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Environmental Impacts of Electrical Generation: A Systemwide Approach

Buehring, W.A. and Foell, W.

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ENVIRONMENTAL IMPACTS OF ELECTRICAL GENERATION: A SYSTEM-WIDE APPROACH

W. A. BUEHRING, W. K. FOELL

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International Institute for Applied Systems Analysis
2361 Laxenburg, Austria

PREFACE

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

This report is concerned with the description of a systems approach to the analysis of environmental impact of electrical generating plants. The research evolved from efforts at the University of Wisconsin on the Wisconsin Energy Models and was extended at IIASA to treat impacts occurring in other regions of the world and to concepts and methodologies under study at IIASA.

Other publications on the management of energy/environment systems are listed at the end of this report.

W. K. Foell

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SUMMARY

The environmental consequences of construction and operation of large electrical generating stations are receiving increasingly closer scrutiny by regulating agencies and members of the public. The issues are extremely complex and involve a host of considerations, such as potential impacts on land use and human health and safety. Furthermore, environmental impacts associated with the energy system, which is defined in this case to include the power plant and all associated fuel industries, may occur outside the region where the electricity is generated. For example, since the state of Wisconsin in the U.S.A. must obtain all its coal and uranium from other regions, none of the environmental impacts of mining are within Wisconsin.

The broad system aspects must be addressed to make rational decisions on acceptable environmental effects. As the decision making process unfolds, it is desirable to take into account *all* the positive and negative aspects of both the proposed plan of action and feasible alternative plans. Since quantification of certain environmental impacts--or even just preparing a list of the "important" impacts--requires some value judgments, achieving such an ideal is difficult. One systematic method for approaching an assessment of alternatives is the subject of this report.

A systemwide perspective of the environmental impact of electrical generation is given by the Electricity Impact Model (EIM) developed at IIASA and the University of Wisconsin-Madison. The model provides quantified environmental impacts as a function of alternative electrical demand and generation forecasts; impact factors are associated with alternative generation systems in terms of electricity generated or of generating capacity. During a simulation these impact factors can vary with time to represent changes in policy or technology. Various policy options have been built into EIM for convenience, and any of the hundreds of impact factors can be varied.

The systems included in EIM for its initial application to Wisconsin were the pressurized water reactor, boiling water reactor, high temperature gas-cooled reactor, liquid metal fast breeder reactor, and coal. The coal system can include plants that burn low sulfur subbituminous coal as well as plants that use high sulfur bituminous; the coal system parameters can also be adjusted to include advanced technology systems, such as fluidized bed combustion. Other systems can be added to EIM by preparing a system flow diagram that indicates, for all points in the system, the flow rate of fuel materials required for a specified quantity of electricity generation. Quantified environmental impacts can then be associated with the fuel flow rate and in turn with the electricity generated.

A general characteristic of EIM is that impacts are associated with the electrical generation that caused them. Therefore, uranium mining accidents that may have occurred two or three years before the electrical generation, and exposure to long-lived radionuclides that may occur many years after the generation, are tabulated in the year of generation.

Environmental Impacts of Electrical Generation: A Systemwide Approach

I. INTRODUCTION

The environmental consequences of construction and operation of large electrical generating stations are receiving increasingly closer scrutiny by regulating agencies and members of the public. The issues are extremely complex and involve a host of considerations, such as land use and human health and safety. Often the most controversial concerns are focused upon the effects in the immediate area of the power plant, when in fact effects of much greater impact may be occurring elsewhere as a direct result of power plant operation. Each component in the electrical energy system must carry out its function in order to produce the electricity at the power plant, with the system boundary defined in this case to include the power plant and all associated fuel industries. Environmental impacts are broadly defined as the effects on land, air, water, structures, and living organisms, including the health and safety of the general public as well as people employed throughout the energy system.

As the decision making process unfolds, it is clearly desirable to take into account all the positive and negative aspects of both the proposed plan of action and feasible alternative plans. If all the impacts were known, the unified framework of an energy system approach could be used to consider the total impacts of long-term policies as well as alternative energy systems in a single process. Unfortunately, all impacts cannot be quantified in a way that will allow achievement of this ideal, but obviously evaluations should attempt to approach it as closely as possible. The broad system aspects must be addressed in order to make rational decisions on acceptable environmental effects.

When decisions must be made on alternative energy sources, at least three important sets of information need to be considered: (1) conventional costs, (2) quantified impacts, and (3) unquantified impacts. These and other factors are in general combined through the value judgment of decision makers, who may be utility executives, regulators, or average citizens (Figure 1).

Conventional costs are the usual costs of doing business. For an electrical generating station they include the capital cost of the plant, the fuel cost, and the operating and maintenance cost.

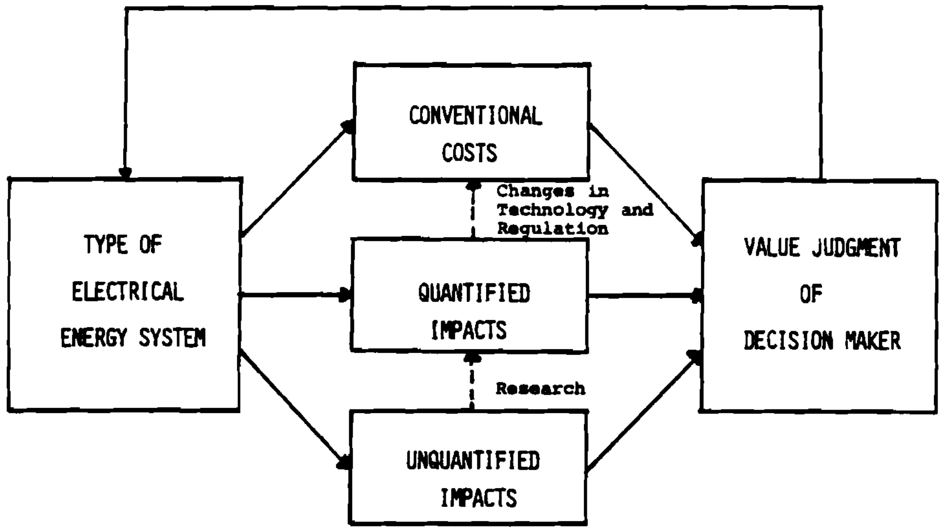

Figure 1. Factors in energy decision making.

