A FRAMEWORK FOR INTEGRATING REGIONAL ENVIRONMENTAL GOALS INTO COAL PRODUCTION AND UTILIZATION STRATEGIES

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March 1980
CP-80-5

Presented at the Coal Issues for the Eighties Program Planning Workshop in Szczyrk, Poland, November 5-9, 1979

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PREFACE

This paper summarizes a proposed approach for incorporating more fully specific regional environmental goals into a coal-based energy planning process. The primary purpose of the paper is to provide a framework for discussion of environmental issues at the IIASA Coal: Issues For The Eighties Program Planning Workshop in Katowice, Poland, November 5-9, 1979.

The overall objectives of the IIASA Coal: Issues For The Eighties program is to bring together representatives of energy and environmental policy makers and the coal industry from many countries; to identify key issues which these groups will jointly face over the next 10-20 years; to identify the ways in which systems analysis can assist in the major policy and inventment decisions; and to engage in a collaborative program of information exchange and research. IIASA's role is essentially catalytic. It is IIASA's task to identify needs and seek to create the conditions in which they can be satisfied through collaborative research. Its unique international -- but non-governmental -- position in the systems analysis field, and the fact that it works in many fields of related concern (Energy, Resources, Environment, Manpower and Health, Management, Technology, etc.) makes it an ideal base for a creative exchange of information, methods and ideas. The collaborative nature of this program is seen to be fundamental to its success in providing improved information and methodologies for those involved in policy decisions.

In conjunction with the consideration of environmental issues, additional program components are focusing on the development and application of procedures for planning, organization, management, and introduction of innovative technology in the coal extraction industry. Those study components are not directly addressed in this paper.

ABSTRACT

This paper presents a framework for incorporating more fully specific regional environmental goals into a coal-based energy planning process. The framework utilizes the developed theory of multiattribute decision analysis to structure the problem of attaining a preferred balance between interrelated coal use and environmental goals. The decision analysis method of "satisficing" is proposed as an approach for focusing on a major regional environmental issue in view of other constraints on coal use target levels, cost, technology, and overall environmental planning. Included is a discussion of the mechanisms for involving decision makers, scientists and other specialists in the assessment process. The proposed framework is illustrated by a hypothetical application to the issue of limiting coal related acid rain and other air pollutant effects in the U.S.-Canadian border regions.

CONTENTS

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INTRODUCTION

Recognition of the limitations of present energy use patterns that rely heavily on increasingly scare supplies of natural gas and oil has led to extensive assessments of the potential for the utilization of alternative more abundant energy resources. Coal has been identified in a number of studies and in several government policy statements as a resource that could provide an increasing proportion of energy requirements for specific countries. Specific regulatory policies have been developed to stimulate substituting coal in the industrial and utility sectors for dwindling supplies of natural gas. At the same time, significant increases in coal-related research and development efforts have occurred to provide the technological basis for increased coal use. Furthermore, policy analysts are evaluating the potential for a world coal market, including both raw coal and coal derived products, such as methanol.

Parallel to the interest in increased coal use, coal related environmental policies and standards have become more demanding in all phases of the coal fuel cycle. In addition to tighter standards on air quality emissions, surface water conservation, and mining area reclamation, new environmental programs for solid waste disposal, resource recovery, and groundwater conservation have been implemented or are being proposed. The full ramifications of these environmental programs to both the coal industry and the overall environment are unknown.

From an industry standpoint, the uncertainties in the coal environmental policy framework make production and use decisions difficult. These environmental considerations are increasingly being recognized as having importance often equalling, or even exceeding, the importance of economic development considerations.

From an environmental standpoint, changes in coal technologies and utilization patterns that result from specific energy or environmental policies can have impacts or tradeoffs in all environmental areas. Technologies required for air emission control, for example, could have significant implications for waste disposal problems. Alternatively, a regional siting pattern and coal technology mix that emphasizes water conservation in water shortage areas will also affect the level and distribution of atmospheric emissions and solid wastes generation.

The first part of this paper provides an analytical structure for dealing with a broad range of coal and environmental planning needs based on modern decision analysis methods. Typical planning constraints and attributes of desired solutions appropriate to program objectives are included. The second part of the paper illustrates the potential application of this methodology to a case study of alternate strategies for limiting acid rain effects of future coal use in the U.S.-Canadian border regions.

A DECISION ANALYSIS FRAMEWORK

The generic procedure for national or regional coal-based energy planning, as illustrated in Figure 1, generally proceeds from projections of future coal demand based on economic analyses of total energy demand and consideration of alternate energy resources and technologies. The more detailed identification of viable coal strategies to achieve target supply levels typically takes into account additional regional factors, one of which is environmental impacts. Variations in coal use strategies which can have an impact on environmental impacts include alternatives in siting patterns, final energy form (e.g., synthetic oil or gas vs. electricity), end use (e.g., industrial vs. residential applications), coal characteristics (e.g., high vs. low sulfur), coal extraction technologies (e.g., deep vs. surface mines), and environmental control technologies. Each of these alternatives may present specific environmental advantages, for example, reduced water impacts, but often with a resultant trade-off of higher economic cost or increased impacts in other environmental areas such as waste disposal and land use.

