COAL, ECONOMICS, AND THE ENVIRONMENT: TRADEOFFS IN THE COAL-ELECTRIC CYCLE

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ABSTRACT

Generating electricity from coal while also meeting environmental emission standards is an important scientific and engineering problem that has economic and societal impacts. In this paper, the question of which coal-energy systems provide for the most economical production of electricity under alternative environmental regulations is addressed using an applied systems analytic approach. The entire system of coal-energy use from the mine to the bus-bar is analyzed, and thus tradeoffs not necessarily realized by conventional industrial practices are studied. The methodology or the process of analysis, as distinct from the method or the analytic procedures, is discussed and outlined, and an approach for applied systems analysis is summarized.

The problem context for coal use in the United States and the potential environmental impacts is developed in some detail. A simple economic context is then described indicating how the cost of the coal-electric fuel cycle may be minimized and understood in economic terms. Cost and operating performance data are reviewed for the technologies involved, and a mathematical programming model is formulated that represents the entire coal-energy system.

Two case studies are then described. The first is somewhat preliminary but detailed, which allows the reader to relate the simple economic context to the first optimal solution of the mathematical programming model, and then easily follow several sensitivity analyses. The other case study builds on these initial results by adding degrees of complexity so that more realistic applications are approached. State-of-the-art data are used in the case studies, and short descriptions of the technologies in each case study are included.

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"*...at any moment a flame may dart out*"
C.G. Jung, Memories, Dreams, and Reflections

1. INTRODUCTION

In this paper an applied systems analysis approach is used to study economic and energy tradeoffs as a result of environmental and resource constraints on the utilization of coal electricity production. This is accomplished by developing and demonstrating a methodology for quantification and analysis of a number of environmental and energy related tradeoffs which are associated with the use of coal and its impact on air quality. These tradeoffs are quantified in terms of parameters for a set of technologies that are designed to supply, process, and transport coal and to generate electricity while controlling residual emissions. The primary question addressed is: Which coal-energy systems provide for the most economical production of electricity under alternative environmental regulations and resource constraints?

This paper is concerned with the application of systems analysis and represents a balance between the sciences and methods of mathematics and operations research and the art of problem solving. The availability of good data is critical for the generation of good results, and concentrating on a "base line" of final results is considered essential. As discussed below, the problem is more important than the method, and the two are considered part of an overall process or methodology. The method of modeling and programming is not unimportant however, but is considered to be a tool much as the carpenter's hammer or plane. Experience, however, is the overwhelming requirement for creating quality results, and it is experience which also guides the selection and use of the proper tool.

2. COAL, ENERGY, AND THE ENVIRONMENT

About eighty-five percent of the fossil fuel resources of the United States are in the form of coal, currently about 4 trillion tons, which are located in large concentrated deposits in many parts of the country.

The US energy economy will thus undoubtedly be dependent on the use of coal, at least for the next several decades, and if wisely managed, for the next several centuries. The capability of coal to supply US energy needs, in an environmentally acceptable manner, is becoming increasingly more significant as the availability of alternative fossil fuels such as oil and gas is diminishing.

Historically, coal has been a keystone energy source, providing much of the energy to industrialize the US economy [1]. Coal is now being called upon again to provide essential energy for the US, especially in the form of electricity, and perhaps in the form of synthetic fuels [2]. In both the short and long run, coal may be viewed as a transition source of energy for the US as well as for much of the world. The next several decades are likely to reveal a transition toward increased uses of coal, while the development of long-term energy sources, such as solar, wind, geothermal, bioconversion, and perhaps nuclear-fusion, will be accompanied by a transition away from coal.

2.1 Coal and Electricity Generation

The near-term transition to coal will mostly be accomplished by the use of conventional methods of electricity generation. The historical use of coal has shown that electric utilities have become the largest consumer; the growth rate of electricity consumption has averaged about seven percent per year [3]. During the next few decades, this increasing use of coal to produce electricity will be met using well established conventional technologies. Electricity may be produced by more advanced technologies using coal, however, these "clean coal" processes are not likely to reach commercial scale until the late 1980's or mid-1990's.

2.2 Coal and the Environment

The generation of electricity from coal may have some important environmental and resource consequences. Air quality is affected by the residual emissions of sulfur oxides, particulates, and nitrogen oxides in the combustion products from coal [4]. Water quality may be impaired directly by both chemical and thermal effluents [5], and indirectly by sludge disposal [6,7,8] and mining operations [9,10]. Land resources are also affected by mining methods [10], and by solid waste disposal of flue gas scrubber sludge and fly ash [6,7]. The potential effects for the environment, including the impact on water and land resources, may also have important social and economic implications for human health, property values, and agriculture [see for instance, 11]. Therefore, the use of coal to produce electricity has multiple and cross-media environmental and resource implications, and thus its use is associated with the classical environmental problem of interdependent cause-effect relationships. Further discussion below includes only those environmental consequences which concern air quality impacts from the use of coal

2.3 Environmental Standards

Various forms of legislation in the United States have been enacted within the late 1960's and 1970's which have as their purpose to mitigate the type of environmental and resource consequences that result from the use of coal. Most notably, the Clean Air Act of 1970 [12], is intended to protect public health and welfare from the consequences of adverse air quality. This statute's mechanism is to establish various forms of air quality standards, based primarily on human health and welfare criteria. These standards have far-reaching social and economic implications for energy-based industries, especially for those with significant environmental emissions, such as coal-based public utility systems. The form and level of each emission standard have important influences on the economics and the energy efficiencies of generating electricity from coal.

2.4 Residuals Control Technology

In order to provide energy from coal while environmental standards are met, a number of technological options are available in various stages of commercialization [13]. These technologies are designed to control or manage the residuals inherent in coal and to ultimately help minimize environmental emissions. These residuals, which primarily consist of sulfur, ash, and nitrogen, are controlled or managed by three general categories of technologies, including preconversion (e.g. coal preparation), conversion (e.g. combustion modification), and postconversion (e.g. flue gas desulfurization). Each of these technologies has associated with it the primary function of residual reduction or removal which is accomplished at a certain cost. It is the nature of these technologies that a greater degree of control, i.e., higher removal efficiency, is accomplished at an ever increasing expense, so that large costs are required to reduce emissions to low levels, and zero-level emissions are unattainable.

It is also characteristic of these technologies that--although their primary function may be to reduce a single residual, or as in some cases several residuals--their operation is such that the removal of other residuals is often affected. In addition to their influence on the multiple residual removal performance, combustion and postcombustion control technologies may operate to influence the performance of the primary energy converter, the coal-fired power plant. Therefore, the coal-electric cycle must be treated as one entire system from the coal mine to the bus-bar.

2.5 A Statement of the Problem

The use of coal as an energy resource to produce electricity in the United States has associated with it a host of tradeoffs that may be analyzed in terms of costs and energy efficiencies required to meet a given level of demand for electricity within a given set of environmental standards. These tradeoffs may involve the selection of alternative technologies or the allocation of fuels as environmental standards are allowed to change. The economic tradeoff is influenced by the type of environmental standard, the energy supply requirement, the operating performance of the available technologies that either supply energy or control emissions, and various exogenous parameters such as the price of raw coal and the distance to the power plant.

3. DEVELOPING THE METHODOLOGY

The methodology, as distinct from the method, is the process by which the final results are obtained. Often the methodology or the process, and the method, which is usually thought of as the analytic technique, are understood to be the same thing. In applying system analysis, it is the results which are most important, and the analytic technique should be used only as a tool to shape and create a desired output. In this section, a discussion of the specific methodology, within the context of section 2, gives the reader an example of the approaches used to study tradeoffs in the coal-electric cycle. In its summary form the methodology is useful for a much wider range of applications.

3.1 The Methodology in Summary

The methodology for applied systems analysis considered here comprises six primary phases of activity, as outlined below, which include: a summary and background of coal use and its environmental implication, an assessment of coal-energy-environmental technologies, cost and operating data development, technological submodel development, a review of mathematical programming models and solution techniques, formulation of a mathematical programming model, and applying the model to obtain specific results.

Analytic aspects of the methodology discussed and demonstrated in this section include formulation of submodels of the operations and cost of a set of technologies that are capable of exhibiting the primary input-output performance characteristics for each technology. These submodels are based on the design criteria selected (by experience); the analysis using these submodels proceeds by considering variations in operation from a given design, with associated variations in costs from a given design cost. An analysis of economic and energy efficiency implications of air quality constraints on the utilization of coal for electricity production is then conducted by integrating these submodels into a mathematical programming format. Optimal solutions, and sensitivity and parametric analyses are conducted using an integer programming model.

The highlight of this paper is a presentation of two case studies which illustrate the methodology. The first is a preliminary but rather detailed study, which allows the reader to follow the analytic development from a simple economic context to the first optimal solution, and then through several sensitivity analyses. The next case study builds on these initial results, adding degrees of complexity that approach more realistic applications.

