisconsin, they are now receiving increased attention in both public and government circles.

In the GDR, the electricity generation technology has been almost exclusively based upon lignite fuel. Although the economic and environmental tradeoffs have been considered in the selection of energy strategies, the available options seem to have been relatively narrow in scope. However, when viewed over a longer term perspective, for example, over the next 50 years, there appears to be a range of alternatives available. As in the other two regions, altering the nature and magnitude of energy demand would seem possible by influencing the economic infrastructure. Similarly, over time it appears feasible for the GDR to choose from a spectrum of supply technologies, including electricity (via nuclear) or a range of non-electrical strategies, for example, district heating.

It is therefore possible to discuss a similar subset of energy/environment policy considerations within each of the three regions studied in the IIASA research project. In each, a variety of different approaches, including the use of models and information systems, is being applied to analyze policies within the appropriate institutional structures. Several publications have described both the models [4] and the institutional structures [5]. In addition, alternative energy/environment scenarios have been developed for each of the regions. The electrical energy options described above form a major segment of the policy analysis in each of the regions, both in their own institutional deliberations and in the scenarios developed at IIASA. However, even if extensive models, information systems and scenarios for a region's energy/environment system exist, the policy analysis and decision process remains a formidable task, primarily because of the complexities described in Section 1.1 of this paper. In the following section, decision analysis is presented as one approach to evaluating alternative policy designs for these complex systems.

1.3 Multiattribute Decision Analysis: A Supplemental Tool for Energy/Environment Policy Design

Energy/environment policy in each of the three regions is based in part on the use of formal models. This is true to the greatest extent in the GDR, to a lesser degree in Wisconsin, and only in a minor way in the Rhône-Alpes. As described in Born et al [5], the GDR models devote considerable attention to specifying energy demand and then to satisfying this demand in some "optimal" manner. The Wisconsin models place more emphasis on alternative scenarios produced by a simulation model, and explicitly relate various demand-supply scenarios to a broadly-based array of environmental impact models. In general, the French models are not regional in nature, but rather are national sectoral planning or forecasting models; environmental impact is usually modelled on a site-specific basis.

If, for the purposes of discussion, we temporarily disregard the differences among the above models, we may view each regional set of models as a technical-economic-environmental model that either describes or prescribes alternative energy/environment futures in terms of a large number of characteristics or attributes. Examples of these model outputs are kilowatt-hours of electricity generated annually, and tons of SO_2 emitted annually from coal-fueled power plants.

In general, these models are meant to be as objective as possible, that is, the models contain a minimum of subjective or value-judgment content. Clearly this is not possible in a strict sense since a model can be no more than a reflection of the model-builder's view of a simplified image of reality. The model hopefully provides the best description that he can produce.

However, because of the earlier-mentioned high degree of complexity of the energy/environment systems, it is often difficult to use the models for evaluating specific policies. With this in mind, we suggest that it may be useful to introduce a preference model into the process. The use of a preference model can provide a convenient framework to help a decision maker evaluate alternatives in terms of the degree to which each of a set of objectives is met.

The relationship between the energy/environment impact model and the preference model is illustrated in Figure 1. The outputs of the impact model are impact levels of the attributes, that is, the altered state of the systems. Examples are the sets of environmental impacts associated with the various regional scenarios. The creation and application of a preference model using multiattribute decision analysis is the primary subject of this paper.

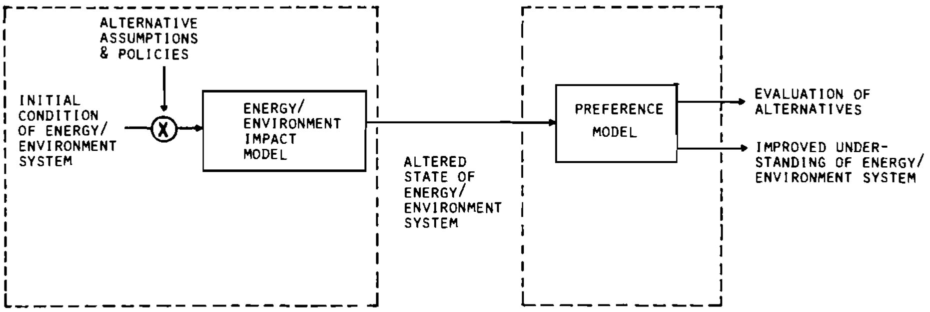

Figure 1. Relationship between impact model and preference model.

1.4 Organization of the Paper

The organization of the remainder of this paper is as follows. Section 2 suggests multiattribute decision analysis for formally addressing some of the complexities of managing energy/environment systems. It provides an overview of the basis and the procedures for deriving the utility functions required for the suggested approach. Section 3 presents an application of this approach to the analysis of an illustrative set of scenarios produced with the aid of the Electricity Impact Model (EIM) of the Wisconsin Regional Energy Model. It includes a brief description of the impact model, the construction of the preference model, and its application to the illustrative scenarios. Section 4 presents some further discussion of the IIASA experience with this approach to energy/environment management, and some of its benefits. Section 5 closes with a discussion of potential methods and opportunities for application, in particular with respect to the three regions studied at IIASA in 1975.