The overall objective of the environmental component of the IIASA study is to develop and test procedures for obtaining an "acceptable" balance between coal use strategies and environmental goals. Conflicts between coal-related environmental impacts and environmental goals may force changes in the economic and resource based projection of future coal demands. However, the proposed study approach will at least initially focus on approaches for coal/environmental planning for fixed regional coal demand projections. This serves the purpose of limiting the initial program objectives but, as will be shown

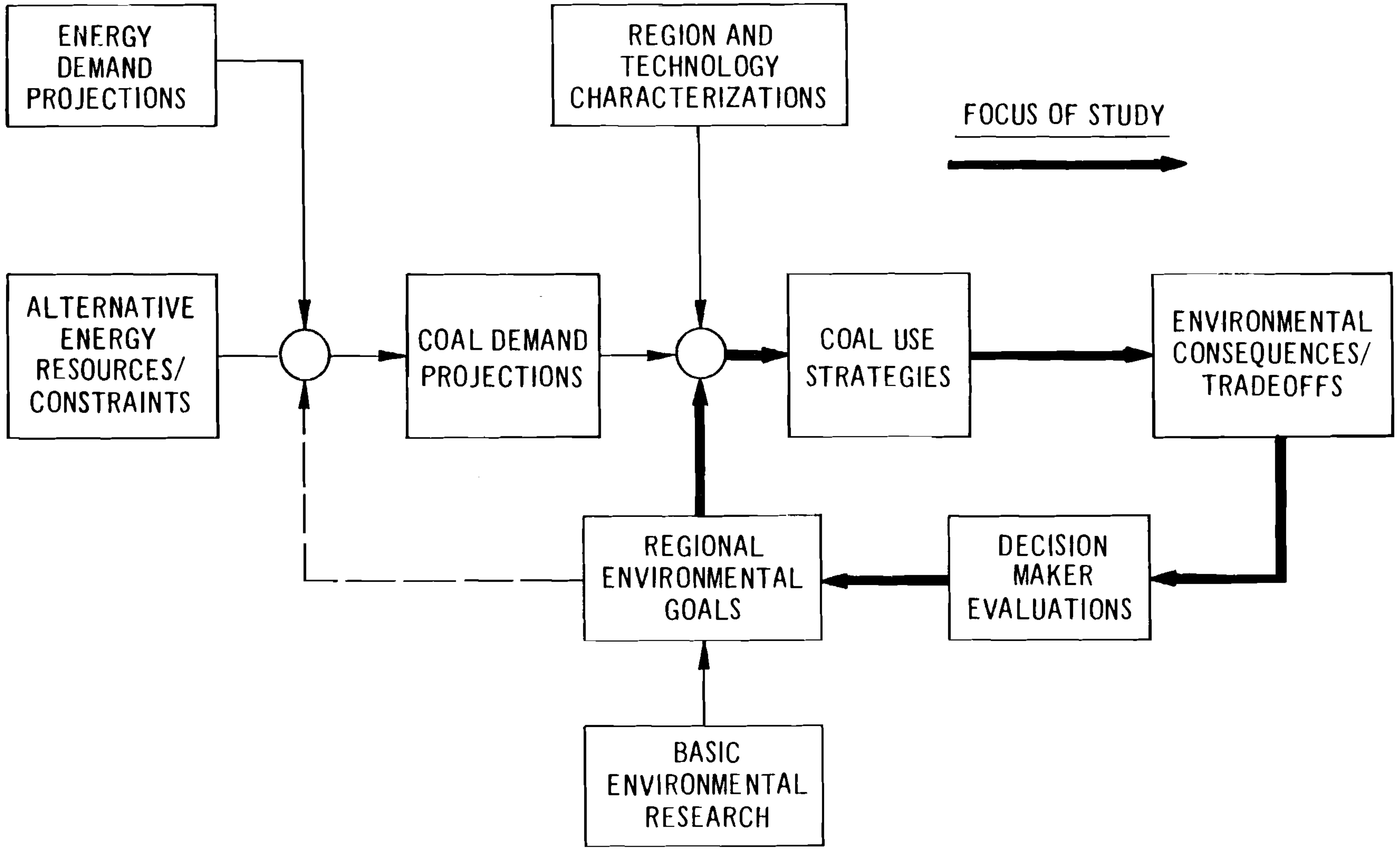

Figure 1. Generalized process for integrating regional environmental goals into coal production and use strategies.

later, these results can be consistently linked through a hierarchical framework to the broader problem of environmental goal impact on future coal demand projections.