Details concerning such items as specific numerical values for data or computer programming systems are not generally discussed as they are available in other published material [13-17]. Instead, an overview of the methodology is presented to give the reader an example of applied systems analysis.

3.2 The Methodology in More Detail

The approach of the applied systems analysis discussed in this paper is outlined as follows:

3.2.1 Summary and Background

In order to develop a general background and context, the first step of the process is to summarize the roles of coal, energy, and the environment in the United States. The significance of the problem and its potential technological solution are reviewed.

3.2.2 Coal Energy Environmental Technologies

A system of technologies is defined by the three general categories of preconversion (e.g. coal preparation), conversion (e.g. combustion modification), and postconversion (e.g. flue gas desulfurization) operations. In addition, coal transportation and electricity generation from coal-fired power plants are included. This definition is according to technological function and defines the specific systems used for further analysis. In this paper, the general nature of these technologies is reviewed and specific technologies used in the case studies of the last section of this paper are reviewed in some detail below.

3.2.3 Cost and Operating Data Development

In order to develop submodels of the cost and performance of the coal-related systems as discussed below, cost and operating data for each technology are very briefly summarized. As is available in detail elsewhere [14], each of these technologies is characterized by primary input-output or operating parameters, which include: residual reduction efficiencies, energy conversion efficiency, operating or load factor, and waste products. Associated with each of these parameters are the fuel, capital, operation, and maintenance costs that would be accounted for under various operating conditions.

3.2.4 Technological Submodel Development

Where useful and where information is available, mathematical submodels are either summarized or developed which describe the operating characteristics of the technologies in the coal-electric cycle. These models are not presented in this paper as they are published in detail elsewhere [14]. In general, these models are developed by statistically determining parametric values from experimental and operating data.

3.2.5 Mathematical Models and Solution Techniques

A good carpenter knows his tools. Therefore, as a part of this methodology a review of literature on energy and environmental modeling is conducted [14]. This is not formally presented in this paper, but a supplemental bibliography is included as Appendix B.

3.2.6 Integer Programming Model

The next step is to integrate all the data and submodels in a common systematic format. Mathematical programming models offer the advantage of optimization as well as the capability for sensitivity and parametric analysis. The theory is well documented, and many of the solution techniques are already preprogrammed on modern computers. However, many problems are not well suited for characterization as mathematical programs; for example, forecasting, or highly nonlinear and time-dynamic problems (see Appendix B). As a part of this methodology, a general integer programming model has been formulated (14,15]. In this paper, a more specific model is presented as a part of the case study analyses. The model is particularly suited for analyzing a set of technological options that are available for producing energy from a fuel while environmental emissions are controlled.

3.2.7 Demonstration Case Studies

Two case studies are formulated which are designed to demonstrate the overall methodology. Representative coal price and coal quality data are selected for major geographic areas of the United States. Associated coal cleaning data are utilized, and a representative set of transportation distances and costs are defined for use in the analysis. A nominally-sized, steam-electric coal-fired power plant is selected, and various emissions control technologies are assumed to be available. Finally, a level of electric energy demand is established which is less than or equal to the power plant generating capacity, so that a reserve capacity is defined. A series of analyses using the integer programming model are then made with the objective of determining economic and technological tradeoffs for the following general conditions:

- variations in cost assumptions for each coal-energy technology,
- changes in emission regulations,
- variations in reserve capacity (energy demand),
- changes in coal price, transportation cost,and other parameters.

The purpose of these demonstration case studies is not to determine tradeoffs for a specific utility system or power plant configuration, but to exhibit the overall systems analysis methodology, and the role of mathematical programming as a tool for analyzing energy and environmental tradeoffs. The overall methodology, however, is useful for addressing specific utility systems, as well as a broader range of energy and environmental issues, which might include clean fuels from coal (e.g. gasification and distribution) or advanced electricity generation (e.g. fluidized bed combustion). In addition, the approach discussed here has elements of general applicability to problems concerned with other areas than energy and the environment.

4. APPLYING THE METHODOLOGY: TWO CASE STUDY ANALYSES

This section illustrates the methodology outlined above by presenting analyses of environmental and resource constraints on the utilization of coal for electricity production. Two case studies are described for coal-electric systems that control sulfur-residual emissions. The description of each case study includes a rationale and background, a system diagram, an outline of the input data, a discussion of results, and a statement of conclusions. Each of these case studies exhibits a number of economic, energy, and environmental tradeoffs which are described using sensitivity analysis and parametric programming.

First, a preliminary case study is presented using the alternatives that represent the production of electric power by conventional coal-fired boilers with the option of controlling sulfer oxides by using combinations of physical coal preparation and flue gas desulfurization. This case study is discussed in some detail, and includes a display of an optimal solution and several sensitivity analyses. The following questions are addressed:

- Which coal-energy technologies provide for the most cost-effective production of electricity from coal while controlling environmental emissions?
- What are the effects of changes in allowable SO_2 emissions in transportation rates (distance) and in raw coal price?

Next, the preliminary case study is considerably expanded by considering technologies commercially available as well as more advanced ones that control sulfur-related residuals in the coal-electric cycle. These technologies include physical coal preparation, chemical coal cleaning processes, flue gas desulfurization, and coal blending. Both Eastern and Western coal regions in the United States are considered for generating electricity with a conventional coal-fired power plant at various points located between the supplies of coal. The following questions are addressed:

- What is the potential "market area" for Western and Eastern US coal used for producing clean electricity?
- How does this change with environmental standards and with raw coal prices?
- What is the least-cost system of existing and more advanced residual management technologies that control sulfur in the coal-electric cycle?
- How do these technologies change for different environmental standards and for different coal characteristics?

Several graphical displays of parametric integer programming are presented.

4.1 Preliminary Case Study: Coal Cleaning and Flue Gas Desulfurization

Physical coal cleaning and flue gas desulfurization are technologies with current commercial potential in the United States. Each has the capability of controlling sulfur-related residuals at different points in the coal-electric cycle, and each has its own set of cost and operating characteristics. These cost and operating factors define various energy and environmental tradeoffs that are associated with technological systems that provide electricity from coal while controlling environmental emissions.

4.1.1 Technological Alternatives

Coal cleaning is accomplished by mechanically separating refuse and sulfur-containing pyritic material from coal. Chemically-bound organic sulfur is not removed. These physical beneficiation techniques are capable or removing up to 40% to 50% of the sulfur and 65% to 75% of the ash contained in coal. The energy content per pound is also upgraded, although a significant fraction of energy in the raw coal may be discarded. In many cases, physical coal cleaning does not produce coal that directly meets environmental emissions standards, although standards for some older facilities may be met.

Flue gas desulfurization (FGD) is accomplished by chemically and physically removing sulfur and particulate material from stack gases. Over 90% of the sulfur and 95% of particulates (depending on particle size) may be removed with scrubbers. Environmental standards for sulfur oxides may be met directly using FGD technologies; however, a significant amount of energy is required and large quantities of ash and sludge are produced.

Combinations of coal-cleaning and flue-gas desulfurization technologies appear promising. Removal of sulfur and ash material by coal beneficiation before combustion reduces the amount of stack gas control required, and consequently reduces sludge and ash handling and disposal quantities, with resultant cost advantages. In addition, transportation charges may be reduced since refuse material can be removed at the mine. The combination of FGD and coal cleaning frequently reduces the utility's capital and operating costs, relatively to FGD alone, and also reduces the overall cost of providing clean electricity.

Alternatives selected for this preliminary case study are shown in Figure 1. Technological activities represent coal mining, physical coal cleaning at two levels, coal transportation, coal-fired electric power generation, and flue gas desulfurization at four levels of control. Also included is the alternative of direct combustion without sulfur oxides control. Economic and technical coefficients used in the preliminary model were collected from a variety of sources, as outlined in Table 1. The data describing coal characteristics are for a typical high-sulfur US Eastern coal used to meet fuel requirements for a 1000 MW conventional coal-fired power plant. Coal washability characteristics have been developed by the US Bureau of Mines and represent average Northern Appalachian data. Electricity generation and flue gas desulfurization costs are from typical US industry sources. The data have generally been selected to represent the general economic characteristics of the years 1974/1975.