Quantified impacts are the focus of the Electricity Impact Model (EIM), described in the next section. They include systemwide effects such as land disturbed for mining and waste storage, water consumption, and pollutants emitted. In the past a typical method used to combine conventional costs and quantified impacts has been to associate a dollar cost with the impact; the dollar cost might be a value judgment of the damage or it might be the cost associated with a technology for reducing or eliminating the impact. When new control technologies become available or new standards are set, some quantified impacts are generally reduced or eliminated while conventional costs usually increase. Thus, transfers among the categories may take place over time as Figure 1 indicates.

The enforcement of strict sulfur dioxide emission standards at coal-fired plants is an example of a regulation that may result in an increase in costs, a decrease in certain unquantified and quantified (in EIM) impacts, and an increase in other unquantified and quantified impacts. The cost increase comes about from the expenses related to purchase and operation of SO_2 removal equipment or the use of expensive low sulfur coal. Some quantified impacts that decrease are the emissions of SO_2 and the associated health impacts on the public (thought to be a small part of the total health impact). Other quantified impacts may increase depending on the strategy used; if SO_2 removal equipment is selected, some land for sulfur sludge disposal will probably be needed. Unquantified impacts that are affected include all other health effects of air pollution and impacts associated with limestone mining necessary for SO_2 removal.

Several approaches to impact quantification for better understanding of energy/environmental policy issues have become available in the last few years. For example, the U.S. Council on Environmental Quality has studied electrical energy systems [1] and has developed the Matrix of Environmental Residuals for Energy Systems (MERES), which served as a basis for a detailed comparison of energy alternatives [2]. Although the objectives of such studies have differed, a steadily improving data base on energy systems has resulted.

Unquantified impacts comprise all other environmental concerns, some of which may not even be recognized. Further research may allow some of these to enter the quantified category as suggested in Figure 1. Others, however, will most likely remain unquantified, because they have just been recognized as potentially important and have not been investigated, because quantification is based almost entirely on value judgment, or because they are not even recognized as impacts.

The decision maker is presented with those three sets of information, and selects the best alternative using his value system. Some may say that as long as applicable standards are being met, the alternative with the lowest conventional cost should be selected. Others may give more weight to the externalities included in the quantified impacts. Still others may feel that certain unquantified impacts or unknowns should receive more attention [3]. Since decisions are being made continuously, combinations of conventional costs, quantified impacts, and unquantified impacts are being transformed into a single figure of merit through value judgments, knowingly or otherwise. A methodology for converting some of this in-the-head analysis into formal analysis using a preference model is presented in Section III, and some conclusions of the research are discussed in the final section

II. DESCRIPTION OF THE ELECTRICITY IMPACT MODEL

The Electricity Impact Model (EIM) was originally developed as a submodel of the WISconsin Regional Energy (WISE) Model, a computerized simulation model that describes technological-economic-environmental interactions in the Wisconsin energy system. However, EIM is structured so that it can be used independently for studies of environmental impacts from electrical generation in other regions. For example, impacts associated with future electrical generation for the Rhône-Alpes region in southern France and the German Democratic Republic have been estimated using a version of EIM implemented at IIASA [5].

A full description of the model is given in Reference [6]. The following is simply a brief outline of its characteristics.

A. Features of the Electricity Impact Model

1. Input-Output

The input required by EIM is first the year, and second the quantity of electricity generation and capacity by fuel source. Additional input is needed to change any of the numerous parameters that describe the reference energy systems. The output from EIM is quantified environmental effects that result from the energy use and the supporting fuel system activities.

The basic structure of EIM is shown in Figure 2. The fuel supply data for each year of computer simulation are combined with impacts associated with reference plants to obtain total quantified impacts by fuel type and year. A reference system for a particular fuel and year may have different impacts than that reference system for the same fuel in another year; this is due to time-dependent factors such as decreased SO_2 emissions per unit electrical generation that result from sulfur removal systems or increased use of low-sulfur coal.