The basic problem of selecting a coal use strategy that achieves an acceptable balance between various environmental impacts, costs and other factors as stated above can be set in a multi-attribute decision analysis formulation as follows:

Define:

E: Set of possible coal use strategies

$E_p \varepsilon E$: Possible strategies producting target coal use level, and meeting other hard (technology) constraints

$Q_p = f(E_p)$: Possible consequences of coal use strategy options, for example,

$$Q_p = \text{range of} \begin{bmatrix} \text{costs} \\ \text{air pollution} \\ \text{water use} \\ \text{water pollution} \\ \text{etc.} \end{bmatrix}$$

Problem:

Find the strategy $\underset{\sim}{X} \varepsilon E_p$ that has a set of consequences Q_o that are minimum according to the decision makers' preferences.

Some basic features of this problem formulation and its solution are graphically illustrated in Figure 2 for the case where two coal strategy consequences, cost of energy produced and sulfate (SO_4) air pollution levels are considered. With this simplified problem, it is easily seen that the preferred strategy is one with consequences somewhere on the boundary indicated with a solid line. For all strategies with consequences on this line (referred to as Pareto-optimal solutions) a decrease in sulfate level can only be achieved by an increase in cost, and vice versa.

To obtain a unique solution, the analyst may specify all consequences in equivalent units, for example monetary value of environmental parameters such as increased air pollutant levels. This approach is severely limited by current inability to adequately place a monetary value on environmental quality. Alternatively, a unique solution is obtained through knowledge of decision-makers' preferrences, or utility function, that in effect weight the relative importance placed by those persons on each consequence.

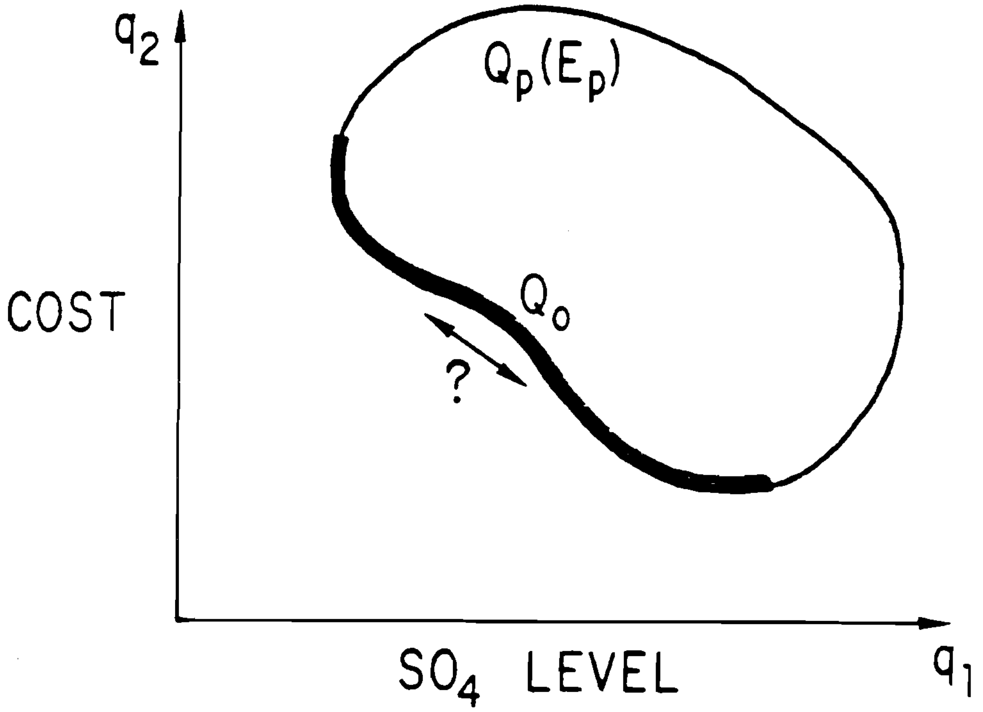

Figure 2. Typical cost and SO_4 level tradeoffs for coal use strategies. Points on heavy line are Pareto-optimal.

The use of utility functions has been well developed theoretically, including procedures for extracting decision-maker relative preferrences, or utility functions, and application of statistical approaches to take into account uncertainty and risks. Reviews of these approaches can be found in the literature. (See for example, references 1,2,3).

Although the theory of multi-attribute decision analysis is well-developed, its practical application often encounters considerable difficulties. These problems of applications typically relate to the following type of issues encountered in obtaining decision-maker relative preferences;

- Time required of decision-makers
- Decision-makers' inconsistency over time
- Modeling difficulties in portraying impacts and tradeoffs of primary concern
- Decision-makers tend to think in terms of independent "acceptable" goals for each consequence.