Table 1. Data for preliminary environmental tradeoff model

Data Item	Units	Value	Source	Comments
Coal mining cost	$/t	10-20	[3]	Coal prices increased dramatically in the 1974-75 time period. The US average price for steam coal in November, 1974 was $11.32/t; in December 1975, $18.78/t (varied parametrically).
Raw Coal				Average characteristics for Northern Appalachian coal.
Heat value	Btu/lb	12,693	[18]	
Sulfur	%	3.01		
Ash	%	15.01		
Cleaned coal Level 1:	Btu/lb	13,652	[18,19]	Eastern US bituminous coal. Data from US Bureau of Mines
Heat value	%	2.06		The yield of level 1 coal is 83.5% of the input; level 2 coal yields is 71.9%.
Sulfur	%	8.60		
Ash	$/t	1.62		
Cost				
Cleaned coal Level 2:				Cleaning cost includes a $1/t refuse disposal charge.
Heat value	Btu/lb	14,057	[20]	
Sulfur	%	1.48		
Ash	%	5.80		
Cost	$/t	3.75		
Coal transportation Cost	$/t	3.00	[20]	Typical US Eastern transportation cost of $0.01/t-mile for 300 miles (varied parametrically).
Coal-fired electric power Plant				Industry Data circa 1974 to 1975. Capital cost is for a bare plant; an installation charge of 50% is assumed.
Size	MW	1,000	[20]	
Heat Rate	Btu/kWh	8,700		
Capital Cost	$/kW	240		
Coal fired electric Power plant			[20,21]	The unit cost for the power plant includes installed capital, operation, and maintenance, but excludes fuel. Refuse disposal costs depend on sulfur and ash content of the coal as well as residual removal rate.
Unit cost	mill/kWh	9.9		
Availability	h/yr	7,000		
Ash disposal cost	$/t	1.0		
Sludge disposal Cost	$/t(dry)	8-18		
Flue Gas Desulfurization				The cost for flue gas desulfurization depends on SO_2 removal rate power plant size, availability, input sulfur content of coal, sludge disposal requirements, utility and materials cost, and other factors. Each power plant activity in the model has its own cost for flue gas desulfurization.
Size	MW	1,000	[21]	
Flue gas	ACFM/MW	2,000		
Unit cost	mill/kWh	2.8-6.2		
Availability	h/yr	7,000		
SO_2 removal	%	50-95		
Energy demand	10^6 MWh/yr	7.0		Equivalent to a 1,000 MW power plant operating for 7,000 hours.
Sulfur oxide Emission Standard	lb $SO_2/10^6$ Btu	1.20	[12]	Clean air amendments of 1970 (values varied parametrically).

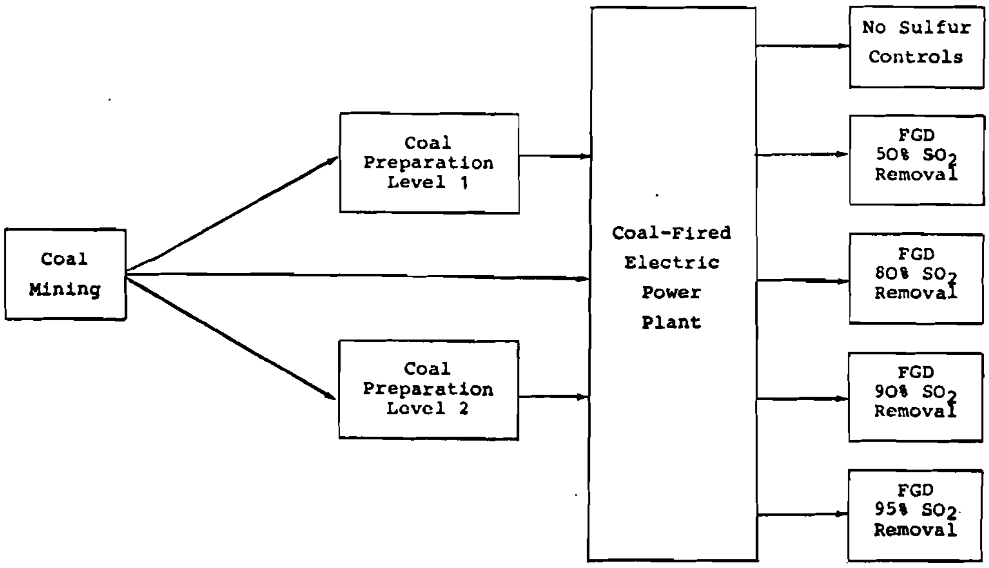

Figure 1. Coal preparation and flue gas desulfurization alternatives for controlling sulfur oxides

4.1.2 A Simple Economic Interpretation

Prior to a discussion of the specific mathematical programming model formulated for the system shown in Figure 1 and a discussion of case study results, a brief economic interpretation using parametric cost curves is discussed.

The data outlined in Table 1 was used to generate the parametric cost curves shown in Figure 2. These curves describe the delivered cost of coal to the power plant as a function of the sulfur content on a per-energy-unit basis. In addition, these curves are parameterized by the price of raw coal. Figure 2 shows the cost to be paid for coal delivered to the power plant by the operator-owner as a function of the sulfur content of the coal. For example, when raw coal is \$10/t, a delivered coal of 1.0 lb sulfur/10^6 Btu will cost \$0.75/10^6 Btu.

Also displayed in Figure 2 are the cost curves for power generation, including flue gas desulfurization, as a function of sulfur content of coal on a per-energy-unit basis. These curves are parameterized by the sulfur-oxide (SO_2) removal efficiency of flue gas desulfurization. For the power plant operator-owner, at any selected or required SO_2 removal efficiency, the cost to generate electricity and control SO_2 emissions are thus shown. For example, at 90% SO_2 removal, power generation and SO_2 removal will cost about \$1.73/10^6 Btu using 2.0 lb sulfur/10^6 Btu coal.

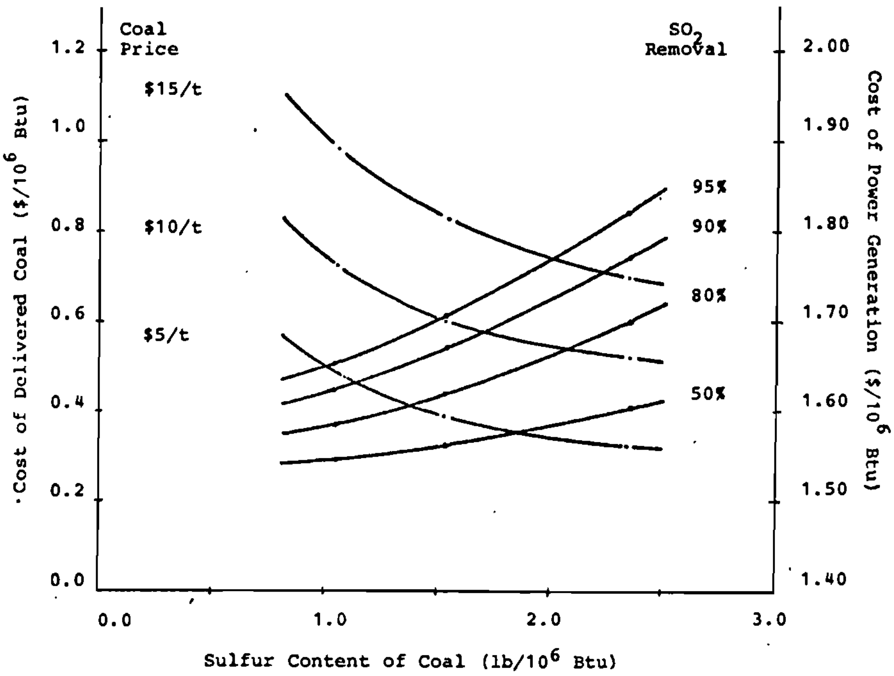

Figure 2. Cost curves for coal cleaning and flue gas desulfurization at the power plant site

According to economic theory, when the marginal cost for changes in the sulfur content of the delivered coal is equal to the marginal cost for power generation and sulfur removal from the stack, an optimal (minimum cost) economic condition is obtained for the specified or required set of parameters. This condition occurs for the sulfur content of coal when the slope of the delivered fuel cost curve is equal to the negative of the slope of the power generation cost curve. It is this particular coal which the power plant operator should purchase. An equivalent mathematical interpretation is also evident. The total cost of the coal-electric cycle is the sum of the two curves shown in Figure 2, and this curve has a minimum at the appropriate sulfur content. This minimum point may be calculated by taking the partial derivative of total cost with respect to sulfur content (marginal cost), and then equating this to zero, which is of course equivalent to equating the marginal costs as previously discussed. The mathematical programming model described below is solved in an equivalent way using a primal-dual modified simplex algorithm to test the equality of primal and dual objective functions.

4.1.3 An Integer Programming Model

The general form of the model used in this case study is an integer program, as formulated in detail in other literature [16]. The solution technique is to solve a number of submodels which are formulated as linear programs, and thus solve the integer program by enumeration. This method involves selecting the appropriate activities such that the objective function remains convex. For this preliminary case study, nonconvexity is introduced as a result of the fixed costs associated with flue gas desulfurization; an initial "first cost" is incurred for operating an FGD facility at any removal efficiency. Only two linear programs are required which generate solutions for situations with and without flue gas desulfurization, i.e., there is only one integer variable.

The variables and parameters used in the preliminary model are described in detail in Appendix A, Tables A-1 and A-2. These variables are measures of the flow of coal, electricity and sulfur through the energy/environmental system shown in Figure 1, and are structural columns of a linear programming matrix that is displayed in Appendix B. The relationships between these variables are expressed by constraining equations. The coal mining, transportation, and cleaning equations express the conservation of coal, and the electricity generation equations are derived using the law of conservation of energy. Sulfur oxide emissions are limited to various levels of emission standards, and energy demands are met by including an additional equation. The total annualized capital and operating cost is the objective function of the linear program and is minimized when a solution is generated. Also, accounting equations have been included so that a variety of technical and economic information is aggregated for any LP solution including: coal mining cost and quantity; coal preparation cost and quantity and energy efficiency; coal transportation cost and quantity; electricity generation cost and efficiency, and sludge disposal cost and quantity.