2. MULTIATTRIBUTE DECISION ANALYSIS

Most of the models developed to assist those making energy policy try to specify the altered state of the energy/environment system resulting from each of the available alternatives. This state is usually described in terms of several factors or attributes. For instance, the policy of introducing nuclear power facilities may result in levels of radioactive waste, of power generated, of water used, of land occupied, of deaths owing to the energy produced or to the lack of energy and so forth. The model might either give point estimates of such levels or present the information in a probabilistic fashion. Then the decision maker is supposed to consider these possible states and to select the best policy from the alternatives.

To effectively process all the information in one's mind is a difficult task. From the outline of the problem given in Section 1, three major complexities leading to this difficulty may be observed:

> Uncertainties about what the impact of any alternative might be, especially when one considers the time frame involved;
>
> The multiple objective nature of the problem and the need to make value tradeoffs among various levels of indicators; and
>
> The difference among the preference structures of the individual members of the decision-making unit, and the lack of systematic procedures for articulating and resolving these differences.

Two general approaches for addressing these issues are an informal qualitative approach and a formal quantitative one[1]. For the informal approach, one processes in his own mind the pros and cons of each of the alternatives and discusses his thinking with other concerned members of the decision-making body; eventually a decision results from either agreement or compromise or ... . The formal approach attempts to quantify the preference structure of each of the decision makers, and to couple this with the implications of the impact model to examine policy. The individual preference models allow one to explore the areas of agreement and disagreement among decision makers.

---

[1] Whether a group opts for the formal or the informal process is itself a decision. Some of the advantages and disadvantages of each are suggested in Keeney and Raiffa [6].

The process itself is important in addressing the third complexity mentioned above. Here, we would like to give a flavor for the formal approach.

The result of quantifying one's preferences is a model of these preferences called a utility function. When multiple objectives are involved, a measure of effectiveness, or attribute, is needed to indicate the degree to which each objective is met. Hence the terminology, multiattribute utility function. This multiattribute utility function is simply an objective function (to be maximized) with one special property: in cases involving uncertainty, the expected utility calculated for an alternative is an appropriate measure of the desirability of that alternative. Thus if one accepts a set of reasonable axioms postulated by von Neumann and Morgenstern [7], one should choose the alternative leading to the highest expected utility.

2.1 Terminology of Multiattribute Utility

Let us introduce the terminology within the framework of energy policy. We are oversimplifying, but let us suppose that there are only four objectives:

$0_1 \equiv$ minimize fatalities;
$0_2 \equiv$ minimize SO_2 pollution;
$0_3 \equiv$ minimize radioactive waste; and
$0_4 \equiv$ optimize energy generated.

For each of these objectives, we need an attribute to measure the degree to which it is met. Suppose that we select the attributes as defined in Table 1 below for this purpose; the selected ranges are based on previous studies. If we define x_i to be a specific level of X_i, then $x_1 = 230$ means that X_1 is equal to 230 deaths; thus our problem is to find a utility function $u(x_1,x_2,x_3,x_4)$ over the four attributes X_1,X_2,X_3,X_4.

Table 1. Attributes and ranges used for utility assessments.

Attributes	Units	Range
X_1 = Total quantified fatalities	Deaths	100 - 700
X_2 = SO_2 pollution	10^6 tons	5 - 80
X_3 = Radioactive waste	Metric tons	0 - 200
X_4 = Electricity generated	10^{12} kWh(e)*	0.5 - 3.0
*Kilowatt-hours of electricity.		

If we have assessed u, we can say (x_1,x_2,x_3,x_4) is preferred to (x_1',x_2',x_3',x_4') if $u(x_1,x_2,x_3,x_4)$ is greater than $u(x_1',x_2',x_3',x_4')$. More importantly, if policy A leads to an expected utility of 11.3 and policy B leads to an expected utility of 9.6, then policy A should be selected over policy B.

2.2 Multiattribute Utility Theory

The main results of multiattribute utility theory are representation theorems that state conditions under which a utility function can be expressed in a specific simple functional form. If such a form is appropriate for an analysis, it is then generally much easier to proceed with the assessments needed to specify the utility function.

The basic notions used in deriving representation theorems are the concepts of preferential independence and utility independence. Let us explain these concepts in terms of our simplified four-attribute problem and then state the representation theorem used in structuring preferences.

> *Preferential Independence:* The pair $\{X_1,X_2\}$ is preferentially independent of $\{X_3,X_4\}$ if one's preference order for x_1,x_2 combinations in (x_1,x_2,x_3,x_4), given that x_3 and x_4 are held fixed, does not depend on the levels where they are fixed.

This assumption is equivalent to saying that the value tradeoffs between fatalities and SO_2 pollution levels do not depend on the radioactive waste and the energy generated. It implies, for instance, that the indifference curves over X_1 and X_2 levels do not depend on X_3 and X_4.

> *Utility Independence:* Attribute X_1 is utility independent of $\{X_2,X_3,X_4\}$ if one's preference order for lotteries[2] on X_1, with x_2,x_3, and x_4 held fixed, does not depend on the levels where they are fixed.

This assumption is equivalent to saying that decisions concerning alternatives for which the impact on SO_2 pollution, radioactive waste, and energy generated is identical can be made by considering the overall impact on fatalities only and that these decisions will be made in the same manner regardless of the levels of SO_2 pollution, radioactive waste, and energy generated.

---

[2] A lottery is defined by indicating all possible consequences which may occur and their associated probabilities. Lotteries on X_1 are lotteries involving uncertainties about the level of X_1 only.