These pragmatic problems of application have led researchers to seek alternate approaches. One such approach, the method of "successive concessions," initially requires only a ranking of consequence priority. [4] This ranking, which is in general easier to determine than a quantitative weighting, is conceptually compatible with the approach commonly use by environmental regulatory agencies when focusing on the real or perceived central environmental issues in a region.

To illustrate the method of successive concessions, assume a consequence ranking:

$$Q = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix} = \begin{bmatrix} SO_4 \text{ level} \\ \text{Cost} \\ \text{Water use} \end{bmatrix}$$

Step 1

Find the strategy with minimum SO_4 level = q_1^o (Scalar Optimization)

Step 2

Find the strategy with minimum cost q_2^o, given the constraint

$$q_1 \leq q_1^o + \Delta q_1 \quad \text{(Concession on } SO_4 \text{ level)}$$

Step 3

Find the strategy with minimum water use q_3^o, given the constraints

$$q_1 \leq q_1^o + \Delta q_1$$

$$q_2 \leq q_2^o + \Delta q_2 \quad \text{(Concession on cost)}$$

An illustration of the first two steps is given in Figure 3. This approach generally requires an iterative procedure to obtain an acceptable solution.

To apply the method of concessions at least some information is assumed available to make acceptable concessions. For example this information may include:

- Cost of coal derived energy that is competitive with oil, gas, nuclear, etc.
- Regional water availability and competing demands
- Water quality standards
- Cost/benefit analysis of environmental impacts
- Information on unavoidable consequences from previous analysis

As an alternate to the method of successive concessions, an approach under the generic title of "satisficing" makes use of this information to set acceptable levels for the lower

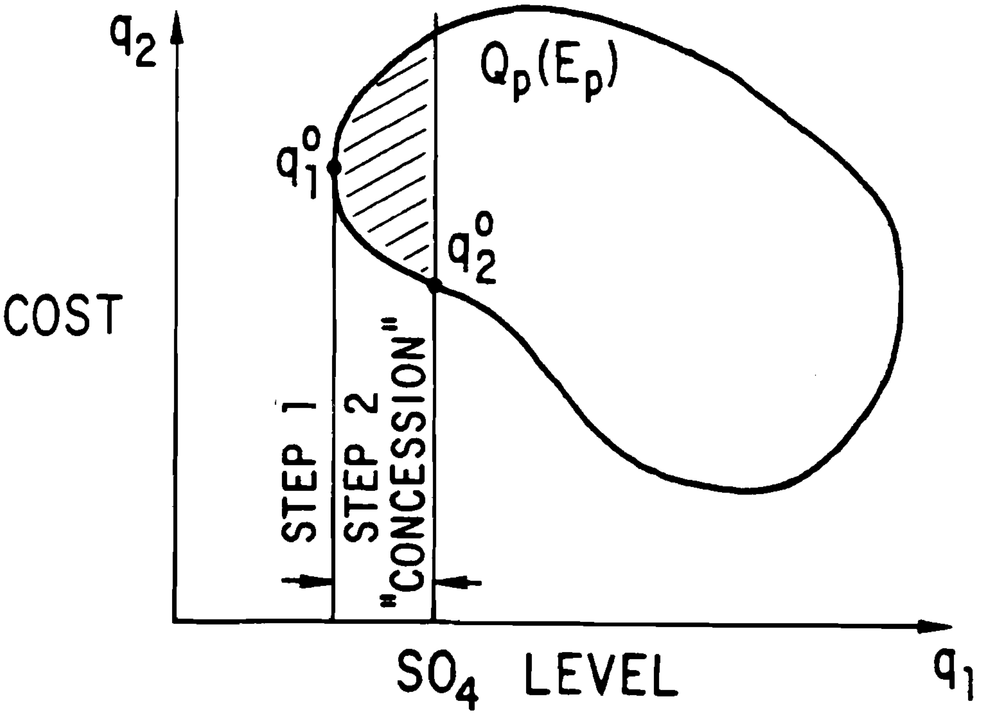

Figure 3. Method of successive concessions with minimum cost given concession on optimal SO_4 level.

priority objectives, thereby converting those objectives into initial soft constraints that may be revised as necessary in subsequent iterations.[5]

To illustrate the method of satsificing, the following approach would be utilized in the previous example:

Step 1

Identify the priority consequence, say $q_1 = SO_4$ level.

Step 2

Establish initial estimates of constraints for the remaining consequences

$q_2 \leq q_2'$ (cost)

$q_3 \leq q_3'$ (water use)

Step 3

Determine minimum q_1^o (Scalar Optimization)

Step 4

DM decides "is the solution acceptable?", with the following possibilities.

A) Yes -- problem is solved

B) No -- would like to reduce q_1, SO_4 level. Return to Step 2 with relaxed constraints selected by DM. For example, since q_3, water use, is low priority

$$q_3 \leq q_3' + \Delta q_3$$

Return to Step 3 to find new minimum $q_1^{o\prime}$

C) No -- willing to increase q_1^o to reduce, say, q_2, the second priority consequence. Set constraint

$$q_1 \leq q_1^o + \Delta q_1$$

Find minimum q_2^o (Scalar Optimization)

The first three steps of this approach are illustrated in Figure 4 for the 2-dimensional case of cost and sulfate (SO_4) air pollution consequences. Again an iterative procedure is generally required to achieve an acceptable solution.