4.1.4 Preliminary Results

The initial results of the preliminary model for sulfur standards set at the current US federal level* are shown in Tables 2 and 3. Using the data described in Table 1, the solution indicates that the least cost alternative involves a combination of coal preparation and flue gas desulfurization technologies. This result is significant for the industry as these two technologies are in different parts of the coal-electric cycle.

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* 1.2 lb $SO_2/10^6$ Btu.

Table 2. Preliminary environmental tradeoff model results and sensitivity analysis, column activities

Activity[a]	Optimal Solution: Units	Optimal Solution: Value	Range Analysis[c]: Input Cost	Range Analysis[c]: Lower Cost/Upper Cost	Range Analysis[c]: Units	Range Analysis[c]: Unit Cost ($10^6/yr)
Mining	10^6t/yr	2.71	10.00	0.0/11.37	$/t	2.71
Cleaning (Level 1)	10^6t/yr	2.26	1.62	0.0/1.78	$/t	2.26
Transportation	10^6t/yr	2.26	3.00	0.0/3.16	$/t	2.26
Coal-Fired Plant with FGD (50%)[b]	10^6MWh/yr	5.22	13.75	13.06/13.79	mills/kWh	5.22
Coal-Fired Plant with FGD (80%)	10^6MWh/yr	1.78	14.31	14.23/14.40	mills/kWh	1.78

[a] Non-zero activities in the basis.
[b] SO_2 removal level.
[c] Results of a linear sensitivity analysis RANGE. Lower Cost/Upper Cost is the level to which the input cost of an activity can be changed before a basis change occurs. Unit Cost reflects the effect upon the objective of a one-unit change in the Input Cost.

Table 3. Preliminary environmental tradeoff model results and sensitivity analysis, row activities

Row	Optimal Solution: Units	Optimal Solution: Value	Range Analysis[a]: Lower Activity	/	Range Analysis[a]: Upper Activity	Marginal Cost[b]: Value	Marginal Cost[b]: Units
Total Cost	$10^6/yr	134.78	-	/	-	0	-
Coal Mining	10^6t/yr	2.71	2.71	/	(d)	10.0	$/t (fob mine)
Coal Cleaning (Level 1)	10^6t/yr	2.26	2.26	/	(d)	13.59	$/t (fob cleaning plant)
Coal Energy Conversion[c]	10^{12}Btu/yr	57.42	57.42	/	(d)	60.8	¢/10^6 Btu (fob power plant)
Electric Power Generation (Total)	10^6MWh/yr	7.00	5.93	/	14.82	20.1	mills/kWh (bus bar)
Sulfur Oxide Emissions	10^6lb SO_2/yr	75.00	35.4	/	88.5	0.075	$/lb SO_2 (emitted)

[a] Results of a linear sensitivity analysis Range. Lower Activity/Upper Activity is the level to which the row activity can be changed before a basis change is required. The original constraint limits are ignored.
[b] Marginal Cost is the dual variable. For coal mining and cleaning this is the market clearing price of the product (a "free on board" plant). For coal transportation it is the competitive price for fuel delivered at the power plant. For electricity generation it is the competitive bus bar price, and for sulfur oxide emissions it is the cost of the equivalent control technology in dollars per lb SO_2 emitted.
[c] Range expressed in terms of power plant output using level 1 coal.
[d] Upper activity is unbounded.

As shown in Table 2, to supply 1000 MW of electricity using high sulfur Eastern US bituminous coal at minimum cost, while the current standard for sulfur oxides average at 2.7 million tons of coal per year would be mined. This coal would be cleaned producing 2.26 million tons of moderate-sulfur coal, and then transported and burned in conventional coal-fired power plants with flue gas desulfurization. This solution for the power-generation variables has the two following interpretations:

- If a single power plant is used to generate electricity, its flue gas desulfurization equipment would operate at a SO_2 removal efficiency between 50% and 80%, i.e., at approximately 60% SO_2 removal.
- If more than one power plant is used to generate electricity, approximately 75% of the power plants would burn the cleaned coal with FGD at 50% SO_2 removal. The additional 25% would burn the same cleaned coal equipped with flue gas desulfurization removing 80% of the SO_2 in the flue gas. The least-cost SO_2 removal efficiency is between 50% and 80% for the combined power plants.

A sensitivity analysis for the input cost of each variable is also shown in Table 2. This information indicates that the cost of cleaning raw coal to level one could be raised from 1.62 to 1.78 $/t, about 10%, without affecting the configuration of the present set of alternatives (the variable levels may change); transportation costs could increase from 3.00 to 3.16 $/t, by about 5%. The cost for power plants with FGD at 50% SO_2 removal could be modified by less than one per cent, while the cost with FGD at 80% SO_2 removal could be varied over the range of 14.23 to 14.40 mills/kWh, also about plus or minus one per cent, without affecting the mix of basic variables in the optimal solution. Therefore, flue gas desulfurization is the most cost sensitive variable (about plus or minus one per cent will cause a change in alternatives), while the cost of cleaning could be increased by as much as 10% without a change in technological options.

Table 3 indicates that the total cost of the coal-electric cycle amounts to about 135 million dollars per year, which is disaggregated by sectors as shown in Table 4. Table 3 also shows the marginal cost or value of the dual variable associated with various constraints. For example, the marginal cost or equivalently the market clearing price of leve-one coal at the output of the cleaning plant is $13.59/t. This may be compared with the mining cost of $10.00/t, which indicates a $3.59/t differential, whereas the cost of cleaning is only $1.62/t. This difference shows the inplied economic value of increasing the energy content (to decrease power generation costs) and decreasing the sulfur content (to decrease FGD costs) of the cleaned cost. The market clearing price of level-one coal delivered to the power plant is about 62¢/10^6 Btu, while the marginal cost of power at the bus-bar is over 20 mills/kWh.

Table 4. Cost by each sector for preliminary environmental tradeoff model, base case ($\$10^6$/year)

Sector	Cost	Per cent (%)
Mining	27.1	20
Cleaning	3.7	3
Transportation	6.8	5
Power Generation	68.9	51
Flue Gas Desulfurization	28.3	20
Total Cost	134.8	100

A range in allowable SO_2 emissions between 35.4 and 88.5 million lb/yr could be permitted and not change the present activity configuration. Also, as shown in Table 3, the cost of sulfur oxide emissions to the atmosphere is about 7.5¢ per pound of SO_2. A control technology that could desulfurize coal for less than 7.5¢ per pound of SO_2 (emitted) would be more cost-effective than the present combination of coal cleaning and flue gas desulfurization. Lastly, if the SO_2 standards were relaxed to allow additional emissions of about 14 million pounds of SO_2 per year (about 19% of the present standard), a savings of over one million dollars would result in the cost of SO_2 control. Thus there is an implied cost-benefit effect for controlling environmental emissions to meet the required standard.

Table 4 shows the cost associated with each sector of the coal-energy system. Power generation accounts for over half of the total, not including flue gas desulfurization. Mining and sulfur control using FGD are nearly cost equivalent at about 20% each, while coal cleaning accounts for only 3% of the total and is about cost equivalent to transportation.

4.1.5 Summary of the Preliminary Case Study

This preliminary analysis has exhibited that there are tradeoffs in the cost and technical parameters associated with sulfur oxide control technologies. It has specifically shown that the cost of providing clean electric power using coal can be reduced by using a combination of coal preparation and flue gas desulfurization options over a range of parameters. This result is technologically significant for the coal-electric industries. In addition, this analysis has demonstrated a methodology whereby the environmental implications of alternative emissions control technologies may be quantitatively analyzed in terms of their effect on other criteria. Many other such tradeoffs exist for the particular system studied in this preliminary analysis.

The next case study extends the application of the methodology by adding new technologies and additional sources of coal so that a more general situation is presented. Also, several parametric analyses are exhibited, using graphical techniques, which show the technological alternatives economically preferred over the complete range of environmental emission standards.

4.2 An Advanced Case Study: Beneficiation, Blending, and Desulfurization

Physical coal cleaning and flue gas desulfurization can in combinations provide a cost-effective means for controlling sulfur-related residuals from coal as discussed in the preliminary case study. In addition to these commercially available technologies, more advanced methods are becoming available that also control sulfur-related residuals, including chemical coal beneficiation and blending. For this case study, a general set of technologies is analyzed to determine the most cost-efvective method of controlling sulfur-related residuals in coal-electric cycles. These technologies include:

- physical coal preparation
- aqueous leaching process
- solvent refined coal (SRC)
- flue gas desulfurization (FGD)
- coal blending

In addition to including advanced technologies, both Eastern and Western US coals are considered for generating electricity with a coal-fired power plant at various locations between the supplies of coal.