Using such independence notions, a multiattribute utility function can be decomposed into parts. The following is an illustration of one such decomposition.

> *Theorem.* Given $\{X_1,X_2,X_3,X_4\}$, if $\{X_1,X_i\}$, $i = 2,3,4$, is preferentially independent of the other two attributes and if X_1 is utility independent of $\{X_2,X_3,X_4\}$, then either
>
> $$u(x_1,x_2,x_3,x_4) = \sum_{i=1}^{4} k_i u_i(x_i), \text{ if } \Sigma k_i = 1, \tag{1}$$
>
> or
>
> $$1 + ku(x_1,x_2,x_3,x_4) = \prod_{i=1}^{4} [1 + kk_i u_i(x_i)], \text{ if } \Sigma k_i \neq 1 \quad ; \tag{2}$$
>
> here u and u_i, $i = 1,2,3,4$, are utility functions scaled from zero to one, the k_i are scaling constants with $0 < k_i < 1$, and $k > -1$ is the nonzero solution to
>
> $$1 + k = \prod_{i=1}^{4} (1 + kk_i) \text{ if (2) holds.}$$

Equation (1) is the additive utility function, and (2) is the multiplicative utility function. More details about these, including suggestions for assessment, are found in Keeney [8]. The important point is that, provided the appropriate assumptions hold, the four-attribute utility function can be assessed by assessing four one-attribute utility functions, u_i, plus four scaling constants, k_i. Such a decomposition makes assessment of u a simpler task.

2.3 Assessing a Utility Function

The actual assessment process requires personal interaction with the decision maker, since his utility function is (and should be) a formalization of his subjective preferences. The utility function allows us to combine in a logically consistent manner the contribution of fatalities, the SO_2 pollution, the radioactive waste, and the electrical energy generated into one index of desirability (namely, utility) for each of the possible states (x_1,x_2,x_3,x_4). To capture the decision maker's preferences requires that he explicitly address two types of issues:

a) Relative desirability of different degrees of achievement of a particular objective, and

b) Relative desirability of some specified achievement of one objective versus another specified degree of achievement of a second objective.

The first type of issue allows us to determine the u_i's in equations (1) and (2), whereas the second type provides the information for specifying the k_i's. Let us illustrate the types of questions used to obtain a utility function.

A question illustrating issue a) above might be presented to the decision maker as follows:

> Suppose you must choose between two alternatives. It seems to you that their impacts in terms of all the attributes except energy generated are about equal. Alternative A, which is the status quo option, has little uncertainty and will result in $1.5 \cdot 10^{12}$ kWh(e) over the next 30 years. On the other hand, alternative B is innovative and has a large degree of uncertainty. Best estimates and experiments indicate that with alternative B, there is about a 50-50 chance of 1.1 or $2.1 \cdot 10^{12}$ kWh(e) in the same period. If you have complete responsibility for the decision, which alternative would you choose?

It is easy to see that B leads to an average of $1.6 \cdot 10^{12}$ kWh(e), but because of the risks involved, the sure 1.5 may be preferred[3].

A question addressing issue (b) above is as follows:

> Two competing policies C and D will result in identical consequences in terms of SO_2 pollution and radioactive waste. Policy C will give you $2.0 \cdot 10^{12}$ kWh(e) but will result in 500 fatalities over the next 30 years. Policy D leads to only $1.4 \cdot 10^{12}$ kWh(e) but the associated deaths are 250. If the responsibility is yours, which of the two policies would you select?

Collectively, the responses to the two questions directly address the uncertainty and multiple objective complexities raised at the beginning of this section. We would naturally expect that if individuals of a decision making unit went through such a line of questioning, they would respond differently. This would result in different utility functions. By examining these utility functions, it may be possible to get a clear indication of the substance and degree of disagreement. This is a first step for resolving the differences.

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[3] It is important to note here that in our oversimplification of the problem to illustrate the concepts, we have neglected the additional value one may give to new technology.

3. APPLICATION OF MULTIATTRIBUTE DECISION ANALYSIS TO ILLUSTRATIVE ENERGY/ENVIRONMENT POLICIES

3.1 Introduction

Multiattribute decision analysis is applied to an illustrative set of alternative energy/environment policies. Specific policies are used to define and generate a scenario. In this example, to describe the impacts of various policies, we use the Electricity Impact Model (EIM) of the Wisconsin Regional Energy Model, described in the next subsection. The construction of the preference model is presented in the second subsection, and the application of the preference model to the illustrative scenarios is the subject of the final subsection.

The generalized framework of the composite environmental model in Figure 1 is made explicit in Figure 2 for the case of a specific set of energy/environment policies. The assumptions specifying a policy are provided as input to the EIM, which produces quantified impacts for that policy, $Q_{111},\ldots,Q_{IJK}$. These impacts are aggregated into a small number of attributes, $X_1,\ldots,X_{11}$, that include "proxy attributes" for recognized unquantified impacts that are considered important. For example, the mass of radioactive waste produced could be used as a proxy for the real and/or imagined impacts of radioactive waste. The preference model, based on the measured utility function for a particular individual, allows one to calculate the expected utility associated with each alternative policy for that individual. The policy option corresponding to the policy with the highest expected utility is the best choice.