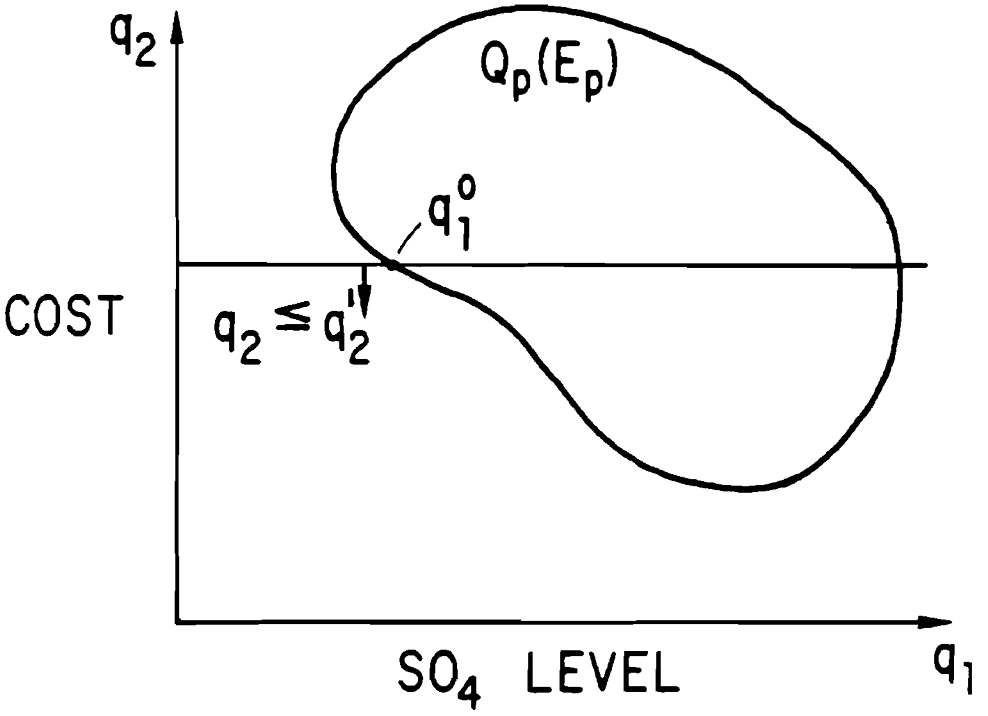

Figure 4. Method of satisficing with minimum SO_4 level given constraint on maximum cost.

Consideration of the above approaches leading to a determination of "acceptable" solutions naturally leads to the question of the relation of these solutions to the "optimal" solution of the multiattribute decision analysis problem as originally formulated. A theoretical link to the optimization problem has in fact been established through the use of a hierarchical analysis as illustrated in Figure 5 [6]. If the scalar optimization as outlined above for the priority consequences is also performed separately for each of the other consequences, with or without constraints for the non-optimized consequences, the combination of these separate solutions using an appropriate weighting function produces the overall optimal solution. Furthermore, the hierarchical approach to finding the optimal solution can be extended to a still higher level to include determination of an optimal level of coal use relative to other energy forms. Although this relation has been theoretically demonstrated, its application is complicated by the requirement for determining a related Lagragian function. Thus, although obtaining the overall optimization may in practice not be easily achievable using these approaches, the theoretical compatibility of "acceptable" and "optimal" solutions lends further credibility to the use of "acceptable" solutions as proposed in this paper.

An additional variation in approaches to achieving acceptable solutions, which is under development at IIASA and elsewhere, proceeds by initially identifying reference objectives (i.e., desired goals) for all of the consequences[7]. A solution is obtained by determining the set of Pareto optimal consequences that are "closest" to the reference objectives according to a