4.2.1 Technological Alternatives

Coal beneficiation by mechanical methods is a well established commercial technology. Now more advanced chemical processes are becoming available which include aqueous leaching processes, such as those developed my Meyers, Ledgemont, and Battelle, and solvent refining of coal, developed primarily by PAMCO [13].

Aquious leaching methods are capable of removing as much as 80% of the total sulfur, which includes mostly pyritic forms. These processes remove only marginal fractions of ash material. Some signigicant organic sulfur is also removed by the Battelle hydrothermal process, as much as 50% to 70% in some cases. The solvent refining of coal removes all of the pyritic sulfur and over 60% of the organic sulfur; the SRC product is also ashfree. Coal blending is yet another method for managing residuals in the coal-electric cycle and may offer a future utility-scale method of meeting environmental standards. Coal blending is not a new technology, but has yet to be practiced significantly with utility-scale plants. These advanced technologies may have more potential for meeting emission standards than physical coal preparation, however, they also have increased costs.

Flue gas desulfurization chemically and physically removes sulfur and particulate material from stack gases. Over 90% of sulfur oxides and 95% of particulates (depending on particle size) may be removed with scrubbers. Emission standards for sulfur oxides may be met directly using FGD technologies, however, a significant amount of energy is required and large quantities of ash and sludge are produced, with cost disadvantages. There are economic, energy, and environmental tradeoffs associated with using various combinations of beneficiation, blending, and desulfurization in the coal-electric cycle. Removal of sulfur and ash material by coal beneficiation before combustion reduces the amount of stack gas control required, and consequently reduces sludge and ash handling and disposal quantities, with resultant cost advantages. In addition, transportation charges may be reduced since refuse material can be removed at the mine. However, coal beneficiation may not be energy-efficient, and the cost of chemical methods may be relatively high. Removal of sulfur after combustion may be efficiently accomplished using flue gas desulfurization, however, the energy efficiency of the power plant is reduced and refuse disposal may be expensive.

Alternatives selected for a case study involving beneficiation, blending and desulfurization are shown in Figure 3. Electricity is generated in a 1000 MW conventional coal-fired power plant using either a typical Eastern or Western US coal. Combination of residual management technologies that may be used include physical coal cleaning at three levels, chemical coal cleaning at two levels, and flue gas desulfurization at four levels of control. Also included is the alternative of direct combustion without controlling sulfur oxides. Economic and technical coefficients used in the case study are outlined in Table 5.

4.2.2 Parametric Analyses

The general form of the model used in this case study analysis is an integer program, as illustrated by example for the preliminary case study. The solution technique is to solve a number of linear programs, thus solving the interger program by enumeration. The structure of each linear program, when aggregated together comprises the integer program. Each of these LP models represents a subsystem of the coal-electric cycle shown in Figure 3, and the variables are structural columns of one of the LP matrices.

Table 5. Data for beneficiation, blending, and desulfurization case study

Data Item	Units	Value	Source	Comments
Coal Mining Cost				The cost of Western US coal was varied parametrically between $3 and $10/t.
Eastern	$/t	10.00	[3]	
Western	$/t	3.00-10.00		
Eastern US Coal				Average characteristics for Northern Appalachian coal.
Raw				
Heat value	Btu/lb	12,693	[18]	
Sulfur	%	3.01		
Ash	%	15.01		
Physically Cleaned				Data from US Bureau of Mines.
Level 1 (cost)	$/t	0.36	[3,18]	The following mass yields of cleaned coal were assumed:
Heat value	Btu/lb	13,230		
Sulfur	%	3.00		
Ash	%	12.50		Level 1 95%
Level 2 (cost)	$/t	1.45		
Heat value	Btu/lb	13,652		Level 2 84%
Sulfur	%	2.06		
Ash	%	8.60		Level 3 72%
Level 3 (cost)	$/t	3.34		
Heat value	Btu/lb	14,057		Coal cleaning cost includes $1/t refuse disposal.
Sulfur	%	1.48		
Ash	%	5.80		
Chemically cleaned				Aqueous leaching characteristics based on 95% removal of pyritic sulfur only, 20% reduction in ash, 5% increase in energy content and a mass yield of 95%.
Aqueous Leaching (cost)	$/t	6-12	[13,14]	
Heat value	Btu/lb	13,328		
Sulfur	%	1.10		
Ash	%	12.10		
SRC (cost)	$/t	15-30	[13,14]	SRC product based on complete removal of pyritic sulfur and 60% organic sulfur, ash-free, uniform energy content of 16,000 Btu/lb and a mass yield of 90%.
Heat value	Btu/lb	16,000		
Sulfur	%	0.40		
Ash	%	0.01		
Western US Coal				Average Western coal characteristics.
Raw				
Heat value	Btu/lb	12.437	[18]	
Sulfur	%	0.68		
Ash	%	8.90		
Physically Cleaned				Data from US Bureau of Mines.
Level 1 (cost)	$/t	0.27	[3,18]	The following mass yields of cleaned coal were assumed:
Heat value	Btu/lb	12,562		
Sulfur	%	0.68		
Ash	%	7,80		Level 1 95%
Level 2 (cost)	$/t	1.12		
Heat value	Btu/lb	12.775		Level 2 86%
Sulfur	%	0.54		
Ash	%	6.10		Level 3 76%
Level 3 (cost)	$/t	2.64		
Heat value	Btu/lb	13,103		
Sulfur	%	0.53		
Ash	%	3.90		
Chemically Cleaned				Aqueous leaching characteristics based on 95% removal of pyritic sulfur only, 20% reduction in ash, 5% increase in energy content, and a mass yield of 95%.
Aqueous Leaching (cost)	$/t	6-12	[13,14]	
Heat value	Btu/lb	13,059		
Sulfur	%	0.46		
Ash	%	7.10		
SRC (cost)	$/t	15-30	[13,14]	SRC product based on complete removal of pyritic sulfur and 60% organic sulfur reduction, ash-free, uniform energy content of 16,000 Btu/lb, and a mass yield of 90%.
Heat value	Btu/lb	16,000		
Sulfur	%	0.18		
Ash	%	0.01		
Coal Transportation Cost	$/ton-mile	0.01	[20]	Typical long distance transportation rate (varied parametrically). Distance from Western to Eastern Mine was assumed to be 1500 miles.
Coal Blending Cost	$/t	0.5-1.00		

Table 5 (cont'd.). Data for beneficiation, blending, and desulfurization case study

Coal-Fired Electric Power Plant				Industry data circa 1974/75.
Size	MW	1,000	[20,21]	
Heat rate	Btu/kWh	8,700		The net heat rate varies with FGD installation. Capital cost does not include installation costs or FGD facilities. Unit cost is total annual operating expense, exclusive of fuel. Refuse disposal costs depend on sulfur and ash content of the coal as well as residual removal rate.
Capital cost	$/KW	240		
Unit cost	mills/kWh	9.9		
Ash disposal cost	$/t	1.0		
Sludge disposal cost	$/t (dry)	8-18		
Flue Gas Desulfurization				The cost for flue gas desulfurization depends on SO_2 removal rate, power plant size, availability, input sulfur content of coal, sludge disposal requirements, utility and materials cost and other factors.
Size	MW	1,000	[13,14,21]	
Flue Gas	ACFM/MW	2,000		
Unit cost	mills/kWh	2.8-6.2		
Availability	h/yr	7,000		
SO_2 removal	%	50-95		
Energy Demand	10^6MWh/yr	7.0		Equivalent to a 1000 MW power plant Operating for 7000 hours per year.
Sulfur Oxide Emission Standard	lb $SO_2/10^6$Btu	1.20	[12]	Clean Air Amendments of 1970 (varied parametrically).