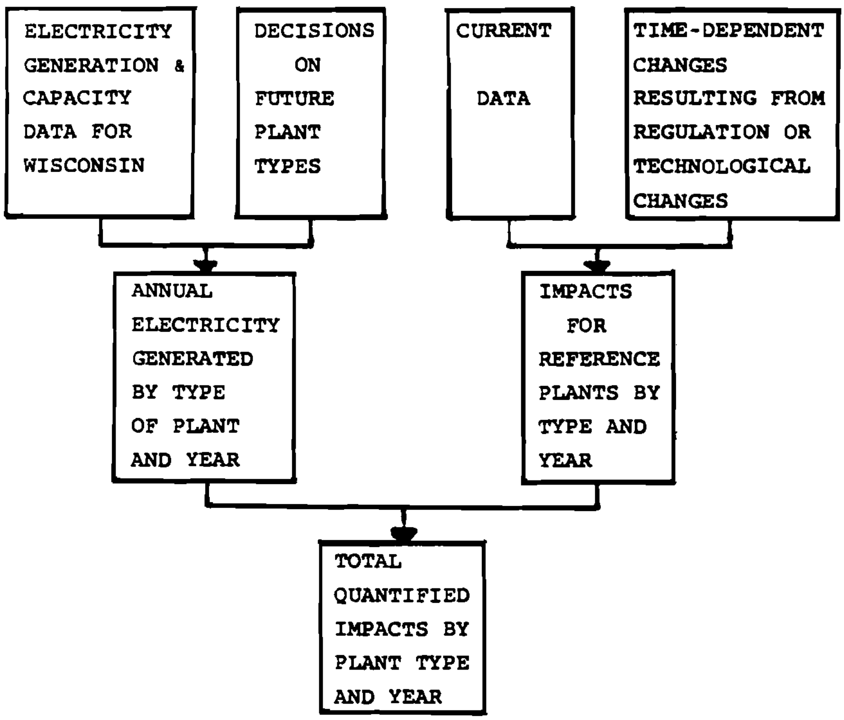

Figure 2. Basic structure of the Electricity Impact Model.

2. Impact Factors

"Impact factors" associated with each type of fuel supply have been determined from collection and analysis of relevant data; they are specified in the model as a function of energy (kWh)[1] or in some cases, electrical capacity (kW)[1]. The total quantified impacts are calculated by multiplying the matrix of impact factors for a particular year and a particular energy source by the energy use from that source. The quantified impacts are given by

$$\begin{bmatrix} Q_{1jk} \\ Q_{2jk} \\ \cdot \\ \cdot \\ \cdot \\ Q_{ijk} \end{bmatrix} = E_{jk} \begin{bmatrix} I_{1jk} \\ I_{2jk} \\ \cdot \\ \cdot \\ \cdot \\ I_{ijk} \end{bmatrix}$$

where

Q_{ijk} = quantified environmental impacts of type i in year j resulting from electrical generation source k,

E_{jk} = electrical generation or capacity for energy source k in year j, and

I_{ijk} = impact factor of type i in year j for energy source k.

The quantified impacts can be summed over index j to obtain cumulative impacts for a particular energy source. Impacts with similar units can be summed: (1) over index i to obtain totals for a particular year and energy source, and (2) over index k to obtain totals for all energy sources in a particular year. However, personal preferences generally determine which impacts can be summed.

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[1]A kilowatt-hour (kWh) is a measure of energy, and a kilowatt (kW), or 1000 watts, a measure of power.

3. Time-Dependent Characteristics

The impact factors have been determined from reviews of impact quantification in the literature as well as independent analysis of the specific regional situation. Many of the factors identified in this manner are directly applicable only to current energy systems. However, impact factors can be modified to reflect changes in technology, regulation, population, or other considerations. The impacts associated with annual electrical generation of a 1000 MWe unit in 1970 are not necessarily the same as for annual generation from the same unit in 1980.

As an example, underground coal miners face the well-known health hazard of black lung disease, more properly known as coal workers' pneumoconiosis (CWP). The advanced states of CWP spread progressively in the absence of exposure to coal dust, which is the original cause of the problem, and may lead to death or total disability. A certain fraction of the underground coal miner labor force became disabled in 1970 because of this disease. If their disability rate could be shown to be related to coal production over a period of time, a certain quantity of coal miners' disability could be associated with each unit of coal obtained by underground mining. However, the CWP disability rate should diminish as new standards become operative and new miners join the work force. By studying the data and the statements of experts, one can estimate a CWP impact factor that decreases as a function of time. Thus, as a result of a new regulation, the impact factor, total disability from CWP per unit of underground coal, is a function of time.

A general characteristic of EIM is that impacts are associated with the energy use that caused them. Therefore, uranium mining accidents that may have occurred two or three years before the electrical generation, and exposure to krypton-85 and tritium (H3) that may occur many years after the generation, are tabulated in the year of the generation. A mathematical expression using a Green's function that describes the impacts at time t' due to electrical generation at time t is

$$Q(t) = E(t)\int_{t'} I(t,t')\, dt'$$

where

$Q(t)$ = quantified environmental impacts associated with electrical generation at time t,

$E(t)$ = electrical generation at time t, and

$I(t,t')$ = impacts that occur at time t' per unit energy use at time t.

It should be noted that the time at which the impacts occur is not specified in EIM; I(t,t') is not provided. The impacts are associated with the energy use that caused them.

B. Problems of Impact Aggregation and Classification

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

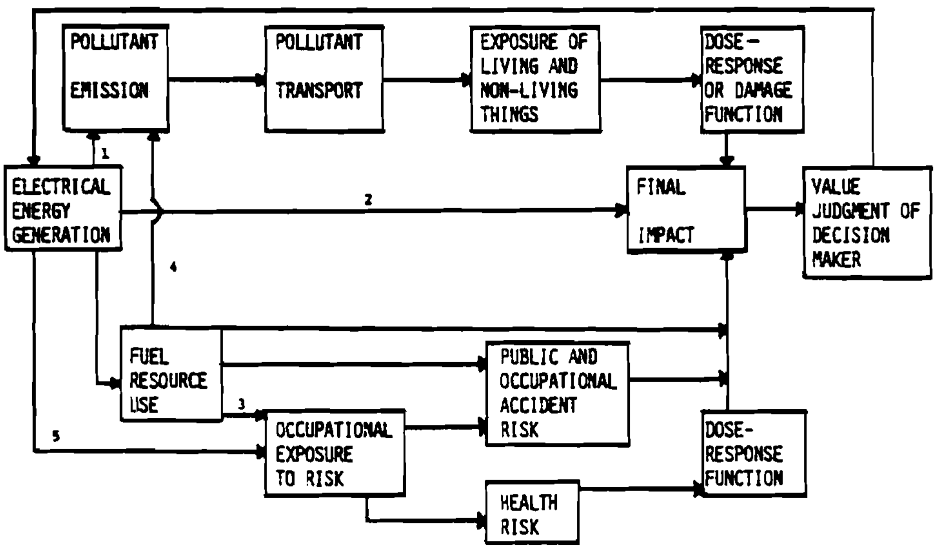

Figure 3. Electrical energy impact pathways.