3.2 The Electricity Impact Model (EIM)

The EIM [9,10], originally constructed as part of the Wisconsin Regional Energy Model [11], provides a list of quantified environmental impacts associated with a specified regional electricity demand and supply mix over a period of time. The primary input to the model is a set of assumptions about: quantity and sources of electrical generation as a function of time[4]; and important parameters, possibly time-dependent, that affect impacts. The primary output is an array of quantified environmental impacts associated with supporting fuel industries as well as the power plant itself. These systemwide impacts occur as a direct result of the electricity generation; a significant portion of the impacts may be imposed in regions other than the region where electricity is generated. For example, uranium is mined in the western part of the United States to fuel nuclear reactors located in Wisconsin.

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[4] This information can be provided by other models, such as other submodels of the Wisconsin Regional Energy Model.

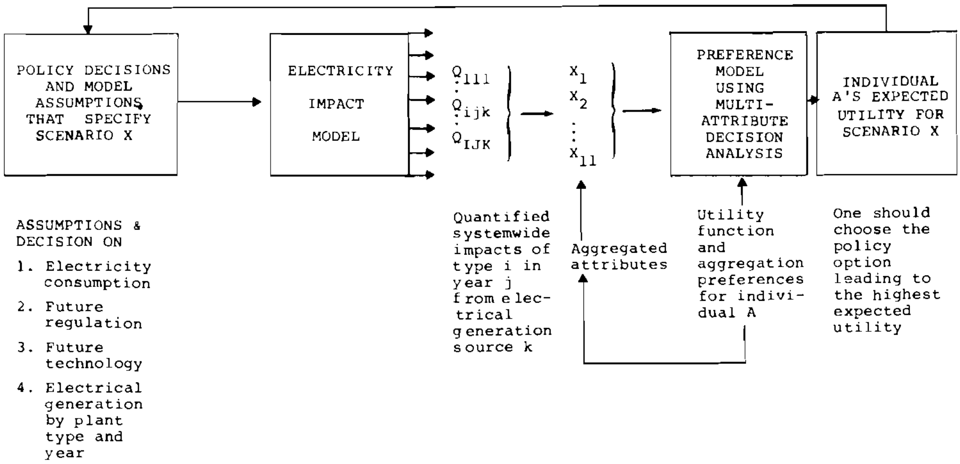

Figure 2. Composite environmental impact model.

While it is difficult to display in a general fashion how the use of electricity results in final impacts, Figure 3 shows the pathways for the majority of effects. Final impact as used here is the quantitative result that has a minimum of value judgment associated with it. Pathway 1 includes impacts such as air pollution from coal-fired plants, radioactive releases from the nuclear reactor, chemical releases from the power plant, and waste heat. The direct effects of electrical generation shown as Pathway 2 are effects at the power plant such as land and water use. Pathway 3 accounts for occupational health and risk, such as uranium mining accidents and uranium miners' exposure to radiation. Pollution from fuel cycle operations, such as radioactive releases from nuclear fuel reprocessing plants, is represented by Pathway 4. Occupational health and accident risk at the power plant itself is shown as Pathway 5. To compare future alternatives, the decision maker must combine these quantified final impacts with the unquantified impacts, the conventional costs, and other factors that affect his decision process.

The calculation of impacts from a particular energy system in a particular year is based upon impact factors that relate impacts to a unit of electricity generation for a reference plant in a specified year. The impact factor can be varied as a function of time to simulate changes in technology

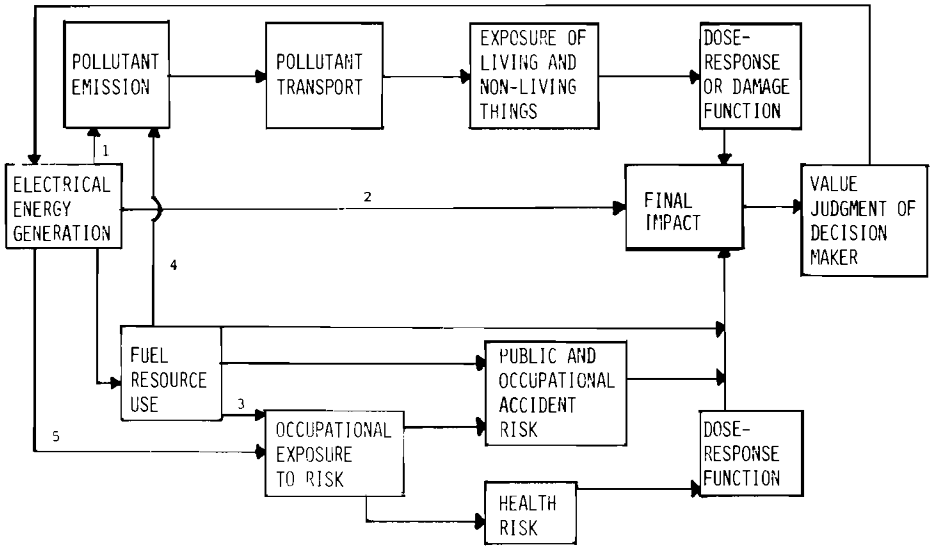

Figure 3. Electrical energy impact pathways.

or regulation. There are nearly 100 individual impact factors associated with each energy system in the EIM. The total number of impact categories in the EIM is well over 100 since some energy systems have unique impact categories, for example, cases of black lung disability from underground bituminous coal mining.