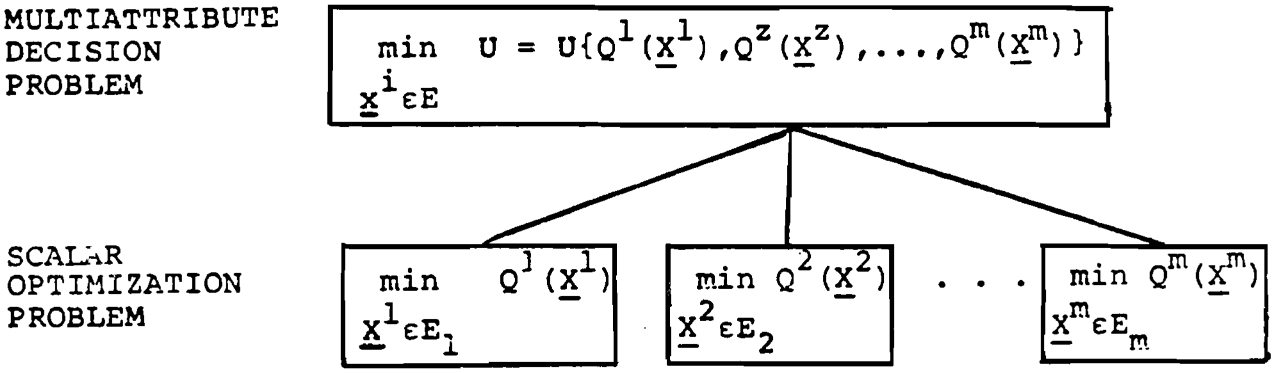

Figure 5. Hierarchical multiattribute decision analysis based on constrained scalar optimization of individual attributes.

defined norm. This resultant solution can be retroactively used to identify a utility function that would give the same solution if used in an optimization approach.

The involvement of decision makers is a key element in each of the above approaches and thus warrants further consideration. Considerable research has been conducted into procedures for making this involvement effective (see for example references 1,2,3), including psychologically oriented "soft-science" aspects related to human interactions. The discussion in this paper will be restricted to a summary of an apparently effective approach reported by C.S. Holling (ed.) and based on a previous collaborative IIASA study to develop an adaptive approach to environmental impact assessment and management [8]. From this study evolved recommendations for specific procedures for decision making based on a number of studies of renewable resource problems in different national settings: renewable resource management and disease control in Venezuela and Argentina; range and wildlife management in the United States; developmental and oceanographic problems in Europe; ecological process studies in the Soviet Union; renewable resource and pest management systems in Canada. Although these issues are not directly related to environmental problems associated with coal use, the successful development of effective approaches to decision making with a variety of environmental issues provides the impetus for the consideration of adopting these broadly defined techniques in the Coal: Issues for the Eighties program.

A basic element of the proposed procedure is the convening of a series of workshops involving a core group of analysts and key specialists including policy makers, environment and resource managers, and scientists. The role of the specialists is to focus the analysis on the issues critical to decision making, to define viable strategy options, and to provide the analysts with an access to relavent input data. An important function at the initial workshop is the development of the basic structure of the model to be used for assessing strategy options. Compared to the more familiar approach of having analysts independently develop the modeling tools, participation by decision makers and scientists ensures that the model output will produce results related to relavent decision issues and that state-of-the-art knowledge on dynamics of environmental impacts is included.

The role of the core group is to coordinate workshop activities and to implement the defined assessment model for the iterative determination of optimal or acceptable strategies as described previously in this paper. Subsequent workshop sessions are convened to evaluate interim model results and prescribe further steps in considering additional alternatives, or possible modelling revisions as required to move toward an acceptable balance between tradeoffs.

A CASE STUDY EXAMPLE

To illustrate the approaches proposed in the preceeding discussion for integrating regional environmental goals into coal production and utilization strategies, this section of the paper considers various aspects of an ongoing decision making process for limiting transboundary air pollutant effects related to coal utilization in the U.S. and Canada boundary regions. The decision making process in this example centers on the jointly announced intention of the U.S. and Canadian governments to develop a formal cooperative bilateral air quality agreement [9].

This recognized need to control transboundary air pollutants stems from various factors. A primary factor is recent data that shows that precipitation in these regions has become increasingly more acidic, as illustrated in Figure 6. This increase in acid precipitation is at least partially due to increases in sulfur and nitrogen air pollutant compounds [10]. There is increasing concern that this acidic precipitation can have a profound impact on the prevalent natural aquatic and terrestrial ecosystems in parts of this region where geological conditions provide minimal buffering capacity [11,12,13]. In addition to impacts on natural ecosystems, these air pollutants can also have a deleterious effect on human health, visibility, building materials, and commercial forest and crop production.