The specific classification of impacts in EIM is shown in Figure 4. After selection of generation sources, cooling systems, and any changes as a function of time, the model calculates impacts according to the type of electrical generation and year that it takes place. The impacts are classified into the general categories of land, air, water, human health and safety, and a miscellaneous category that includes fuel resource use, efficiency, and solid waste. A slightly more detailed breakdown is shown for human health and safety impacts inside Wisconsin. Such classifications depend on the preferences of the decision maker and could range from a few categories to separate categories for every impact factor in EIM.

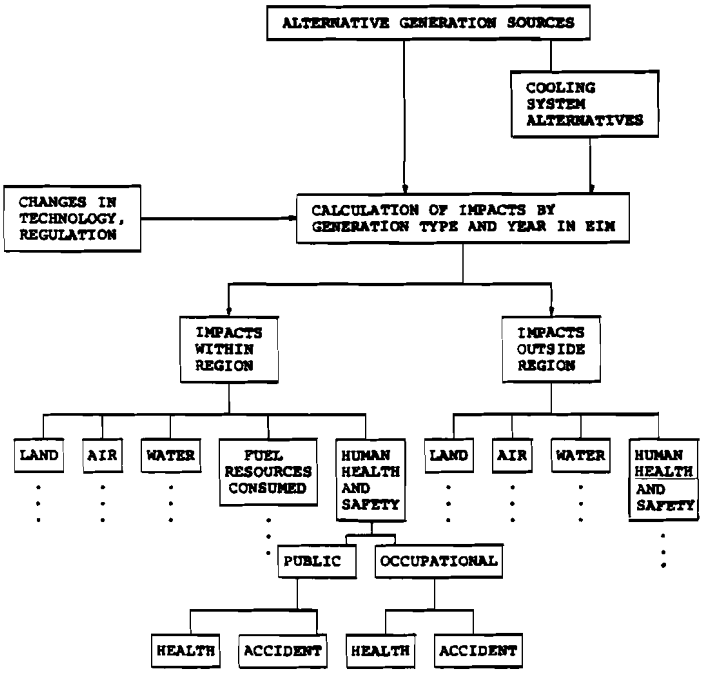

Figure 4. Illustrative classification of impacts in EIM.

Another problem of display is the location of impacts and their associated causes. The four classes selected are:

- Impacts that occur within the region because of energy use within the region,
- Impacts that occur outside the region because of energy use within the region,
- Impacts that occur within the region because of energy export to other regions,
- Impacts that occur outside the region because of energy export to other regions.

This classification helps to clarify the degree to which impacts are exported to other regions because of electricity use within the region, and are suffered within the region because of export to other regions.

C. Reference Electrical Generating Systems

Several generating systems based on coal and nuclear fission were selected for detailed modeling in the original version of EIM. The time period of interest was through the year 2000, and the region was Wisconsin, where various forms of coal and nuclear generation are the only major options currently under consideration for this time period [4].

The reference coal system, shown in Figure 5, can be adjusted to include advanced technology possibilities, such as fluidized bed combustion, as well as for various combinations of mining methods and coal sources. The characteristics of the reference system will be altered when such changes are made, as Table 1 indicates. For example, a shift to more western coal means fewer coal mining fatalities, because western coal is assumed to be surface-mined, a type of mining that has relatively low accident rates. The specification of the capacity at a site and the number of people living in the vicinity of the plant are important components in the estimation of certain quantified human health impacts that result from exposure to air pollution. The SO_2 emissions from the reference plant using bituminous coal must be reduced by over 70 percent to meet an emission standard of 1.2 pounds per million BTU input. Stack gas treatment systems for reducing SO_2 emissions are assumed to be available in the Wisconsin Base Case. Power plant efficiency and all related impacts, as well as emissions and health effects, are affected by the decision to use this equipment.

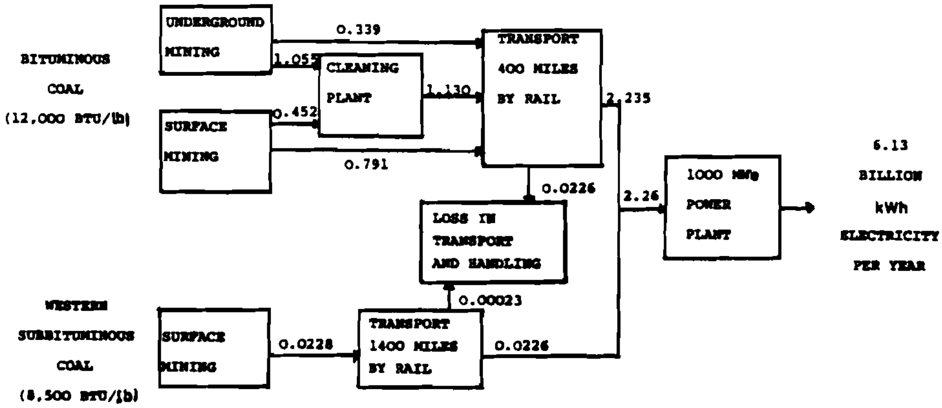

Figure 5. The coal energy system: coal flow rates are in millions of tons per year for 1970 reference system; waste management is required throughout the system.