Since all impacts cannot be quantified, the output of the EIM cannot be considered a complete set of impact information. Environmental impacts can be divided into quantified impacts or those included in the EIM, and unquantified impacts, or all other impacts not included in the EIM. Some impacts are unquantified because: a) they have just been recognized as potentially important and therefore have not been investigated; b) because they are not even recognized as impacts; or c) quantification is based almost entirely on value judgment. However, merely specifying and defining the impacts to be calculated requires some value judgments. Two examples of recognized unquantified impacts that are not included in the EIM are: the potential long-term global climatic effects of continued CO_2 release from fossil fuel combustion [12]; and the potential long-term risks associated with radioactive waste [13]. Such potential impacts are difficult to quantify in conventional terms, but concerns over such recognized unquantified impacts can be included in multiattribute decision analysis by defining an appropriate attribute.

Since there is uncertainty associated with each of the impact factors in the EIM, the levels of impacts determined by the model could be expressed in terms of a probability distribution. The impacts estimated by the EIM do not have explicit probability distributions associated with them because, in general, the available data do not warrant the increased effort required to incorporate probability distributions in the model. However, if any of the quantified impacts were expressed in terms of probability distributions, the decision analysis framework presented in the previous section would become even more useful. In such a case, the probability distributions and utility functions would be integrated to provide expected utility. If the total impact of an alternative was quantified by probability density function $p(\underline{x})$ over consequences $\underline{x} \equiv (x_1,\ldots,x_{11})$, then the expected utility $E(u)$ for that alternative is given by

$$E(u) = \int u(\underline{x})p(\underline{x})d\underline{x} \quad , \tag{3}$$

integrated over all possible consequences. The ability to handle preferences under uncertainty is one of the strengths of utility theory. This quantification of probabilities and utilities greatly facilitates the use of sensitivity analyses.

3.3 Construction of the Preference Model

As shown in Figure 2, utility must be assessed in order to construct the preference model. The first utility assessments based upon the results of the EIM were carried out over the eleven attributes given in Table 2 [14]. These attributes are an aggregation of the numerous impact categories provided by the EIM. Since the selection of attributes also depends on preferences and value judgments, another set of attributes may be more appropriate for a particular individual. For example, some people may feel that since occupational risks are presumably taken voluntarily, occupational fatalities should be considered separately from public fatalities. The first attribute is the sum of all quantified health and accident fatalities, both occupational and public. Therefore, there should be interaction between the utility assessment and the specification of the aggregated attributes as indicated in Figure 2.

From the eleven attributes used in the initial study, a set of four was selected to simplify the problem for the purpose of demonstrating the methodology in this paper. The four attributes and their ranges for utility assessments were given in Table 1. The ranges are representative of the cumulative impacts and electrical generation that may occur for a variety of scenarios for Wisconsin over the period 1970 through 2000.

Table 2. Attributes for initial application of multiattribute decision analysis to the Wisconsin electrical energy system.

Attributes	Units*
1. Total quantified fatalities	Deaths
2. Permanent land use	Acres
3. Temporary land use	Acres
4. Water evaporated	10^{12} gallons
5. SO_2 emissions	10^6 tons
6. Particulate emissions	10^6 tons
7. Thermal energy needed	10^{12} kWh(th)
8. Radioactive waste	Metric tons
9. Nuclear safeguards	Tons Pu_f produced
10. Health effects of chronic air pollution exposure	Tons lead emitted
11. Electricity generated	10^{12} kWh(e)

*Pu_f is fissile plutonium; kWh(th)is thermal kilowatt-hours; and kWh(e) is electric kilowatt-hours. Source: [14].

Preliminary utility assessments were completed for five individuals from the Rhône-Alpes, the GDR, and Wisconsin. The group included a mixture of decision makers and energy/environment specialists. The non-Wisconsin individuals were made aware of current trends in Wisconsin electricity use so that they could understand the ranges of that attribute. The first-cut assessments presented here required two to three hours from each of the individuals whose utility function was measured.

The assessment procedure was divided into five steps:

Familiarizing the "decision maker" with the concepts of utility theory as discussed in Section 2;

Verifying preferential independence and utility independence assumptions;

Assessing single-attribute utility functions;

Assessing the scaling constants; and

Checking for consistency.

Some results of the assessments are given here; details of the assessment procedure are described in Keeney [14].

The utility function u_i over attribute X_i is set equal to zero at the least desirable level of X_i in the range, and set equal to one at the most desirable level of X_i in the range. The shape of the function is determined by asking questions of type (a) discussed in the previous section. The results for individual B are given in Figure 4. The shapes of the curves indicate that for fatalities, SO_2, and electricity generation, individual B preferred the midpoint of the range to a lottery that resulted in a 50 percent chance of the most desirable level and a 50 percent chance of the least desirable level. In the case of radioactive waste, individual B preferred the "best-worst" lottery over a certain 100 metric tons of waste. Several of the utility functions for the other individuals were linear; in that case the individual was indifferent between the midpoint and a 50-50 lottery involving the extreme levels of the attribute. Individual D felt that the most preferred level of electrical generation was approximately $1.5 \cdot 10^{12}$ kWh(e) and that the least desirable level in the range was $0.5 \cdot 10^{12}$ kWh(e). Therefore, his utility function for that attribute has a peak and is less than 1.0 at the highest value of electricity generation.