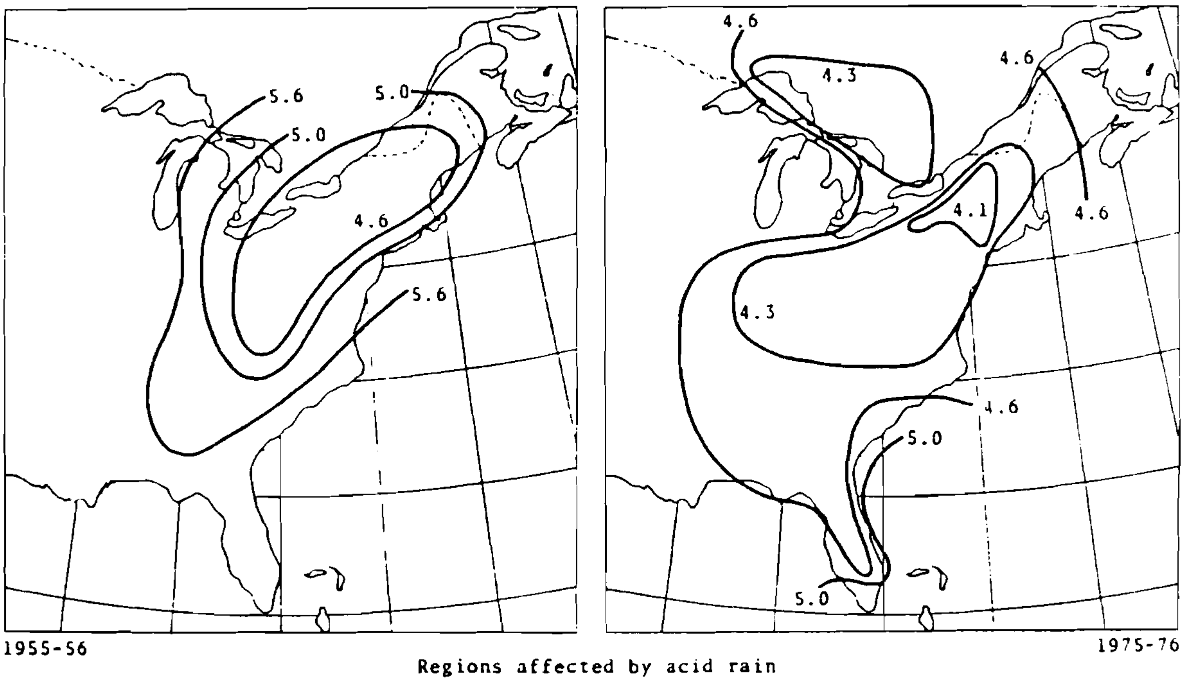

Figure 6. Isopleths showing annual average pH of precipitation in eastern North America (adapted from ref. 10).

Limiting the levels of these air pollutants and their effects in this region involves a much larger geographic area since the residence time of certain nitrogen and sulfur compounds in the atmosphere may be several days during which they may be transported several hundreds to thousands of kilometers--distances that are comparable to the extent of eastern North America.

Although the relative impacts of individual air pollutant emission sources on this region is not directly available, an indication of their importance can be obtained by considering national emission data files. It has been estimated [14,15,16] that of the total 1975 SO_2 anthropogenic emissions of 25.7 million metric tons per year in the U.S., 81% result from utility and other combustion facilities. For Canada 32% of the total of 5.0 million metric tons per year of SO_2 emissions is from combustion sources and 44% is from non-ferrous smelters. For 1975 NO_x emissions, 52% of 22.2 million metric tons per year total emissions in the U.S. is from combustion sources, and 32% of 1.9 million metric tons per year total in Canada are from such sources. A significant percentage of NO_x emissions - 45% in the U.S. and 63% in Canada - results from transportation emissions.

The high percentage of sulfur and nitrogen emissions from combustion sources clearly indicates the important role that must be given to controlling both current and future sources of this type in strategies for limiting future acid precipitation in the U.S. and Canada. For sulfur emissions in particular, the involvement of strategy planning for future coal use, and possibly further controlling emissions on existing coal use, is critical. The necessity of considering coal strategy options in the environmental planning is given increased emphasis because of the current U.S. policy for increased reliance on coal as an energy source with as much as a doubling, or more, of U.S. coal production and use projected for the 1975-1990 period [17].

With this as background, the decision making or planning process for limiting U.S.-Canadian transboundary air pollutants in view of increased coal use can be discussed in relation to the proposed generalized framework described in the preceeding section. As of this writing this ongoing decision making process has not been explicitly structured to conform to the generalized framework described in this paper and the following discussion is not intended to be a critical review of the ongoing process which takes into account various unique controlling technical, institutional, and legal factors that are beyond the scope of this paper. Rather, the purpose of the following is to discuss from a broader perspective how components of the proposed framework could in general be effectively utilized in a realistic situation based on observations of an ongoing coal/environmental planning problem.

Following the decision analysis methodology termed "satisficing" in the previous section the following components are required:

- Organizing workshops involving a core analysis group and policy makers, scientists and other specialists
- Defining coal utilization objectives
- Definding coal strategy constraints for energy costs, siting, technology options, and environmental impacts other than transboundary air pollutants
- Determining strategies for minimizing transboundary air pollutants in view of defined constraints
- Iterations to obtain an "acceptable" balance of tradeoffs.