The four nuclear systems included in the model are:

- Pressurized water reactor (PWR),
- Boiling water reactor (BWR),
- High temperature gas-cooled reactor (HTGR), and
- Liquid metal fast breeder reactor (LMFBR).

The PWR and BWR are the favored reactor types in the U.S.A. The HTGR may become commercially competitive in the near future. The LMFBR is many years away from commercial operation and is not expected to make any contribution to Wisconsin's electrical generation before the mid-1990s.

The reference PWR system has more fuel cycle industries than the coal system, as shown by a comparison of Figures 5 and 6. The fuel cycle shown is for a once-through cooling system; if a closed-cycle cooling system, such as cooling towers, is used, the efficiency of the reactor is reduced and material flow rates must be increased to achieve the same net electrical output[2]. EIM has seven cooling options: once-through, spray

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[2]The model user is responsible for specifying the cooling system distribution. The model calculates efficiencies and corresponding material flow rates.

Table 1. Some characteristics of the reference coal-fired electrical generation system for Wisconsin (Source: [6]).

	Bituminous Coal from Midwestern States	Subbituminous Coal from Western States
Fraction of coal used in Wisconsin	0.99*	0.01*
Coal heat content per unit mass (BTU/lb)	12,000	8,500
Sulfur content (weight percent)	2.5	0.6
Ash content (weight percent)	10.0	10.0
Source of coal	Outside region	Outside region
Percent surface-mined	50*	100*
Surface area disturbed by surface mining (m^2/MT)	1.4	0.089
Coal mining fatalities per million metric tons mined:		
Underground mining	0.72*	-*
Surface mining	0.13*	0.13*
Coal shipping distance (km)	640	2,240
Metric tons coal by train	9,100	9,100
Public fatalities per million train-km	2.3	2.3
Power plant heat rate (BTU/kWh) with:		
- Once-through cooling	8,805	9,412
- Natural draft wet cooling towers and SO_2 stack gas removal equipment	9,197	9,831
Capacity at a single site (MWe)	2,000	2,000
Millions of people within 80 km:		
Urban site	6.30	6.30
Average site	2.25	2.25
Rural site	0.30	0.30
Fraction of ash collected	0.99*	0.99*
Fraction of SO_2 collected	0.0*	0.0*
Trace element emissions	Proportional to ash	Proportional to ash
Percent of coal cleaned:		
Underground mined	70	-
Surface-mined	30	0.0
Disabling black lung disease per million metric tons mined underground	0.47*	-

*Assumed to vary as a function of time in the Wisconsin Base Case. Only initial conditions (1970) are listed.

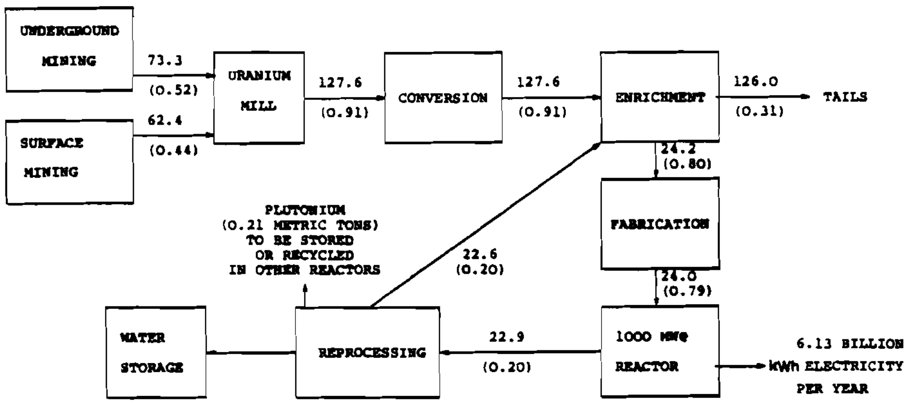

Figure 6. The pressurized water reactor reference system: uranium flow rates are in metric tons per year (U235 in parenthesis) for 1970 reference system; waste management is required throughout the system.

canals, artificial lake, and four types of cooling towers. Other characteristics of the reference PWR system are listed in Table 2, and details of all reference systems are given in [6].

The quantified impacts for the 1970 reference coal system are shown in Table 3. They are associated with 6.1 x 10^9 kWh generation in that year. However, a 1980 reference coal system has different impacts because of assumptions concerning parameters, such as:

- Declining accident rates per ton mined,
- Declining black lung disease per ton mined underground,
- Declining average efficiencies because of increased use of closed cycle cooling systems,
- Increased use of western coal,
- Increased use of SO_2 control systems, and
- Improvement in particulate collection devices.

Table 2. Some characteristics of the reference pressurized water reactor system for Wisconsin (Source: [2]).

Percentage of uranium from surface mines	54 percent[1]
Grade of the ore (percent U_3O_8 in ore)	0.2 percent
Uranium mining fatalities per thousand metric tons U_3O_8:	
- Underground mining	0.79
- Surface mining	0.20
Land disturbed for surface mining of uranium (m^2/MT of ore)	0.75
Source of uranium	outside region
U235 content in enrichment tailings	0.25 percent
Uranium recycle	yes
Plutonium recycle	no
Fresh fuel enrichment (percent U235)	3.3
Spent fuel enrichment (percent U235)	0.89
Equilibrium burnup	33,000 megawatt-days (MWd) per metric ton
Kr85 in spent fuel	0.34 Curies (Ci) per MWd
Tritium in spent fuel	0.021 Ci per MWd
Average capacity factor for reactor[2]	0.70
Power plant heat rate (BTU/kWh) with:	
- Once-through cooling	10,595
- Natural draft wet cooling towers	10,796
Noble gas release at reactor	0.45 μCi/kWh[3]
Tritium release at reactor	0.045 μCi/kWh
Occupational radiation exposure at reactor	450 man-rem per 1000 MWe-year[4]
Millions of people within 80 km of reactor	same as for coal in Table 1

(1) Assumed to vary as a function of time in the Wisconsin Base Case. Only initial (1970) conditions are listed.