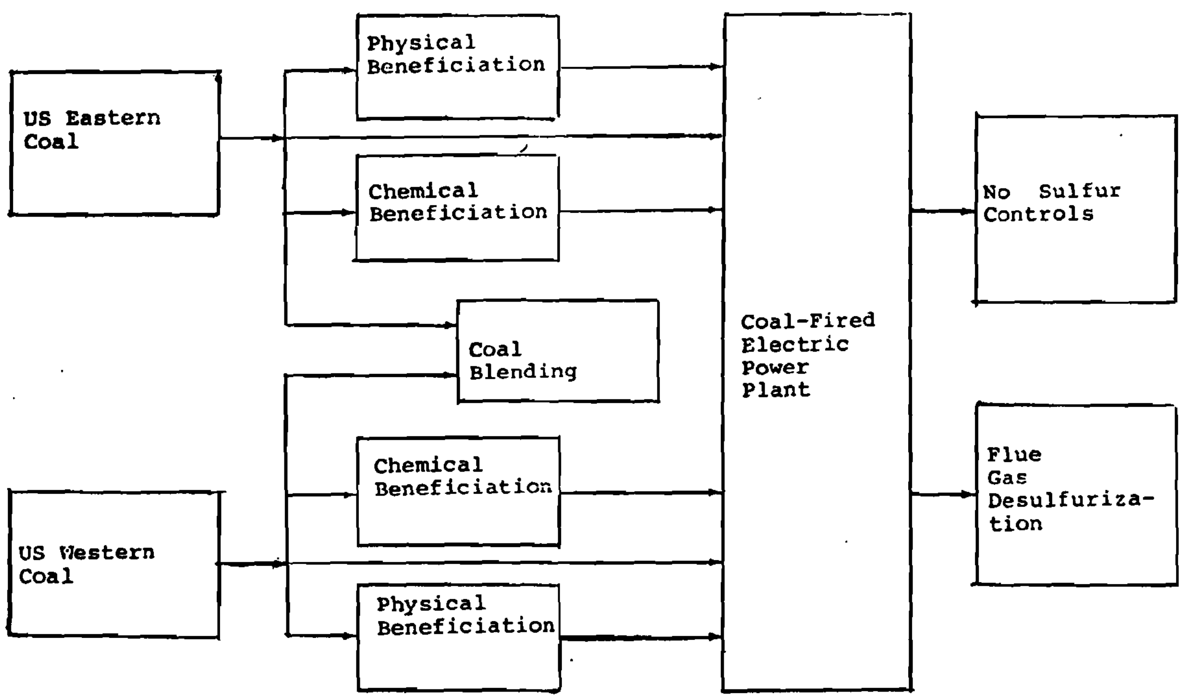

Figure 3. Beneficiation, blending and desulfurization alternatives for US eastern and western coal

Two basic sets of analyses are presented which address the two general questions stated above:

- Parametric Transportation Rates and Coal Prices: The cost coefficients for the transportation activities are varied using a parametric objective function routine for Western US coal price set at $6.00 per ton, and SO_2 emissions constrained at the current federal standard of 1.2 lb $SO_2/10^6$ Btu.
- Parametric Emission Standards: The constraint on the SO_2 emissions row is varied using a parametric right-hand-side routine for Western US coal prices set at $6.00 per ton, and the power plant located at both Western and Eastern US coal mine sites, as well as at an intermediate point.

Parametric Transportation Rates

In order to determine the effect of transportation rates (or equivalent transportation distances) raw coal prices, on the least-cost set of technologies for the sulfur subsystem of Figure 3, a set of parametric runs of the LP models are presented. Each LP model is run using the same parametric cost algorithm which allows transportation rates to vary in a manner such that electric power is generated at a point between the supplies of Eastern and Western US coal. This model thus represents market competition between these two coals. This algorithm was run for the set of data with Western coal set at the different values of $3, $6, and $10 per ton, while Eastern US coal is maintained at a constant price of $10 per ton. The cost of chemical cleaning of Eastern US coal is set at two different values to analyze a range of costs for this critical technology:

1. capital and operating cost (exclusive of coal) for the aqueous leaching process was set at $6/t, and the SRC cost is set at $15/t.
2. capital and operating cost (exclusive of coal) for the aqueous leaching process was set at $13/t, and the SRC cost is set at $30/t.

Environmental standards are set at the current US federal level of 1.2 lb $SO_2/10^6$ Btu. The results for Western US coal at $6/t are displayed in Figure 4.

For Western coal at $6/t and Eastern coal at $10/t, Figure 4 shows that the "market area" for Western coal is about 1300 miles from the mine. That is, the minimum cost technological option is to use Western coal for up to this distance from the mine location. The chemical cleaning of Eastern coal at low cost is the least-expensive method for producing electricity near the Eastern mine. The use of blending at a cost of $1/t is slightly more expensive than the direct use of one or the other coals, so that no significant cost savings are likely to be expected by using this residual control method at the current federal standard (for Western coal at $6/t).

These conclusions for tradeoffs near the coal mine depend on the linearity of the transportation rate with distance. As there is an "economy of distance" for transporting coal [13], long-distance transportation would be preferred over short distance hauls. Therefore, the long distance transportation of Western coal may be favored over short hauls of Eastern coal, and conclusions near the Eastern mine (approximately less than about 500 miles) would represent a minimum "market area" for Western coal and maximum "market area" for Eastern coal.

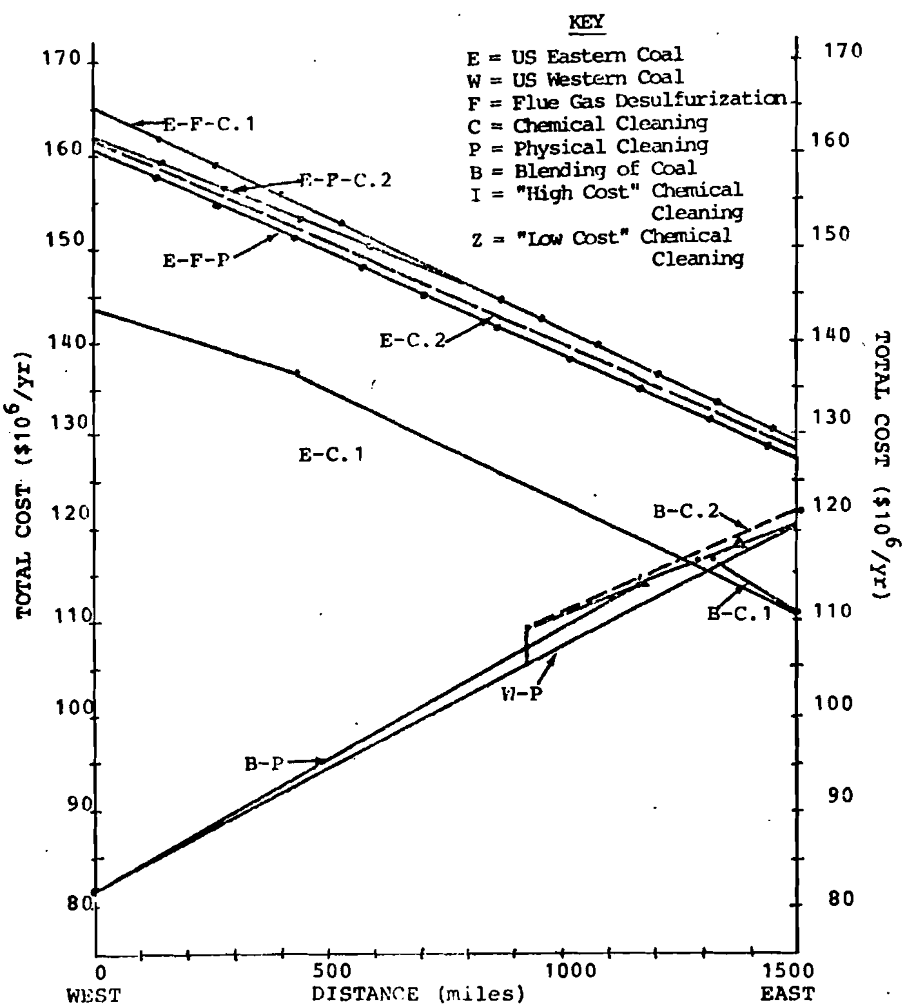

Figure 4. Sulfur Subsystem Costs as a Function of Power Plant Location with Western Coal at $6/t

Parametric Environmental Standards

In order to determine the effects of changes in SO_2 standards on the least-cost set of technologies for the sulfur subsystem of Figure 3, a set of parametric runs of the LP models are presented. Each LP model is run using the same parametric right-hand-side algorithm which allows annual SO_2 emissions to vary from a completely uncontrolled condition to a situation representing maximum attainable control (LP infeasibility). This algorithm is run for the set of data in Table 5 for power plant locations at the Western and Eastern mines. In addition, Western coal prices were set at $6.00 per ton for each run, and chemical cleaning was set at two different cost levels as in the parametric transportation runs above. Each one of the LP models is run several times, thus enumerating all possibilities of the general integer programming model. The results are displayed in Figures 5 and 6.

Shown in Figures 5 and 6 is the total annual cost (objective function) of each system of technological alternatives for meeting SO_2 emission standards. Sulfur dioxide emissions are expressed in both millions of pounds per year and pounds per million Btu heat input. The emission standard in terms of pounds of SO_2 per million Btu heat input is only approximate, as the thermal efficiency of the power plant is affected by flue gas desulfurization operations; changes in power plant efficiency due to changes in input coal characteristics are not included. The range of 0.3 to 2.4 is accurate to within a few per cent on each figure; this range includes current State and US Federal Standards.