As a minimum the workshop should include representatives of energy and environmental planners from both the U.S. and Canada, preferrably from both national and state or province levels. The administrative level of persons to be involved is dependent on whether the output of this process is a final decision to be implemented or only recommendations to be provided to higher level authorities responsible for final decision making. But in either case the participants should be familiar with objectives and constraints of the final decisions to be made. The scientists' role is to transmit the best available information on the known and potential impacts of the air pollutants and the physical mechanisms of pollutant transport and available models. In the case of acid precipitation and its effects, significant gaps currently remain in this desired knowledge and thus the scientists role in this case, as with many issues involving environmental impacts, includes providing a clear indication of the limits of knowledge. In view of the available scientific information and uncertainties the initial workshop sessions would be oriented toward defining air quality objectives, expected coal use levels, coal strategy alternatives and constraints for achieving those levels, and outlining the basis for modeling strategy alternatives to assess tradeoffs. In the actual ongoing decision making process related to the U.S.-Canada transboundary air pollutants, various diverse groups of scientists and planners have in fact been convened to discuss these issues, albeit often with more limited objectives or somewhat different strategies for achieving decisions or recommendations for decisions that can be implemented.

The proposed approach for coal/environmental planning assumes availability of projections for total regional coal utilization. For the U.S. and Canada these projections are available from studies by utilities, industry, and national and regional energy planners. Thus for this case study what is required is a consolidation of these studies into a single projection or range of projections. As required these projections can be provided in detail which give limits on: coal availability of different types, coal use by sectors of the economy, coal conversion technology, emission control technology, regional siting patterns, etc. In addition to physical and technology constraints, limitations on cost of coal-derived energy must be included so that coal remains competitive with other energy forms.

Under the proposed approach the coal strategy options for limiting air pollution are to be constrained by a limitation in impacts on other environmental media such as water, solid waste, and land use. As a minimum these limitations should be compatible with existing environmental protection regulations or plans.

Having defined the constraints for the coal strategy options, the analysis proceeds by determining the minimum air quality impact achievable within the range of strategy options. Various air quality criteria may be used for determination of an optimal strategy given the constraints. The most straightforward criteria is minimizing total emissions. More refined criteria that make use of information on pollutant transport and impact mechanisms could be a minimization of cumulative human exposure in all regions, minimization of peak exposure, or a minimization of exposure in regions with sensitive ecosystems.

In general, it can be expected that additional coal strategy options and constraints will need to be iteratively considered to obtain the desired "acceptable" balance between the minimized air quality impact and other associated environmental tradeoffs.

A generalized mathematical formulation for the constrained air quality minimization problem is presented in the Appendix.

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APPENDIX: CASE STUDY MODEL FORMULATION

This appendix provides a conceptual mathematical formulation for a coal strategy optimization problem that minimizes air quality impact under various constraints. The basic variable is:

$X_{ij...t}$: Level of coal-derived energy consumed where

i: final energy form (electricity, synfuels)
j: user (industry, residential, transportation)
k: user location (region)
l: coal conversion technology
m: conversion siting
n: coal source, classification
o: coal preprocessing technology
t: time

Constraints*

1. Total coal derived energy consumed in the region

$$X_t \geq \bar{X}_t^1$$

2. Sector and region market potential for specific energy forms

$$X_{ijkt} \leq \bar{X}_{ijkt}^2$$

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*$X_{a...b} \equiv \sum X_{ij...t}$, where the summation is over all subscripts except a...b

3. Maximum cost for energy form that is competitive.
   Let $P_{ij\ldots t}$: unit production cost for $X_{ij\ldots t}$, then

   $X_{ij\ldots t} = 0$, for $P_{ij\ldots t} > \bar{P}_{ijkt}$ (competing energy price)

4. Maximum transport distance for coal and final energy form. Transport distance limitations can be included as part of total production cost limitations in 3.

5. Maximum quantities of coal and energy in final form that can be transported.

   $X_{kmt} \leq \bar{X}^3_{kmt}$, $X_{mnt} \leq \bar{X}^4_{mnt}$

6. Siting and technology limitations due to other environmental goals. In the most general linear form,

   $\sum \underline{C}_{i'ij\ldots t} \; X_{ij..t} \leq \underline{\underline{\bar{X}}}^{5}_{i't}$,

   where $\underline{C}$ is the impact transfer vector, and $\underline{\underline{\bar{X}}}^{5}_{i't}$ is the maximum allowable impact in region i′ at time t.

7. Limits on availability of new technology

   $X_{1t} \leq \bar{X}^6_{1t}$, $X_{ot} \leq \bar{X}^7_{ot}$

8. Limits on regional coal extraction

   $X_{nt} \leq \bar{X}^8_{nt}$

9. Coal import limits

   $$X_{m'n't'} \equiv \sum_{\substack{m \varepsilon m_1 \\ m \varepsilon n_1}} X_{mnt} \leq \bar{X}^9_{m'n't'} \quad \text{(see constraint 5)}$$

The solution requires a minimization of air quality impact (or other impact) which is expressed in the form (see constraint 6)

$$q_1 = \sum C^{a}_{i'ij\ldots t} \; X_{ij\ldots t}$$

The final "acceptable" solution may require a concession on air quality limits or other previously defined constraints.