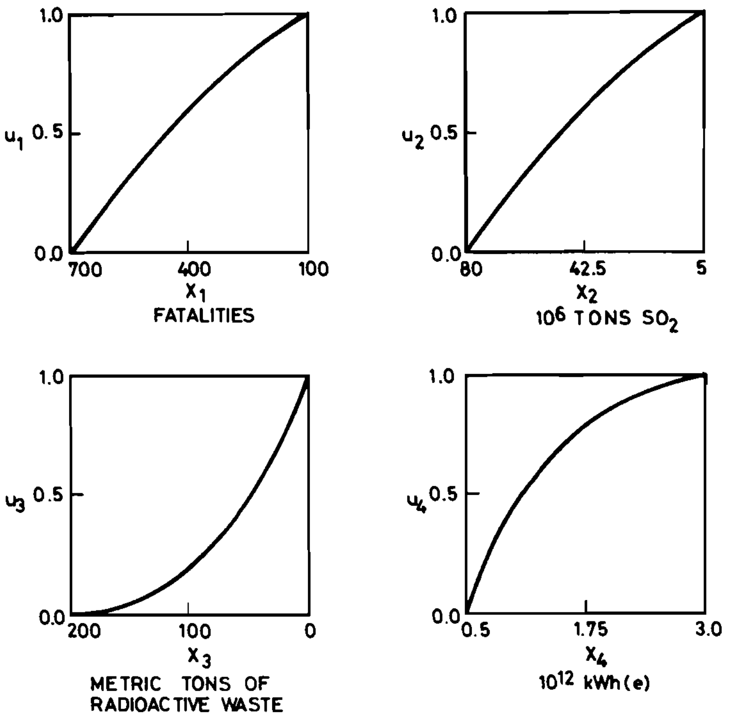

Figure 4. Utility functions for individual B.

The scaling constants for the utility functions are shown in Table 3. Three of the individuals' overall utility functions turned out to be multiplicative and the other two additive. The values of the k_i depend strongly on the ranges of the attributes shown in Table 1. If the range of one of the attributes were changed, *all* k_i would change. Since the k_i do not necessarily sum to 1, comparison of the absolute values of the k_i's among different people has no meaning. Comparison of the k_i's for an individual indicates the relative importance of each of the attributes for the specified ranges. Total quantified fatalities had either the largest or the second largest k_i in all five cases. Electricity generation ranked first in importance for the only individual who did not have k_1 larger than the other k_i.

Table 3. Utility function scaling constants for five individuals.

	Fatalities	SO_2	Radioactive Waste	Electricity Generated	Multiplicative scaling constant (Eqn. 2)
Individual	k_1	k_2	k_3	k_4	k
A	0.30	0.05	0.015	0.030	13.8
B	0.60	0.016	0.14	0.10	0.8
C	0.33	0.275	0.0	0.55	-0.4
D	0.65	0.02	0.24	0.09	-- *
E	0.61	0.14	0.14	0.11	-- *

*These individuals had additive utility functions (Eqn.1).

Consistency checks were carried out on the assessments and some adjustments were made in each of the cases. However, some inconsistencies remained unresolved because of time limitations. It should be emphasized that the utility functions presented here are the results of brief initial assessments; it is anticipated that further assessment of these individuals would lead to some changes.

3.4 Application of Utility Functions to Policies

The scaling factors in Table 3 and the $u_i(x_i)$ specify completely the multiattribute utility function, $u(x_1,x_2,x_3,x_4)$. These five first-cut utility functions were used to evaluate expected utilities associated with several policies for electrical generation in Wisconsin over the period 1970 through 2000. The levels of the four attributes and the expected utilities for each of the individuals are listed in Table 4. The reference case--attributes at extreme levels--is listed simply for orientation; it uses the "most desirable levels", that is, the lowest impacts and highest electrical generation, and results in an expected utility of 1.0. Since individual D preferred a lower level of electricity generation to the maximum 3.0, his expected utility was not 1.0 for the reference case.

The implications of the remaining four policies in Table 4 are output from the EIM. Policy 1 has most of the generation at coal-fired plants with relatively good pollution control. Nuclear power contributed only about 20 percent of the cumulative generation from 1970 through 2000. Policy 2 has the same electricity generation, and nearly 60 percent is from nuclear sources. Policy 3 has about 40 percent of the generation from nuclear sources and the remainder from coal-fired plants that use low-sulfur coal obtained from surface mines that are more than 2000 kilometers from the power plants. Policy 4 has about 25 percent less electrical generation, and coal-fired plants produce about 75 percent of the total generation.

If it is assumed that the individuals expressed their true preferences and that they act in a logically consistent manner, the expected utilities can be used to indicate their overall preferences. Under these conditions, Table 4 shows that all five individuals should prefer one or more of the other policies to policy 3. This is primarily the result of the large number of fatalities expected for policy 3 and the relatively high scaling factor each of the individuals placed on fatalities (Table 3).

Individual C indicated a strong preference to achieve a certain level of electrical generation, and therefore he had higher expected utilities from policies 1, 2, and 3 than from policy 4, which had a lower level of electricity generation. Individuals A, B, and E would be almost indifferent between policy 2, with high generation mainly from nuclear sources, and policy 4, with lower generation and less nuclear penetration.

No strong preferences are evident between policies 1 and 2, although all five individuals show slightly higher expected utility for policy 2. Thus, if the purpose of the assessment were to indicate whether a mostly coal or mostly nuclear future is preferred by the decision maker, further analysis would be necessary. If these techniques were applied to a real policy study, the attribute list would be expanded to include other impacts and to include conventional costs.