(2) Capacity factor is the actual generation (kWh) divided by the maximum possible generation of the unit continuously operated at full power.

(3) $\mu Ci = 10^{-6} Ci$.

(4) The value listed is associated with annual operation of each 1000 MWe of capacity regardless of capacity factor. A man-rem is a measure of population exposure to radiation. One person exposed to one rem and one million people exposed to 10^{-6} rem are both equivalent to one man-rem.

Table 3. Quantified impacts* for the 1970 reference coal system: annual impact for reference 1000 MWe plant for 0.70 capacity factor in 1970.

	QUANTITY	UNIT
Fuel Resource, Efficiency, and Solid Waste		
1. Coal requirement after cleaning losses	.227+07	Tons
2. Transportation and handling loss of coal	.227+05	Tons
3. Coal plant thermal discharge to water	.792+10	kWh(th)
4. Coal plant thermal discharge to air	.174+10	kWh(th)
5. Total train-miles for coal shipments	.186+06	Miles
6. Input energy required throughout coal fuel system	.159+11	kWh(th)
7. Ash collected at coal power plant	.219+06	Tons
8. Sulfur retained at coal power plant	.000	Tons
9. Limestone mined for sulfur removal	.000	Tons
10. Coal cleaning plant solid waste	.372+06	Tons
Land Use		
11. Land disturbed for surface mining of coal	.343+03	Acres
12. Land disturbed for coal surface mining (not reclaimed)	.343+02	Acres
13. Land subsidence from underground coal mining	.227+03	Acres
14. Land for ash disposal at the power plant	.475+01	Acres
15. Land for sulfur sludge disposal at power plant	.000	Acres
16. Land for disposal of solid waste from underground mining	.829+00	Acres
17. Land for disposal of solid waste from cleaning	.313+01	Acres
18. Waste storage area for coal fuel cycle	.870+01	Acres
19. Land use at plant and fuel cycle facilities (coal)	.115+04	Acres
Impacts on Water		
20. Acid mine drainage from coal mining (mostly water)	.114+06	Tons
21. Sulfuric acid in coal mine drainage	.800+03	Tons
22. Dissolved iron in coal mine drainage	.200+03	Tons
23. Siltation from surface mining	.247+04	Tons
24. Coal cleaning plant blackwater solids	.376+03	Tons

Table 3 (continued).

Impacts on Air

25. Flyash emission at coal power plant	.538+04	Tons
26. Sulfur dioxide emission at coal power	.111+06	Tons
27. Nitrogen oxides (as NO_2) emission at coal power plant	.188+05	Tons
28. Carbon dioxide emission at coal power plant	.538+07	Tons
29. Carbon monoxide emission at coal power plant	.833+03	Tons
30. Hydrocarbon emissions at the power plant	.269+03	Tons
31. Aldehyde emissions at the power plant	.538+01	Tons
32. Mercury emission at coal power plant	.449+01	Tons
33. Beryllium emission at coal power plant	.215+00	Tons
34. Arsenic emission at coal power plant	.538+00	Tons
35. Cadmium emission at coal power plant	.538-02	Tons
36. Lead emission at coal power plant	.968+00	Tons
37. Nickel emission at coal power plant	.215+01	Tons
38. Vanadium emission at the power plant	.177+01	Tons
39. Uranium (U238) or Ra226 emission at power plant	.484-01	Curies
40. Thorium (Th232) or Ra228 emission at power plant	.161-01	Curies
41. Coal cleaning plant dust emissions	.376+04	Tons

Human Health and Safety

42. Coal mine accidents (fatalities)	.874+00	Deaths
43. Coal mine accidents (nonfatal injuries)	.365+02	NFI
44. Coal mine accidents (severity in person-days lost (PDL))	.715+04	PDL
45. Coal cleaning plant occupational ratalities	.169-01	Deaths
46. Coal cleaning plant occupational nonfatal injuries	.158+01	NFI
47. Coal cleaning plant occupational severity	.165+03	PDL
48. Coal transportation accidents (occupational fatalities)	.596-01	Deaths
49. Coal transportation accidents (occupational nonfatal injuries)	.596+01	NFI
50. Coal transportation accidents (occupational severity)	.542+03	PDL
51. Coal transportation accidents (public fatalities)	.689+00	Deaths
52. Coal transportation accidents (public nonfatal injuries)	.177+01	NFI
53. Coal transportation accidents (public severity)	.449+04	PDL
54. Coal power plant accidents (occupational fatalities)	.250-01	Deaths

Table 3 (continued).

55.	Coal power plant accidents (occupational nonfatal injuries)	.110+01	NFI
56.	Coal power plant accidents (occupation severity)	.227+03	PDL
57.	Cases of total disability from black lung disease	.490+00	Cases
58.	Cases of simple black lung disease (some disability)	.107+01	Cases
59.	Public fatalities from acute SO_2 exposure	.580-02	Deaths
60.	Days of aggravation of heart and lung disease from SO_2	.282+04	Days
61.	Excess asthma attacks from acute SO_2 exposure	.718+03	Attacks
62.	Total occupational fatalities, health and accident, for coal	.147+01	Deaths
63.	Total occupational nonfatal injuries for coal	.462+02	NFI
64.	Total occupational severity for coal	.110+05	PDL
65.	Total deaths in coal fuel cycle (annual)	.216+01	Deaths
66.	Total nonfatal injuries in coal fuel cycle (annual)	.358+04	NFI
67.	Total person-days lost in coal fuel cycle (annual)	.191+05	PDL

Note: NFI = Nonfatal injuries

PDL = Person-days lost

.227 + 07 means 0.227×10^7

*This table lists only those impacts included in EIM as of November 1975. As indicated in the text, the selection of this limited set of impacts is clearly subjective.