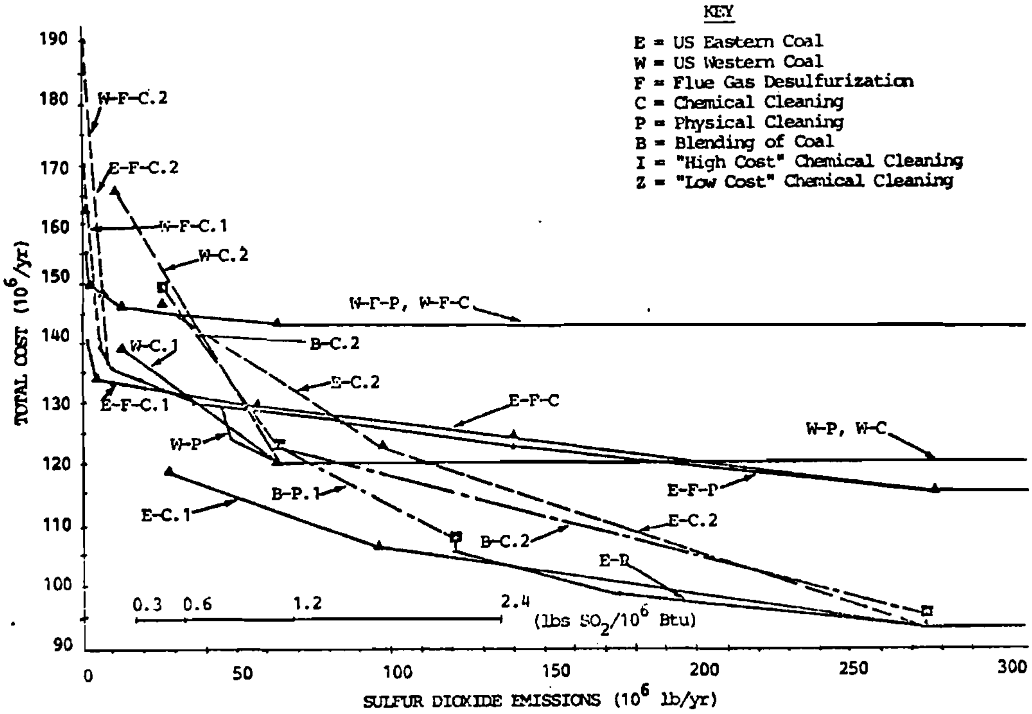

Figure 5. Coal-Electric fuel cycle costs for a US power plant located at the western coal mine site with western coal at $6/t

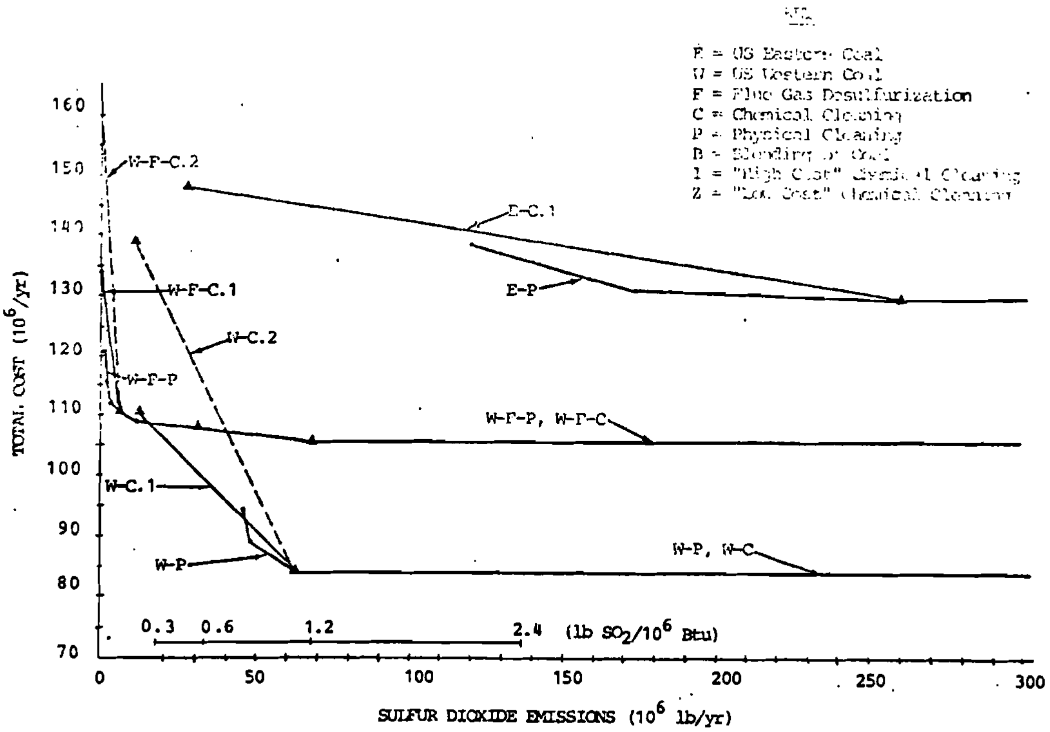

Figure 6. Coal-Electric fuel cycle costs for a US power plant located at the eastern coal mine sit with western coal at \$6/t

Parametric So_2 emission runs for power plants located at the Western mine are shown in Figure 5. The direct burning of Western coal at \$6/t is by far the least-cost alternative for meeting the current standard of 1.2 lb SO_2 per million Btu. For tighter standards, physically cleaned coal would reduce emissions further, but soon would be infeasible before 0.6 LSMB. Chemical cleaning could further reduce SO_2 emissions to approximately 0.3 LSMB, and would be used before FGD at either high or low cost. To reduce emissions further than about 0.3 LSMB, flue gas desulfurization is required, eventually in combination with physical and chemical cleaning. Combinations of these technologies using low-sulfur Western coal can reduce SO_2 emissions to less than 0.05 LSMB. The physical and chemical cleaning of high-sulfur Eastern coal, transported to the West is also shown in Figure 5.

Parametric SO_2 emission runs for the power plant located at the Eastern mine for \$6/t Western coal are shown in Figure 6; a significant diversity of alternatives is available. To meet the current federal new source performance standard of 1.2 LSMB either raw Western coal, chemical cleaning or flue gas desulfurization are required. Low-cost chemical cleaning is the least-expensive option (E-C.1); raw Western coal (W-P) would be preferred if the cost of chemical cleaning were greater

(E-C.2). At higher SO_2 emission levels, chemical and physical cleaning of Eastern coal is the least-cost option, with coal blending perhaps an economic choice (B-P.1) if chemical cleaning costs were greater. At tighter standards, physical and chemical cleaning of Western coal would be economic alternatives, to be replaced by flue gas desulfurization with physical and chemical cleaning of Eastern coal at more stringent standards. For extremely strict standards (less than approximately 0.05 LSMB) Western coal would again be used with FGD and coal cleaning.

The best technological alternative may be determined by tracing the least-cost path as a function of SO_2 emissions, considering price, availability of coals and technologies.

4.2.3 Summary of the Case Study Results

The least-cost method of generating clean electric power from coal for the sulfur subsystem shown in Figure 3 is displayed as a function of the power plant location in Figure 4. The following summarizes the primary results of this set of parametric programming runs:

- Western US coal has a substantial "market area" as compared to the use of Eastern coals.
- If the cost of chemical cleaning of Eastern US coal is at the low end of its range, it may be the least-cost method of meeting federal standards for SO_2 near Eastern US mines.
- Flue gas desulfurization is in general not a cost-effective technology, and is economically competitive with chemical coal cleaning of Eastern US coal only when the cost of cleaning is at the high end of its range.
- Coal blending at a cost of $1/t may slightly increase the total cost over that for utilization of either coal only.
- Conclusions near the Eastern coal mine depend on the assumption of linear transportation rates. However, these rates are nonlinear for short distances, which tend to favor the long distance transportation of Western coal. Therefore, tradeoffs represent minimum "market areas" for Western coal and maximum "market areas" for Eastern coal.

As a function of emission standards, the least-cost technological alternative may be determined by tracing the minimum-cost set of curves for various SO_2 emission levels; this is the solution of the general integer programming model. These solutions are outlined for each set of curves, for low and high chemical cleaning costs, as shown in Figures 5 and 6. When generating electric power at a Western US mine site, the following conclusions were reached:

- Raw Western US coal, when burned directly, was capable of meeting an emission standard of about 1.1 lb $SO_2/10^6$ Btu, and was the least-cost alternative over a wide range of standards. Physical coal cleaning, and then chemical cleaning and flue gas desulfurization became cost-effective technologies as the SO_2 standards were made more stringent;
- Combinations of coal cleaning and flue gas desulfurization were capable of reducing emissions to less than 0.05 lb $SO_2/10^6$ Btu.

When generating electric power at an Eastern US mine site, the following conclusions were reached:

- When the cost of chemically cleaned Eastern US coal was at the low end of its range, the chemical cleaning process provided for the least-cost alternative for SO_2 emission standards from about 0.5 to 2.4 lb $SO_2/10^6$ Btu;
- When the cost of chemically cleaned Eastern US coal was at the high end of its range, then physical cleaning of Western coal and blending of Eastern and Western coal were the most cost effective options to replace chemical cleaning;
- Flue gas desulfurization was not cost-effective until SO_2 emission standards were tightened to the limits of physically cleaned Western coal (about 0.8 lb $SO_2/10^6$ Btu). And if the cost of chemical cleaning was at the low end of its range, then flue gas desulfurization was not cost-effective until SO_2 emission standards were tightened to the limits of chemically cleaned Western coal (about 0.23 lb $SO_2/10^6$ Btu).