Table 4. Expected utilities for five individuals for several policies.

Attributes and Expected Utilities	Reference Case: Attributes at Extreme Levels	Policy 1: Mostly Coal, Good Pollution Control	Policy 2: Mostly Nuclear	Policy 3: Low Sulfur Coal from Distant Mines & Some Nuclear	Policy 4: Mostly Coal with Less Electricity
Total quantified fatalities	100	380	240	680	280
SO_2 pollution (10^6 tons)	5.0	12	8.0	8.6	9.5
Radioactive waste (metric tons)	0.0	61	160	110	54
Electricity generated (10^{12} kWh(e))	3.0	1.7	1.7	1.7	1.3
Expected utility for individual A	1.00	0.53	0.66	0.14	0.65
B	1.00	0.56	0.63	0.14	0.65
C	1.00	0.76	0.83	0.64	0.41
D	0.92	0.62	0.66	0.24	0.73
E	1.00	0.65	0.72	0.31	0.74

The utilities in Table 4 can also be directly used if uncertainty is incorporated into the models. For example, if individual A had a choice between:

Alternative 1: Definite impacts of policy 1, and

Alternative 2: A 50 percent chance of the impacts of policy 2 and a 50 percent chance of the impacts of policy 3,

he should prefer alternative 1, since his expected utility for this is 0.53 and for alternative 2 is only 0.5(0.66 + 0.14) = 0.40. This expected utility feature is one of the main reasons for using multiattribute utility for analyzing problems where uncertainties are important. In this particular example, the uncertainties could be associated with the levels of impacts or the ability to carry out the policies.

4. BENEFITS OF THE PROCESS AND IMPLEMENTATION

In the last section, we observed how a utility function can assist one in evaluating policy. The process of assessing the utility function has many benefits in itself. It can be a substantial aid in identifying and sensitizing individuals to important issues, generating and evaluating alternatives, isolating and resolving conflicts of judgment and preference among members of the decision-making team, communicating among the several decision makers and, in this particular application, identifying improvements needed in the impact model.

4.1 Communication

The assessment of preferences forces individuals to be more precise in deciding why they feel certain levels of attributes are important. Clearly policy makers must face such issues regularly. However, owing to the complexities that cloud their choices, the value tradeoffs involved are sometimes unclear. The assessment formalization helps to make the tradeoffs more explicit. With a better understanding of one's own tradeoffs, it should be easier to communicate them to others. The communication then serves as a catalyst to identify parts of the problem that were previously overlooked. For example, the initial reaction to a tradeoff involving human fatalities and other impacts is often discomfort as one must effectively place a value on human life (or a reduction in someone's lifetime). The viewpoint eventually reached is that such tradeoffs are practical questions that must be addressed for rational decisions.

4.2 Identifying and Sensitizing Individuals to Important Issues

When one assesses preferences, it is often the case that the respondent says, for example, "I can't answer that definitely, because it depends on ...". This indicates important structural relationships sometimes not present in the model. For instance, in our simplified example given in Section 2, a decision maker may say that tradeoffs between fatalities and energy generated depends on who is dying, how, and when. If this is important for making the decision, then obviously the decision maker should have the information when the decision is made. In trying to informally analyze the entire problem, such issues are sometimes overlooked.

As mentioned earlier, some people feel that occupational risks are partially compensated by salary premiums, and therefore occupational health and safety should be considered separately from health and safety of the general public, who expose themselves to the risks involuntarily. In addition, some people feel that a disabling illness that gradually leads to death is worse than a fatality caused by an accident. The timing of the impacts must also be addressed. Radiation health impacts may not appear for many years after the exposure due to the electrical generation, while uranium mining fatalities occur some years before the generation occurs. The generation itself may be taking place over a period of years. Thus, in the limit, one can imagine separate impact categories for occupational health impact in time period 1, occupational accident impact in time period 1, public health impact in time period 1, and so forth. The method for aggregating these impact categories is part of the preference assessment.

4.3 Isolating and Resolving Conflict

Roughly speaking, the scaling factors in equations (1) and (2) designated by the k_i's indicate the importance of the respective attributes, given the possible ranges of concern. If these differ for individuals, it may be possible to go behind the answers and to get at the reasons why they differ. For example, one might find that an individual who originally assessed a rather large k_2 (associated with SO_2 pollution) relative to k_1 (associated with fatalities) had knowledge of large detrimental impacts of SO_2 of which other individuals were not aware. Upon reflection, some individuals may then change their preferences in a manner to reduce the conflict.

The assessment process, a period of reflection and discussions with other people, resulted in some changes in scaling factors and single-attribute utility functions for at least one of the individuals involved in this study [14]. The explicit statements concerning one's preferences that are required during assessment are sometimes difficult to provide, especially when one must associate for the first time some unquantified effects with a proxy variable. After such an experience, individuals may be more likely to discuss their judgments about particular attributes that are weighted more heavily by some than others.

4.4 Improvements in Impact Models

The three above mentioned advantages of the formalism of preference models have desirable effects for the development of the impact model. It helps to focus on what impacts should be modelled, on structural relationships and interdependencies that indicate how to model these impacts, and on data needed for a responsible modelling effort. The modellers are made aware of additional areas of concern and what proxy variables are appropriate for impacts that are difficult to quantify in conventional terms.