For example, the EIM base case assumptions result in a decline of coal mining fatalities (Impact 42 in Table 3) from 0.87 per 1000 MWe-year in 1970 to 0.29 per 1000 MWe-year in 1980.

D. Typical Results of EIM

The annual electrical generation in Wisconsin for a typical case study is shown by Figure 7. Nuclear plants are arbitrarily assumed to be half of all new capacity installed after 1982; PWR's are assumed to remain the preferred reactor type. The average growth rate of total electrical generation is 4.7 percent per year during the period.

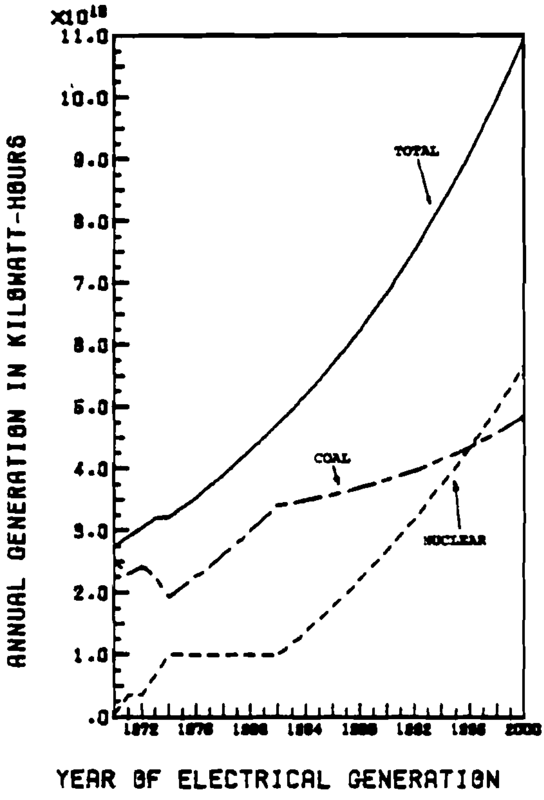

Figure 7. Annual generation in the WISconsin base case.

The effect on coal mining fatalities of shifting the source of coal used for Wisconsin's electrical generation was studied with EIM. The four different mining scenarios starting in 1976[3] were:

- All coal from undergroun bituminous mines,
- All coal from surface bituminous mines,
- All coal from western subbituminous mines, and
- A mixture of coal sources.

The results in Figure 8 show the number of expected coal mining fatalities for each of these mining scenarios; the assumed

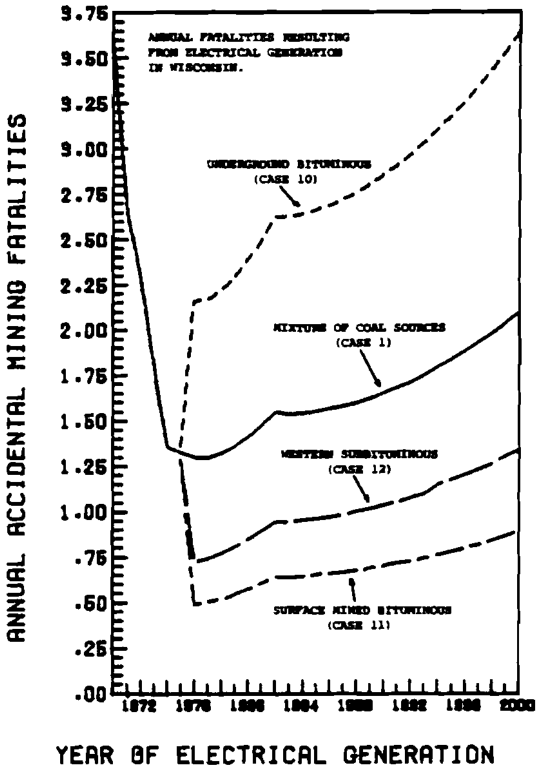

Figure 8. Type of coal mining and mining fatalities.

[3] 1970 through 1975 are based on actual data.

generation for all cases is plotted in Figure 7. If all coal is obtained from underground bituminous mines, the expected fatalities are significantly greater than for surface-mined coal. The western subbituminous mining fatalities are somewhat higher than with surfaced-mined bituminous because the same accident rates per ton are assumed and more tons of western coal are needed to produce a unit of electricity.

Public and occupational radiation exposure that can be associated with the nuclear generation (Figure 7) is plotted in Figure 9[4]. The occupational exposure at the reator is significantly greater than any other category shown (note the

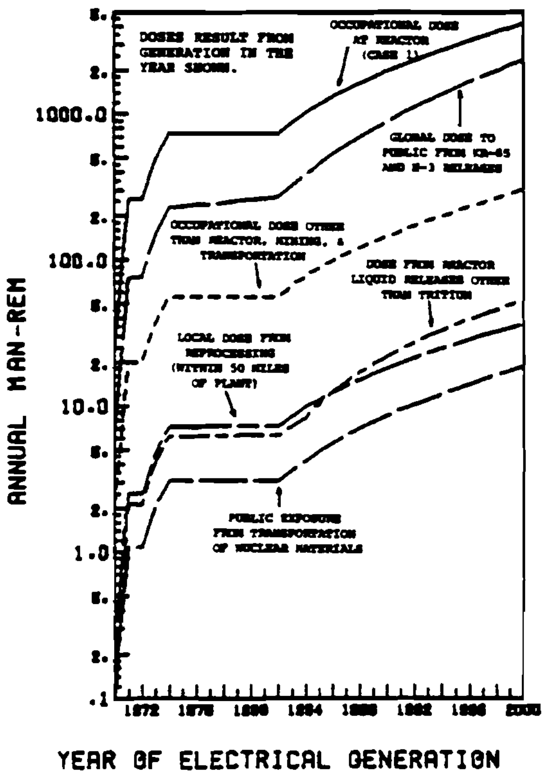

Figure 9. Public and occupational radiation exposure. (Doses result from generation in the year shown.)