5. SUMMARY AND CONCLUSIONS

In this paper, an applied systems analysis approach has been used to study economic and energy tradeoffs as a result of environmental and resource constraints on the utilization of coal to produce electricity. This has been accomplished by using a methodology and approach as outlined above, to conduct two case studies which illustrated some practical results.

The question of which coal-energy systems provide for the most economic production of electricity under alternative environmental regulations is specifically addressed to parametric changes in transportation rates and allowable environmental emissions. The entire system of coal-energy use from the mine to the bus-bar is analyzed, and thus tradeoffs not necessarily realized in conventional industrial practices have been studied. The results of the two case studies are presented and summarized in the preceding section.

This paper has been concerned with the application of systems analysis and attempts to represent a balance between the sciences and methods of mathematics and operations research and the applied art of problem solving. The availability of good data is considered to be of primary importance for this process to be successful. Good data are developed from experience in a particular field, where judgement concerning the chosen numerical values, and the accuracy of those values, leads to more credible and realistic results.

REFERENCES

[1] Schmidt, R.A., and G.R. Hill, Coal: Energy Keystone, *Annual Review of Energy*, 1, 1976.

[2] Alpert, S.B., and R.M. Lundberg, Clean Liquids and Gaseous Fuels from Coal for Electric Power, *Annual Review of Energy*, 1, 1976.

[3] Council on Wage and Price Stability, *A Study of Coal Prices*, US Government Printing Office, Washington, D.C., 1976.

[4] Commission on Natural Resources, The National Academies of Sciences and Engineering, and the National Research Council for the Committee on Public Works, *Air Quality and Stationary Source Emission Control*, US Senate, Serial Number 94-4, US Government Printing Office, Washington, D.C., 1975.

[5] Temple, Barker and Sloane, Inc., *Economic Analysis of Effluent Guidelines Steam Electric Powerplants*, EPA 230/2-74-006, PB-239-315, 1974.

[6] Evans, R.J., *Potential Solid Waste Generation and Disposal from Lime and Limestone Desulfurization Processes*, US Bureau of Mines, Washington, D.C., IC 8633, 1974.

[7] Radian Corporation, *Evaluation of Lime/Limestone Sludge Disposal Options*, US Environmental Protection Agency, PB-232-022, November, 1973.

[8] Weir, A., *Environmental Effects of Trace Elements from Ponded Ash and Scrubber Sludge*, Electric Power Research Institute, Palo Alto, California, EPRI 202, September, 1975.

[9] Warner, D.L., *Effect of Mining Operations on Ground Water Levels in the New Lead Belt, Missouri*, Office of Water Resources Research, US Department of the Interior, Washington, D.C., PB-241-343, December, 1974.

[10] Foreman, W.E., *Impact of Higher Ecological Costs on Surface Mining*, US Bureau of Mines, Washington, D.C., PB-240-441, July, 1974.

[11] Johnson, W.H., Social Impact of Pollution Control Legislation, *Science*, 192, 14 May 1976.

[12] US Congress, *Clean Air Amendments of 1970*, PL 91-604, US Government Printing Office, Washington, D.C., 1970.

[13] Ferrell, G.C., *Energy Utilization and Environmental Control Technologies in the Coal-Electric Cycle*, Lawrence Berkeley Laboratory, Berkeley, California, 1977.

[14] Ferrell, G.C., *Coal Energy and the Environment: Analysis of Economic and Energy Efficiency Implications of Environmental and Resource Constraints on the Utilization of Coal to Produce Electricity*, Ph.D. Thesis, University of California, Berkeley, California, 1976.

[15] Ferrell, G.C., and C.R. Glassey, Coal Energy and the Environment: An Analysis of Tradeoffs in the Coal-Electric Cycle, presented at the XXIII International Meeting of the Institute of Management Sciences, Athens, Greece, July 25-27, 1977 (available from G.C. Ferrell, International Institute for Applied Systems Analysis, 2361 Laxenburg, Austria).

[16] Ferrell, G.C., Mathematical Programming Techniques for the Analysis of Energy and Environmental Tradeoffs, presented at the Eighth IFIP Conference on Optimization Techniques, Würzburg, FRG, September 5-10, 1977 (available from G.C. Ferrell, International Institute for Applied Systems Analysis, 2361 Laxenburg, Austria).

[17] Ferrell, G.C., Coal Utilization and Environmental Control Technology Assessment, *Proceedings of the 1977 International Conference on Cybernetics and Society*, IEEE Press, Washington, D.C., 1977.

[18] Cavallaro, J.H., et.al., *Sulfur Reduction Potential of the Coals of the United States*, US Bureau of Mines, Washington, D.C., RI 8118, 1976.

[19] Commerce Technical Advisory Board, *Report on Sulfur Oxide Control Technology*, US Department of Commerce, Washington, D.C., September, 1975.

[20] Ferrell, G.C., et.al., *Regional Energy System for the Planning and Optimization of National Scenarios*, US Energy Research and Development Administration, Washington, D.C., ERDA-76-109, June, 1976.

[21] PEDCO-Environmental Specialists, Inc., *Flue Gas Desulfurization Process Cost Assessment*, draft report, Cincinnati, Ohio, May, 1975.

APPENDIX A

Table A-1. Integer programming activities and parameters for the preliminary case study of coal cleaning and flue gas desulfurization

Activities

M(k) = The level of mining of type k coal (10^6t/yr).

C(k) = The output of coal cleaning plant producing coal with sulfur content k (10^6t/yr).

T(k) = The amount of coal transported of type k (10^6t/yr).

E(p,k) = Electric energy generated by plant type p using coal type k. Plant type p refers to a coal-fired power plant with or without flue gas desulfurization at various SO_2 removal efficiencies (10^6MWh/yr).

Integer Variables

IE(n) = { o if electric energy is not produced by set of plant types P_n
1 if electric energy is produced by set of plant types P_n }

Parameters

D = Electric energy demand (10^6MWh/yr).

y(k,k') = Mass yield of type k' coal cleaned by using type k coal.

btu(k) = Energy content of type k coal (10^6Btu/t).

sul(k) = Sulfur content of type k coal (%).

h(p,k) = Heat rate of electricity producing facility p using type k coal (10^6Btu/MWh).

sa(p,k) = Fraction of sulfur remaining in the bottom ash when coal type k is combusted in facility p (%).

s(p) = Fraction of sulfur removed using facility type p (%).

Ns = New source performance standard for sulfur oxide emissions (lb $SO_2/10^6$Btu).

vm(k) = Total cost of mining type k coal ($/t).

vc(k) = Total cost of cleaning coal of output type k ($/t).

vt(k) = Total cost of transporting coal of type k ($/t).

ve(p,k) = Variable cost of producing electricity from facility p using coal k (mills/kWh).

fe(n) = Fixed cost of producing electricity for set of facilities P_n (mills/kWh).

APPENDIX A (cont.)

Table A-2. Integer programming rows and activity constraints for the preliminary case study of coal cleaning and flue gas desulfurization.

Rows

MINING, CLEANING AND TRANSPORTATION

$$M(k) - \sum_{k} C(k')/y(k,k') - T(k) = 0, \qquad k = \text{raw coal}$$

CLEANING AND TRANSPORTATION

$$C(k') - T(k') = 0, \qquad k' = \text{cleaned coal}$$

ELECTRICAL ENERGY CONVERSION*

$$T(k)\ Btu(k) - \sum_{p} E(p,k)\ h(p,k) = 0, \qquad k = \text{all coals}$$

$$\sum_{p,k} E(p,k) \geq D$$

SULFUR DIOXIDE EMISSIONS (NEW SOURCE STANDARDS)

$$\left[\sum_{p,k} E(p,k) \cdot \left(h(p,k)/Btu(k)\right) \cdot sul(k) \cdot [1-sa(p,k)] \cdot [1-rs(p)]\right] \cdot 2 \cdot 2000 - \left(\sum_{k} T(k)Btu(k)\right) \cdot Ns \leq 0$$

OBJECTIVE FUNCTION (COST)

$$\text{Minimize Cost} = \sum_{k} M(k)\ vm(k) + \sum_{k} C(k)\ vc(k) + \sum_{k} T(k)\ vt(k) + \sum_{p,k} E(p,k) \cdot ve(p,k) + \sum_{p \epsilon P_n} fe(n) \cdot IE(n)$$

Activity Constraints

NONNEGATIVITY

$$M(k) \geq 0$$

$$C(k) \geq 0$$

$$T(k) \geq 0$$

$$E(p,k) \geq 0$$

INTEGER VARIABLE

$$\sum_{p \epsilon P_n} E(p,k) \leq Y_n \cdot IE(n)$$, where Y_n is a suitably large but otherwise arbitrary positive constant.

*By convention all coal is transported to the power plant. If the distance from mine or cleaning facility is zero then the cost of transportation is zero.