4.5 Generating Alternatives

Because of different preferences, we may find that a particular "best" overall alternative is rated very good by most of the members of the decision group, but rather low by a few. By detailed examination, it might be clear that the reason it is low is attribute X_3, for example. Then by focussing thought on alternatives that might improve things on attribute X_3, the group may come up with an alternative that is much better for those whose preferences were low and which is only slightly worse for the others. Conceivably, one might even find a new alternative that is better for everyone. Because of the complexity of the problem, it is sometimes possible to generate such "dominant" alternatives.

5. POTENTIAL IMPLEMENTATION OF THE METHODOLOGY

This report described a methodology for using decision analysis in conjunction with environmental impact analysis of energy systems. In addition to the methodology presented, a simplified example was presented for evaluating several energy/environment policies in the state of Wisconsin. It was shown how a utility function can assist one in evaluating alternative policies, and that the *process* of assessing the utility function also has many benefits in itself. This section points toward the future and suggests some possible mechanisms and benefits of application of this methodology in the three regions studied in the IIASA research program.

Because each of the three regions has a very different set of energy/environment models as well as greatly differing institutional structures for decision and policy making, the use of decision analysis would differ in each case. It might be more applicable to specific policy issues in a given region than in others. However, in view of the many man-years of scientific effort that have been devoted to constructing energy/environment models in each of the countries, it does not seem at all unreasonable to consider devoting a modest amount of time to the construction of preference models for use with impact models. A relatively small amount of effort may have a significant effect. Some alternative approaches to the application of the methodology are outlined below for each of the three regions.

5.1 Wisconsin

Energy/environment decision and policy makers in Wisconsin operate within a relatively decentralized structure, that is, the decision making is diffuse. As a consequence, the information and technical expertise is also distributed broadly throughout a number of agencies and offices. The methodology described in this report could be used to conduct formal assessments of decision makers and policy makers at various levels of government to provide them with a better understanding of the tradeoffs among the many complex issues. Clearly, in this case the method would not be used to provide a recipe for overall formal decision making but rather as a tool to improve communication, clarify some of the more complex issues, help generate alternatives, and to help individual decision making units in the system.

A second use of the methodology would be the assessment of the scientific and technical staff of the Wisconsin energy and environment commissions to aid them in structuring their research priorities. One of the major objectives of this application is the identification of gaps in knowledge and in methodology. In Wisconsin, the approach might be of value to the Public Service Commission, the Department of Natural Resources, the Department of Transportation, the State Planning Office and perhaps others.

A less conventional, and as yet untested use of this methodology, would be as a means of interaction with public interest groups for the purpose of clarifying their understanding of and positions on energy/environment issues. For example, in Wisconsin the Environmental Defense Fund, the Sierra Club, and the League of Women Voters might be appropriate clients for this method. It would help not only to clarify the issues and perhaps raise the level of the discussions, but it might also help these public interest groups to arrive at their positions on a specific issue. Clearly, this use is not without its problems; it is understandable that a user of such an approach must be convinced that it will provide him with additional information on which to make his decisions and with which he can better achieve his objectives.

Another as yet untried application would be its use as a pedagogical tool in formal public presentations or discussions in the energy/environment area, for example, with the use of an interactive computer model on closed circuit television. In this case the methodology would serve as a communications tool.

5.2 Rhône-Alpes

Each of the above suggested applications for Wisconsin is also of potential use in the Rhône-Alpes, but because the region has far less decision capability within the government, the applications of the methodology would be different. Use of the methodology as an aid in laying out research priorities might be appropriate for helping French national agencies to understand the regional aspects of their policies and to establish their research priorities related to regional questions. Electricité de France has a major nuclear power expansion planned for the Rhône-Alpes region. The use of an impact model in conjunction with a preference model could help to clarify the issues as perceived by local groups in that region. From another perspective, we found interest on the part of local agencies in using this approach as a discussion tool. During the IIASA Workshop on Management of Energy/Environment Systems in November 1975 [4], various local French participants expressed interest in further experimentation with the method.

5.3 The German Democratic Republic

Each of the above approaches could also be applied in one way or another in the GDR. However, because there is much greater use of formal government planning in the GDR, less emphasis would probably be given to its use in interaction with local and public groups. It seems admirably suited for use in efforts to obtain appropriate objective functions for formal optimization models in the energy and environment sectors. One major problem associated with the use of formal optimization procedures is defining suitable objective functions and constraints. Clearly, these objective functions and constraints should take into account a multitude of costs, benefits, system attributes, and the like; decision analysis could help considerably to determine the ways in which these should be combined within a formal optimization procedure. Research is currently underway at IIASA to develop a formalism for incorporating decision analysis into formal optimization procedures for energy/environment system planning [4].

The above suggestions are only indicative of possible uses of decision analysis as a tool for embedding impact models into an institutional framework for policy design and analysis. Such an approach would require in each of the three regions the development of some knowledge of decision analysis and utility theory. Admittedly, the use of the technique is as much an art as a science. However, the same could be said about building an impact model from an infinite array of possible environmental impacts.

In ending this discussion, we must add the obvious caveat. Even though a preference model combined with an impact model can be used to evaluate alternatives, the answers and implications for action are all conditional on the model being a complete representation of the real world. This is clearly never the case. The composite model can serve as an aid to decision makers but it cannot and should not ever replace them or their judgment in making decisions.

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Appendix

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