[4]A manrem is defined at the bottom of Table 2.

logarithmic scale). In addition, the occupational dose at the reactors is concentrated on a few hundred individuals, whereas the global dose to the public from Kr85 and H3 is spread over billions of people. EIM includes several other categories of radiation exposure that are not displayed in Figure 9; all quantified radiation exposure is used to estimate expected health effects.

III. UTILITY THEORY IN DECISION MAKING

The preceding sections of the paper have outlined some methods of environmental impact quantification. In some cases the boundary between personal preferences, or value judgments, and technical evaluation of impacts is not well defined. The Electricity Impact Model is based on the principle that the technical evaluation of impacts should be as objective as possible and therefore should result in a list of quantified impacts, expressed in units or dimensions that are reasonably familiar or easily explained to most people. Clearly, the process of impact selection requires subjective judgments by the technical evaluator. In addition, the evaluation of alternate energy strategies and their resulting impacts requires a judgment on the combined set of impacts. To combine the quantified impacts, the recognized unquantified impacts, and the conventional costs for a particular alternative on a consistent basis, one approach is multiattribute utility theory [7, 8, 9]. This theory provides a convenient framework for a decision maker to evaluate alternatives in terms of the degree to which each of a set of objectives is met. The alternative to a preference model is to continue using in-the-head analysis for these complex judgments.

The steps in multiattribute utility analysis of integrated regional energy systems are indicated in Figure 10. The energy system model was designed with flexibility for testing energy policies. The construction of alternative energy scenarios provided the driving function for EIM. The categorization of the output from EIM provides some of the input to the utility assessment. Selection of a set of characteristics that properly represents the impacts and costs associated with each alternative to be evaluated may involve significant aggregation of quantified impacts into a relatively small number of categories, often referred to as attributes. However, the aggregation of impacts is itself a subjective judgment that must be discussed with the decision maker, as is depicted by the iterative feedback loop in Figure 10. Recognized unquantified impacts of concern to the decision maker can be identified and included in the analysis by determining an appropriate proxy variable that can be measured. This process may result in some changes in the model and its output, as indicated in Figure 10.

A utility function must be assessed for each attribute. This requires ranges to be set for all attributes; for reasonable sets of assumptions, all possible values of an attribute should

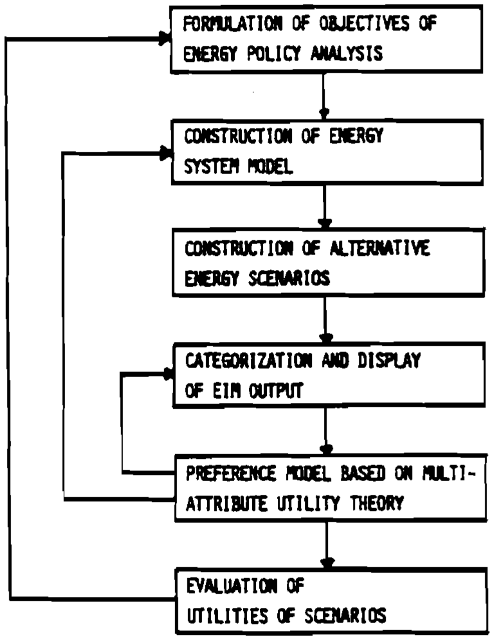

Figure 10. Multiattribute utility analysis of integrated regional energy systems.

fall within the selected range. The utility is scaled from zero, at the least desirable value of the attribute in the range, to one, at the most desirable. The shape of the function over the rest of the range must be determined by asking questions of the decision maker.

The overall utility function is a mathematical combination of scaling constants and the utility functions for the individual attributes. The values of the scaling constants are determined by further questioning of the decision maker and are dependent on the ranges selected for the attributes. The overall utility function provides a figure of merit which allows comparison among alternatives on a consistent basis.

Since one cannot predict exactly what the consequences of each alternative considered will be, uncertainty is associated with the levels of the attributes. If, for a particular alternative, the data were available to specify the probability distribution associated with each attribute, the utility theory approach would become still more useful. The ability to handle preferences under uncertainty is one of the strengths of utility theory. An illustrative utility assessment using EIM results is described in Reference [10], and more detailed examples are given in References [6] and [8].

IV. CONCLUSION

The Electricity Impact Model provides a convenient and powerful tool for organizing and displaying many of the systemwide quantified environmental impacts that must be considered for a comprehensive evaluation of alternatives. The model does not provide a single figure of merit, but rather a set of quantified impacts to which value judgments must be applied. The model is structured to allow the user to carry out sensitivity analyses on important parameters and to test policy alternatives. In conjunction with the decision-making framework outlined in the previous section, the results of the model can be used to compare impacts on a consistent basis that takes into account the preferences of the decision maker. Initial applications to Wisconsin, Rhône-Alpes (France), and the German Democratic Republic have demonstrated that the model is a useful quantitative tool for policy analysis of energy/environment systems.

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